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By

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Professor Peter Berck, Co-Chair
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Abstract

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Two common desires for individuals are to live in a society with a healthy and sustainable environment, and a growing and productive economy. Through environmental regulatory policy, governments pursue these objectives on behalf of their electorate. It can often be a difficult balancing act, however, as these objectives do not always fit well together. Industrial activities that drive and stimulate the economy often have negative and lasting impacts on the environment. In this dissertation, I look at the modeling of this tradeoff in both a static and dynamic setting, and in relation to two significant environmental concerns: climate change and aquatic ecosystem acidification.

In the first essay, co-authored with Peter Berck, we consider the impact of an increase in regulated abatement standards on static measures of economic welfare. By limiting emissions, these standards effectively decrease a key factor of production. Using a theoretical general equilibrium model, we show that all else equal, an increase in regulated abatement will therefore decrease utility and make individuals in the economy worse off. While we generally expect utility to be concave in abatement, when accounting for changes in the household's consumption and input supply decisions, and the corresponding impacts on income, we find this will not always be the case. Using a CGE model of the California economy, we then consider the impact of both carbon reduction measures, and a rising carbon price, on indicators of economic welfare in California. We find that environmental and economic objectives do not always have to be at odds, and that under certain conditions, both the carbon reduction measures and the rising carbon price can lead to increases in indicators of economic welfare. We also find that although conditions for non-concavity of the welfare function exist in California, our primary indicator of economic welfare, real State Personal Income, is concave in the carbon price.

In the second essay, I look at the application of optimal regulatory policy to achieve the recovery of a group of freshwater lakes from acidification. Assuming a social planner is able to perfectly regulate the emissions of local firms, I develop a dynamic programming model where the planner's objective is to minimize a social disutility function, consisting of the damages from acidified lakes and the cost of emissions abatement, subject to state equations that describe the impact of emissions reductions on lake water quality. To parameterize the state equations, I use a panel data set that monitors the recovery of 32 acidified lakes located in the region surrounding

Sudbury, Ontario, Canada over a 24-year period. I then use numerical methods to solve the control problem for the optimal path of emissions reductions, and the expected rate of lake recovery. My results show that optimal emissions reductions rely heavily on the assumed level of damages, and the current state of the lakes. If lakes are already in a recovery state, then at most reasonable estimates of environmental damages, further optimal abatement is zero. I also find that as the level of damages increases, the optimal abatement policy "jumps" to full abatement of emissions, and there is only a narrow region of lake quality where partial abatement is optimal. Due to the slow recovery process, however, it is possible for lakes to remain in this narrow interim region for extended periods of time, and for partial abatement to be optimal over this entire period.

In memory of Zanna, 1980 – 2006

Your spirit and love for nature lives on.

Thank you for the ever-present inspiration to slow-down,
and appreciate the natural world; particularly the lakes and the trees.

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I buy a lot of greeting cards. As many people who have shaken their head at my refusal to join Facebook or to "Skype" over the years will tell you, there are certain areas where I dig my heels in against modern forms of communication. One of the cards I bought in my first year at Berkeley had the Franklin D. Roosevelt quote, "When you get to the end of your rope, tie a knot and hang on." I had a reason for buying it, I'm sure, but it never made it into the mail and has since sat in a file folder under my desk. Little did I know how often I would look back on this quote, and how it would prove to be "words to live by" through much of my graduate school career. It has been a rocky path at times, and I owe thanks to many people, a number of whom, at times, had more determination than I had for seeing me make it through to the end.

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Chapter 1: Introduction

1.1 The Economy versus the Environment

Throughout history the early stages of economic growth has often come at the expense of the environment. In a relationship that has since come to be known as the "Environmental Kuznets Curve," Grossman and Krueger (1995) show that pollution and per capita national income have an inverted-U relationship. That is, at low levels of per capita national income pollution levels tend to be increasing as income increases. Once income hits a threshold level pollution then begins to decline. One of the explanations Grossman and Krueger present for the decline in pollution with continued economic growth is that as individuals become wealthier, they demand a cleaner environment and governments respond through stricter environmental standards and laws. Grossman and Krueger also note that current low-income or developing countries are not destined to follow the same historical paths of increased environmental damages with initial levels of economic growth. Rather, with new and cleaner production technologies, knowledge of the environmental hazards of unregulated growth, and increased awareness of environmentally favorable policies and practices, it is hopeful that developing countries will find ways to increase their national income without sacrificing the environment. The question of how to create and implement efficient environmental regulatory policy, and understanding the effects of regulatory policy on economic welfare, is therefore an important issue for both developed and developing countries alike.

Environmental regulatory policy generally has one or both of the following goals. The first goal, relevant for all countries, is to lessen or prevent new, or further damages to the environment. The second goal, relevant primarily for developed countries that have incurred negative environmental impacts from historical industrial activity, is for regulatory policy to aid in the recovery of the environment from previous damages. In this dissertation I consider environmental regulatory policy in each of these contexts. In the first essay, co-authored with Peter Berck, we consider climate change regulation, where the primary policy goal is to reduce greenhouse gas emissions and mitigate the damages from climate change. Our objective is to understand the impact of fixed regulatory emissions reduction measures, and a rising carbon price, on various indicators of economic welfare. In the second essay I consider regulation for the reduction of acid rain pollutants such as sulphur dioxide (SO_2) and nitrogen oxides (NO_x), where the primary policy goal is to reduce emissions so as to prevent further damages from acid rain, and to allow previously acidified ecosystems to recover. I focus exclusively on the recovery goal, and develop a dynamic model with the objective of understanding how to implement optimal abatement policy to achieve the recovery of an acidified aquatic ecosystem.

In the remainder of this introduction I provide background information on the environmental problems considered in the next two chapters. I also discuss the motivation for the regulatory policies under examination, and provide a more complete overview of the methodologies, results, and contributions of each chapter to the literature. Section 1.2 discusses Chapter 2, and section 1.3 discusses Chapter 3. Section 1.4 provides some brief concluding remarks.

1.2 Greenhouse Gas Emissions & Climate Change

1.2.1 Climate Change History

Human activities have been contributing to the concentration of greenhouse gases in the atmosphere for thousands of years. Initially these contributions were comparatively small; primarily they came from the cutting and burning of forests to expand agricultural lands or to fuel "Iron Age" furnaces (Christensen, 2013). With the advent of the Industrial Revolution, however, the burning of fossil fuels began, and human contributions rapidly accelerated, reaching a worldwide total of almost 30 billion metric tons of CO_2 in 2008 (World Bank, 2012). For almost 200 years following the start of the Industrial Revolution, the impact of increasing fossil fuel emissions on atmospheric chemistry was unknown. Revelle and Seuss (1957) first raised the possibility of climate change by noting the slow rate at which atmospheric CO_2 is dissolved in the ocean. They pointed out this slow rate of transfer, combined with an exponentially increasing use of fossil fuels, was likely to result in rising levels of atmospheric CO_2, which in turn could impact weather and climate across the earth. They called for an improvement in CO_2 atmospheric monitoring data, and in that same year, Scripps Oceanic Institute, with Revelle as director, instituted the Atmospheric Carbon Dioxide program. Under the program, monthly measurements of atmospheric CO_2 were taken from the Mauna Loa Observatory on the island of Hawaii. It was only a few years later when the data collected through the program revealed that CO_2 concentrations in the atmosphere were increasing by 1-2 parts per million (ppm) each year. Data collection has continued at the Mauna Loa observatory for the past 45 years, and atmospheric concentrations of CO_2 have increased by nearly 25% over the collection period; from 312 ppm in the initial 1957 measurements to 388 ppm in 2010 (Christensen, 2013).

While previous uncertainty around climate change related to the impact of rising fossil fuel emissions on atmospheric CO_2 levels, current uncertainty relates to the implications, or expected damages, of elevated CO_2 levels. Possible sources of damages from rising temperatures (which are themselves unknown) include changing weather patterns, melting glaciers and ice sheets, rising sea levels, and changes in plant and wildlife ecosystems (Christensen, 2013). With a subset of damages from climate change already present, and larger sources of potential damages looming, governments across the world have begun to consider and implement policies to achieve reductions in greenhouse gas emissions. Their shared goal is to identify policies to reduce emissions while minimizing economic losses, and the welfare costs to individuals. Recognizing this goal, a significant area of the climate change economics literature is devoted to evaluating the relative efficiency of policy options for greenhouse gas emissions reductions, and to assessing the economic and welfare impacts of specific policies. The essay in Chapter 2 focuses primarily on this latter area. We develop a simple general equilibrium model to examine the effect of increased abatement standards on economic welfare. We then use a computable general equilibrium (CGE) model of the California economy to determine the specific economic impacts of California's emissions reduction policies, and a rising carbon price. To further develop the background for the CGE model, the next subsection provides an overview of California's climate change policy.

1.2.2 California Climate Change Policy

California has a strong history of climate change regulation. It began with a greenhouse gas emissions monitoring requirement established in 1988 through Assembly Bill (AB) 4420. This bill directed the California Energy Commission to study global warming and establish an inventory of sources of greenhouse gas emissions. In 2001, the California climate change registry was established through Senate Bill (SB) 1771. The registry was designed in anticipation of future policies for emissions reductions, and gave companies, cities, and government agencies the option of recording greenhouse gas emissions, and receiving credit for early reductions. With the implementation of AB 1492 in 2002, regulation began to shift decisively from monitoring emissions to mandating emissions reductions. This bill required the California Air Resources Board (CARB) to develop regulations to reduce emissions from passenger vehicles, light-duty trucks and non commercial vehicles sold in California. Following quickly in 2003, California entered a partnership with Washington and Oregon and created the West Coast Global Warming Initiative. Under this initiative, the states agreed to work together on climate change programs. In 2006 Governor Schwarzenegger made a significant advancement in emissions reduction regulation by signing Executive Order S-3-05. This was a two-part order; the first part called for California to reduce its greenhouse gas emissions to 1990 levels by 2020, and the second part called for a reduction to 80% below 1990 levels by 2050. The first part of the order was passed into law later that same year as AB 32: California's Global Warming Solutions Act (California Air Resources Board, 2008).

In December 2007 CARB approved the 2020 emissions limit for AB 32 to be 427 million metric tons of CO_2 equivalent ($MMTCO_2E$). Projected emissions in 2020 along a business as usual path is 596 $MMTCO_2E$, placing California's abatement target at 169 $MMTCO_2E$. This is a reduction of 42 $MMTCO_2E$ from average 2002-2004 emissions. To achieve this target, California is taking a comprehensive approach to emissions reductions, dividing the economy into "capped" and "uncapped" sectors. A full description of California's approach is provided in its 2008 Climate Change Scoping Plan (California Air Resources Board, 2008).

The capped sectors, which face an overall reduction target of 146.7 $MMTCO_2E$, are California's current, largest emissions contributors: transportation, electricity and natural gas, and the oil and gas industry. In the Scoping Plan CARB lays out two avenues for emissions reductions in these sectors. The first are specific emissions reductions measures that implement regulatory standards, recommend voluntary actions, and introduce other fees and programs to directly reduce emissions. These include, among others, California's Light Duty Vehicle Greenhouse Gas Standards (previously called for in 2002 under AB 1492), programs for improving electrical and natural gas energy efficiency, a low carbon fuel standard, and a renewable portfolio standard. While primarily regulatory based, many of the proposed measures also include compliance flexibility and market mechanisms to help aid sectors in meeting the targets. Combined, these measures are expected to contribute 112.3 $MMTCO_2E$ in emissions reductions, leaving an additional 34.4 $MMTCO_2E$ to be met through the second avenue for reductions; establishment of a cap and trade program. The cap and trade program was announced in the Scoping Plan as a regional market system linking with partners in the Western Climate Initiative (WCI). The WCI is the successor to the West Coast Global Warming Initiative, and included an expanded membership of Arizona, New Mexico, Montana, Utah, and the Canadian provinces of British Columbia, Manitoba, Ontario and Quebec.[1] Under the cap and trade program, emissions permits will be given or auctioned to firms in the capped sector. The amount of permits in California will be set to achieve the capped sector reduction target of 146.7 $MMTCO_2E$. By fixing the amount of allowed carbon emissions in the capped sectors, the cap and trade program also sets a fixed, positive price of carbon. The benefits of this positive carbon price are that it encourages the market to find innovative ways to reduce emissions outside of the policies specified by the measures, and it also provides increased flexibility for firms working to adapt to the emissions limits (California Air Resources Board, 2008).

The uncapped sectors identified for additional emissions reductions in the Scoping Plan include High Global Warming Potential, Forestry, Recycling and Waste, "Other" Industry such as cement, Agriculture, Water, Commercial and Residential Building, and State and Local Government. Counted emissions reductions in these sectors are expected to total 27.3 $MMTCO_2E$. Further possible emissions reductions in these sectors are noted, but not explicitly counted towards the 2020 target as they are not additive with the reductions from previous measures.[2] Emissions reductions in non-capped sectors are achieved solely through the implementation of policy measures. These sectors are not included in the cap and trade program due to challenges associated with the sector structures, and with tracking and precisely measuring sector emissions.

Together, counted emissions reductions in the capped and uncapped sectors are expected to total 174 $MMTCO_2E$ in 2020, putting California slightly ahead of its target. Exact emissions reductions from the measures are of course unknown, but with the wide breadth of policy measures across multiple sectors, as well as the flexibility in the "cap" under the cap and trade program, it is currently expected that California will meet its 2020 goal (California Air Resources Board, 2008). In the essay in Chapter 2, we use a CGE model of California to consider the welfare implications of achieving this goal. The next subsection provides a brief overview of our methodology and results.

1.2.3 CGE Model of California's Climate Change Policy

In Chapter 2, co-authored with Peter Berck, we start with a theoretical approach and develop a simple general equilibrium model of the economy to predict the impact of increased abatement standards on economic welfare. We assume in the model that pollution is a costless input to production. By increasing output at zero cost, economic theory suggests that utility should be concave in pollution. That is, pollution increases utility, but due to decreasing marginal utility in output, it should do so at a declining rate. Conversely, if we consider a decrease in pollution, or increased abatement, then the marginal utility cost of abatement should increase as abatement increases. In a pure endowment economy, however, we see this is not necessarily the case. When output decreases, and prices of input goods such as labor goes down, households may respond by decreasing their supply of input goods. This results in utility gains from increased consumption of input goods such as leisure. In this scenario it is possible for utility to then be convex in pollution.

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[1] As of 2012, membership in the WCI had fallen to California and the Canadian provinces. It is not clear whether this reduced membership will impact California's emissions reduction targets for the cap and trade program.

[2] For example, the Green Building measure in the Commercial and Residential Buildings sector potentially double counts emission reductions from increased energy efficiency measures in the electricity and natural gas sectors.

We next turn our attention to evaluating the welfare impacts of California's climate change policy. Results from a CGE model of the California economy predict maximum emissions reductions from the Scoping Plan measures of 124 $MMTCO_2E$, approximately 25 $MMTCO_2E$ less than the reductions predicted by the Scoping Plan. The difference is due to the fact that for certain reduction measures, particularly those in the electrical and natural gas sectors, the CGE model predicts an increase in emissions. This is the result of a rebound effect that lowers consumer prices in these sectors, which is attributable to an initial decrease in demand in response to the measures. In the CGE model, the "rebound" in private commodity demand from lower prices is met by an increase in imports, which increases total carbon emissions counted by California.[3] Similar to the Scoping Plan, we find the cumulative effect of the emissions reduction measures will have a positive economic impact in many areas of the economy, including an increase in real state personal income (SPI), employment opportunities, and the real wage rate, and a decrease in the overall price level.

We also consider the welfare effects of a rising carbon price, which proxies the effects of a cap and trade program. To achieve the 2020 emissions reduction target of 169 $MMTCO_2E$ using both the carbon reduction measures and the cap and trade program, the CGE model predicts the carbon price would have to be set at \$25-\$30 per metric ton. Assuming 100% of the revenues from the carbon price are returned to factors, the model predicts that carbon prices at this level will raise real SPI, our primary welfare measure in the CGE model, through an increase in factor income. If further emissions reductions are targeted, and the carbon price continues to rise, then the effects of a rising overall price level and decreased employment opportunities from higher production prices will ultimately lead to a decline in real SPI. We find the point at which real SPI begins to decline depends on the definition of state income. In particular, if we account for the income earned by California residents both in- and out-state, the value of leisure or nonmarket labor for unemployed Californians, and the benefits of emissions reductions as a result of the rising carbon price, then the range of carbon prices over which real SPI is rising will significantly increase.

Relating the theoretical model and empirical CGE results, we find that when pollution has a price, abatement can often be achieved at a net savings to the economy, and decreases in pollution can increase economic welfare. We also find that although conditions for convexity of the welfare function exist in California, our primary measure of economic welfare in the CGE model, real SPI, is concave in the carbon price. The key contribution of this essay is showing the varied economic effects of climate control policies, particularly the rising carbon price associated with a cap and trade system. The results show that an aggressive emissions reduction plan, such as that undertaken by California, will not always lead to decreases in economic welfare. This suggests that governments considering climate change regulation do not necessarily need to trade off the economic well being of their citizens in order to contribute to the mitigation of damages from climate change.

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[3] AB 32 requires CARB to address emissions from electricity sources both in and outside of the state. The CGE model, however, only applies the measures to domestic production. Imported electricity and natural gas is generated at a fixed carbon intensity. If imported electricity and natural gas is also made "cleaner" then although the rebound effect would still exist, the increase in carbon production will be lower, closing some of the gap between the Scoping Plan and CGE model predictions.

1.3 Sulphur Dioxide, Nitrogen Oxide, & Acidification

1.3.1 Acidification History

Like climate change, acidification can be traced back to the start of the Industrial Revolution and in this case, increasing emissions of sulphur dioxide (SO_2) and nitrogen oxide (NO_x). While the existence of acid rain and its potentially damaging impacts were first noted in the 1800s (Ducros, 1845), (Smith, 1872), it was again the mid-1900s when a better understanding of the scope of the acid rain problem, and its impact on aquatic and terrestrial ecosystems began to emerge (Norton & Veselý, 2005). In particular, while greenhouse gas emissions are global pollutants, acidifying emissions are local pollutants with long-range transboundary effects. That is, localized SO_2 and NO_x emissions do not create worldwide acidification, but they do result in damages outside the boundaries of the emitting region. Many of the first observations of widespread surface water acidification and fish kills were in Scandinavia, (Odén, 1968), (Dannevig, 1959), which incurred damages as a result of acidifying emissions in the United Kingdom and Central and Eastern Europe. Similarly, acidification has been widely observed in the northeast United States, and is largely attributable to industrial activities in the U.S. mid-west and southeastern Canada (Menz & Seip, 2004).

The degree of acidification in a particular aquatic or terrestrial ecosystem depends on its ability to neutralize the flow of increased acid deposition. Neutralization occurs by the weathering of calcium from bedrock and soils, and acidification is therefore most prevalent in regions that are more chemically resistant to weathering. Other ecosystem characteristics that increase susceptibility of acidification are thinner soils and glacier deposits, higher rainfall, and a higher production of organic acids (Norton & Veselý, 2005). The damages to ecosystems that fall into an acidified state are significant, and there has been a concerted effort across countries worldwide to reduce acidifying emissions and work towards achieving the recovery of acidified soils and lakes. Since the 1970s, Canada, the U.S., and Europe have all established national regulatory policies, and entered into international agreements, to achieve emissions reductions (Menz & Seip, 2004). Across North America and Europe, these policies and agreements have resulted in a decline in SO_2 and NO_x emissions of 50-85%, and 0-30% respectively (Norton & Veselý, 2005). There are two challenges, however, in designing optimal policy to achieve these emissions reductions. The first, directly related to the transboundary effects of acidifying emissions, are that the costs of regulation, and the benefits of decreased acidification, are often born by different countries. The second is that the value of ecosystem recovery is uncertain, and the exact impacts of emissions reductions on the rate of recovery are unknown, making it difficult to balance the costs and benefits of an optimal emissions reduction strategy. The essay in Chapter 3 focuses on this latter challenge. Specifically, I examine optimal emissions reductions in an acidified region surrounding Sudbury, Ontario, Canada. This region is somewhat unique in that the cause of acidification can be traced primarily to a single, point source of emissions under the regulatory authority of the Ontario and Canadian government. As a result, I am able to abstract away from the transboundary issues of optimal acidification policy, and focus exclusively on the balancing of costs and benefits. The next subsection provides the background on acidification and recovery in the Sudbury area.

1.3.2 Acidification & Regulation in Sudbury

Vale Canada Limited and Xstrata are nickel-mining firms that operate in Sudbury, Ontario, Canada. Both firms were bought out in the mid-2000s and under previous ownership, were known as INCO and Falconbridge respectively. Operating under these names in the 1960s, they comprised the largest point source of SO_2 emissions in the world (Norton & Veselý, 2005), emitting an average 2238 kt per year, and a maximum of 2568 kt in 1960.[4] Operations at both firms began in the early 1900s, and expanded rapidly from there. For over fifty years, thousands of kilotons of SO_2 emissions were sent without regard into the atmosphere. The result was severe acidification of the terrestrial and aquatic ecosystems surrounding Sudbury. Beginning in the mid-1940s, research began to emerge on the effects of acidification on plants and soils in the Sudbury area (Beamish, 1976). Studies in the early 1960s showed evidence of decreasing water quality of lakes and ponds in the immediate Sudbury area, and by the mid-1970s, it was clear that acidification was occurring in a much larger region surrounding Sudbury (Beamish, 1976). A 1974-1976 chemical survey by the Ontario Ministry of the Environment (MOE) of 209 lakes in a 5300km^2 area surrounding Sudbury confirmed the extent of the damage; identifying a large zone of low pH lakes extending northeast-southwest of Sudbury and finding substantial losses of fish populations within this zone (Conroy N. I., 1978).

At the same time as the extent of damages from historical SO_2 emissions were being realized, the Government of Ontario began implementing its first emissions reduction policies as part of the Ontario Environmental Protection Act (Scott, Acid Rain: What We Know, What We Did, What We Will Do, 1989). In 1969, Falconbridge received its first order to reduce its daily SO_2 emissions from 1,028 tons per calendar day to 465 tons by 1975. Following quickly thereafter in 1970, INCO received a much stronger order, requiring a reduction in calendar day SO_2 emissions from 5,200 tons to 750 tons by 1978. Both firms failed in meeting these initial regulations. Falconbridge received an extension on their initial order to 1978, which they subsequently met. INCO's order was replaced in 1978 with a new order, requiring a more manageable reduction to 3,600 tons of SO_2 per calendar day by 1982. This too was replaced in 1980 when the MOE switched to regulating emissions by "working day." The new regulation required INCO to make an immediate reduction in working day emissions to 2,500 tons, and a further reduction to 1,950 tons by 1983.

By 1984, total emissions at INCO and Falconbridge had fallen to 770 kt per year. In 1985, Ontario introduced the Countdown Acid Rain program to meet its federal requirements, for SO_2 emissions reductions. Under the program, INCO and Falconbridge were required to reduce their annual emissions to 265 kt, and 100 kt respectively by 1994. Both firms exceeded these targets, emitting in 1994 a combined total of 216 kt per year.

In 2000, as part of the Canada Wide Acid Rain Strategy for Post 2000, the MOE established targets for INCO and Falconbridge to reduce emissions to 50% below their 1994 limits by 2015. In 2005, the Ontario Environmental Protection Act added increased structure to this regulation, requiring that INCO reduce its emissions to 265 kt of SO_2 in 2006, 175 kt from 2006-2014, and 66 kt from 2015 forward. Falconbridge's reduction targets were set at 66 kt from 2006-2014, and 25 kt from 2015 forward. Both firms are currently meeting these targets.

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[4] Data on historical emissions is provided by the Freshwater Ecology Unit in Sudbury Ontario, a joint partnership of Laurentian University, the Ontario Ministry of Environment, and the Ontario Ministry of Natural Resources. INCO (Vale Canada) was, and is, a substantially larger firm than Falconbridge (Xstrata), generally emitting over 85% of emissions in the Sudbury area.

In 2010, Vale Canada Limited (formerly INCO) had total annual emissions of 109 kt of SO_2, and Xstrata (formerly Falconbridge) had emissions of 24 kt (Environment Canada, 2012).

Lake monitoring data suggests recovery of many of the freshwater lakes surrounding Sudbury began with the initial emissions reductions in the 1970s. A 1981-83 follow-up survey of lakes showed improvements in water quality relative to the original 1974-76 survey, with many lakes showing an increase in pH and decreases in sulphate concentrations (Keller & Pitblado, 1986). An ongoing annual monitoring program, in place since the 1981-83 follow-up survey, continues to track the recovery process of 44 lakes. Indicators of water quality have continued to improve over the course of the monitoring program, showing an average increase in pH across all lakes from 1981-2004 of 0.95 pH units. In the essay in Chapter 3, I use this monitoring data to parameterize an optimal control problem, where I consider how to optimally implement emissions reductions to achieve the recovery of freshwater lakes from acidification. The next subsection provides a brief overview of this work.

1.3.3 Optimal Abatement Policy for Acidification Recovery

In Chapter 3, I develop an optimal control model for the recovery of a group of representative freshwater lakes from acidification. I assume the social welfare function has a negative value, and includes two sets of costs that a social regulator must balance against each other. The first is the ecological costs of continued lake acidification, which I define as a quadratic function of the deviation of the state variables, pH and alkalinity of lake water, from their "undisturbed" or natural levels. The second is the economic costs that firms must incur to abate emissions below a fixed "business as usual" level. I assume the social regulator minimizes the objective function by choosing the exact level of emissions the firm will emit. Point source emissions of the firm relate to acid depositions at the lake site through a linear equation. By choosing emissions, the regulator therefore determines exact depositions at the lake site. The state equations for pH and alkalinity are a function of lagged values of pH and alkalinity, and lake site acid depositions. The alkalinity state equation is a simple linear function of lagged alkalinity and acid depositions. The pH state equation is defined similarly, but includes an additional interaction term between alkalinity and depositions. This additional term captures the non-linear relationship between pH and acid depositions, which depends on alkalinity levels (the acid neutralizing capacity of the water).

I estimate the state equations using the panel data set described at the end of section 1.3.2 above. The data monitors the recovery of 44 acidified lakes located in the surrounding Sudbury area over a 24-year period. Annual lake site acid depositions are set equal to total annual emissions by Inco and Falconbridge, weighted by the inverse of the lake's distance from Sudbury. The results of the estimation indicate an upward trend in both pH and alkalinity, with a decrease in emissions corresponding to an increase in both variables. I also find the coefficient on the interaction term in the equation for pH to be negative. This is consistent with a lake in the early stages of acidification recovery, where alkalinity generally recovers more rapidly than pH (Norton & Veselý, 2005).

Using the estimation results, information on abatement costs for INCO and Falconbridge, and a grid of estimates for the damages from acidification, I solve the control problem for the optimal path of emissions reductions. I find the emissions reduction policy relies heavily on the assumed level of damages, and at most reasonable estimates, optimal abatement is zero. An important point to remember in considering this result, however, is that the data for estimation of the state equations does not include the period from 1976-1981, which is the period during which the initial recovery from acidification began (Keller & Pitblado, 1986). These results must therefore come with the caveat that they are only applicable to regions where acidification is underway. In these areas additional emissions reductions may contribute little to the rate of ongoing recovery, and as continued abatement investments will be costly to the firm, they are not necessarily optimal. I also find that as the level of damages increases, the optimal abatement policy will "jump" to full abatement of emissions, with only a narrow region of lake quality where partial abatement is optimal. Due to the slow recovery process from acidification, however, it is possible that recovering lakes will remain in this narrow region for extended periods of time, and partial abatement will an optimal long-term policy. Lastly, I find the pH level at which the policy switches from zero to full abatement is decreasing in the level of damages, and increasing in alkalinity. This last result relates to the interaction term in the state equation for pH. The negative coefficient implies that costly emission reduction policies to increase pH will be more effective at higher levels of alkalinity. Therefore, as alkalinity increases, abatement is desirable over an increasing range of pH levels.

There are two contributions of this essay to the literature. The first is that it considers optimal regulatory policy with the goal of achieving the recovery of lakes from acidification, and the second is that it uses data on actual lake recovery to estimate how lake water quality responds to changes in point source SO_2 emissions. While the numerical solution provides insights on how optimal policy should react to changing environmental conditions and the valuation of damages from acidification, there are limitations in the theoretical model that detract from the usefulness of the results for actual policy recommendation. These limitations are identified and discussed in the conclusion to Chapter 3, and provide a strong basis for future work.

1.4 Conclusion

My objective in this dissertation is to better understand two types of environmental regulatory policy. I first consider static policy measures to reduce greenhouse gas emissions, and mitigate the damages from climate change. The primary result from this essay is that the environment and the economy do not always have to be at odds, and in certain scenarios, emissions reductions policies can also increase economic welfare. I then consider a dynamic policy designed to achieve the recovery of a damaged aquatic ecosystem from acidification. I find the optimal policy depends significantly on changing environmental conditions, and the optimal level of regulation may either increase or decrease with initial improvements in environmental quality. Together these results highlight that optimal environmental policy is far from obvious, and it is important to take a comprehensive approach to policy design that considers a multiple of environmental and economic factors.

Chapter 2: The General Equilibrium Welfare Effects of Climate Change Policies

2.1 Introduction

More stringent regulations to reduce greenhouse gas emissions are under consideration, and coming into law, in many parts of the world and at many levels of government. In the United States, as of October 2011, 38 states had climate action plans in place or in development (Center for Climate and Energy Solutions, 2011). As climate action plans become more widespread, there is an increasing need for, and interest in determining optimal policy instruments for emissions reduction. Goulder et al (2008) provide an overview of the literature on instrument selection, concluding that while no one instrument is best, flexible incentive based policies such as environmental taxes and auctioned allowances are typically preferred. Aldy et al (2009) consider the design of climate mitigation policy, and in an application to the electricity sector, Fischer and Newell (2008) examine how to bring together various emissions reduction measures to design an optimal policy portfolio.

The key consideration for studies evaluating policy instruments, and for governments in implementing climate change policy, is the impact of selected measures on economic welfare. In this essay, we examine the welfare effects of climate change policies in a theoretical general equilibrium setting, and with a computable general equilibrium (CGE) model of the California economy. The CGE model incorporates the full portfolio of California emissions reduction measures that are being undertaken to meet the emissions reduction targets of Assembly Bill (AB) 32: California's Global Warming Solutions Act. With the results of the CGE model, we contrast the predicted economic impacts of climate change mitigation policy calculated using real-world data against those that are predicted by theory.

There is significant literature that considers the effects of theoretical environmental taxes and quotas on welfare in a general equilibrium setting. Bovenberg & de Mooij (1994), Bovenberg & van der Ploeg (1994), and Parry (1995), consider the impact of environmental taxation in markets with pre-existing labor distortions. They show that environmental taxes can further distort the household's labor supply decision and will generally lead to a negative welfare effect, known as the "tax interaction" effect. Goulder (1995a) examines specifically the effects of a carbon tax and finds a similar result. Goulder (1995b) provides a more positive assessment of the potential impacts of environmental taxation, and in analytical and numerical results, considers scenarios under which a double dividend is possible when revenues from the environmental tax are used to reduce marginal tax rates in other sectors.[5] Goulder et al (1997) and Parry & Bento (2000) also provide a more positive outlook, presenting models where the revenue recycling effect of environmental taxes can lead to welfare gains. In a specific discussion of carbon abatement policies, Parry et al (2000) show that revenue neutral carbon taxes can be welfare improving at any level of carbon damages, and quotas can be welfare improving if the damages of carbon exceed a minimum threshold.

A second area of the literature uses CGE models to consider the effects of specific environmental regulation on economic indicators. Early models by Jorgensen and Wilcoxen

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[5] The double dividend, discussed by Pearce (1991), suggests that the revenue from environmental taxes can be used to offset other distortionary taxes. Goulder (1995b) discussed three propositions for the double dividend (weak, intermediate, and strong).

(1990, 1993) use general equilibrium models to look at the effect of environmental regulation (mandated pollution abatement and investment) on the growth in U.S. GNP, and at the industry specific effects of a carbon tax. In an application to California, Fisher and Despotakis (1988) develop a CGE model to represent the aggregate and sectoral effects of a rising oil price on the California economy. In a follow-up article (Fisher & Despotakis, 1989), they use the same base model to consider the effects of an energy tax on California's energy consumption. Another early model by Bergman (1991) simulates the effects of reductions in SO_2, NO_x, and CO_2 emissions by including in the CGE model a market for tradable emissions permits. The model results show the impact of emissions reductions on price indices, output, and consumption in various economic sectors. More recent work by Pizer et al (2006), focuses on developing a CGE model to evaluate both traditional market based climate change policy instruments, and non-market policies such as renewable portfolio and fuel economy standards. On a global level, Nijkamp et al (2005) examine the incorporation of international climate change policy instruments, such as international emissions trading and the Clean Development Mechanism, into the GTAP-E CGE model of international trade.

As state governments develop action plans for addressing climate change, recent research focuses increasingly on the choice of specific policy instruments by states (Pollak et al, 2011), and the potential effectiveness of state action plans for emissions reductions, and sector specific measures (Lutsey & Sperling, 2008), (Lutsey & Sperling, 2009). In work specific to California, California's Climate Action Team (CAT) (2006) use a CGE model of the California economy, the Environmental Dynamic Revenue Assessment Model (EDRAM-08), in an initial assessment of California's Climate Action Plan. Roland-Holst (2006a, 2006b) also conducts numerous studies specific to California's climate reduction measures using the Berkeley Energy and Resources (BEAR) CGE Model. Both the studies by CAT and Roland-Holst, as well as a third report by the Center for Clean Air Policy (CCAP) (2006), suggest that California's climate change reduction targets can be achieved at zero cost to consumers, and will lead to improvements in key economic indicators such as the employment rate and real personal income. Stavins et al (2007) argues against these results, claiming they underestimate the costs of meeting California's future emissions targets. More recent studies using EDRAM-08 are conducted by the California Air Resources Board and reported in California's 2008 Climate Change Scoping Plan (2008), and by Berck and Xie (2010). Both studies consider the economic impacts of the full set of emissions reduction measures outlined in the Scoping Plan. Similar to the 2006 studies, they find the Scoping Plan measures will be welfare improving for California, although Berck and Xie note that individual sectors will gain and lose differentially.

Our work spans these three areas of the literature, considering the welfare effects of abatement policy from a theoretical and CGE approach. First using a theoretical general equilibrium model, we examine the welfare effects of regulated abatement standards in a pure endowment economy where pollution is a costless input to production. By limiting emissions, abatement standards effectively decrease a key factor of production. We show that all else equal, an increase in regulated abatement will decrease utility and make individuals in the economy worse off. While we do not consider pre-existing tax distortions, we find the shape of the utility function is dependent on household factor supply decisions. In particular, concavity of the utility function is only certain if preferences are homothetic, and if households respond to an increase in abatement with an increase in the supply of labor and other net input goods. If households instead choose to consume greater amounts of leisure and other net input goods then they effectively compensate themselves for the decrease in utility from higher abatement levels. This is a noteworthy policy result as it implies that households will not necessarily be made increasingly worse off by increasingly stringent abatement standards. It therefore creates the opportunity for more aggressive abatement policies at lower than expected welfare costs.

In the second part of the paper, we use the EDRAM-08 CGE model of the California economy to look at the effect of both carbon reduction measures, and a rising carbon price, on the level of carbon abatement, and various indicators of economic welfare. The analysis of carbon reduction measures is similar to the 2006 studies previously completed by Roland-Holst, CAP, and CCAT, and the 2008 studies conducted by CARB and Berck and Xie. Our analysis differs slightly, however, in that we are less interested in the exact impacts of California's specific climate change strategy, and more interested in using California as an example to understand how a portfolio of mitigation policies affects an economy. As a result, we run the CGE model with a superset of the measures from the 2008 Scoping Plan, including a small number of additional measures that were identified in the background data for the Plan, but not included in the final version. We also allow the carbon price to rise to a maximum of $160, well beyond the fixed carbon price that would likely emerge from the cap and trade program outlined in the Scoping Plan. With this larger price range we offer insight on how the competing positive and negative welfare impacts of a positive carbon price will interact, and how the net effect will change as the price rises. Lastly, we allow for various definitions of the welfare measure, and compute welfare results that extend beyond the basic output of the EDRAM-08 model.

Unlike the theoretical model where we assume the direct cost of pollution reductions is zero, we see in the Scoping Plan that many of the carbon reduction measures can be achieved at a net savings to the economy. As a result, when the price of carbon remains at zero, we observe an increase in welfare in response to many of the initial reduction measures. As the carbon price increases, due to the conflicting impacts on economic welfare just noted, we find that real state personal income (SPI) follows an inverted U-shaped path. It rises due to the revenue recycling effect at low levels of the carbon price, and begins to decline due to the rising overall price level and decreased employment opportunities at higher levels of the carbon price. We also find the point of decline changes in response to our definition of state income. In particular, if we apply a broader definition of state income that places a value on out-of state and nonmarket labor, as well as the benefits of increased abatement, then real SPI will rise over a higher initial range of the carbon price.

The remainder of this essay proceeds as following. In section 2.2 we describe and work through the results of the theoretical general equilibrium model for regulated abatement in an endowment economy. In section 2.3 we introduce in greater detail the EDRAM-08 CGE model, and describe how California's carbon reduction measures are implemented within the model. We proceed in section 2.4 to discuss the results of the CGE model, considering first the model results where only the carbon reduction measures are implemented, and second the results where the carbon reduction measures are implemented in conjunction with a rising carbon price. Lastly, section 2.5 presents some brief concluding remarks.

2.2 Theoretical Model

For the basis of the theoretical model we assume there is a competitive economy that has a single negative externality in production, gunk.[6] Our objective is to determine how welfare

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[6] The externality is named gunk in honor of Bob Solow.

changes in response to changes in the allowable level of gunk. We are also interested in the shape of the welfare function, and its rate of change in response to increased regulation, which corresponds to larger decreases in allowable gunk. The remainder of this section works through the derivations to obtain these results.

Following the framework of Diamond and Mirrlees (1971), we assume the economy is characterized by a vector of goods $\left(x_1, x_2, \ldots, x_N\right)$, with corresponding prices q_i for each of the n goods. Positive values denote net inputs to production (factors), and negative values denote net output (produced) goods. The first good is special in that it is purely a produced good, so $x_1 < 0$ and output from our production function is $-x_1$. The (concave) production function for good 1 is $\left(-x_1\right) = F\left(x_2, \ldots, x_N\right) g(a)$. Gunk, the pollutant is "a"; $g_a > 0$ and $g_{aa} < 0$, so that polluting, *ceteris paribus*, increases the output of good one at a decreasing rate. That is, it acts just like an un-purchased input in the production of good one.

Next we assume a representative household has an endowment of goods, $\left(T_2, \ldots, T_N\right)$, which it allocates between consumption and input supply to producers. The household derives income solely from its endowment of goods, and does not receive any government transfers, nor does it have any initial monetary wealth. Total income is therefore given by $m = \sum_{i=1}^{N} q_i T_i$.

Subject to its budget constraint, the household maximizes its utility function, $U\left(x_1, x_2, \ldots, x_N\right)$, by choice of goods $\left(x_1, x_2, \ldots, x_N\right)$. The utility function is continuous and quasiconvex in all goods. From the first order conditions for utility maximization:

$$\frac{\partial U}{\partial x_i} = \lambda q_i \tag{2.2.1}$$

where λ is the marginal utility of income. Solving these first order conditions gives the uncompensated demand function for each good, $z_i(q)$. Taking into account the initial endowment vector, we can calculate the net factor supply and net output demand functions for each good (taken to be twice differentiable in the relevant region), as $T_i - z_i(q) = x_i^D(q)$. That is, $x_i^D(q)$ is the endowment of the good less the household's aggregate demand for the good. We assume the budget constraint is strictly satisfied, so that payments received for net factor supply are exactly equal to payments made for net output demand. That is, $\sum_{i=1}^{N} q_i x_i^D(q) = 0$.

On the production side, the firm's objective is to maximize profits subject to being on the production possibility frontier for the first good:

$$\begin{aligned} &\max \pi = \sum_{i=1}^{N} q_1 x_1 \text{ subject to } \left(-x_1\right) = F\left(x_2, \ldots, x_N\right) g(a) \\ &\Rightarrow \pi = q_1 F\left(x_2 \ldots, x_N\right) g(a) + \sum_{i=2}^{N} q_i x_i \end{aligned} \tag{2.2.2}$$

From the first order condition for profit maximization:

$$-q_1 \frac{\partial F}{\partial x_i} g(a) + q_i = 0 \tag{2.2.3}$$

Solving the system of first order conditions gives the factor demand and output supply functions for firms, $x_i^S(q)$. In a market equilibrium, the factor demand and output supply of firms is equal to the net factor supply and net output demand of households, $x_i^D(q) = x_i^S(q) = x^*(q)$. We normalize good one to have a price of one, and the market clearing prices of the remaining goods are determined by their marginal products. Specifically, prices are $q_i = \frac{\partial F}{\partial x_i} g(a)$, in accord with equation (2.2.3) above.

To understand the effect of regulated abatement on production we consider the production possibility frontier for good 1 in a market equilibrium. Bringing $F(x_2,\ldots,x_N)g(a)$ to the left hand side of the production possibility frontier and totally differentiating with respect to a:

$$\begin{bmatrix} -1 & -g(a)\frac{\partial F}{\partial x_2} & \cdots & -g(a)\frac{\partial F}{\partial x_N} \end{bmatrix} \begin{bmatrix} \frac{\partial x_1}{\partial q_1} & \cdots & \frac{\partial x_1}{\partial q_N} \\ \vdots & \ddots & \vdots \\ \frac{\partial x_1}{\partial q_N} & \cdots & \frac{\partial x_N}{\partial q_N} \end{bmatrix} \begin{bmatrix} \frac{\partial q_1}{\partial a} \\ \vdots \\ \frac{\partial q_N}{\partial a} \end{bmatrix} - F\frac{\partial g}{\partial a} = 0 \tag{2.2.4}$$

Substituting in for the prices of goods 2 though to N we find that:

$$\begin{bmatrix} -1 & -q_2 & \cdots & -q_N \end{bmatrix} \begin{bmatrix} \frac{\partial x_1}{\partial q_1} & \cdots & \frac{\partial x_1}{\partial q_N} \\ \vdots & \ddots & \vdots \\ \frac{\partial x_N}{\partial q_1} & \cdots & \frac{\partial x_N}{\partial q_N} \end{bmatrix} \begin{bmatrix} \frac{\partial q_1}{\partial a} \\ \vdots \\ \frac{\partial q_N}{\partial a} \end{bmatrix} - F\frac{\partial g}{\partial a} = 0 \tag{2.2.5}$$

Recall the representative household's budget constraint is strictly satisfied, and in equilibrium is given by $\sum_{i=1}^{N} q_i x_i^*(q) = 0$. The effect of a change in the equilibrium price of good i on the budget constraint can therefore be expressed as:

$$x_i^* + \begin{bmatrix} q_1 & \cdots & q_N \end{bmatrix} \begin{bmatrix} \dfrac{\partial x_1}{\partial q_i} \\ \vdots \\ \dfrac{\partial x_N}{\partial q_i} \end{bmatrix} = 0 \tag{2.2.6}$$

Moving x_i^* to the right hand side and substituting this result into equation (2.2.6) above we get:

$$\begin{bmatrix} x_1^* & \cdots & x_N^* \end{bmatrix} \begin{bmatrix} \dfrac{\partial q_1}{\partial a} \\ \vdots \\ \dfrac{\partial q_N}{\partial a} \end{bmatrix} = F\frac{\partial g}{\partial a} \tag{2.2.7}$$

Note that by our price normalization, there are no changes in q_1 and $\frac{\partial q_1}{\partial a}$. Therefore, equation (2.2.7) tells us the sum of the change in the values of the netput vector for goods 2 through to N is equal to the shift of the production possibility frontier for x_1. The effect is positive since F and $\frac{\partial g}{\partial a}$ are both positive. This implies that a decrease in allowable gunk will lead to a decrease in output of good 1.

Next we consider the effect of a change in allowable gunk on the utility of the representative household in equilibrium. Substituting the equilibrium net aggregate demand functions into the direct utility function gives the indirect utility function $V(q'T,q)$. Taking the derivative with respect to a:

$$\frac{\partial V(q'T,q)}{\partial a} = \begin{bmatrix} \dfrac{\partial V}{\partial q_1} & \cdots & \dfrac{\partial V}{\partial q_N} \end{bmatrix} \begin{bmatrix} \dfrac{\partial q_1}{\partial a} \\ \vdots \\ \dfrac{\partial q_N}{\partial a} \end{bmatrix} \tag{2.2.8}$$

From Roy's identity:

$$\frac{\partial V}{\partial q_i} = \lambda x_i^* \tag{2.2.9}$$

where λ is the marginal utility of income, $V_m(a)$. Substituting equations (2.2.9) and (2.2.7) into the derivative of the indirect utility function:

$$\frac{\partial V(q'T,q)}{\partial a} = \lambda \begin{bmatrix} x_1^* & \ldots & x_N^* \end{bmatrix} \begin{bmatrix} \frac{\partial q_1}{\partial a} \\ \vdots \\ \frac{\partial q_N}{\partial a} \end{bmatrix} = V_m F \frac{\partial g}{\partial a} \tag{2.2.10}$$

From this equation we see that welfare increases unambiguously with respect to a, or alternatively, that if the level of allowable gunk decreases, then utility will unambiguously decrease in an economy with either a single individual or one in which the marginal utility of income is constant across individuals. Equation (2.2.10) depends only on Walras' Law and so holds even in economies where there is no representative agent.

We now explore the rate of change in our welfare measure. To do so, we take the derivative of the right hand side of equation (2.2.10) with respect to a:

$$\frac{\partial^2 V(q'T,q)}{\partial a^2} = \begin{bmatrix} \frac{\partial V_m}{\partial q_1} & \ldots & \frac{\partial V_m}{\partial q_N} \end{bmatrix} \begin{bmatrix} \frac{\partial q_1}{\partial a} \\ \vdots \\ \frac{\partial q_N}{\partial a} \end{bmatrix} \cdot \left(F \frac{\partial g}{\partial a} \right) + V_m \left(\frac{\partial F}{\partial a} \frac{\partial g}{\partial a} + F \frac{\partial^2 g}{\partial a^2} \right) \tag{2.2.11}$$

Using Roy's Identity to solve for $\frac{\partial V_q}{\partial m}$, the second derivative of the indirect utility function with respect to income and prices for good i can be rewritten as:

$$\frac{\partial V_m}{\partial q_i} = \frac{\partial V_{q_i}}{\partial m} = V_{mm} x_i + V_m \frac{\partial x_i}{\partial m} \tag{2.2.12}$$

Substituting this expression back into equation (2.2.11) and simplifying, we can rewrite the second derivative of the utility function with respect to abatement as:

$$\frac{\partial^2 V(q'T,q)}{\partial a^2} = V_{mm} \left(F \frac{\partial g}{\partial a} \right)^2 + V_m \left[\frac{\partial x_1}{\partial m} \ldots \frac{\partial x_N}{\partial m} \right] \begin{bmatrix} \frac{\partial q_1}{\partial a} \\ \vdots \\ \frac{\partial q_N}{\partial a} \end{bmatrix} F \frac{\partial g}{\partial a} + V_m \frac{\partial F}{\partial a} \frac{\partial g}{\partial a} + V_m F \frac{\partial^2 g}{\partial a^2} \tag{2.2.13}$$

Indirect utility is concave in abatement if the above expression is negative. Given our assumptions on $g(a)$ the last term is unambiguously negative, and the first term is non-positive if we assume homothetic preferences, which imply $V_{mm} \leq 0$. A sufficient condition for the third term to be negative is that F is decreasing in a. This means that if there is a regulated reduction in allowable levels of gunk, then this must increase the "netput" of goods other than the first.

That would mean either an increase in the supply of net inputs (which comes from a decrease, for example, in the demand for leisure), or a decrease in the consumption of other net output goods. Lastly, the second term will be negative if $\sum_{i=1}^{N} \frac{\partial x_i}{\partial m} \frac{\partial q_i}{\partial a} < 0$. The price of net input goods increases with a while the price of net output goods decreases, so this expression will hold with certainty only if net output goods are normal and net input goods are inferior. Since endowments in the model do not change, this requires that as prices of endowed goods decrease, net inputs increase, or alternatively, households decrease demand for the input. For example, if the price of labor decreases, as we would expect with a decrease in a, then for the indirect utility function to be guaranteed concave in abatement, households must respond by choosing to consume less leisure. If households instead treat leisure as a normal good, and choose to consume more leisure when the price of labor falls then the increase in utility from added leisure time may offset the decline from lower income, and the higher price level of output goods. It is possible in this scenario that the second term of equation (2.2.13) is positive. If also large enough to outweigh the negative effects of the other terms, then the rate of change of utility will be less negative as the level of regulated abatement increases. In this case utility will be convex in the level of allowable gunk.

2.3 Computational General Equilibrium Model

We next want to consider the impact of an increase in regulated abatement on the economic indicators of a CGE model. We complete the numerical simulations using the Environmental Dynamic Revenue Assessment Model (EDRAM-08), a CGE macroeconomic model of the California economy. It was first developed in the late 1990s for use by the California Department of Finance, and has more recently been used by the California Action Team (California Environmental Protection Agency, 2006) to evaluate the economic impacts of the greenhouse gas reduction measures included in California's Climate Change Scoping Plan (California Air Resources Board, 2008).[7] A full The Scoping Plan outlines how California will meet the greenhouse gas reduction targets identified in Assembly Bill 32: Global Warming Solutions Act. In the following subsections we discuss the carbon reduction measures of the Scoping Plan, provide a description of the EDRAM-08 model, and introduce how the model generates both carbon and abatement.

2.3.1 Carbon Reduction Measures

Appendix I of the Scoping Plan provides descriptions of 51 measures for emissions reductions.[8] There are 43 measures recommended for implementation to meet the targets of AB-32, and an additional 8 measures identified as potential low cost options to be used under a cap and trade program. Of the 51 measures, 4 are lacking estimates on the costs and savings of implementation, and 2 of the measures have high, outlier allowance prices (exceeding the maximum included allowance price of $157 by $300 and $1900). These measures are not included in our analysis as in the former case their impact cannot be represented in the model, and in the latter case, the allowance price is considered to be prohibitively high for

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[7] A full technical description of the EDRAM model is available in Berck et al (1996)

[8] Appendix I does not include measures for the Water Sector as the 2008 Scoping Plan does not have costs and savings estimates for this sector.

implementation. An additional 4 measures not listed in the Scoping Plan are identified on the background spreadsheet data for the July 2008 version of EDRAM-08 and are included in the analysis. The total number of measures considered in the analysis is therefore 49.

Information on the costs and savings of each measure is taken first from Appendix I of the Scoping Plan, and second from the July 2008 background spreadsheet data. The specific sectors affected by the changes in costs and savings are taken from the spreadsheet data. Appendix I provides only a single cost and savings estimate for each measure. If the spreadsheet indicates multiple sector effects, then the amount of the dollar change in purchases is either divided equally across the number of sector effects, or if the background spreadsheet provides a prior estimate of the cost or savings breakdown, then the amount of the dollar estimate is divided according to the prior proportions.[9] If the background spreadsheet does not identify the affected sectors then the sectors are chosen based on the overview of the measure, and the description of the assumptions for costs and savings provided in Appendix I of the Scoping Plan.

2.3.2 Model Description

We use a July 2008 version of EDRAM-08 that was modified for evaluation of the Scoping Plan measures, and observe the results from two categories of model runs. The base year for all model runs is 2007. In the first category of model runs, we assume the price of carbon affects only the decision on whether to implement specific Scoping Plan measures. A measure is implemented in the model whenever the per unit cost of the associated emissions reductions (the allowance price[10]) is less than or equal to the current price of carbon. In the model run, the measures that are economically feasible at the current price of carbon are implemented, but the "economy-wide" carbon price remains at zero. The net economic impact of an increase in regulated abatement therefore comes strictly from the introduction of new measures to reduce greenhouse gas emissions in specific sectors. In the second category of runs, we assume the price of carbon affects the decision to implement sector specific measures, and is positive in the actual model run. In this case the net economic impact of an increase in regulated abatement comes from both the reduction of greenhouse gas emissions in specific sectors, as well as the economy wide response across all sectors to a higher carbon price.

The impact of a specific emissions reduction measure is captured in the model through changes in the dollar value of purchases between sectors. The base level of purchases is recorded in the Social Accounting Matrix (SAM). In each model run, the SAM is multiplied by a matrix of scaling factors (initially set to 1), which captures any changes in purchases as a result of the measures. Savings from a measure are reflected by a decrease in purchases between

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[9] For example, suppose the Scoping Plan indicates a measure will result in a savings of $200, and the spreadsheet indicates the savings will result in a decrease in purchases from sector A to B, and from sector C to D. If the spreadsheet provides no prior indication of the savings breakdown then we assume purchases from A to B and from C to D both decrease by $100. Alternatively, if the spreadsheet previously indicated a total savings of $100 with a $75 reduction in purchases from A to B and a $25 reduction in purchases from C to D, then we assume that with the updated estimate from the Scoping Plan of $200 in total savings, purchases from A to B decrease by $150, and purchases from C to D decrease by $50.

[10] We calculate the allowance price from the perspective of the social planner, taking into account the full amount of costs and benefits associated with the measures. Specifically, the allowance price is calculated as the net cost of implementing the measure divided by the total expected greenhouse gas emissions reductions, i.e., it is the per "greenhouse gas" unit cost of implementing the reduction measure. The information on net costs and expected emissions reductions for each measure is taken from Appendix I of the Scoping Plan.

sectors, which leads to a decrease in the scaling factor. Costs are reflected by an increase in purchases, which leads to an increase in the scaling factor. For example, the Pavley I standard is the first phase of California's Light-Duty Vehicle GHG Standards, which require reductions in tailpipe GHG emissions from passenger vehicles. Savings from the measure are a result of a decrease in fuel consumption. This is represented in the model through a decrease in the scaling factor for the dollar value of retail gasoline purchases made by consumers through commodity transportation expenditures, as well as a decrease in the scaling factor for the purchases by all industry sectors from oil refineries. Costs from the measure are a result of higher vehicle costs. This is represented in the model through an increase in the scaling factor for consumer commodity transportation purchases in all industry sectors, and an increase in the scaling factor for purchases made by all industry sectors from automobile manufacturing. A list of the industry and commodity sectors included in the EDRAM-08 Model is provided in Appendix A, and a list of emissions reductions measures, along with corresponding model impacts, is provided in Appendix B.

2.3.3 Carbon Production & Abatement

In the model carbon is generated by three "carbon producing sectors:" electrical power generation and distribution, natural gas distribution, and oil refineries. Domestic carbon is generated by the dollar value of purchases by these sectors from the petroleum and natural gas extraction sector, and imported carbon is generated by net imports into each of these sectors. Total carbon is equal to the sum of domestic and imported carbon across all three sectors. The initial model run, where no measures are implemented and the carbon price is equal to zero, gives the business as usual amount of carbon in the model. Total abatement is then equal to the reduction in domestic and imported carbon as a result of the measures, and in the second category of model runs, the rising carbon price. Domestic abatement comes from a reduction in carbon producing purchases, which can come either from a decrease in domestic supply in the carbon producing sectors or from a decrease in the scaling factor for these purchases. Imported abatement comes from a reduction in net imports in the carbon producing sectors. Decreases in net imports are generally motivated by a decrease in domestic demand, or an increase in the domestic price.

2.4 Model Results

2.4.1 Carbon Reduction Measures & Carbon Price of Zero

We begin by calculating the static and dynamic conservation supply curves for the model runs where the price of carbon remains fixed at zero. We calculate the static conservation supply curve as the expected change in domestic carbon, which is a result of the cumulative sector specific impacts of all measures implemented at an allowance price, plus the change in net imported carbon as calculated by the dynamic model. The dynamic conservation supply curve, alternatively, is equal to the actual change in domestically produced and imported carbon as calculated in the model run. The resulting curves are shown in Figure 2.1. Total economy wide abatement is shown in the top panel, and total abatement in each sector is shown in the three lower panels.

The estimate of "net import abatement" is the same in both the static and dynamic curves, and with the information on costs and savings of the measures provided in the Scoping Plan, the static model accurately calculates the effect of the measures on the matrix of scaling factors for purchases. Therefore, deviations between the two curves are solely a result of differences in estimates of post-measure domestic supply in the carbon producing sectors.[11] In particular, the estimates of post-measure domestic supply in the static model do not account for changes in normalized prices, and changes in household commodity consumption shares.[12] These variables have significant impacts in the dynamic model on domestic demand, imports, and exports, which are the determinants of domestic supply.[13] Figure 2.2 maps the conservation supply curves for domestic abatement only, and more clearly highlights the impact of the variations in domestic supply on predicted abatement.

For the majority of measures discussed in the scoping plan the total reduction in purchases as a result of the measures is greater than the increase. These are "net savings" measures, and effectively have a negative allowance price. In the dynamic model, the implementation of all measures with an effective allowance price of zero or less results in 129.5 million metric tons (MMT) of carbon abatement. In the static model, estimated carbon abatement from these same measures is 114.0 MMT. The measures with the largest impact on abatement, in order of implementation, are the Pavley I Light Duty Vehicle GHG Standards, Electrical and Natural Gas Energy Efficiency Standards, and the Low Carbon Fuel Standard.[14] The following subsections discuss abatement effects specific to these measures, as well as the cumulative abatement effects of the positive price allowance measures.

2.4.1-1 Pavley I Light Duty Vehicle Greenhouse Gas Standards

The Pavley I measure is implemented at an effective allowance price of -361. Its estimated impacts on total and domestic abatement are shown in Figures 2.1 and 2.2 at the first vertical dotted line. The estimated savings of Pavley I are an $8.8 billion decrease in consumer commodity transportation purchases from the retail gasoline sector, and a $2.6 billion decrease in purchases from the oil refineries sector, divided across all industry sectors that use oil refinery production as an input.[15] These savings are primarily a result of a decrease in gasoline purchases due to increased vehicle efficiency. The estimated costs of Pavley I are a $1.1 billion increase in consumer commodity transportation expenditures from all industries which have a positive transportation consumption share, and a $0.3 billion dollar increase in purchases by the

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[11] Purchases made by the carbon producing sectors from the petroleum and natural gas sector are determined by the domestic supply in each of the carbon producing sectors, the scaling factor for purchases, and a fixed input-output coefficient. Therefore, at a fixed scaling factor for purchases, decreases in domestic supply translate directly into decreases in domestic carbon produced (and an increase in abatement).

[12] Commodity consumption shares in the model are determined using the Almost Ideal Demand System of Deaton and Muellbauer (1980).

[13] The equation for domestic supply (DS) is *Domestic Supply = Domestic Demand + Exports - Imports*

[14] The Pavley I Light Duty Vehicle GHG Standards are implemented at an effective allowance price of -361, the Electrical and Natural Gas Energy Efficiency Standards at an effective allowance price of -109, and the Low Carbon Fuel Standard at an effective allowance price of 0.

[15] A reduction or increase in purchases across multiple sectors is divided according to the base level proportion of purchases in the SAM matrix. For example, suppose sector A and B originally purchase $400 and $100 from sector C, and a measure results in a decrease in total purchases by both sectors of $50. This is divided as a $40 reduction in purchases by sector A, and a $10 reduction in purchases by sector B.

automobile manufacturing sector, divided across all industry sectors from which it purchases inputs. These costs are attributable to the higher price of automobile parts, a higher end price for increased fuel-efficient vehicles, and increased consumer expenditure on other modes of transportation (as consumers substitute away from more expensive automobiles).

Total predicted abatement in the static model for the Pavley I measure is 46.6 MMT of carbon, and abatement in the dynamic model is 51.4 MMT. In both models abatement is primarily driven by the decrease in retail gasoline demand. This leads to a large decrease in the domestic demand for the oil refinery sector, which in turn leads to a decrease in the domestic supply of oil refineries, and a decrease in purchases by oil refineries from the petroleum and natural gas sector. Countering this main source of abatement is a small rebound effect observed in both the commodity transportation and retail gasoline sectors. The initial decrease in consumer expenditures in the retail gasoline sector leads to a decrease in the normalized price of retail gasoline products, as well as a decrease in the normalized price of transportation commodities. This, combined with the increase in commodity transportation expenditures on more expensive vehicles and alternative modes of transport, leads to a small increase in the consumption share of commodity transportation, from an average of 11.1% of household commodity expenditures to 11.4%. As a result, domestic demand in the retail gas industry (as well as other transportation sectors) goes up, offsetting some of the initial decrease in demand attributable directly to the measure. These secondary price and consumption share effects are captured only in the dynamic conservation supply curve, and are shown in the upper middle panel of Figure 2.1, where abatement in the oil refinery sector in the dynamic model is less than abatement in the oil refinery sector in the static model.

A second secondary effect not accounted for in the static conservation supply curve is a decrease in the consumption share of commodity fuel expenditures, from an average of 1.9% of household commodity expenditures pre-Pavley I to 1.5% post-Pavley I. This is attributable to a positive price elasticity between the normalized transportation commodity price, and the consumption share of commodity fuel expenditures. The decrease in commodity fuel consumption shares leads to a decrease in fuel consumption by private households, which results in a decrease in domestic demand in the natural gas and electrical distribution sectors, and therefore a decrease in domestic supply in these sectors, as well as net imports. As shown in the lower panels of Figure 2.1, the decrease in domestic supply leads to positive abatement in both the domestic and net import sectors. The static model shows a small increase in abatement in these sectors attributable to the decrease in net imports, but does not capture the domestic abatement from the decrease in domestic supply.[16] This underestimate of abatement in the electrical and natural gas distribution sectors in the static model outweighs its overestimate of abatement in the oil refineries sector. The net effect, as noted previously, is that total estimated economy abatement along the static conservation supply curve is 4.8 MMT less than abatement along the dynamic conservation supply curve.

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[16] As shown in Figure 2.2, which plots domestic abatement, the static model actually predicts a decrease in abatement in the electrical distribution and natural gas sectors from Pavley I. This is a result of the predicted increase in purchases by oil refineries from input supplying sectors. In the static model where consumer consumption expenditures are held constant, this increase in purchases leads to an increase in domestic supply in the electrical distribution and natural gas sectors.

2.4.1-2 Electrical and Natural Gas Energy Efficiency Standards

The initial measures for Electrical Energy Efficiency, and for Natural Gas Energy Efficiency are both implemented at an effective allowance price of -109. Their estimated impacts on total and domestic abatement are shown in Figures 2.1 and 2.2 at the second vertical dotted line. For both measures, increased efficiency is achieved primarily through building standards, appliance standards, and investor owned utility energy efficiency programs. The increased efficiency leads to savings in fuel commodity expenditures; expenditure in the electrical distribution sector is estimated to decrease by $5.1 billion, and expenditure in the natural gas distribution sector is estimated to decrease by $1.4 billion. Costs are attributable to expenditures the electrical and natural gas sectors must make to improve efficiency of their operations. Specifically, purchases made by the electrical distribution sector and by the natural gas sector from all other industries that supply them with inputs are estimated to increase by $3.4 billion and $0.96 billion respectively. While the Scoping Plan estimates a cumulative GHG reduction of 19.5 MMT of carbon as a result of these measures, both the dynamic and the static model indicate that abatement will actually decrease. The predicted decrease in the static model is -18.7 MMT of carbon, and the actual decrease from the dynamic model is -17.6 MMT. Most of this observed increase in carbon production is a result of an increase in imported carbon, which is attributable primarily to secondary price and commodity consumption share effects.

The first order effects of the energy measures on abatement are quite small. In the static model, the decrease in commodity fuel expenditures leads to a decrease in domestic demand in the electrical and natural gas distribution sectors, and a decrease in predicted domestic supply. However, an increase in expenditures by these industries to achieve the efficiency gains increases the scaling factor for purchases from the petroleum and natural gas sector. In both sectors the increase in the scaling factor for purchases offsets the decrease in domestic supply, and as a result, leads to a net increase in carbon production. The increase in expenditures also increases the scaling factor for purchases from the oil refineries sector. This increases the intermediate demand for goods in the oil refineries sector, which leads to a small increase in domestic supply, and an additional increase in carbon production in this sector. These first-order, sector specific results are shown by the non-model domestic conservation supply curves in the lower panels of Figure 2.2.

When the secondary effects of the measures are considered in the dynamic model, there is a significant decrease in anticipated abatement. First, there is again a rebound effect, this time as a result of the decrease in commodity fuel expenditures in the electrical and natural gas distribution sectors. This leads to a decrease in the normalized price of commodity fuels, and a net increase in private consumption demand in both sectors. At the same time, however, the increased costs which these sectors incur to achieve efficiency gains leads to an increase in their average and domestic normalized prices. The higher average price leads to a decrease in intermediate demand, and a decrease in government demand in these sectors. The net effect is a small decrease in domestic supply in both sectors, with the increase in consumer consumption mostly offsetting the decrease in intermediate and government demand. Again, however, this decrease in domestic supply is offset by an increase in the scaling factor for purchases from the petroleum and natural gas sector. The end result is that domestic carbon production increases by a small amount; by 4.6 MMT in the electrical distribution sector and by 2.0 MMT in the natural gas distribution sector. More significant, however, is that the higher domestic price leads to a decrease in exports and an increase in imports. This leads to large increases in the amount of net imported carbon; an additional 7.6 MMT in the electrical distribution sector and 8.8 MMT in the natural gas distribution sector. The end result is that the increased efficiency measures decrease total abatement by 12.2 MMT in the electrical distribution sector and by 10.8 MMT in the natural gas sector.

Lastly, the oil refineries sector in the dynamic model is influenced by secondary effects which decrease the average share of commodity transportation expenditures by households from 11.6% to 10.3%.[17] This is the result of a positive price elasticity between the normalized price of commodity fuels and the consumption share of commodity transportation expenditures. This leads to decreases in private consumption demand in oil intensive industry sectors such as retail gas and air transportation. The decrease in intermediate demand from the transportation sectors more than offsets the increase in intermediate demand predicted for oil refineries as a result of the first order effect of the efficiency measures. As shown in the middle upper panel of Figure 2.1, this increases abatement in the oil refineries sector by 3.7 MMT. The net overall effect, however, is still being driven by changes in production and net imports in the electrical and natural gas distribution sectors, and as shown in the top panel of Figure 2.1, overall abatement as a result of the measures decreases by a significant amount.

2.4.1-3 Low Carbon Fuel Standard

`The third major measure, the Low Carbon Fuel Standard (LCFS), is expected to have equal costs and savings and is implemented at an allowance price of zero. Its estimated impacts on total and domestic abatement are shown in Figures 2.1 and 2.2 at the final vertical dotted line. The LCFS reduces GHG emissions through a requirement that by 2020, transportation fuels sold in California meet a low carbon intensity standard. The Scoping Plan specifies that costs and savings as a result of the measure will be primarily born by the retail gas sector. Specifically, the Scoping Plan estimates a reduction of $11,000 billion in purchases by the retail gasoline sectors from oil refineries, and an increase in purchases by the retail gasoline sector of $6812.5 from agriculture, and $4187.5 billion from the basic chemical manufacturing sector. These savings and costs are incurred as the retail gas sector turns away from conventional, high carbon fuel sources provided by oil refineries, and towards lower carbon options, such as biofuels, offered by the agricultural and chemical manufacturing sectors. As shown in the upper panel of Figure 2.1, the static model of conservation supply predicts these costs and savings will lead to an increase in abatement of 44.3 MMT of carbon, while the dynamic model shows an increase in abatement of 47.0 MMT.[18]

For the LCFS measure, virtually the entire change in abatement is attributable to the primary effect of the decrease in purchases from the oil refinery sector. This decreases intermediate and domestic demand for oil refinery production, and as a result, domestic supply and net imports in the sector also fall. This leads to the observed carbon abatement. Domestic

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[17] Note that in comparison to the static model, this decrease in commodity transportation shares “undoes” the increase in shares that was observed as a result of the Pavley I measure. This brings the dynamic and static transportation consumption shares closer, and as shown in the upper middle panel of Figure 2.1, they track much closer from this point on.

[18] A second measure, the High GWP (Global Warming Potential) Refrigerant Tracking/Reporting/Repair/ Deposit Program is also implemented at an allowance price of zero. However, its impact on production flows is very small and additional abatement as a result of the measure is negligible (less than 0.005 MMT of carbon in the static and dynamic model). The observable changes in abatement in Figure 2.1 can therefore be fully attributed to the LCFS measure.

and imported abatement in the oil refineries sector accounts for 44.2 MMT of the overall abatement observed in the static model, and 46.6 MMT of the overall abatement observed in the dynamic model. The difference of 2.4 MMT between the two models is due to a small increase in the normalized price in the retail gasoline sector (from 0.994 to 0.995) in the dynamic model, which leads to a small decrease in domestic supply in the sector. In both the static and dynamic model, the LCFS measure has only a very small effect on production in the electrical and natural gas distribution sectors, with the combined increase in abatement across both sectors being only 0.4 MMT and 0.2 MMT of carbon respectively.

2.4.1-4 Positive Allowance Price Measures

Measures implemented at a positive allowance price tend to be less effective at achieving abatement, and either have only a small increase, or in some cases, lead to a decrease in the overall abatement level. In particular, the cumulative effect on overall abatement of all measures implemented at a positive allowance price is negative. At the maximum allowance price in the analysis of 157, where all 48 measures are implemented, total carbon abatement in the static and dynamic model runs are 102.4 and 123.8 MMT respectively. This is a decrease in abatement of 10.2% in the static model, and 5.0% in the dynamic model, from the levels observed at an allowance price of zero.

The decreases in abatement are driven primarily by measures implemented in the electricity and natural gas sector. As previously seen with the primary electrical and natural gas efficiency measures discussed above, measures in these sectors tend to have a strong rebound effect attributable to the effects of decreased commodity fuel expenditures by private households, and increased costs in the specific industry sectors. Over the course of the measures implemented at a positive allowance price, the normalized price of commodity fuels decreases from 0.791 to 0.752, and the consumption share increases slightly from 1.7% to 1.8%. At the same time, the increase in costs leads to an increase in normalized domestic prices in both the electrical and natural gas sectors, which decreases intermediate goods and government demand. The increase in private commodity demand is therefore met through an increase in net imports. The increase in costs as a result of the measures has the additional, first order effect of increasing the scaling factor for purchases made by the electrical and natural gas sectors from the petroleum and natural gas sector. As seen previously, the increase in the scaling factor offsets the decrease in domestic supply. The net effect, as shown in the lower panels of Figures 2.2 and 2.1 respectively, are that domestic abatement in both sectors is relatively constant, and total abatement decreases due to the increase in carbon from net imports.

Production in the oil refinery sector is generally unaffected by the positive allowance price measures in the electricity and natural gas sector. The anticipated primary affect is a slight increase in carbon due to the costs of the measures, which generally are an expected increase in purchases from the oil refineries sector, and therefore intermediate demand. As shown in the upper middle panel of Figure 2.1, this leads to a small decrease in abatement in the static model. In the dynamic model, however, this decrease in abatement is offset by a decrease in the consumption share of commodity transportation expenditures, from 10.3% to 10.0%. As discussed previously, this decreases demand in key carbon producing industries, and the net effect is a very small increase in abatement in the oil refineries sector in the dynamic model.

2.4.2 Carbon Reduction Measures & Positive Carbon Price

We next consider the effects of a positive price of carbon in the general equilibrium model, implemented in conjunction with the carbon reduction measures. Our analysis covers the carbon price range of zero to 160, which as noted previously, results in implementation of 48 carbon reduction measures. We assume the "Business as Usual" (BAU) scenario is a carbon price of zero with no measures implemented. We also define a price of "0+" where the carbon price remains at zero, but 27 "net savings" measures with an allowance price less than or equal to zero are implemented. The "0+" price captures the initial effects of these measures, generally observed in the figures that follow as large jumps away from the BAU scenario. As net savings measures these jumps generally represent a positive economic impact; for example, a decrease in the price level and an increase in the real wage rate and the number of working households. Starting at a carbon price of one, the price rises in increments of one, and the figures reflect primarily the effect of a rising carbon price, as well as the occasional smaller jump attributable to the implementation of a new positive allowance price measure.[19]

A positive price of carbon has three primary effects in the general equilibrium model. First, it increases the domestic price in the carbon producing sectors, which results in an increase in the average price of domestic consumption, and a decrease in domestic demand. Second, the model is defined so that revenues from the carbon tax collected on domestic production and net imports are returned to in state capital. As a result, capital income is generally increasing as the carbon price increases.[20] Third, a positive carbon price effectively increases the world price of imports and exports in carbon producing sectors. This results in a decrease in imports in these sectors and an increase in exports.

The following two subsections look at the abatement effects of the carbon reduction measures and rising carbon price, and the anticipated impact of these regulations on household welfare, as measured by real state personal income (SPI). The third subsection looks more closely at the population and labor effects of the regulations, and considers how real SPI changes when we expand the definition of state income to include nonmarket labor and out of state income (earned by previously employed in-state workers), and when we close off the economy to household migration. Lastly, in the final subsection we consider how real SPI further changes in response to the application of green accounting principles.

2.4.2-1 Abatement

Total overall abatement, and abatement in each of the three carbon producing sectors for an increasing carbon price is shown in the four panels of Figure 2.3. Total abatement across all sectors, and total abatement in each individual sector is increasing at a relatively linear rate. The breakdown between domestic and net import abatement, however, varies across sectors.

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[19] Measures with observable impacts are the additional energy efficiency standards in the electrical and natural gas sectors, implemented at an allowance price of 2 and 3 respectively, the Renewable Portfolio Standard implemented at an allowance price of 84, and a reduction in coal generation, implemented at an allowance price of 100. These are "net cost" measures and generally have a negative impact on economic indicators.

[20] As shown in Figure 2.5, real capital factor income is increasing at a decreasing rate. At high values of the carbon price, high prices in industry sectors lead to decreases in factor demand and a rising price level decreases the real value of nominal income. This outweighs the effect of the returns from the carbon tax and factor income begins to decrease.

In the oil refineries sector there are no exports, so the change in abatement comes solely from the decrease in domestic demand, which is attributable to the increase in the aggregate domestic price. This decrease in domestic demand is met primarily by a decrease in domestic supply, as well as a smaller decrease in imports. Domestic and net import abatement are both increasing at a linear rate, although domestic abatement, as shown in the upper middle panel of Figure 2.3, is significantly higher and increasing at a faster rate in response to the rising carbon price.

In the electrical distribution sector, the decrease in domestic demand due to the rising price of carbon is met primarily through a decrease in imports. The amount not met by the decrease in imports is offset in the domestic supply calculation by an increase in exports due to the higher effective world price. The net effect is that total domestic supply remains relatively constant. Domestic abatement sits between 1.4 and 4.3 MMT of carbon over the entire range of the rising carbon price, and changes in its level is driven primarily by the carbon reduction measures. Net import abatement, alternatively, increases at a linear rate in response to the rising carbon price. Like domestic abatement, however, it is subject to small jumps as a result of the introduction of new measures.

Lastly, in the natural gas distribution sector the primary effect of the rising carbon price is a significant increase in exports. This is attributable to the higher carbon intensity of traded goods in this sector (6.88 in the natural gas sector, relative to 2.88 in the electrical distribution sector and 3.75 in oil refineries), which leads to a higher effective increase in the world price. The increase in exports in the natural gas sector more than outweighs the decrease in domestic demand due to the higher aggregate domestic price. As a result, domestic supply increases as the carbon price increases and, as shown in the lower panel of Figure 2.3, domestic abatement is decreasing. Conversely, however, the increase in exports decreases net imports, and as a result, net import abatement increases as the carbon price increases. As the "carbon credit" for exported goods is greater than the "carbon debit" for domestic production, the net effect of the increase in exports is an increase in total abatement in the sector.

2.4.2-2 Household Welfare

We next want to consider the impact of a positive carbon price on the welfare of households, which we proxy by real SPI. Real SPI depends on real household income, which is determined primarily by real factor income. Real factor income, in turn, depends on factor rental rates, factor demand, and the amount of the carbon tax returned to factors. The real rate of return to factors depends on the cumulative change in factor demand across all industry and government sectors. This means that most of the change in real labor income, and the change in real capital income not attributable to returns from the carbon tax, can be traced primarily to changes in factor demand, and in the price level. Total real factor income is allocated among household groups, *H*, by fixed factor income shares.

The price level in the model is defined by household group and is equal to the household group's consumer price index (CPI). CPI is defined by a weighted sum of commodity consumption shares, $CS_H(c)$, and prices, $P(c)$, where *c* indexes the commodity sectors.[21] Specifically, it is defined as:

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[21] The nine commodity sectors in the model are food and beverage, shelter, fuel and utilities, household furnishing and operation, apparel and its upkeep, transportation, medical, entertainment, and other goods and services.

$$\log\left(CPI_H\right)=\sum_c CS_H\left(c\right)\log\left(P\left(c\right)\right)$$

We calculate the economy-wide CPI as the population weighted average of the CPI for each individual household group. As the carbon price increases, the normalized commodity price increases in eight of the nine commodity sectors. The largest price increase, from 0.791 to 1.077, is for fuels, and is matched by only a small decrease in the fuel consumption share of an average 0.1% across households. The second largest commodity price increase, from 0.904 to 0.952, is for transportation, and is matched by a notable increase in the transportation consumption share of an average 1.4% across households.[22] As consumption shares are not noticeably falling in the sectors where price is most significantly increasing, the net effect of the rising carbon price is an increase in the household, and economy-wide CPI estimates. This has a negative effect on the value of real factor income.

We next consider the sources of changes in factor demand. In industry sectors, changes in factor demand, relative to their initial levels, move closely with changes in domestic supply. That is, the elasticity of factor demand for labor and capital with respect to changes in domestic supply is approximately equal to one. An increasing carbon price therefore impacts factor demand primarily through changes in domestic supply.[23]

As stated previously, the primary effect of the increasing carbon price is an increase in normalized prices in the carbon producing sectors. This has two secondary effects which impact domestic supply across all sectors. First, non-carbon sectors that use production from the carbon producing sectors as inputs must now pay higher input prices. This leads to a higher normalized domestic price in these sectors, which will tend to decrease domestic demand, and decrease exports. The effect on imports is harder to predict as imports are positively related with both domestic demand and domestic price. Generally, however, even if the effect of a decrease in domestic demand dominates and imports decrease, it will not fully offset the decreases in domestic demand and exports, and domestic supply will decrease. The second secondary effect is that the higher prices in the carbon producing sectors increase the normalized commodity prices for fuel and transportation. This leads to a change in consumption shares among the commodity groups, which depends on both the price elasticity of the commodity shares with respect to the fuel and transportation commodity prices, as well as the income elasticity of the commodity shares with respect to real household disposable income after savings. If commodity spending in a sector decreases, then when combined with the first secondary effect of higher normalized domestic prices, domestic supply in the sector will generally decrease.[24] Alternatively, if commodity spending in a sector increases, then when combined with the first secondary effect, the change in domestic supply in the sector will depend on the relative magnitudes of the two opposing effects.

As the carbon price increases, its primary and secondary effects result in an increasing trend in domestic supply in 21 of the 119 industry sectors, and a decreasing trend in domestic

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[22] The increase in consumption share is due to the positive price elasticity between commodity fuel prices and commodity transportation consumption shares.

[23] The additional variables explaining changes in domestic supply are changes in the rental rates for capital and labor, and changes in the industry value added price. Factor demand is decreasing in the rental rates and increasing in the value added price.

[24] There is one exception to this result, the apparel industry sector, where the decrease in imports is larger than the decrease in domestic demand and exports. In this case domestic supply must increase to satisfy the domestic demand that was formerly met by imports.

supply in the remaining 98. The net effect is a decrease in both labor and capital demand, as shown in the upper and lower panels respectively of Figure 2.4. Relative to the business as usual levels, the combined effect of the carbon reduction measures and the rising carbon price leads to a decrease in labor demand of 0.1125 million jobs, and a decrease in capital demand of $1.8891 billion. If we take into account that the zero price allowance measures cause labor demand to initially jump up by 0.1411 million jobs, then the estimated impact of carbon price on labor demand is more than doubled, with the increase in price from 0 to 160 leading to a decrease in labor demand of 0.2544 million jobs.

For capital, the zero price allowance measures lead to an opposite demand effect, resulting in a decrease in capital factor demand of $1.6574 billion. This is attributable to the fact that the carbon reduction measures decrease domestic supply primarily in the carbon producing sectors, which are capital intensive. Similarly, the allowance price measures implemented between one and three dollars cause capital demand to drop by an additional $0.3221 billion. The initial effect of the rising carbon price is not apparent until the price of four dollars, at which point capital demand begins to increase due to the positive returns to capital income from the carbon tax. As the carbon tax continues to increase, however, the cost of the tax and the rising price level outpace the positive returns, and capital factor demand again begins to decline. Relative to the capital demand level at an allowance price of $3, the net effect of the rising carbon price is a decrease in capital demand of $0.1658 billion.

As shown in the middle panel of Figure 2.5, the decrease in labor demand as the carbon price increases leads to a relatively linear decrease in real labor income. The rate of decline is attributable to the declining demand for workers, the resulting decline in the real wage rate, as well as the rising price level. The change in real capital income as the carbon price increases is shown in the lower panel of Figure 2.5. As noted previously, in the current model runs, all of the revenues from the carbon tax are returned to capital. At low price levels, the increase in capital factor demand, combined with the returns from the carbon tax, more than offsets the negative effect of the rising price level. As the carbon price continues to increase, however, capital factor demand falls and the decrease in demand, combined with the decreasing real rental rates and rising price level, outweighs the increase in revenue from the tax returns. Real capital factor income therefore begins to decrease. Total real factor income from both capital and labor is shown in the upper panel of Figure 2.5. The increase in real capital income initially dominates, but as the growth in real capital income declines and real labor income continues to decrease, growth in total real factor income also slows and then begins to decline at an approximate carbon price of 38.

We calculate total real factor income as the sum over all households of real labor and real capital income, where real capital income includes 100% of the revenues from the carbon tax, collected on both domestic and "net import" carbon. Total real state personal income (SPI) is then equal to the sum over all households of real factor income after taxes and after payments to foreigners, and real government transfer payments. Due to the rising price level, the real value of domestic factor income taxes, and factor payments to foreigners are decreasing as the price level increases. In addition, after the introduction of the zero price allowance measures, and at low levels of the carbon price, real government transfer payments are increasing due to an increasing number of nonworking households.[25] Similar to real factor income, however, the

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[25] The number of nonworking households increases with the introduction of the zero price allowance measures due to an increase in in-migration, discussed in more detail in the next section. It continues to increase as the carbon price rises due to the decrease in labor factor demand previously discussed.

growth in real transfer payments is ultimately outpaced by the rising price level and the value of real transfer payments begins to fall. The net effect of these additional changes is that real SPI is initially increasing at a faster rate than real factor income. It also reaches its maximum point at a higher carbon price of 51, and then declines at a faster rate. The path of real SPI in response to the rising carbon price is shown as the solid line in the upper panel of Figure 2.6.

An alternative calculation of SPI can be done using the Stone Index (Stone, 1953) in place of the CPI. The Stone Index is defined similarly to the CPI, except that commodity consumption shares remain fixed at their initial levels. It therefore varies only in response to changing prices, and captures explicitly the effects of the rising price level. A comparison between the economy-wide CPI, and the economy-wide Stone Index for households is shown in the lower panel of Figure 2.6. The most significant deviation in the two indices comes as a result of the zero price allowance measures. As discussed in the previous section, these measures cause a significant decrease in the commodity price of fuels and transportation, as well as a decrease in consumption shares in both sectors. The decrease in consumption shares decreases the weight placed on the lower prices in the CPI calculation, and as a result, CPI decreases by a smaller amount than the Stone Index in response to the zero price measures. As the carbon price increases, the Stone Index increases faster than the CPI, primarily because it places greater weight on the rising price of fuel, and at low values of the carbon price, the rising price of transportation. As a result, while SPI as normalized by the Stone Index is initially higher than real SPI, it decreases at a more rapid rate, peaks at a lower carbon price of 45, and ultimately decreases below real SPI. Real SPI normalized using the Stone Index is shown as the dash- dot line in the upper panel of Figure 2.6.

2.4.2-3 Population, Migration & the Labor Market

The labor market equilibrium condition in the model requires that the number of working households be equal to the factor demand for labor multiplied by a constant, job correction factor.[26] This implies that when labor demand decreases, the number of working households in the economy must also decrease. The model provides two options for households that are unable to find employment due to decreasing labor demand; either the households can remain in the economy and transition to a non-working status, or the household can exit the economy through the migration equation. In both cases, when using real state personal income as a measure of household welfare, the welfare of households that transition out of a working state as a result of the increasing carbon price is lost. For households that migrate out of the economy, their out of state earnings are not captured as the real state personal income equation includes only earnings from domestic labor supply. Alternatively, for households that transition to a non-working status, their receipt of government transfer payments is acknowledged, but any positive welfare they receive from having more leisure time, or supplying nonmarket labor, is unaccounted for.

Changes in the percentage of working households as a consequence of the rising carbon price stems primarily from changes in the real wage rate. As noted previously, CPI increases with the carbon price, leading to a decrease in the real wage rate. Labor supply elasticity with respect to the wage rate is negative across all household groups, so the decrease in the real wage rate leads to a decrease in the percentage of working households. Specifically, relative to the

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[26] The job correction factor is equal to the ratio of the total number of working households to the total number of jobs, both at their initial values. Its value is 0.694, implying there is 0.694 households per job, or alternatively, 1.44 jobs per household.

business as usual scenario, the implementation of the carbon reduction measures and the carbon price lead to a decrease in the percentage of working households from 76.4% to 76.2%. If we account for the positive economic impact of the initial zero price measures, which increase the percentage of working households to 76.6%, then the rising carbon price effectively decreases this percentage by 0.4%. This is equivalent to approximately 66,700 fewer households working "in state" in the model. The percentage, and the number of working households relative to the rising carbon price are shown in the upper and lower panel of Figure 2.7.

Out-migration in the model depends on the ratios of real household disposable income,[27] the percentage of non-working households, and spending on public education to their initial values, and their respective migration elasticities. In-migration depends on the inverse of these ratios, and the same migration elasticities. The migration elasticity with respect to real household disposable income and public education spending is positive, while the elasticity with respect to the percentage of non-working households is positive. In- and out-migration, and the total number of in-state households for an increasing carbon price are shown in the upper and lower panels of Figure 2.8. The implementation of the zero price measures causes the total number of households in the model to initially jump up, corresponding to a positive jump in in-migration and a negative jump in out-migration. As the carbon price increases, however, the negative effect of an increasing percentage of non-working households and decreasing public education spending outweighs the initial positive effect of an increase in real household disposable income, and in-migration decreases while out-migration increases. Overall, the total number of households in the model decreases by approximately 23,000 relative to the business as usual scenario, and by approximately 85,500 relative to the "zero price measures" scenario.

To obtain a measure of household welfare that does not exclude households that either transition to a nonworking status, or move out of state, we can calculate an adjusted SPI that includes estimates of the income or wellbeing of these households. As we are interested primarily in the effects of the rising carbon price on household welfare, we use the "0+" price, where all zero price measures are implemented, as our base case scenario. This leads to a higher starting level for both real SPI, and number of working households, than the business as usual baseline.

We can calculate average household income from labor employment as:

$$\text{Average Household Income} = \frac{\text{Total Labor Factor Income}}{\text{Working Households}}$$

As the carbon price increases, the number of working households generally declines at a faster rate than total labor factor income. The above measure of average labor income is therefore generally increasing as the carbon price increases. If we assume previously working households receive the same average income from working out of state, or an equivalent level of welfare from in state unemployment, then we can calculate an adjusted estimate of labor income as:

$$Y(L)' = Y(L) + (HW^0 - HW) \cdot \text{Average Household Income}$$

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[27] Real household disposable income is equal to after tax real SPI. As taxes are relatively constant throughout the model, real household disposable income moves closely with real SPI, first increasing as the carbon price increases and then decreasing.

where $Y(L)$ is the unadjusted level of labor income, HW^0 is the number of working households in the zero price measures scenario, and HW is the number of working households at the current carbon price. Using the adjusted estimate of labor income, the model calculates a labor adjusted real SPI, shown as the dashed line in Figure 2.9. The labor adjusted real SPI augments the original real SPI by including a proxy measure of income for all households that were initially working in-state after implementation of the zero price measures. The adjustment factor is increasing in both the change in the number of working households and average labor income. The difference between the real SPI, shown as the solid line in Figure 9, and real labor adjusted SPI therefore grows as the carbon price increases, and the real labor adjusted SPI initially increases at a faster rate. Similar to the real SPI though, the increase in CPI from the rising carbon price eventually outpaces the nominal growth in income, causing the real labor adjusted SPI to begin to decline at an approximate carbon price of 85. It declines at a slower rate than real SPI, however, and therefore remains above real SPI at all levels of the carbon price.

As a simple experiment, we can also consider what happens to the results of the model in a closed labor economy where no migration is allowed. The market equilibrium condition for labor supply must still hold, which means that if factor demand goes up and the labor market cannot rely on in-migration to supplement the work force then the wage rate must rise to encourage a greater number of nonworking households to seek employment. Likewise, if factor demand goes down and working households cannot exit the state, then there is an excess supply of workers that cannot be cleared and the wage rate must fall. These expected wage effects, and corresponding labor demand effects, are shown in the upper and middle panel of Figure 2.10. The initial positive economic effects of the zero price measures leads to a higher increase in labor demand, and a lower increase in the normalized real wage rate in the open economy where employers can recruit out of state workers to satisfy excess labor demand. In the closed economy, alternatively, employers are constrained by the initial population base. To expand the workforce the wage rate must increase by a larger amount, and labor demand therefore increases by a smaller amount. Specifically, when migration is allowed the normalized real wage rate increases only slightly from 100 to 100.03, whereas in the closed economy it jumps from 100 to 100.29. As the carbon price then begins to increase, the normalized real wage rate decreases at a faster rate in the closed economy, and eventually decreases below the wage rate in the open economy. When workers do not have the option of exiting the state they will be willing to work at lower wages in order to maintain their in-state employment. The result on the industry side is that labor demand decreases at a slower rate. As the price of carbon continues to increase, labor demand in the closed economy will therefore increase above labor demand in the open economy. Lastly, it is interesting to note that in moving from the open to the closed labor market, the maintenance of the labor supply equilibrium is met almost entirely through adjustments in labor demand and the wage rate. As shown in the bottom panel of Figure 2.10 the percentage of non-working households in the closed and open labor market are very similar, with the percentage increasing at a marginally lower rate in the closed labor market.

We can also consider how real SPI changes in response to the rising carbon price in the closed labor economy. The advantage of the closed economy when considering changes in real SPI is that our population base is constant, and we do not lose the income of in-state individuals who exit the model for employment out of state. The result, as shown by the dotted line in Figure 2.9, is a smoother path for real migration adjusted SPI in the closed economy. Originally real SPI increases by a smaller amount in the closed economy, as the lower factor demand relative to the open economy outweighs the higher wage rate and results in lower levels of factor income.

As the carbon price continues to increase, however, the rate of decline in unemployment is lower in the closed economy, and the increasing factor demand relative to the open economy begins to outweigh the faster declining wage rate. The increased labor demand keeps total factor income and thereby household income high, and real migration adjusted SPI declines at a slower rate.

2.4.2-4 Green Accounting

Our original calculation of real SPI is equivalent to a Gross Domestic Product calculation in that it includes only the value of income received by households within the state. The labor adjusted SPI calculation is closer to a Gross National Product calculation as we include a proxy in the real SPI calculation for income that is earned out-of-state by domestic households. It is an augmented version of GNP, however, in that it also places a value on nonmarket in-state labor, or leisure time, As a final step, we consider what happens when we apply the principles of "green accounting" to the real SPI calculation, and account for the fact that as the carbon price increases, the reduction in carbon provides increasing welfare to households through the reduction of carbon damages.[28] This is in keeping with the recommendation of Bergman (2005), that environmental CGE models quantify the benefits of pollution abatement and convert them to a monetary measure of environmental benefit.

Meta-analyses by Tol (2005, 2008) find that estimates of the social cost of carbon in climate change models depend heavily on assumptions regarding the discount rate and risk premiums. Reasonable estimates for these values, however, put the mean social cost of carbon in 1995 dollars in the range of \$16 - \$25 per metric ton (tC). Using the historical calendar year averages for CPI in the United States and California (California Department of Finance, 2012), this converts to a social cost of carbon in 2007 California dollars in the range of \$23 - \$36 per tC. For our estimates of avoided damages we assume a social cost of carbon in the middle of this range, \$29.50 per metric ton, which converts to \$0.0295 billion per MMT.

Real green adjusted SPI, which is adjusted for both the inclusion of out-of-state and nonmarket labor, and the benefits of reduced carbon, is shown as the upper dotted-dashed line in Figure 2.9. With the implementation of the zero price allowance measures, which lead to abatement of 129.5 MMT of carbon, real green adjusted SPI originally jumps up to a level approximately \$3.8 billion higher than real SPI. As the carbon price begins to increase, a \$1 increase in price generally leads to an increase in abatement of just under 2 MMT. Green adjusted SPI therefore increases at a nominally faster rate than labor adjusted, and real SPI. As the carbon price increases, the effect of a higher carbon price on marginal abatement decreases, falling to approximately a 1.0 MMT increase in abatement in response to a \$1 increase in the carbon price. The growth in the difference between real and labor adjusted SPI, and green adjusted SPI is therefore decreasing as the carbon price increases. Lastly, the growth in CPI due to the rising carbon price outpaces the growth in benefits from higher factor income and higher avoided damages at an approximate carbon price of \$101, at which point real adjusted green SPI begins to decline. Relative to labor adjusted real SPI, which begins to decline at an approximate price of \$85, accounting for the additional benefits of reduced damages from carbon further

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[28] Mäler (1990) and Hartwick (1991) both introduce the idea that the conversion from Gross National Product to Net National Product should include a deduction for the consumption of fixed capital, as well as a deduction (or addition) representing the change in a country's natural resource stock. By increasing abatement through the carbon tax, we are preserving the stock of clean air, which we treat as an increase in the value of the airshed.

increases the price range over which an increasing price of carbon can lead to increasing economic welfare.

2.5 Conclusion

In recent years California has been a leader in climate change regulation. In the CGE model results presented above, we see that contrary to the results of our simple theoretical model that predict a decrease in welfare from any increase in the regulated level of abatement, California's focus on carbon reduction measures that provide significant savings opportunities from decreased consumption in carbon producing sectors has the potential to create improvements in economic welfare. The "net savings" measures, which can be efficiently implemented at a zero price of carbon, are shown in the CGE model to be effective at achieving high levels of abatement. By lowering the overall price level and increasing employment opportunities, they also lead to a significant increase in real SPI. These results are consistent with the 2006 reports on California's initial climate change action plan (California Environmental Protection Agency, 2006), (Center for Clean Air Policy, 2006), (Roland-Holst, 2006a, 2006b), and the 2008 reports on California's Scoping Plan measures (California Air Resources Board, 2008), (Berck & Xie, 2010). It is prudent to note that we do not directly address the criticisms levelled against the 2006 studies by Stavins et al (2007). These include a lack of account of additional measure costs such as changes in product quality, required technological adaptation, or additional policies required to meet the measure targets. It is difficult to account for these costs in a CGE model as they are indirect, and difficult to measure. To the extent that they exist, however, our results for the zero price allowance measures may overstate the true positive economic impact. A more thorough investigation of how to best acccount for these additional costs is an area for future work.

With the introduction of a positive carbon price we begin to observe the negative economic impacts predicted by the theoretical model. The overall price level of production goods begins to rise, and production in carbon producing sectors, as well as related sectors that use output from carbon producing sectors as inputs, falls. In response, there is a decrease in labor demand, and an increase in out migration as households seek employment opportunities out of state. At low levels of the carbon price, the effect of these negative economic impacts on real SPI will be offset through the revenue recycling effect, which increases factor income through an increase in capital demand, and by returning to capital inputs 100% of the revenues raised by the tax. We consider only a lump sum revenue recycling effect, which is generally expected to create a smaller positive welfare effect than when revenues from the carbon tax are used to reduce marginal tax rates in distorted factor markets (Goulder, 1995b); for example, a reduction in personal income tax rates. This suggests that if we were to allow marginal tax rates to vary in response to the carbon price, then there are potentially further welfare gains from the rising carbon price that can be realized.

Currently, the carbon price at which real SPI begins to decline depends on the interplay between the opposing effects discussed above, as well as the definition of state income. If we include in our estimate of state income the welfare of nonworking households in-state, and working households that move out of state, as well as the positive effect of the reduction in damages from lower carbon emissions, then nominal state income will generally be increasing with the carbon price. The rising carbon price will thus have a positive impact on economic welfare over a significantly larger range of prices.

In the theoretical model we are unable to predict the shape of the indirect utility function with respect to increasing levels of abatement. In the solution to the CGE model, however, we see that for all specifications of state income, real SPI is concave with respect to the carbon price. The condition for convexity of the indirect utility function with respect to abatement exists as labor supply in the model is a normal good. The real wage rate decreases as the carbon price (abatement) increases. This is equivalent to a decrease in the price of leisure, and in response, the number of nonworking households increases; i.e., households choose to consume more leisure in response to the lower price. The input supply decision of households, however, is only one component of the expression that determines the shape of the indirect utility function. In the EDRAM-08 model the remaining components which favor concavity; particularly normal net output goods, and a decrease in output in non-carbon producing sectors in response to the rising carbon price; outweigh the effect of the household's input supply decision. The result is that our welfare measure, real SPI, is consistently concave in increasing levels of abatement.

These results show that in practice climate change regulation does not always come at a cost to economic welfare. Policy options exist for achieving mandated emissions reductions at a net savings to society, and effective management of the revenues from a positive carbon price can allow reasonable levels of the tax to be welfare improving. If governments identify and promote cost effective methods for achieving abatement, and if the full benefits of an abatement program are included in estimates of economic welfare, then well designed climate action plans can achieve significant abatement levels while also improving the wellbeing of individuals.

2.6 Figures

Figure 2.1: Dynamic & Static Conservation Supply Curves

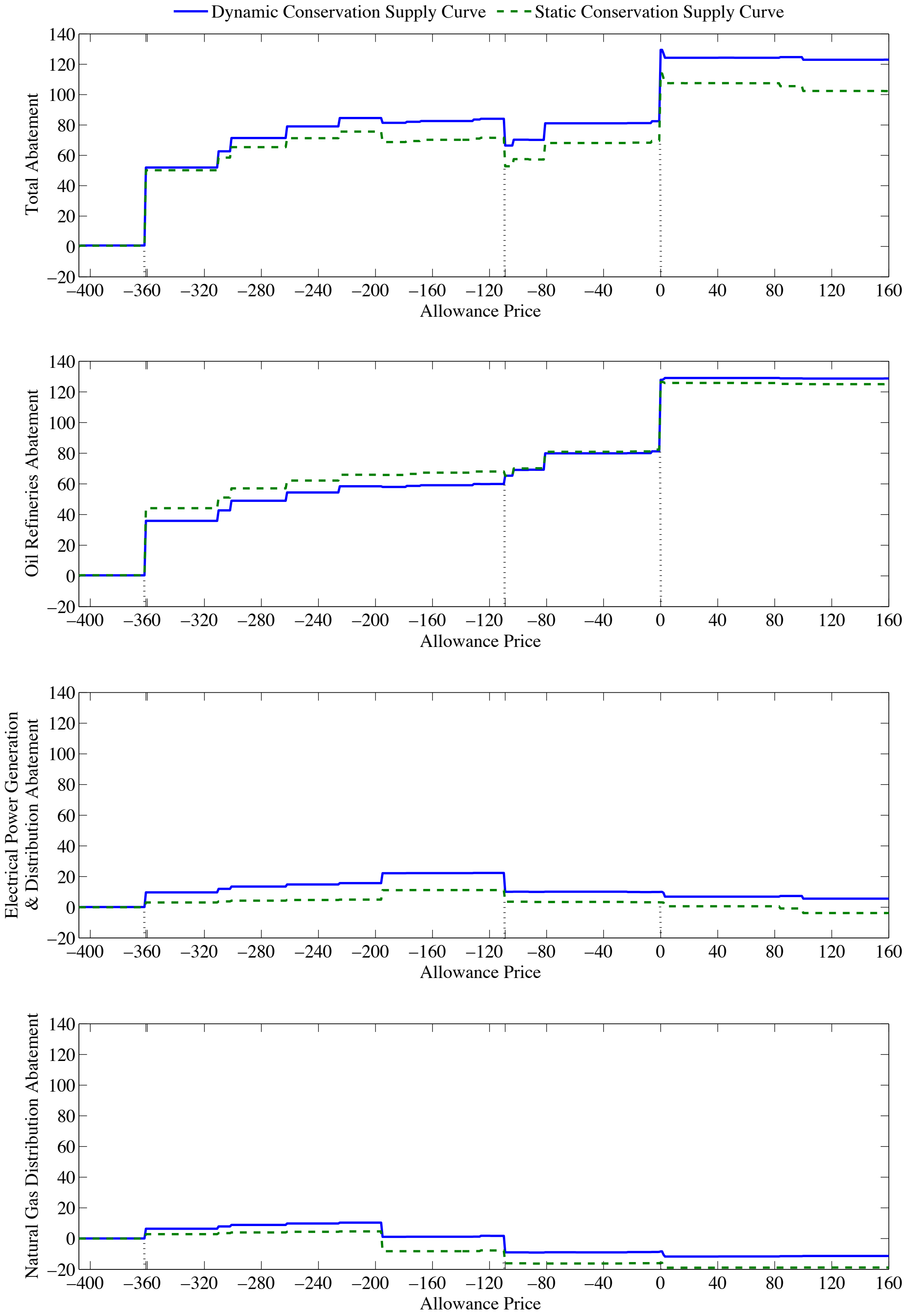


Figure 2.2: Domestic Dynamic & Static Conservation Supply Curves

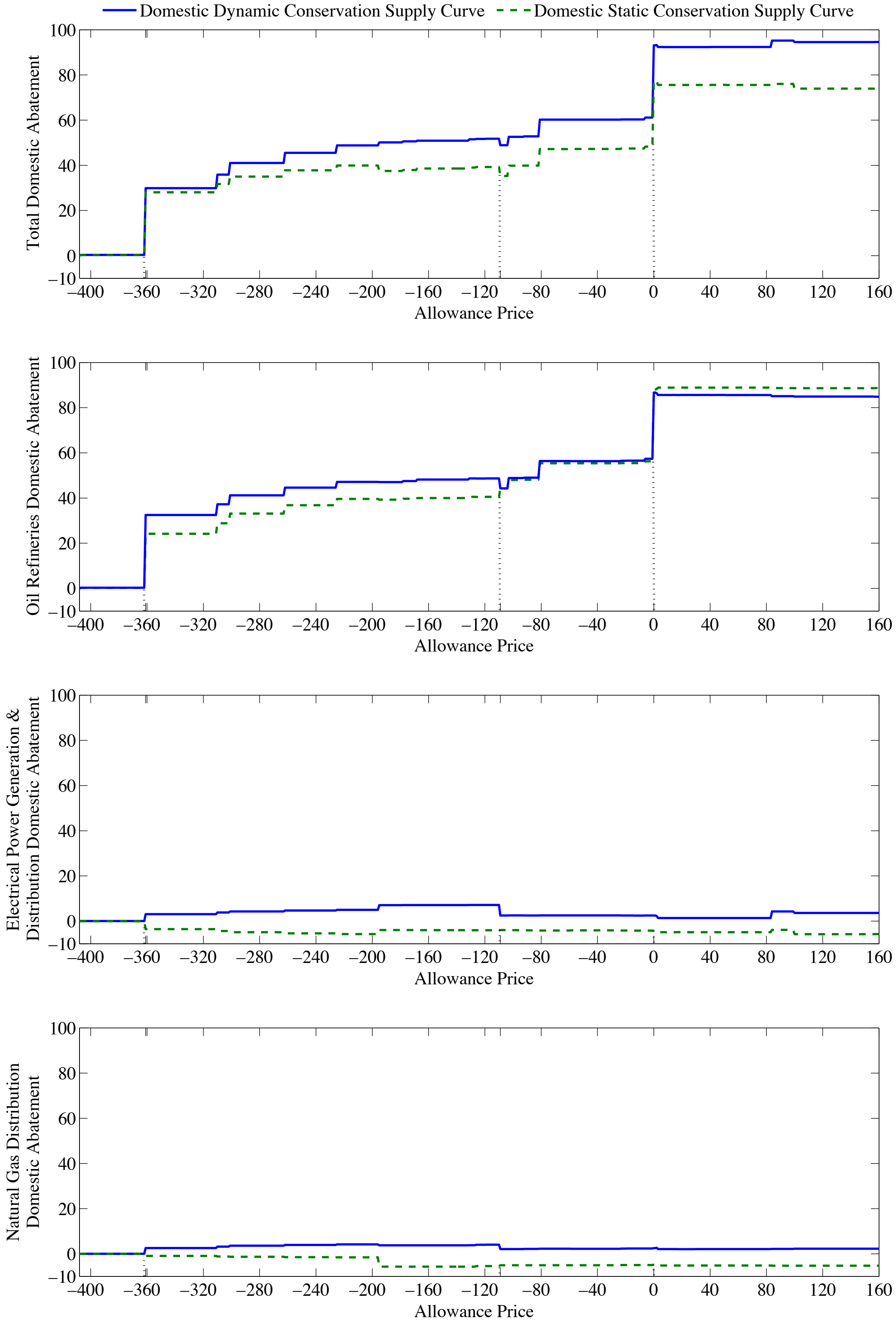


Figure 2.3: Dynamic Conservation Supply Curves, Positive Carbon Price

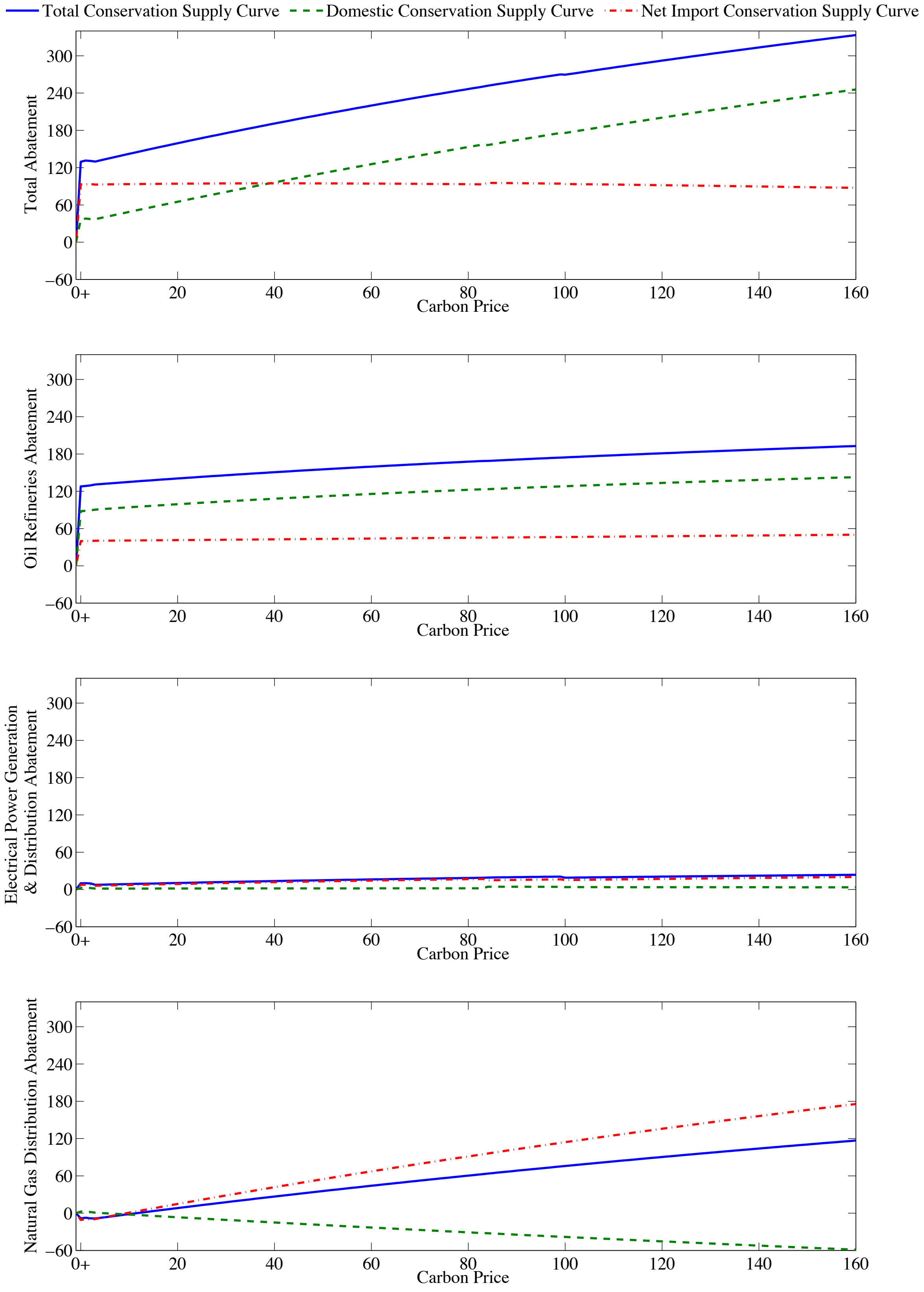
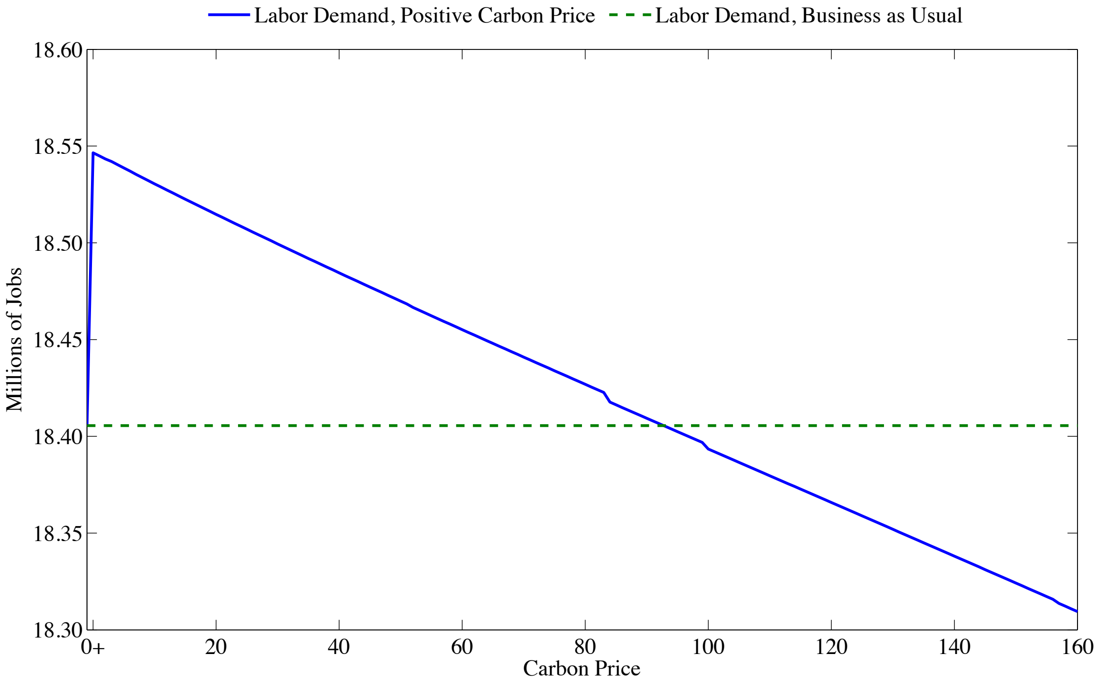


Figure 2.4: Labor and Capital Factor Demand, Positive Carbon Price



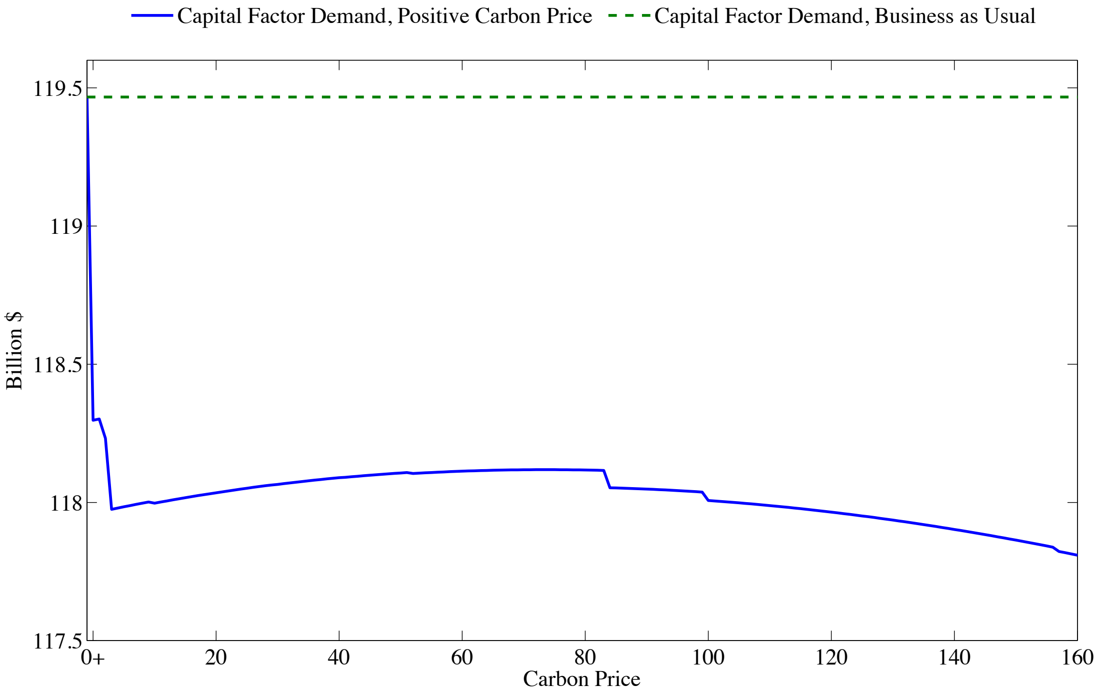


Figure 2.5: Real Factor Income, Positive Carbon Price

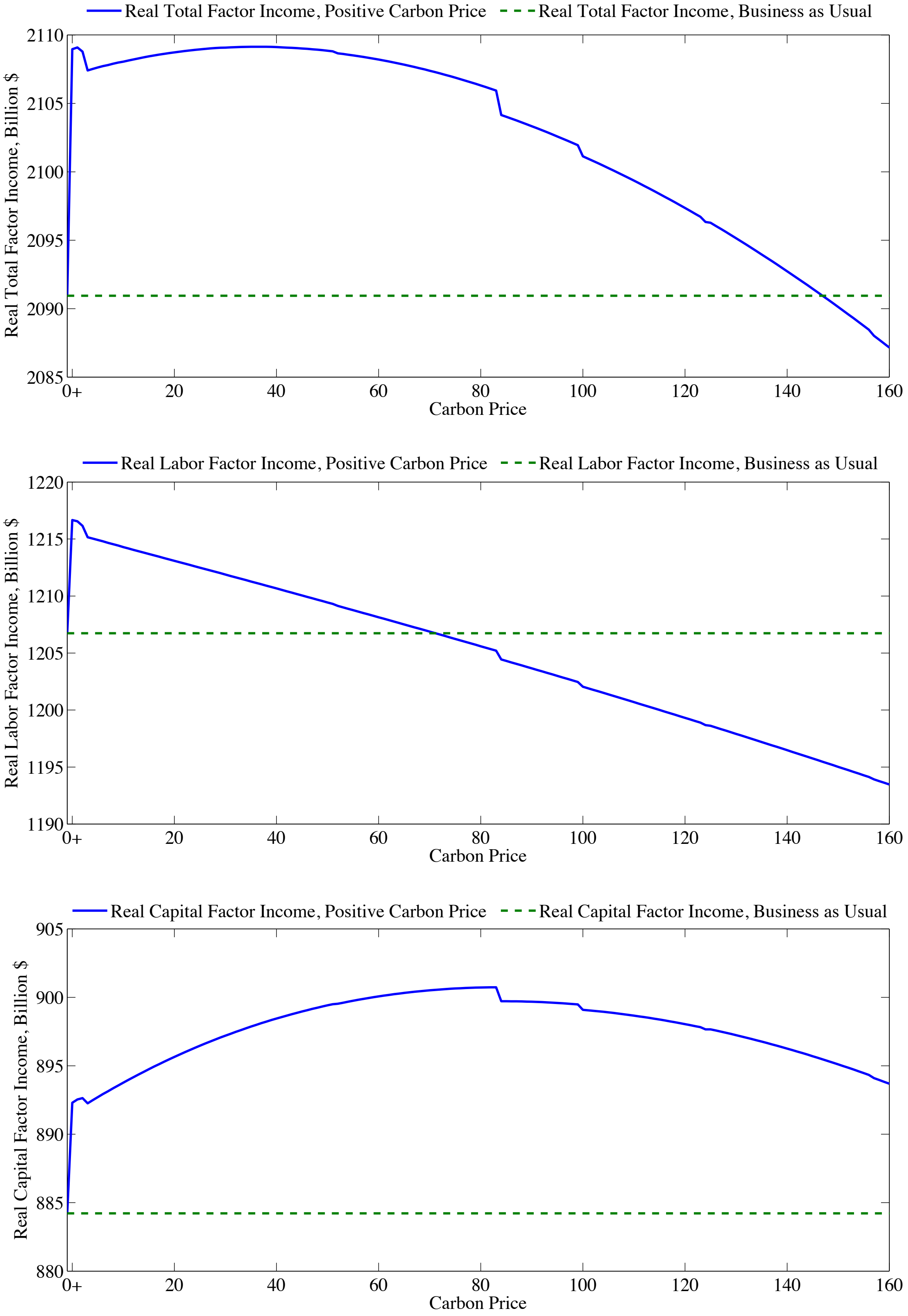


Figure 2.6: Real State Personal Income (SPI)

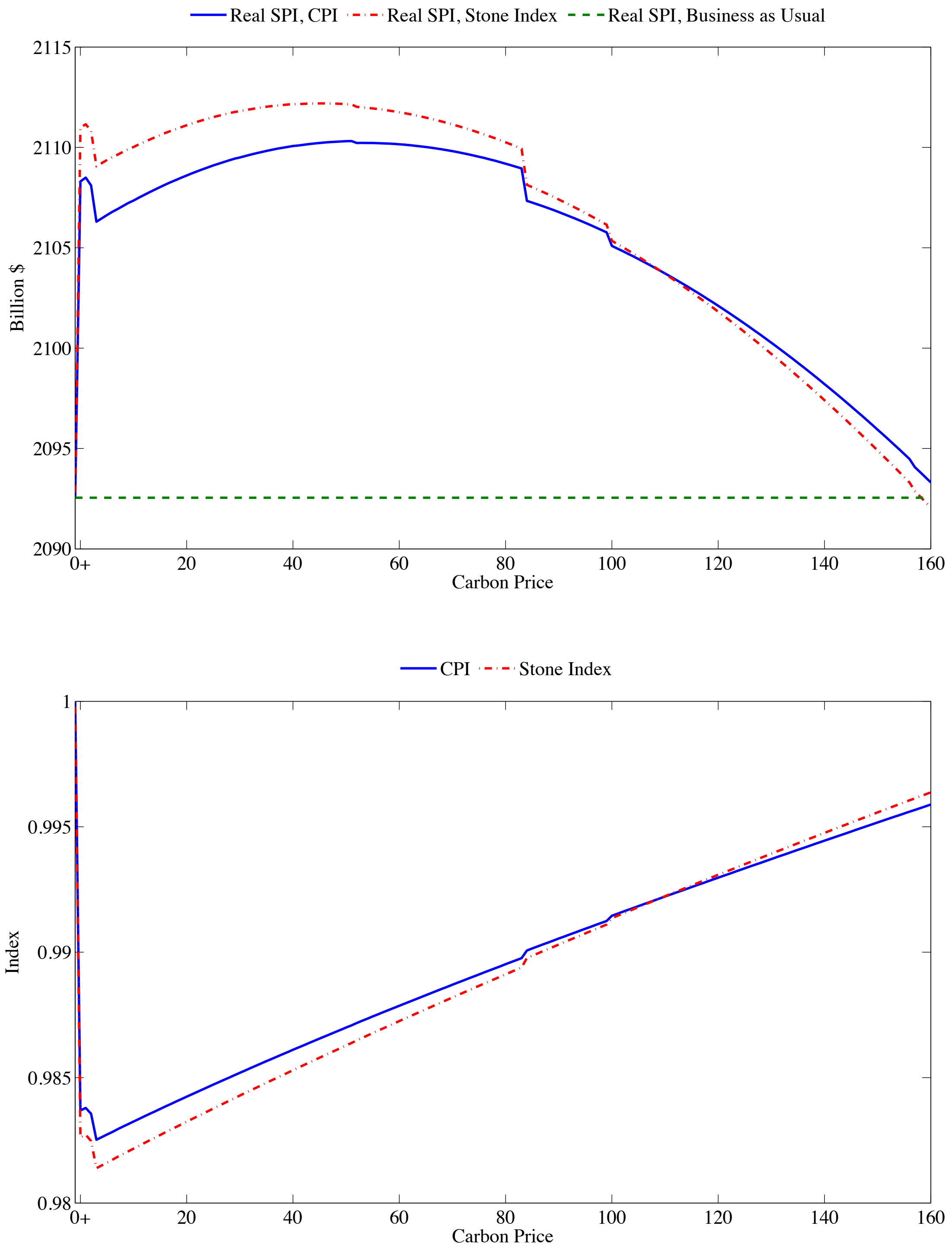


Figure 2.7: Working Households

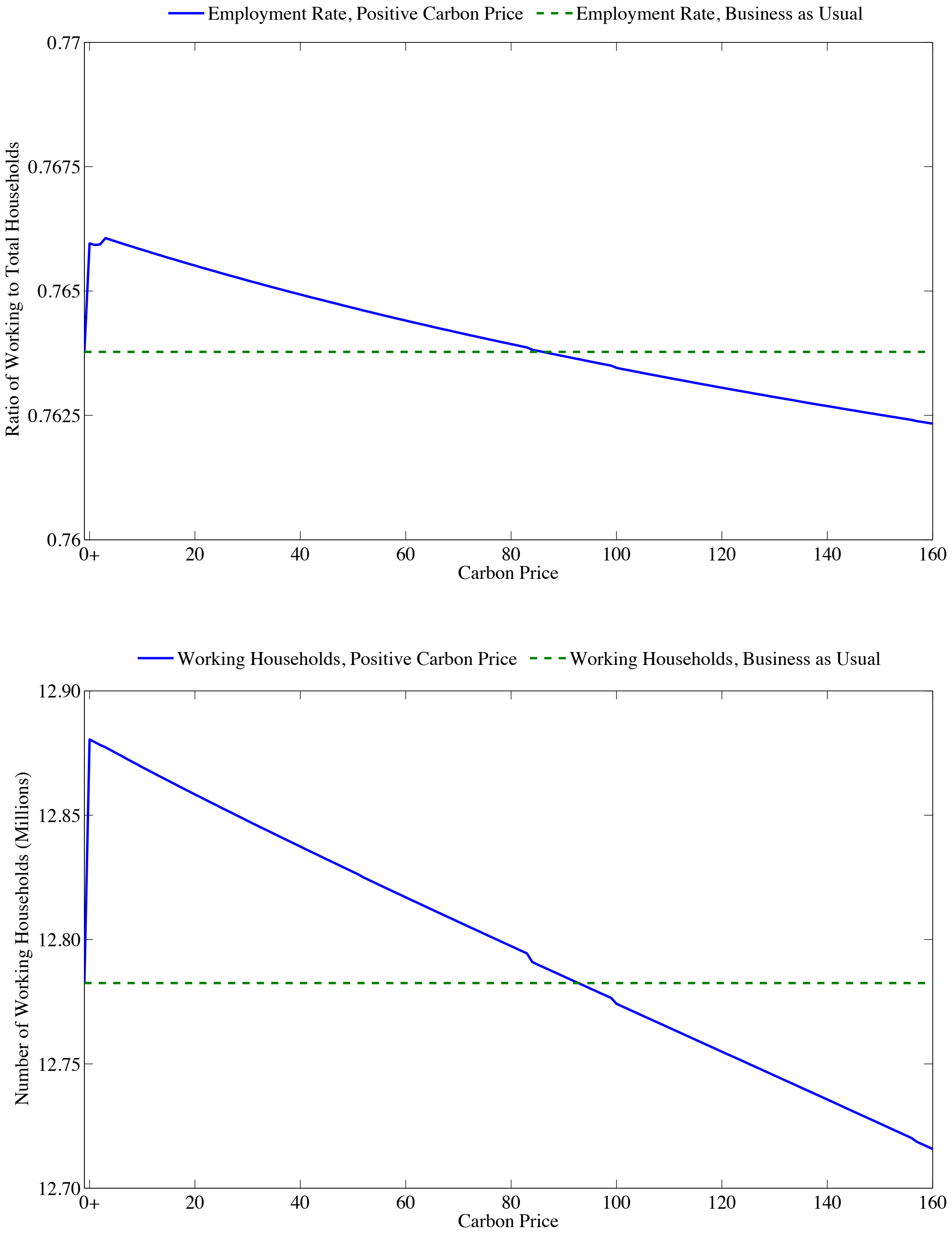


Figure 2.8: Migration & Population

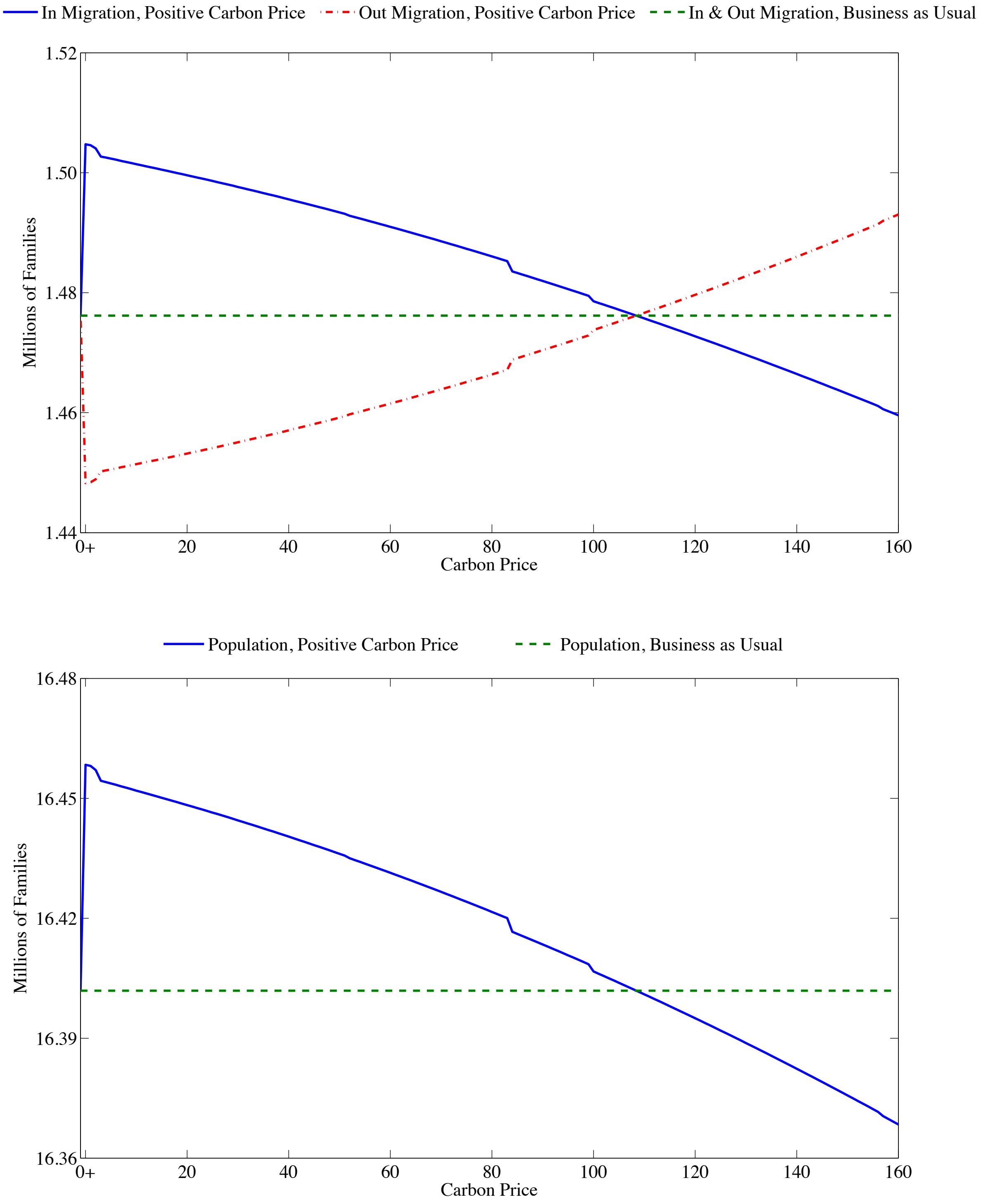


Figure 2.9: Adjusted Measures of Real SPI

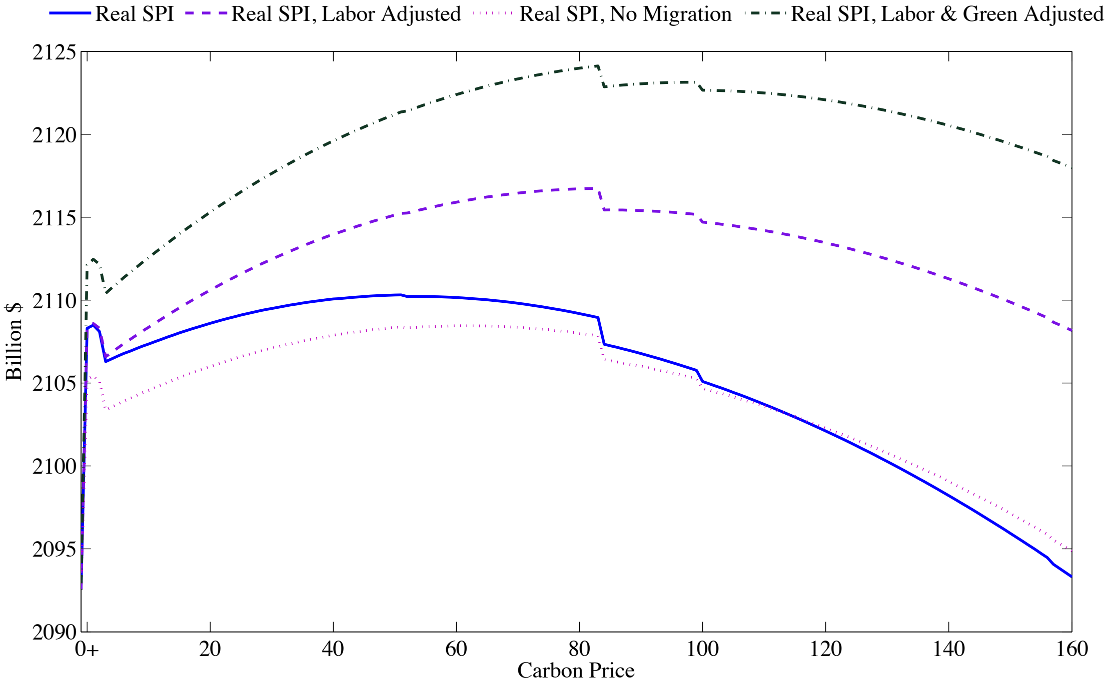
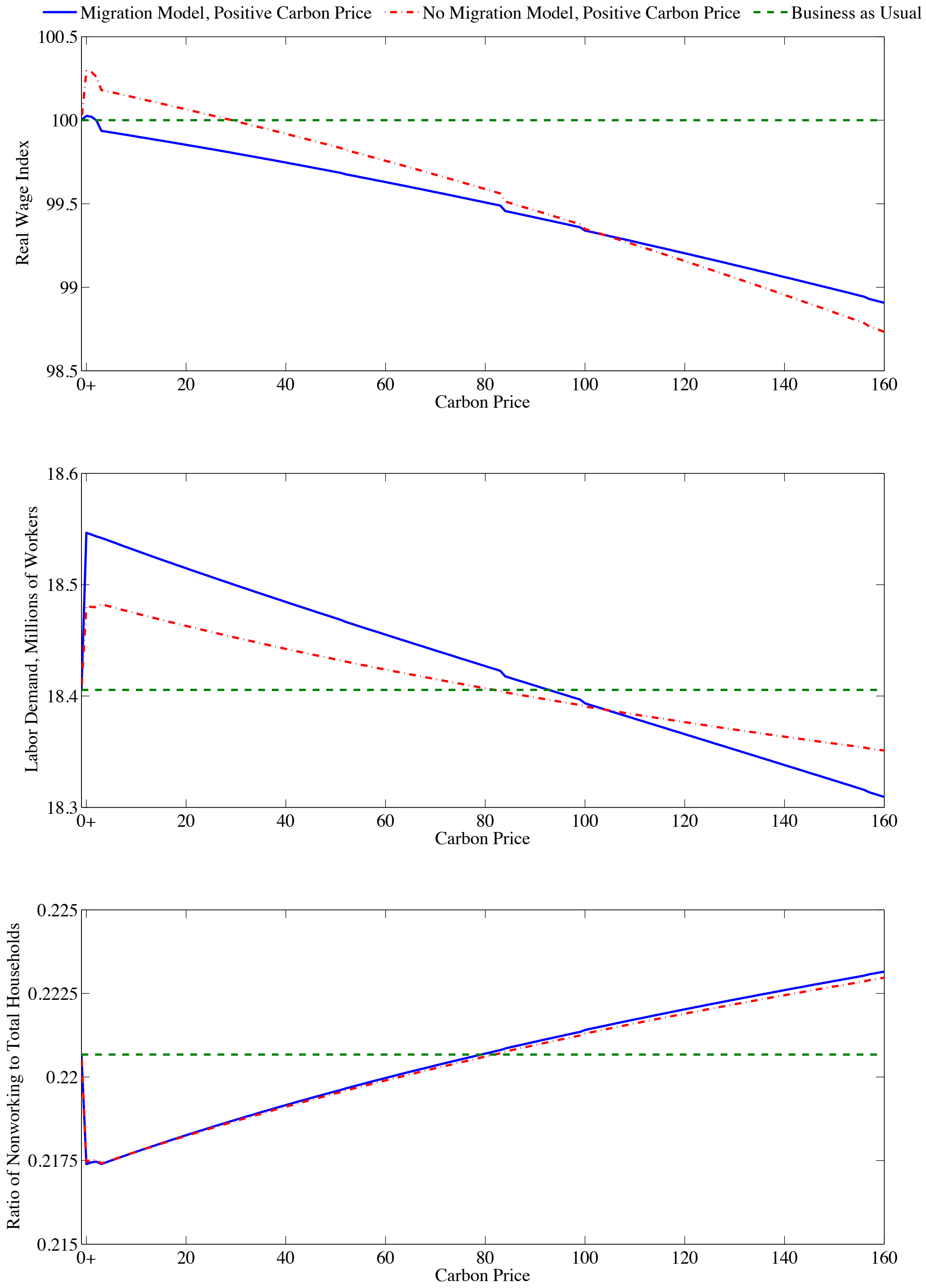


Figure 2.10: No Migration Model



2.7 Appendices

Appendix A: Industry & Commodity Sectors

INDUSTRY SECTORS
Agriculture, Forestry and Fishing
1. Agriculture
2. Cattle
3. Dairy
4. Forestry
Mining
5. Petroleum and Natural Gas Extraction
6. Mining
Utilities
7. Electrical Power Generation and Distribution
8. Natural Gas Distribution
9. Water Distribution and Sewage Treatment
Construction
10. Residential Construction
11. Nonresidential Construction
12. Street and Bridge Construction
13. Utility Infrastructure Construction
14. Other Construction Related Industry
Manufacturing
15. Food Manufacturing
16. Food Processing
17. Other Food Related Industry
18. Beverage and Tobacco Products
19. Textile and Leather Manufacturing
20. Apparel Manufacturing
21. Wood Products Manufacturing
22. Pulp and Paper Mills
23. Paper Products Manufacturing
24. Printing
25. Oil Refineries
26. Industrial Gas
27. Chemical and Drugs Manufacture
28. Basic Chemical Manufacture
29. Soaps and Detergents Manufacture
30. Other Chemical Products Manufacture
31. Plastics Manufacture
32. Glass Products Manufacture
33. Cement
34. Concrete
35. China and Clay Products

36. Primary Metals
37. Aluminum
38. Metal Fabrication
39. Machinery Manufacture
40. Refrigeration and Air Conditioning
41. Computer Manufacture
42. Communications Equipment Manufacture
43. Electronic Components Manufacture
44. Electronic Instruments Manufacture
45. Electronic Recording Media Manufacture
46. Electrical Equipment Manufacture
47. Automobile Manufacturing
48. Other Vehicle Manufacture
49. Motor Vehicle Body Manufacture
50. Motor Vehicle Parts Manufacture
51. Ship Building and Repair
52. Other Vehicle Manufacture
53. Aerospace Manufacture
54. Furniture
55. Laboratory and Dental Equipment
56. Miscellaneous Manufacturing
Wholesale Trade
57. Vehicle Services
58. Wholesale Durable Goods
59. Wholesale Non Durable Goods
60. Wholesale Gas
61. Wholesale Trade
Transportation and Warehousing
62. Transportation
63. Air Transportation
64. Railroad Transportation
65. Waterway Transportation
66. Truck Transportation
67. Public Transportation
68. Other Transportation
69. Vehicle Transportation
Retail Trade
70. Retail Vehicle and Parts
71. Retail Furniture
72. Retail Electronics and Appliances
73. Retail Building Materials
74. Retail Food and Beverage
75. Retail Health and Personal Care
76. Retail Gasoline Stations
77. Retail Clothing and Accessories

78. Retail Sporting Goods, Books, Music
79. Retail General Merchandise
80. Retail Miscellaneous
81. Retail Nonstore
Information
82. Motion Picture Industry
83. Other Broadcasting and Recording Industry
84. Telecommunications
85. Internet and Information Services
Finance, Insurance and Real Estate
86. Financial Services
87. Insurance
88. Banking
89. Real Estate
90. Other Financial
Services
91. Legal Services
92. Accounting
93. Architecture
94. Design
95. Computer Related Services
96. Consulting
97. Research
98. Advertising
99. Other Professional Services
100. Business Services
101. Temporary Administrative Services
102. Security Services
103. Building Maintenance
104. Other Administrative Services
105. Waste Management
106. Landfills
107. Education
108. Medical Services
109. Hospitals
110. Nursing
111. Day Care
112. Recreation and Entertainment
113. Amusement Parks
114. Hotels
115. Full Service Restaurants
116. Fast Food
117. Caters and Mobile Food Services
118. Drinking Establishments
119. Personal Services

COMMODITY SECTORS
1. Food and Beverage
2. Shelter
3. Fuel and Utilities
4. Household Furnishing and Operation
5. Apparel and its Upkeep
6. Transportation
7. Medical Care
8. Entertainment
9. Other Goods and Services

Appendix B: Measures Description

Measure Number[29]	Measure Name	Allowance Price	Measure Shock		
			“Selling” (Output) Sector	“Purchasing” (Input) Sector	Value[30]
TRANSPORTATION SECTOR					
T-1	Pavley I – Light Duty Vehicle Greenhouse Gas Reduction Standards (Adopted Regulation)	-361	Automobile Manufacturing	Industry	316
			Oil Refineries	Industry	-2618
			Industry	Commodity Transportation	1056
			Retail Gasoline Stations	Commodity Transportation	-8763
	Pavley II – Light Duty Vehicle Greenhouse Gas Reduction Standards (Adopted Regulation)	-262	Industry	Commodity Transportation	594
			Retail Gasoline Stations	Commodity Transportation	-1643
T-2	Low Carbon Fuel Standard (LCFS)	0	Agriculture	Retail Gasoline Stations	6812.5
			Basic Chemical Manufacture	Retail Gasoline Stations	4187.5
			Oil Refineries	Retail Gasoline Stations	-11,000
T-3	Regional Transportation-Related Greenhouse Gas Reduction Targets	-310	Street and Bridge Construction	CA Government Spending Transportation	250
			Industry	Local Government Spending Transportation	250
			Retail Gasoline Stations	Commodity Transportation	-2054
T-4	Vehicle Efficiency Measures				
	Tire Pressure Program	-131	Retail Vehicles and Parts	Commodity Transportation	151.92
			Retail Gasoline Stations	Commodity Transportation	-224.1
	Tire Tread Standard	-407	Vehicle Parts	Commodity Transportation	0.625
			Retail Gasoline Stations	Commodity Transportation	-123
	Low Friction Engine Oils	-225	Retail Vehicles and Parts	Commodity Transportation	520
			Retail Gasoline Stations	Commodity Transportation	-1150

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[29] Listed measure number matches to the measure numbers in the Scoping Plan. “Other” indicates a measure not included in the Scoping Plan, but listed in the background spreadsheet data for the EDRAM-08 model.

[30] Units is millions of dollars. A negative amount indicates a reduction in purchases (savings) by the “Purchasing” sector from the “Selling” sector, while a positive amount indicates an increase in purchases (costs). Measures with an amount of “0” or “TBD” are not included in the model run.

Measure Number[29]	Measure Name	Allowance Price	Measure Shock		
			"Selling" (Output) Sector	"Purchasing" (Input) Sector	Value[30]
T-4	Solar Reflective Automotive Paints and Window Glazing	-6	Automobile Manufacturing	Commodity Transportation	360
			Retail Gasoline Stations	Commodity Transportation	-366
T-5	Ship Electrification at Ports (Adopted Regulation)	0	Electrical Power Generation and Distribution	Waterways Transportation	0
			Oil Refineries	Waterways Transportation	0
T-6	Goods Movement Efficiency Measures	TBD	Industry	Transportation	TBD
			Oil Refineries	Transportation	TBD
T-7	Heavy-Duty Vehicle Greenhouse Gas Emission Reduction (Aerodynamic Efficiency)	-81	Industry	Truck Transportation	1747
			Oil Refineries	Truck Transportation	-2268
T-8	Medium- and Heavy- Duty Vehicle Hybridization	-168	Industry	Truck Transportation	93
			Oil Refineries	Industry	-177
T-9	High-Speed Rail	0	TBD	TBD	0
Other	Feebates for New Vehicles	-301	Automobile Manufacturing	Commodity Transportation	594
			Retail Gasoline Stations	Commodity Transportation	-1800.18
Other	Heavy Duty Engine Efficiency	-178	Industry	Truck Transportation	26
			Oil Refineries	Truck Transportation	-133
ELECTRICITY AND NATURAL GAS SECTOR					
E-1	Electrical Energy Efficiency (32,000 GWh)	-109	Industry	Electrical Power Generation and Distribution	3402
			Electrical Power Generation and Distribution	Commodity Fuel and Utilities	-5065
	Additional Electricity Efficiency (8000 GWh)	3	Industry	Electrical Power Generation and Distribution	1276
			Electrical Power Generation and Distribution	Commodity Fuel and Utilities	-1266
CR-1	Natural Gas Energy Efficiency (800 million therms)	-109	Industry	Natural Gas Distribution	963
			Natural Gas Distribution	Commodity Fuel and Utilities	-1433
	Additional Natural Gas Efficiency (additional 200 million therms)	2	Industry	Natural Gas Distribution	369
			Natural Gas Distribution	Commodity Fuel and Utilities	-367

Measure Number[29]	Measure Name	Allowance Price	Measure Shock		
			"Selling" (Output) Sector	"Purchasing" (Input) Sector	Value[30]
CR-2	Solar Water Heating (AB 1470 Goal)	2086	Industry	Commodity Household Furnishing and Transportation	452
			Natural Gas Distribution	Commodity Fuel and Utilities	-160
E-2	Increase Combined Heat and Power	-195	Industry	Natural Gas Distribution	1108
			Machinery	Industry	362
			Electrical Power Generation and Distribution	Industry	-2781
E-3	Renewable Portfolio Standard (33% by 2020)	84	Industry	Electrical Power Generation and Distribution	3672
			Petroleum and Natural Gas Extraction	Electrical Power Generation and Distribution	-1889
E-4	Million Solar Roofs	481	Electrical Equipment Manufacture	Commodity Household Furnishing and Transportation	1348
			Electrical Power Generation and Distribution	Commodity Fuel and Utilities	-339
Other	Reduce Coal Generation by 20,000 GWh	100	Industry	Electrical Power Generation and Distribution	850
INDUSTRY SECTOR					
I-1	Energy Efficiency and Co-Benefits Audits for Large Industrial Sources	TBD	TBD	TBD	TBD
I-2	Oil and Gas Extraction Greenhouse Gas Emission Reduction	-18	Machinery Manufacture	Petroleum and Natural Gas Extraction	0.4
			Industry	Petroleum and Natural Gas Extraction	-4.1
I-3	Greenhouse Gas Leak Reduction from Oil and Gas Transmission	-19	Machinery Manufacture	Petroleum and Natural Gas Extraction	0.51
			Industry	Petroleum and Natural Gas Extraction	-17.7
I-4	Refinery Flare Recovery Process Improvements	-119	Machinery Manufacture	Oil Refineries	6.65
			Industry	Petroleum and Natural Gas Extraction	-46.1

Measure Number[29]	Measure Name	Allowance Price	Measure Shock		
			“Selling” (Output) Sector	“Purchasing” (Input) Sector	Value[30]
I-5	Removal of Methane Exemption from Existing Refinery Regulations	43	Industry	Oil Refineries	3.3
			Oil Refineries	Industry	-2.7
I-Other	Carbon Intensity Standard for Cement Manufacturers	-1	Industry	Cement	19.34
			Petroleum and Natural Gas Extraction	Cement	-22.75
	Carbon Intensity Standard for Concrete Batch Plants	0	Industry	Concrete	0
			Cement	Concrete	0
	Waste Reduction in Concrete Use	-23	Industry	Concrete	55
			Nonresidential Construction	Concrete	-83
	Refinery Energy Efficiency Process Improvements	-103	Machinery Manufacture	Oil Refineries	64.5
			Petroleum and Natural Gas Extraction	Oil Refineries	-415
	Oil and Gas Extraction Combustion Related Greenhouse Gas Emission Reduction	-92	Machinery Manufacture	Petroleum and Natural Gas Extraction	51.9
			Electrical Power Generation and Distribution	Petroleum and Natural Gas Extraction	55
			Industry	Petroleum and Natural Gas Extraction	-273.8
	Greenhouse Gas Combustion Related Emissions Reduction from Oil and Gas Transmission	-14	Machinery Manufacture	Petroleum and Natural Gas Extraction	2.81
			Electrical Power Generation and Distribution	Petroleum and Natural Gas Extraction	12
			Industry	Petroleum and Natural Gas Extraction	-16.3
	Industrial Boiler Efficiency	-126	Machinery Manufacture	Industry	22.85
			Natural Gas Distribution	Industry	-149.7
	Stationary Internal Combustion Engine Electrification	-23	Electrical Power Generation and Distribution	Industry	77.9
			Machinery Manufacture	Industry	17.9
			Natural Gas Distribution	Industry	-60.9
			Oil Refineries	Industry	-41.9
Other	Glass Manufacturing Efficiency	41	Machinery Manufacture	Glass Products Manufacture	14.6
			Natural Gas Distribution	Glass Products Manufacture	-8.5

Measure Number[29]	Measure Name	Allowance Price	Measure Shock		
			"Selling" (Output) Sector	"Purchasing" (Input) Sector	Value[30]
RECYCLING & WASTE SECTOR					
RW-1	Landfill Methane Control	52	Industry	Landfills	52
HIGH GLOBAL WARMING POTENTIAL					
H-1	Motor Vehicle Air Conditioning Systems: Reduction of Refrigerant Emissions from Non-Professional Servicing (Discrete Early Action)	12	Motor Vehicle Parts Manufacture	Commodity Transportation	3
H-2	SF6 Limits in Non-Utility and Non-Semiconductor Applications (Discrete Early Action)	1	Machinery Manufacture	Industry	0.22
			Basic Chemical Manufacture	Industry	-0.14
H-3	Reduction of Perfluorocarbons in Semiconductor Manufacturing	18	Industry	Electronic Components Manufacture	2.6
H-4	Limit High Global Warming Potential Use in Consumer Products (Discrete Early Action)	1	Industry	Other Chemical Products	0.06
H-5	High Global Warming Potential Reductions from Mobile Sources				
	Low Global Warming Potential Refrigerants for New Motor Vehicle Air Conditioning Systems	7	Automobile Manufacturing	Commodity Transportation	15.8
	Air Conditioner Refrigerant Leak Test During Vehicle Smog Check	4	Retail Vehicles and Parts	Commodity Transportation	1.69
	Refrigerant Recovery from Decommissioned Refrigerated Shipping Containers	9	Basic Chemical Manufacture	Truck Transportation	1.69
	Enforcement of Federal Ban on Refrigerant Release During Servicing of Dismantling of Motor Vehicle Air Conditioning Systems	17	Machinery Manufacture	Vehicle Services	1.69
	High Global Warming Potential Reduction from Stationary Sources				
H-6	High Global Warming Potential Refrigerant Tracking/Reporting/ Repair/Deposit Program	0	Industry	Retail Food and Beverage	1
			Basic Chemical Manufacture	Retail Food and Beverage	-3.6
	Specifications for Commercial and Industrial Refrigeration	1	Electrical Equipment Manufacture	Industry	1.24
			Electrical Power Generation and Distribution	Industry	-0.66
	Foam Recovery and Destruction Program	30	Waste Management	Industry	9

Measure Number[29]	**Measure Name**	**Allowance Price**	**Measure Shock**		
			"Selling" (Output) Sector	**"Purchasing" (Input) Sector**	**Value[30]**
H-6	SF6 Leak Reduction and Recycling in Electrical Applications	-1	Industry	Electrical Power Generation and Distribution	0.3
			Basic Chemical Manufacture	Electrical Power Generation and Distribution	-0.42
	Alternative Suppressants in Fire Protection Systems	18	Basic Chemical Manufacture	Building Maintenance	2
			Industry	Basic Chemical Manufacture	-0.2
	Residential Refrigeration Early Retirement Program	-59	Electrical Equipment Manufacture	Commodity Household Furnishing and Operation	18.9
			Electrical Power Generation and Distribution	Commodity Household Furnishing and Operation	-24.8
AGRICULTURE					
A-1	Methane Capture at Large Dairies	157	Metal Fabrication	Dairy	156.3
FORESTRY					
F-1	Sustainable Forest Target	10	Forestry	California Spending Other	50

Chapter 3: Impact of Emissions Reductions on Acidified Lake Recovery

3.1 Introduction

Freshwater lakes offer significant value to society through both market and nonmarket benefits. Market benefits include drinking water, transportation and recreation opportunities, and irrigation, while nonmarket benefits include biodiversity, support for terrestrial and aquatic ecosystems, natural beauty, and the simple "existence value" that individuals derive from knowing healthy lakes are a part of the environment (Wilson & Carpenter, 1999). In many regions, the provision of these benefits is being threatened by two sources of environmental damages; eutrophication and acidification. Both eutrophication and acidification occur when there is excess deposition of pollutants in a lake, which overload its natural chemical balance. Both can also be tracked to human sources, with eutrophication occurring primarily as a result of agricultural fertilizers, and acidification attributable to industrial emissions. Given the impacts of these damages on lake benefits, there is increasing concern and interest in determining how to properly manage pollutant depositions so as to either prevent freshwater lakes from moving into an acidified or eutrophic state, or to aid them in recovery from these states.

In this essay I focus on the optimal management of point source industrial emissions to aid in the recovery of freshwater lakes from acidification. I develop a dynamic programming model of lake recovery that accounts for damages from acidification, the cost of emissions reductions, and the current environmental state of the lake. Using numerical solution methods, I consider how the optimal abatement policy changes in response to changing environmental conditions, and different assumptions for the degree of damages from acidification.

Integrated Assessment Models (IAMs) are broadly used in environmental and resource economics to capture the interaction between economic objectives and constraints, and dynamic environmental systems. As ecologists recognize, the complex dynamics of environmental systems substantially affect the states of the world in which the economic system operates (Batabyal et al, 2003). IAMs have therefore become an important tool for linking environmental and economic systems, and are used extensively in the literature considering the impacts of acidification and eutrophication.

IAMS applied to lake dynamics focus primarily on the problem of eutrophication. A eutrophic lake may be reversible, hysteretic, or irreversible.[31] This variance in lake type is an important component of eutrophication models. Carpenter et al (1999) develop a general model of eutrophication in which they solve for the optimal phosphorus input rates to a single lake under various assumptions regarding certainty over the reversibility of the lake, and the value of the discount rate. While the model is based on deterministic lake dynamics, an important observation of Carpenter et al is that in a more realistic situation where sources of variability exist, reductions in phosphorus input levels should be below the optimal rates the model describes. They note this result extends to other situations where pollution causes nonlinear changes in an ecosystem state, such as acid deposition. Nævdal (2001) focuses on the varying

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[31] A reversible lake is one in which eutrophication can be reversed by the reduction of pollution input controls alone. A hysteretic lake is one that can be reversed from its eutrophic state, but requires a perturbation to the lower phosphorous steady state using interventions such as aluminum sulphate treatment or biomanipulation. An irreversible lake is one in which no feasible reduction of pollution input controls or chemical intervention can bring the lake out of its eutrophic state (Carpenter et al, 1999).

reversibility of lakes and the threshold effects of eutrophication. He finds the optimal path for the reduction of nutrients into the lake is dependent on whether the lake is eutrophying in the initial time period, the number of times it is optimal for the lake to cross the threshold, and whether a eutrophying lake is reversible. Hein (2006) develops a eutrophication model with threshold effects and two steady states, one corresponding to a eutrophic lake and a second corresponding to an oligotrophic lake.[32] He uses an explicit ecological-economic model in which lake dynamics are modeled by a set of equations obtained through regression analysis of long-term water quality data for a shallow lake ecosystem. He combines this with information on the supply of ecosystem services and the costs of different control measures to determine the optimal control policy on nutrient inputs to the lake.

When using IAMs to look at the impact of acidification, the focus has been primarily on terrestrial ecosystems. The first major work by Kaitala et al (1992) considers the optimal emissions regulatory policies of Finland and the Soviet Union within a game-theoretic framework. In another application to Europe, Schmieman and van Ierland (1999) develop an optimal control model to identify cost effective European abatement policies for the combined reduction of SO_2 and NO_x. Schmieman et al (2002) expand upon previous work by considering the interaction between the problems of acidification and tropospheric ozone pollution. All of these papers solve an optimal control problem, in which a social welfare function representing economic objectives is maximized subject to environmental state equations that describe how soil quality changes over time. The solutions provide estimates of the optimal emission rates, and abatement strategies, for the prevention of soil acidification.

In this essay I focus on developing an economic-ecological model of lake acidification. I use the terrestrial acidification models to understand the dynamics of acid deposition, and the eutrophication models to understand the non-linearities of lake response to changes in chemical depositions, and the process of recovery from a polluted state. While I use previous work as a basis for developing my model, I also make a number of contributions to the literature. First, I model the dynamics of lake acidification, and set up an optimal control framework for evaluating the implementation of emissions reductions for the recovery of acidified lakes. In addition, while I develop the theoretical model for a representative lake, I estimate the state equations using a panel data set which tracks the water quality of a region of freshwater lakes located in Northern, Ontario, Canada. Finally, whereas previous work on acidification focuses on preventative measures for the deterioration of soil quality, I develop a model which emphasizes recovery from acidification, with the ultimate goal of returning a lake to its natural state.

Terrestrial and aquatic acidification in Northern Ontario is primarily attributable to nickel mining activities by two firms, INCO and Falconbridge, both of which are centered in the City of Sudbury.[33] At their peak in 1960, total annual sulphur dioxide emissions from smelter operations in Sudbury exceeded 2,560 kilotonnes (kt). This represents more than 4% of estimates of total global anthropogenic sulphur dioxide emissions at the time (Freedman, 1995), (Lefohn et al, 1999). Estimates indicate over 7,000 lakes located within a 17,000 km^2 area of Sudbury were

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[32] An oligotrophic lake is characterized by low nutrient content and low plant growth. The lake waters are clear and oxygen levels are high, particularly in the bottom waters. Oligotrophic lakes are therefore a good environment for many fish species, and generally provide high recreational benefits.

[33] The facilities of INCO and Falconbridge continue to mine nickel in the Sudbury region. However, both firms were bought out in the mid-2000s and now operate under new company names. INCO is now known as Vale, and Falconbridge as Xstrata. I refer to both firms by their historical names throughout this essay.

acidified to pH < 6.0, the point at which significant biological damage starts to occur (Keller et al, 1999).

Beginning in 1970, the Government of Ontario introduced a series of intensifying controls on SO_2 emissions, and by 2005, emissions by INCO and Falconbridge had been reduced to over 90% below their peak 1960 levels. Over this same time period, substantial water quality improvements in the lakes surrounding Sudbury, measured by increases in the pH and alkalinity levels of lake water, were observed. In this essay I focus on the period of 1981-2004, during which 44 acidified lakes located within 128 km of Sudbury were annually sampled as part of the Sudbury Environmental Study (SES) Extensive Monitoring Programme. This provides me with a panel data set of water quality observations that are improving over a time period of significantly decreasing SO_2 emissions. Specifically, the results of the monitoring programme indicate an average increase in the pH of lake water from 4.87 to 5.57, and an average increase in alkalinity from -0.91 to 0.29. Over this same time period, total annual SO_2 emissions in the Sudbury area were reduced from 847 kt per year to 243 kt.

My objective is to parameterize and solve a dynamic programming problem that determines how to optimally implement emissions reductions intended to achieve the recovery of a group of representative lakes in the Sudbury area from acidification. I assume the regulator chooses the level of SO_2 emissions each period to minimize a social welfare function, which I define as the sum of the disutility from lake acidification and the cost of abatement by firms. I measure the disutility of lake acidification by the deviation of current period pH and alkalinity levels from the expected pH and alkalinity levels of a lake in its natural state. The cost of abatement by firms is a quadratic function that is increasing in the level of abatement. Since abatement cannot be directly observed, I approximate it by the difference between the level of emissions chosen by the regulator, and the level of emissions I expect the firms to choose in the absence of regulation. Within the model, I assume lake water quality changes over time according to linear state equations for both pH and alkalinity. The state equations are a function of lagged values of lake water quality (pH and alkalinity levels from the previous period), and an estimate of acid depositions at a particular lake site in the current period. I use observed emissions by INCO and Falconbridge, and the data on lake recovery from the SES extensive monitoring programme, to estimate the parameters for the state equations. Consistent with the programme results, I find water quality is increasing over time, and that decreases in acid depositions will have a positive effect on water quality.

In the final step, I use the estimated state equations to solve the dynamic programming problem for the optimal path of emissions reductions by a single firm over the period of 1981-2004. As I am solving the problem for a group of representative lakes, I assume the initial values of lake water quality are equal to the average value in 1981 of pH and alkalinity for the 44 lakes in the SES extensive monitoring programme. I further assume the firm's chosen level of emissions in the absence of regulation is equal to the total 1981 level of emissions by INCO and Falconbridge of 837 kt. I find the solution to the dynamic programming problem relies heavily on the assumption of the level of damages from deviation of a lake from its natural state. At reasonable estimates of damages, the simulated path of optimal emissions reduction is very small, and significantly below observed levels of abatement over the same time period. As the value of damages increases, the control rule approaches a step function where the optimal policy is to abate all emissions when lake quality is low, and none of the emissions when lake quality is high. In this solution, there is only a narrow, intermediate range of pH where partial abatement is optimal. The pH level at which optimal abatement jumps from zero to full abatement is decreasing in the level of damages, and increasing in the value of lake water alkalinity.

It is important to note in considering the result of zero abatement at reasonable levels of damage estimates that emissions reductions in the Sudbury area began over 10 years prior to the start of the period for which annual data on lake water quality is available, and that combined emissions of INCO and Falconbridge decreased by over 1700 kt from their peak during this prior period. While changes in lake acidification are expected to lag behind changes in depositions (Chestnut & Mills, 2005), reports on initial acidification recovery of the Sudbury area lakes (Keller & Pitblado, 1986), as well as the early water quality data, suggest that it was during this earlier period of initial emissions reductions that the state of the lakes "switched" from constant or deteriorating water quality, to a state in which water quality is beginning to increase.[34] As I do not have annual observations of lake water quality from this time period I am unable to construct a data series to capture the effects of initial emissions reductions, and in particular, the necessity of these emissions reductions for the "switching point" in quality to be reached. Rather, the annual data from the later time period seem to be capturing much of the inertia from initial reductions, and suggest that once the recovery process of the lake has begun, further decreases in acid depositions will have only a marginal effect on the rate of recovery. In my current specification of the model, the benefits of continuing abatement are therefore relatively small, while the costs to the firm remain large. This leads to the observed optimal policy solution, and suggests that if the regulator is implementing emissions reductions solely to improve lake quality, then once the recovery process has begun, continued investment in costly abatement will not be optimal.

The remainder of the essay proceeds as follows. Section 3.2 provides an overview of the scientific literature on acidification dynamics. Section 3.3 presents the theoretical model for the dynamic programming problem, and the state equations to be estimated. Section 3.4 describes the data, and section 3.5 presents the estimation strategy and results. Section 3.6 discusses the numerical solution to the optimal control problem. Finally, section 3.7 offers some brief concluding remarks, as well as a discussion of future work.

3.2 Acidification Dynamics

The primary pollutants responsible for acidification are sulphur dioxide (SO_2) and nitrogen oxides (NO_x).[35] These pollutants are derived from a number of sources, with the largest contributors being power stations, industrial plants, and vehicle emissions. Acidification of ecosystems is a result of excessive wet and dry depositions of acid. Wet depositions occur when SO_2 and NO_x reach the atmosphere, where they react with the moisture and undergo oxidation, resulting in the formation of sulphuric and nitric acids. These acids exist primarily in the clouds and are transported to the ground through rain or snow. Dry depositions, alternatively, occur in a dry atmosphere through a series of complex photochemical reactions in which highly reactive oxidizing agents such as ozone produce sulphuric and nitric acids. Acids from these reactions are transported to the ground in gaseous or particulate form. Wet deposition is relatively easy to quantify, while quantification of dry deposition is more difficult since gases and particulates are

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[34] There are 41 lakes with a pH measurement in both 1981 and 1982 (the first two years of the study). Average pH of these lakes increases from 4.85 to 4.94, and individual pH increases in 36 of the 41 lakes.

[35] The science in this section is based on the discussion of acidification in Chapter 5 of Mason (2001) and Chapter 1 of Charles (1991).

more widespread; they enter surface and groundwater basins, are absorbed by vegetation, and are dissolved by precipitation.

In addition to the wet and dry depositions from the atmosphere, freshwater is affected by acidic inputs through indirect atmospheric depositions via run-off in the catchment, and from the generation of acidity within the catchment. Given these two additional sources, acidification of freshwater lakes is most likely to occur in areas with thin soil where there are insufficient base cations freely available to neutralize the deposition of acid to the soil. Similarly, land use also influences the rate of acidification, with acid deposition generally increasing in forested areas.

The process of acidification can be divided into three stages, as shown in Figure 3.1 (adapted from Mason (2001)). It begins with the increasing deposition of sulphate and nitrate ions, which have a negative charge. The lake water responds by an increase in the positive charge, H^+, which measures acidity.[36] However, this can be matched by a decrease in one of the other negative charges in the water. This is what occurs in the first stage of Figure 3.1 when the alkalinity of the water, which has a negative charge, is positive. In this stage, the positive alkalinity acts as a buffer against increases in acid deposition and the concentration of H^+ ions.[37] The end result is a decrease in the negative charge (alkalinity) and no change in the positive charge (H^+), so that pH remains at its natural level, and the aquatic ecosystem remains stable. Some lakes with a high buffering capacity will never move beyond this stage. However, more generally, a lake will move into the second stage where the alkalinity buffer is lost, and continued acid deposition results in increases in H^+, large decreases in pH, and the beginning of damages to the aquatic ecosystem. In the third and final stage, the loss of alkalinity is complete and the pH stabilizes at some low level, typically below five. In this state the lake is acidic and there are typically increasing levels of metals with positive charges, particularly aluminum. This results in the extermination of fish populations and a decrease in the diversity of other aquatic life.

There are two methods for reversing the acidification of freshwater lakes. The first is a reduction in emissions, which is typically accomplished by a switch to cleaner production technologies, such as the installation of scrubbers at emitting sources. There has been a significant reduction in acidifying emissions since the 1970s; however, this has yet to lead to recovery of all lakes. While sulphuric and nitric acids in precipitation have declined, a large amount of acid remains deposited in soils and wetlands. Therefore, while direct deposition of acidic inputs is decreasing, depositions via run-off in the catchment and from the generation of acidity within the catchment remain. A second method for reversing acidification is the liming of waters. In liming either pulverized limestone, hydrated lime or quicklime is added to the lake water to neutralize the acid. This method of recovery has more immediate results, but its effectiveness depends on the retention time of water in the lakes. Lakes with short retention times must be relimed either annually or biannually, and those with longer retention times will generally re-acidify 5 to 10 years after liming. While liming is effective in restoring water chemistry, ecological recovery is not guaranteed, and it is typically an expensive alternative with localized results. Since acidification is a widespread problem, the general consensus is that the causes and not the symptoms of acidification must be addressed, and reductions in emissions

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[36] pH is defined as the negative logarithm of the concentration of H^{++} ions in the water, pH = -log [H^+]. As the concentration of H^+ ions in the lake water increases, the water becomes acidified, and pH falls.

[37] The major component of alkalinity in most surface waters is bicarbonate, HCO_3^-. When alkalinity is positive, bicarbonate is positive, and will combine with the hydrogen ion to form aqeueous carbon dioxide and water: $HCO_3^- + H^+ \rightarrow CO_2 + H_2O$, so that the increased acid deposition has no effect on the acidity of the lake water.

should be the main tool used in reversing acidification. As a result, in the remainder of this essay I focus on emissions reductions as the sole policy tool in achieving lake recovery.

3.3 Theoretical Model of Lake Recovery

I begin by developing an optimal control model for the recovery of a single representative lake from acidification. I assume the problem is solved by a social regulator, whose objective is to minimize the damages from lake acidification and the cost of abatement by firms, subject to state equations describing how the lake is recovering over time. The following subsections work through the components of this model.

3.3.1 Economic Objective Function

Following Nævdal (2001), I assume there is a social regulator who is concerned about the state of the lake, and define preferences such that any deviation from the lake's “natural state" causes increasing disutility. I define the state of the lake by the observed pH and alkalinity levels, and assume the natural state is exogenously defined to represent the necessary conditions for biological recovery from acidification.[38] In a given period, I assume the disutility from the degree of acidification is given by:

$$U\left(P_t, L_t\right) = \frac{A}{2}\left(P_t - \bar{P}\right)^2 + \frac{B}{2}\left(L_t - \bar{L}\right)^2 \qquad (3.3.1)$$

where P_t and L_t are the observed pH and alkalinity of the lake in period t, $\bar{P}$ and $\bar{L}$ are the pH and alkalinity of the lake in its natural state, and A and B are positive parameters. I assume $P_0 < \bar{P}$ and $L_0 < \bar{L}$, i.e., the starting point for the lake is in a state of acidification. Since the utility function provides a measure of disutility it is convex, and at the starting point ($t = 0$), $U'\left(P_t, L_t\right) < 0$, $U''\left(P_t, L_t\right) > 0$, so the degree of disutility is decreasing as the deviation of P_t and L_t from $\bar{P}$ and $\bar{L}$ increases.

The regulator must balance the desire for returning the lake to its natural state with the costs of doing so. I consider only the cost of abatement undertaken by local firms emitting SO_2.[39,40] Following Kaitala et al (1992), I assume the cost function defines the minimum cost envelope of the entire range of sulphur abatement options for firm j in a given time period. In any given period, however, I observe actual emissions by a firm, and not abatement. Therefore, I define the abatement cost function by the following quadratic equation:

$$C^j\left(E_t^j\right) = \psi_1^j + \psi_2^j\left(\bar{E}^j - E_t^j\right) + \psi_3^j\left(\bar{E}^j - E_t^j\right)^2 \qquad (3.3.2)$$

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[38] A convenient definition for the natural state of a lake is a return to its predisturbance state. However, this may not be an accurate definition since recovery will typically take several decades during which time the lake in a healthy state may naturally evolve due to either internal chemical processes or external factors such as climate change. Therefore, a more accurate definition for the natural state is the reference data approach that defines recovery as a return to a state that is typical of the least-disturbed lakes in the area (Gunn & Sanday, 2003)

[39] I define local firms as those that are subject to regulation.

[40] From this point forward, I consider only the effects of changes in SO_2 emissions on the acidification and recovery of lakes. I ignore the effects of NO**x** since the local firms under consideration are all industrial plants where the primary pollutant is SO_2 and emissions of NO**x** are minimal.

where $\bar{E}^j$ are the SO$_2$ emissions of firm j in the absence of regulation, E_t^j are the observed emissions of firm j in period t given regulation, and ψ_1^j, ψ_2^j, ψ_3^j are positive parameters. Actual abatement is therefore given by $\left(\bar{E}^j - E_t^j\right)$. The cost function is convex in emissions, and I require that abatement be non-negative in all periods, $\left(\bar{E}_j - E_t^j\right) \geq 0$, so abatement costs are increasing as actual emissions decrease, $C'\left(E_t^j\right) < 0$, $C''\left(E_t^j\right) > 0$.

Combining equations (3.3.1) and (3.3.2) gives the social welfare function, which the social regulator aims to minimize:

$$SW\left(P_t, L_t\right) = \frac{A}{2}\left(P_t - \bar{P}\right)^2 + \frac{B}{2}\left(L_t - \bar{L}\right)^2 + \sum_j \left(\psi_1^j + \psi_2^j\left(\bar{E}^j - E_t^j\right) + \psi_3^j\left(\bar{E}^j - E_t^j\right)^2\right) \tag{3.3.3}$$

I assume the regulator's control variable in minimizing equation (3.3.3) is emissions of local firms, E_t^j. Following the previous literature, I assume the regulator specifies an emissions cap for each firm in every period, and that observed emissions of firms are exactly equal to their regulated amount. The regulator can therefore precisely determine acid depositions from local firms at the lake site in each period. These acid depositions will impact water quality at the lake site, which I measure by the state variables pH (P_t), and alkalinity (L_t). These relationships are further described in the next subsection.

3.3.2 Acid Deposition & Lake Dynamics

Following the previous literature on acidification (Kaitala et al, 1992), (Schmieman & van Ierland, 1999), (Schmieman et al, 2002), I assume there is a linear relationship between SO$_2$ emissions and acid deposition at a lake site. Acid deposition will be affected by several stochastic factors beyond actual SO$_2$ emissions, most notably the amount of precipitation a lake receives and the buffering capacity of the land surrounding the lake. Precipitation is exogenous to the model, and monitoring buffering capacity for the land over time requires the introduction of an additional state equation. For simplicity, I disregard these factors and assume the acid deposition equation is a linear transformation of all current emissions impacting the environmental state of the lake. The equation for acid depositions is thus given by:

$$D_t = \sum_m c^m E_t^m \tag{3.3.4}$$

where c^m is a weighting factor relating emissions from firm m to acid depositions at the lake, m is the total number of firms with emissions impacting the lakes, $m \geq j$, and $\left(m - j\right)$ is the number of firms not under control of the regulator. I further assume the acid deposition equation is deterministic and the regulator knows the emissions of the $\left(m - j\right)$ firms not subject to regulation.[41] With this assumption, the regulator can accurately predict how changes in the emissions of regulated firms will impact the environmental state of the lake.

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[41] A more complicated model is found in Kaitala et al (1992) who sets up the optimal control problem within a game theoretic framework. He solves the problem for the cooperative solution, where regulators jointly maximize their social welfare functions, and the non-cooperative solution, where regulators consider only the acidification

The state equations for alkalinity and pH describe changes in the environmental state of the lake. Starting from a state of acidification, the desired chemical response to a reduction in acid depositions is an increase in alkalinity and pH. If the lake water follows this desired response path then alkalinity and pH will increase together until the lake returns to its natural state. As alkalinity increases, the effect of changes in acid deposition on pH will begin to decrease. This is the mechanism through which the pH of the water stabilizes to the level corresponding to its natural state. In this state, the lake is able to resist reasonable changes in acid deposition since the restored alkalinity provides a buffering capacity which allows the water to neutralize itself. However, if the acid deposition exceeds some critical threshold then the lake will move out of its natural state and again begin to decline into an acidified state.

The chemical recovery of a lake is a dynamic process, and is dependent on the lake's chemical history. Therefore, I include the lagged value of pH in its state equation. With the inclusion of lagged pH I capture the entire history of the effects of acid deposition on pH. Any measured influence of acid deposition in the current period is therefore conditioned on this history, and will represent only the effect of new information (Greene, 2003). The next term in the state equation for pH is the lagged value of acid deposition, which captures the direct effect of acid deposition from the previous period on the current period's pH. I also include an interaction term between the lagged values of alkalinity and depositions. This term captures the non-linearity of pH response to changes in emissions. Finally, I include an error term with mean zero and variance σ^2. This term accounts for the stochastic factors impacting changes in pH each period. The state equation for pH is therefore given by:

$$P_{t+1} = \beta_0 + \beta_1 P_1 + \beta_2 \left(\sum_m c^m E_t^m \right) + \beta_3 L_t \left(\sum_m c^m E_t^m \right) + \epsilon_{t+1} \tag{3.3.5}$$

I define the state equation for alkalinity analogously to the state equation for pH. In this case, however, I do not include the last interaction term since the level of pH does not affect how alkalinity responds to changes in acid deposition. Therefore, the state equation for alkalinity is given by:

$$L_{t+1} = \gamma_0 + \gamma_1 L_t + \gamma_2 \left(\sum_m c^m E_t^m \right) + \upsilon_{t+1} \tag{3.3.6}$$

Together the state equations for pH and alkalinity document how the lake responds to emissions levels chosen by the social regulator, and can be used to predict the lake's recovery path in response to various policies for emissions reductions.

3.3.3 Dynamic Programming Problem

Combining the objective function and the state equations from the previous subsections, I obtain the following discrete time optimal control problem for the social regulator:

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dynamics in their region given a fixed emissions strategy of their opponent. In Kaitala's framework, my model corresponds to the derivation of a non-cooperative solution to the optimal control problem.

$$\min_{E_t^j} \sum_{t=0}^{\infty} \delta^t \left(\frac{A}{2}\left(P_t - \bar{P}\right)^2 + \frac{B}{2}\left(L_t - \bar{L}\right)^2 + \sum_j \left(\psi_1^j + \psi_2^j \left(\bar{E}^j - E_t^j\right) + \psi_3^j \left(\bar{E}^j - E_t^j\right)^2 \right) \right) \quad (3.3.7)$$

$$\text{s.t.} \quad P_{t+1} = \beta_0 + \beta_1 P_1 + \beta_2 \left(\sum_m c^m E_t^m \right) + \beta_3 L_t \left(\sum_m c^m E_t^m \right) \quad (3.3.8)$$

$$L_{t+1} = \gamma_0 + \gamma_1 L_t + \gamma_2 \left(\sum_m c^m E_t^m \right) \quad (3.3.9)$$

$$E_t^j \geq 0 \ \ \forall \ \ j \quad (3.3.10)$$

where δ is the appropriate discount factor.

The discrete time dynamic programming equation corresponding to equation (3.3.7) is:

$$\begin{aligned} J\left(P_t, L_t\right) = \max_{E_t^j} - \Bigg(& \frac{A}{2}\left(P_t - \bar{P}\right)^2 + \frac{B}{2}\left(L_t - \bar{L}\right)^2 + \ldots \\ & \ldots + \sum_j \left(\psi_1^j + \psi_2^j \left(\bar{E}^j - E_t^j\right) + \psi_3^j \left(\bar{E}^j - E_t^j\right)^2 \right) + \delta J\left(P_{t+1}, L_{t+1}\right) \end{aligned} \quad (3.3.11)$$

s.t. Equations (3.3.8), (3.3.9), (3.3.10)

For simplicity in notation, from this point forward I express the disutility function as $U\left(P_t, L_t\right)$, the cost function as $C^j\left(E_t^j\right)$, the state equation for pH as $f\left(P_t, L_t, E_t^m\right)$, and the state equation for alkalinity as $g\left(P_t, L_t, E_t^m\right)$. With this formulation of the problem, I cannot exclude the possibility that the non-negativity constraint on emissions will be binding in certain states. Therefore, along the optimal solution path, emissions in each period must be chosen so that the following Euler equilibrium conditions are satisfied:

$$-C_{E_t^j}^j(t) + \delta\left[J_P(t+1) f_{E^j}(t) + J_L(t+1) g_{E^j}(t)\right] = \mu_t^j \quad (3.3.11)$$

$$J_P(t) = -U_P(t) + \delta\left[J_P(t+1) f_P(t)\right] \quad (3.3.12)$$

$$J_L(t) = -U_L(t) + \delta\left[J_P(t+1) f_L(t) + J_L(t+1) g_L(t)\right] \quad (3.3.13)$$

$$E_t^j \geq 0, \ \mu_t^j \geq 0, \ E_t^j - \mu_t^j \quad (3.3.14)$$

where μ_t^j measures the current and expected future reward from a marginal decrease in emissions by firm j in period t (Miranda & Fackler, 2002). The conditions along the optimal path require that in every period, each local firm reduces its emissions until either the long-run marginal reward from further decreasing emissions, or emissions themselves, are zero. In addition to satisfying the above Euler conditions, the steady state solution to the problem must also satisfy the following state stationarity conditions:

$$P^* = f\left(P^*, L^*, E^{j*}\right) \quad (3.3.15)$$

$$L^* = g\left(P^*, L^*, E^{j^*}\right) \tag{3.3.16}$$

So in the steady state, pH, alkalinity and regulated emissions are all constant from one period to the next.

3.4 Data Summary

The Co-operative Freshwater Ecology Unit, a joint partnership of Laurentian University, Ontario Ministry of the Environment, and Ontario Ministry of Natural Resources, and located in Sudbury, Ontario, Canada, provided the data for this essay. The data fall into three general categories; lake water quality data which was collected by the Cooperative Freshwater Ecology Unit as part of the Sudbury Environmental Study (SES) Extensive Monitoring Programme, data on emissions from local firms (INCO and Falconbridge), and data on the physical characteristics of lakes included in the SES extensive monitoring programme. I further describe these three data groups in the following subsections.

3.4.1 Lake Water Quality

The SES extensive monitoring programme began as a chemistry survey of 209 lakes from 1974-1976. This survey revealed significant acidification, and loss and depression of fish populations in a 5,300 km^2 area around Sudbury, which included 650 km^2 of lake surface area (Conroy et al, 1978). A second chemistry survey of 250 lakes was subsequently conducted from 1981-1983. In 1983, 44 lakes that had an observed pH of less than 5.5 in at least one of the previous surveys were chosen for continued monitoring. These lakes were sampled once per year, during the summer-stratified period. This essay uses annual observations of pH and alkalinity recorded from 1981-2004 for 43 of these lakes.[42] Figure 3.2 shows the location of the lakes in relation to Sudbury.[43]

Lake water samples are taken either from a location near the lake center, or near the center of a main basin on a very large lake. From 1981 to 1994 lake water samples were collected as non-volume weighted tygon tube composites through the two, upper stratified layers of the lake. If the lake was too shallow for thermal stratification then the sample was collected to 1 meter above the lake bottom. Beginning in 1995, sampling methods changed to the use of a four-liter plastic jug immersed by hand to completely below the lake surface. In its 2006 data report (Keller et al, 2006), the Freshwater Ecology Unit conducts an analysis of the difference between water samples collected using the collected tube composite and surface grab sampling methods.[44] Of 22 chemical variables, they find significant differences in results for 8 of the

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[42] For the majority of years in the sample, the laboratory value of alkalinity is reported as the total inflection point. The total inflection point is routinely measured by titration of the water with strong acid or base until the inflection point is reached. At this point, the acid neutralizing capacity of the water is zero. A positive alkalinity indicates a net strong base in the water, and a negative alkalinity indicates a net strong acid. The exception to measuring by total inflection point is 1995 and 1996 where the laboratory value of alkalinity is the fixed-endpoint alkalinity value. For these years, I use inflection point alkalinity values calculated by the Cooperative Freshwater Ecology Unit, and reported in their 2006 data report (Keller et al, 2006).

[43] The map of the location of lakes is provided by the Cooperative Freshwater Ecology Unit. Whitson Lake, immediately North-East of Sudbury, is the 44th lake in the SES study, and the only one for which I do not have data.

[44] The analysis of water samples is conducted using data from 15 Ontario Ministry of Environment long-term monitoring lakes in Northeastern Ontario where the two collection methods were simultaneously used on sampling

variables, including pH, which is significantly lower in tube composite samples. Since I am interested in determining how emissions reductions influence the increase of pH over time, I recognize this change in sampling methods may cause an upwards bias in my results.[45]

Due to outliers in the measured chemical values, and some years in which alkalinity and pH were not measured, there are 13 lakes for which one or both of the observations on pH and alkalinity are missing for a single year. For each lake I choose to drop these years from the data set, thereby creating an unbalanced panel. Since my estimation equations are dynamic, in addition to losing the observations from the year in which the measurements are not taken, I must also drop from my sample the observations from the year immediately following. The result is that I drop from my sample 25 periods of observations.[46] Water quality summary statistics for lakes remaining in the sample are provided in Table 3.1.

As noted previously, the acidification of Sudbury area lakes occurred primarily as a result of sulphur dioxide emissions from smelter operations in the Sudbury area. The goal of the SES extensive monitoring programme is to assess the impacts of emissions reductions from these operations on lake water quality, and to provide ongoing documentation of the recovery of lakes from acidification. Damage from acidification typically begins to occur when the pH of a lake drops below 6.0. However, an observed pH of 5.5 or less was used to identify lakes for inclusion in the SES extensive monitoring programme as this is the approximate threshold at which damage to acid-sensitive sport fish begins to occur (Keller et al, 2006). None of the lakes included in the programme were part of the region's Experimental Liming Program (Yan et al, 1995), so observed improvements in lake water quality over the study period can be strictly attributed to emissions reductions. While not a random sample of all lakes impacted by SO_2 emissions, the data are representative of those lakes that suffered significant biological damage, and which are the primary targets of emissions reductions introduced to aid in the recovery of lakes from acidification.

3.4.2 Local Emissions

The two major mining facilities in the Sudbury area are INCO and Falconbridge. Historically, INCO has been the largest point source of SO_2 emissions in North America, with peak emissions in the 1960s of over 2,500 kt of SO_2 per year (Scott, 1989). While substantially smaller than INCO, Falconbridge is still one of the main pollution sources in Ontario, with peak emissions in the 1960s of around 300 kt per year. The first environmental regulations introducing caps on the emissions of INCO and Falconbridge came into effect in the early 1970s. From 1970-1980, INCO reduced its emissions by 59%, and Falconbridge by 64%. The major program introduced during the study period, however, was the Countdown Acid Rain Program, which began in 1985. Relative to 1980 emission levels, it required both INCO and Falconbridge to achieve a 60% reduction in their emission levels by 1994 (Scott, 1989). These 1994 emission levels remained the standard through to the end of 2005. Regulation in 2000, 2002 and 2004 set

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dates in the summer-stratified period. Comparisons between results from the mean grab and mean tube composite samples were conducted using paired t-tests.

[45] While the change in sampling methods does create a potential bias, I expect it will be somewhat mitigated by the fact that the majority of emissions reductions are observed prior to 1995. Total Sudbury emissions are reduced by 66.4% between 1981 and 1995, whereas the reduction between 1995 and 2004 is a more modest 14.6%.

[46] I drop only 25 observations because for one lake, the data is missing for the first period of observation, which is not included in my estimation for any of the lakes. Therefore, for this lake, I only drop the observation for the following year.

new caps that came into effect in 2006, and provides annual emissions limits for both firms through 2015 (Canadian Institute for Environmental Law and Policy, 2005), (INCO, 2005), (Ontario Ministry of the Environment, June 2004). A summary of the current and future emissions caps faced by INCO and Falconbridge at the start and end of the study period is provided in Table 3.1.[47]

Currently I only have data on annual sulphur dioxide emissions for INCO and Falconbridge.[48] These data are available from the Ontario Ministry of the Environment, and were provided by the Cooperative Freshwater Ecology Unit. While INCO is much larger than Falconbridge, both firms had comparable emissions reductions of approximately 73% between 1981 and 2004. I do not have specific information on the annual acid deposition at each lake site resulting from sulphur dioxide emissions. To estimate depositions, I weight the annual total emissions from INCO and Falconbridge by the inverse of the lake's distance from Sudbury. Relating this estimation method to the depositions equation, (3.3.4), I am assuming the local regulated firms are the only firms with emissions impacting the lakes, $j = m$.[49] I also assume c^m is the same for both my local firms, and is equal to the inverse of the distance of each lake from Sudbury. The distance measurement is provided by the Cooperative Freshwater Ecology Unit. Summary statistics for actual sulphur dioxide emissions, and for the estimates of depositions at each lake site included in the sample, are provided in Table 3.1. Figure 3.3 provides a comparison between actual sulphur dioxide emissions and their regulated amount.[50]

3.4.3 Physical Characteristics of SES Lakes

Data on time-invariant physical characteristics of the lakes are also provided by the Cooperative Freshwater Ecology Unit. Characteristics available for all lakes are the direction of the lake from Sudbury (upwind or downwind), lake area, elevation, shoreline length, and whether there is road access. For a subset of lakes, data is also available for mean depth,

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[47] My theoretical model assumes the regulator sets an annual emissions cap for each firm and that firms' emissions are exactly equal to this cap. This does not accurately reflect the regulatory environment in Sudbury where INCO and Falconbridge face a single, current emissions cap extending between 2 and 10 years, and in most cases, a future emissions cap which they work towards meeting during this time period. As a result, I often observe actual emissions that are significantly lower than the current cap. To accurately model this scenario emissions from each firm must be defined as a state variable, where the state equation describes observed emissions as a function of the regulator's control variables, and the current and future emissions caps. I choose to follow previous literature in assuming emissions of firms are the control variable for the regulator. This is for simplicity in solving the optimal control model, and is also due to the endogeneity problem that arises when estimating observed emissions as a function of the current and future emissions caps.

[48] In addition to the other major emitting firms in Ontario, there are also firms in Michigan and the Ohio Valley with SO2 emissions that will have some impact on the lakes around Sudbury. As a result of a number cross-border agreements for the reduction of acid depositions, many of these firms will have undertaken similar emissions reductions to INCO and Falconbridge during my study period. The exclusion of these firms' emissions from my dataset will therefore result in an upwards bias in my estimation of the impact of a decrease in Inco and Falconbridge emissions on pH.

[49] I have data on SO2 emissions from other major emitting firms in Ontario for 1985, 1990, 1995 and then 2001 forward only. On average, Inco and Falconbridge are responsible for over 55% of emissions in the province. In addition, other major emitting firms are between 260 and 430 kilometers away from Sudbury. This suggests Inco and Falconbridge are the two dominant sources of acid depositions for lakes in the Sudbury area.

[50] The downward spike in emissions observed in 1982 is the result of a prolonged shutdown of the INCO and Falconbridge smelters from June 1982 until March 1983. This was the combined result of a labor dispute at INCO, high energy prices and low nickel prices.

maximum depth, and volume. The Cooperative Freshwater Ecology Unit calculated lake area and shoreline length using the mapping software MapInfo, while the other data are collected from a variety of available sources (Keller et al, 2006). Summary statistics for data describing the physical characteristics of the lakes are provided in Table 3.1.

Differences in lake characteristics can lead to differences in the response of individual lakes located in the same region to changes in acid depositions (Kopáček et al, 2002). In particular, similar to lakes that are recovering from eutrophication, a lake acidified by increasing acid depositions may be reversible, hysteretic, or irreversible.[51] Some lakes may also be acidified in their natural state, in which case I do not expect to observe a significant recovery over time. I do not directly observe which of the study lakes fall into each of these categories; however, there are large differences in the recovery rates of lakes. The pH of the most improved lake increases by 1.97 between 1981 and 2004, while the pH of the least improved increases by only 0.14. I use the lake characteristic data to better understand these differences in recovery rates, and to test the accuracy of my state equations for pH and alkalinity, which in their simple linear form, do not allow for differing types of lakes, nor for the "representative lake" to be of a hysteretic type.

3.5 Estimation & Results

My next objective is to estimate the parameters of the state equations for pH and alkalinity, using the functional forms described in equations (3.3.5) and (3.3.6). I begin by discussing the estimation strategy, and the results of the initial estimates. I then conduct two sets of robustness tests. The first robustness test looks at the exclusion of additional explanatory variables (precipitation data and lake specific characteristics) from the state equation functional forms. The second test considers the accuracy of the assumption that the weighting factor relating emissions to acid depositions at a specific lake site is equal to the inverse of the lake's distance from Sudbury.

3.5.1 State Equation Estimation

I begin the initial estimation by assuming the error components of each state equation are made up of two terms; ϵ_{it} and υ_{it}, which are iid over i and t, and α_i and η_i, which are random variables that capture unobserved heterogeneity among the lakes. I further assume strict exogeneity of the error terms, $E\left[\epsilon_{i,t} \middle| \alpha_i, \bar{x}_{i,1}, \ldots, \bar{x}_{i,T}\right] = 0$, $E\left[\upsilon_{i,t} \middle| \eta_i, \bar{y}_{i,1}, \ldots, \bar{y}_{i,T}\right] = 0$ where I let $\bar{x}_{i,t}$ and $\bar{y}_{i,t}$ be the vectors of right hand side variables in the state equations for pH and alkalinity respectively. I expect the random variables, α_i and η_i, will be correlated with the observed regressors $\bar{x}_{i,t}$ and $\bar{y}_{i,t}$, particularly the lagged values of the dependent variables in each state equation. This is because certain time invariant characteristics of the lake, such as the types of soil or vegetation found on surrounding land, may impact both the natural state of the lake, and the rate at which it recovers from acidification. Therefore, I use the least squares dummy variable estimator to estimate a fixed effects model of the following form:

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[51] A hysteretic lake is one that may have multiple stable states corresponding to the same environmental conditions.

$$P_{i,t} = \beta_0 + \beta_1 P_{i,t-1} + \beta_2 D_{i,t-1} + \beta_3 L_{i,t-1} D_{i,t-1} + \alpha_i + \delta_t + \epsilon_{i,t} \tag{3.5.1}$$

$$L_{i,t} = \gamma_0 + \gamma_1 L_{i,t-1} + \gamma_2 D_{i,t-1} + \eta_i + \delta_t + v_{i,t} \tag{3.5.2}$$

Results from the estimation of equations (3.5.1) and (3.5.2), using the fixed effects model, are provided in column (1) of Tables 3.2 and 3.3 respectively.[52] The results from the estimation of both equations are mostly as expected. The coefficients on the lagged dependent variables are positive, significant and less than 1, indicating the state equations for pH and alkalinity are stable, and there is a general trend of improving water quality over time. The coefficients on depositions are negative and significant, indicating that current values of pH and alkalinity are increasing as lagged depositions decrease. Finally, the coefficient on the interaction between depositions and alkalinity in the state equation for pH is negative and significant, although only at the 10% level. The low level of significance suggests the interactive relationship between pH, alkalinity and depositions is not well defined in the data. A contributing factor to this is likely that the recovery of lakes from acidification will often take much longer than 24 years, and the data captures only an interim period of recovery. In addition, the lakes are surveyed relatively early in the recovery process, during which time alkalinity will generally be more responsive than pH to changes in depositions. In this case, pH only starts responding to changes in deposition after alkalinity has already been increasing. This is consistent with the negative sign on the interaction between depositions and alkalinity.

3.5.2 Robustness Check: State Equation Specification

When previously deriving my theoretical model, I choose to ignore certain variable factors, such as precipitation, in order to simplify the estimates of acid deposition, and thereby the solution to the optimal control model. I now check the impact of this simplifying assumption by adding to both regression equations an interaction term for lagged precipitation and depositions. I use data on annual precipitation that includes total rain and snowfall. Due to the remoteness of many of the lakes, I only have data from two weather stations, one which is representative of the lakes located South (upwind) of Sudbury, and a second that is representative of the lakes located North (downwind) of Sudbury. For each lake, I interact the lagged annual precipitation from the appropriate monitoring site with the estimate of lagged depositions at the lake. The results from estimating my regressions with this added term are given in column (2) of Tables 3.2 and 3.3. In the estimation of both state equations, the direct effect of precipitation on the impact of depositions is negligible, with the coefficient on the interaction term virtually equal to zero. The inclusion of the additional term, however, does alter

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[52] Given the lagged dependent variable in both state equations, using the least squares dummy variable estimator leads to a violation of the strict exogeneity assumption. The typical correction for this is to use the Arellano-Bond estimator, which is an IV variant of the first differences estimator. Judson and Owen (1999) show that the Arellano-Bond estimator should be used when T = 20 , but when T = 30 the least squares dummy variable estimator performs just as well or better than the alternatives that correct for endogeneity. As my sample has T = 24 time periods, this suggests it would be best to use the Arellano-Bond estimator. However, as this is a first differences estimator it eliminates the constant from the estimation. With this correction, I therefore cannot solve the optimal control problem as my theoretical model relies on the constant in order to achieve increasing pH and alkalinity over time. As solving the control problem is my main objective I instead use the least squares dummy variable estimator, recognizing this introduces a bias to my results. The bias, however, should be small relative to that from a shorter panel.

the previous results. In the state equation for pH, the coefficient on lagged pH slightly decreases, while the coefficient on depositions decreases by just over 50%. I observe the same results in the state equation for alkalinity, although the effects are larger, with the coefficient on depositions decreasing by more than 100% with the inclusion of the precipitation term.

To determine which of the functional forms for the state equations is more accurate I calculate the predicted paths for pH and alkalinity over the period 1981-2004, given observed emissions and precipitation over this time period, and using the significant parameter estimates from columns (1) and (2) of Tables 3.2 and 3.3. I use the average value of pH and alkalinity across all sample lakes in 1981 as the starting value for both paths. The comparison of the predicted paths with the actual average values of pH and alkalinity over the time period is shown in the two panels of Figure 3.4. The actual path is shown by the solid line, the predicted path using the original state equation is shown by the dashed line, and the predicted path with precipitation in the state equation is shown by the dash-dot line. The basic state equation, and the state equation with precipitation, predict paths for pH that are virtually indistinguishable. For alkalinity, however, the basic state equation provides a more accurate prediction over the full time period, with the precipitation inclusive state equation predicting a sharp increase in alkalinity at the start of the time period which is not representative of the true alkalinity path.[53] These results suggest that omitting precipitation from the state equations does not negatively impact their accuracy for predicting the paths of pH and alkalinity.

As previously mentioned, my original state equations assume that all lakes are of the same type, and do not allow for lake specific characteristics to affect water quality recovery. To better understand the impact of this assumption, I add to both regressions interaction terms for lagged depositions and a set of time-invariant lake characteristics.[54] In the results, presented in column (3) of Tables 3.2 and 3.3, I include characteristics available for all lakes; lake area, direction from Sudbury, elevation, shoreline length, and whether there is road access. In the state equation for alkalinity, addition of these variables has only a small effect. None are significant, and the impact on estimation of the variables from the original state equation is almost identical to that from adding the precipitation term. I observe more significant results in the state equation for pH. The coefficient on direction from Sudbury is negative and significant, indicating that as expected, a decrease in depositions has a greater effect on the pH of lakes that are down wind of Sudbury. The coefficient on elevation is positive, suggesting lakes at higher elevations are slightly less responsive to changes in depositions than lakes at lower elevations. Finally, the coefficient on road access is negative and significant, indicating a decrease in acid depositions will have a greater effect on lakes that are closer to population areas. Inclusion of these extra variables also has a large effect on the coefficients on lagged pH and depositions. Relative to the results with no interaction terms, the coefficient on lagged pH decreases by almost 0.04, and the coefficient on depositions more than triples.

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[53] The precipitation inclusive state equation for alkalinity does more accurately predict the high levels of alkalinity observed towards the end of the time period. However, as this is a relatively short time period of approximately 6 years it is reasonable to assert the basic state equation provides a more accurate description over the full time period. Comparing the sum of squared errors, 1.1097 for the basic state equation and 4.2211 for the state equation with precipitation, supports this assertion.

[54] With eutrophication of lakes, a significant variable in this context is depth. Often referred to as the shallow lakes problem, shallow lakes are more likely to be either hysteretic or irreversible as they tend to have higher rates of phosphorous recycling, making them unresponsive to phosphorous input controls (Carpenter et al, 1999). I am interested in seeing if there are any similar characteristics of acidified lakes that are significant in determining how and whether they recover from acidification.

Using the significant parameter estimates from columns (1) and (3) of Tables 3.2 and 3.3, I can compare the predicted paths for pH and alkalinity using the basic state equation, and the state equation inclusive of lake characteristics.[55] The comparison of the predicted paths with the actual paths of pH and alkalinity is shown in Figure 3.4. The actual path is shown by the solid line, the predicted path using the original state equation is shown by the dashed line, and the predicted path with lake characteristics in the state equation is shown by the dotted line. In this case it is evident for both pH and alkalinity that the original state equations provide the more accurate prediction. While the pH prediction path is still relatively close, the alkalinity prediction path is consistently, and significantly, below the true alkalinity path. This is likely due to the lack of significance of the lake characteristic data in the regression results.

I also estimate the equations using the full set of characteristics available for only a subset of the lakes. However, I do not report these results as they are not readily interpretable. In the state equation for pH, the only significant variable is the coefficient on lagged pH. In the state equation for alkalinity the coefficient on lagged alkalinity, weighted emissions, and the interaction terms for lake area, volume, mean depth and maximum depth are significant, but many of the coefficients have unexpected signs. I suspect the lack of results in this estimation is due to the reduced sample size since I use observations for only 36 lakes. To check this, I re-estimate the regressions reported in column (3) of Tables 3.2 and 3.3 using only data from the 36 lakes for which all characteristics are available. For each state equation I find the only significant coefficients are the lagged dependent variables. This suggests the smaller sample size is driving the lack of results when I include the additional lake characteristics as dependent variables.

3.5.3 Robustness Check: Acid Depositions

As discussed in section 3.4.2, I do not have accurate information on annual acid depositions at each lake site, and therefore do not have a good estimate of c^m. I use as a rough estimate the inverse of the lake's distance from Sudbury. To see how my results change using an alternative estimate for c^m, I re-estimate my three fixed effects regressions using the inverse of the lake's squared distance from Sudbury as the estimate for c^m. The results from these regressions are reported in columns (4) of Tables 3.2 and 3.3, and are qualitatively similar to those previously found. The coefficient on the lagged dependent variable is positive, significant, and less than one, and the coefficient on depositions is negative and significant. The coefficient on the interaction term in the state equation for pH remains negative, although is no longer significant.

With the alternative estimate of c^m I do find a large difference in the estimated marginal effect of a decrease in emissions on pH and alkalinity. Using the inverse of the distance from Sudbury as the estimate of c^m, for a lake that is located 60 km from Sudbury, the original state equation indicates a 100 kt decrease in emissions will increase pH by 0.0133, and alkalinity by 0.0347. With the inverse of the squared distance from Sudbury as the estimate of c^m, however, the estimate of the increase in pH is only 0.0020, and for alkalinity is 0.0051.[56] On average,

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[55] In the alkalinity state equation with lake characteristics I include the intercept even though it is not significant. As discussed in a previous footnote, the intercept is necessary for the state path to be increasing over time.

[56] The calculation of the marginal effect of a change in depositions on pH is done assuming alkalinity equals -0.9, the average value of alkalinity across all lakes in 1981.

defining c^m as the inverse of distance rather than distance squared increases the estimate of the marginal effect of depositions on improvements in pH and alkalinity by almost seven times.

To determine which of the estimates of c^m is more accurate I once again calculate the predicted paths for pH and alkalinity over the period 1981-2004, this time using the two alternative estimates c^m and the significant parameter estimates from columns (1) and (4) of Table 3.3 and 3.4. The comparison of the predicted paths with the actual average values of pH and alkalinity over the time period are provided in Figure 3.5. The actual path is shown by the solid line, the predicted path using the inverse distance estimate of c^m is shown by the dashed line, and the predicted path using the inverse distance squared estimate of c^m is shown by the dash-dot line. Neither predicted path is able to capture the volatility of the average values of pH and alkalinity over the period. Both are relatively smooth, with larger than expected increases in pH and alkalinity towards the start of the period (likely due to the large decrease in emissions in 1982 as a result of operation shutdowns), and smaller increases towards the end of the period as both pH and alkalinity appear to approach steady state values. For both pH and alkalinity, the paths generated using inverse distance as the estimate of c^m are closest to the actual paths. I will therefore use the parameter estimates from these regressions when solving for the optimal path of emissions reductions in the next section.

3.6 Numerical Solution to the Optimal Control Problem

My last step is to numerically estimate the solution to the optimal control problem. I first parameterize the social welfare function, and then solve the problem in Matlab using the Miranda & Fackler (2002) computational economics toolbox. The following two subsections explain the parameterization, and present and discuss the numerical solution results.

3.6.1 Parameterization

In past work on acidification and eutrophication, parameterization of the social welfare function has been done through either formal estimation or simple assumption of the parameter values. I currently do not have data on abatement costs, or on measures of disutility from an acidified lake. Therefore, I rely primarily on the latter approach. For simplicity, I also assume there is only one emitting firm. I therefore parameterize only a single abatement cost function, and consider optimal abatement of total emissions in the Sudbury area.

To obtain a rough estimate of the parameters for the abatement cost function, I use values from a Government of Ontario Ministry of the Environment report which provides estimates of the marginal costs of abatement at Inco and Falconbridge under different abatement control strategies (Ontario Ministry of the Environment, June 2004). The average annual operating and maintenance cost of the different abatement control strategies is 6.67 million dollars per year, while the average marginal cost of each kilotonne reduction in emissions is 0.362 million dollars.[57] My theoretical model assumes abatement costs are quadratic; however, this particular

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[57] The three abatement control strategies I include in the reported averages are a Fluid Bed Roaster Off-Gas Control at Inco, a Continuous Converting Technology at Inco, and Acid Gas Scrubbing at Falconbridge. The annual operating and maintenance costs for these three options range from 3 to 9 millions dollars, while the marginal costs of abatement range from 0.13 to 0.50 million dollars per kt. The report also provides an estimate of the capital cost for each of these technologies which I do not consider here. However, this cost should not affect the optimal emissions decision as it is a sunk cost and is independent of the level of emissions. A fourth abatement control

report only provides information on linear abatement costs. As I do not have any good information on the value of the coefficient on quadratic abatement, I assume it is equal to zero and use a linear abatement cost function for the current numerical solution. The final parameter in the abatement cost function is $\bar{E}$, the SO_2 emissions of the firm in the absence of regulation. I assume this value is equal to 837, the total emissions in Sudbury in 1981. Table 3.4 provides the full set of parameter estimates for the abatement cost function.

Freshwater lakes in their natural state will typically vary in the biological populations they support, although most will have a pH between 6.0 and 8.0. In parameterizing the disutility function I choose the optimal level of pH to be 7.0, the level at which lake water is neutral. Defining an optimal level of alkalinity is more difficult as there is no set standard for its value, and it tends to be more variable across lakes. A U.S. EPA classification, however, sets a minimum value of greater than 20 for a lake or pond to be considered "not sensitive" to changes in acid deposition (Addy et al, 2004). As all of the lakes in my sample are far below this level, I set the optimum level of alkalinity at the minimum value for a "well-buffered" lake of 20.

Parameterizing the disutility equation of the social welfare function is more challenging. First, the acidification of lakes can have numerous effects on welfare, many of which relate to non-use value. While non-use values are difficult to measure, they are a significant component of the total value of freshwater ecosystems and ignoring or underestimating their role can result in environmentally degrading policy (Wilson & Carpenter, 1999). The second challenge in parameterization is that I formulate my control problem for the recovery of a representative lake. Actual emissions reductions, however, will have an impact on thousands of heterogeneous lakes, and the optimal emissions path must reflect this. Introduction of individual state equations to separately describe the changes in water quality for any significant number of lakes will make the solution of the control problem intractable. Instead I follow previous literature (Kaitala et al, 1992), (Schmieman et al, 1999), (Schmieman, et al, 2002), and assume that all lakes in the area are homogeneous. I then inflate the parameters of the disutility function so they are representative of the disutility from widespread acidification among a group of representative lakes.

I currently do not have any robust measures of welfare effects from aquatic acidification in the Sudbury area. In a contingent valuation study of terrestrial and aquatic acidification in the Adirondacks region of New York state, however, Banzhaf et al (2006) estimate annual statewide benefits from acidification recovery in the range of \$336 million to \$1.1 billion. They also note that when accounting for statistical uncertainties these damage estimates may either halve, or more than double. Acidification damages in the Adirondacks and the Sudbury area are similar, suggesting these estimates, although broad, can provide a rough approximation of damages from continued acidification of the Sudbury lakes. Given the range of damage estimates I solve the optimal control problem using a range of values for the coefficients of the disutility function. The coefficients correspond to annual damages ranging from approximately \$200 million to \$2.0 billion.

I choose the range of coefficients on pH to be larger than the range of coefficients on alkalinity for two reasons. First is that alkalinity has a much wider range of values that it can reasonably take. A single unit deviation from its optimal value is therefore much less

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technology for which the report also provides cost estimates are Secondary Capture Hoods at Inco. I do not consider this option because the report notes that only one of the Secondary Capture Hoods and the Continuous Converting Technology may be implemented as an abatement control strategy, and the costs of the Secondary Capture Hoods are strictly larger than those for the Continuous Converting Technology.

consequential than a single unit deviation from the optimal value of pH, which represents a 10-fold increase in acidity of the lake water. Second is that low levels of alkalinity do not directly affect fish populations and other ecosystems in the lake. Therefore, deviations in alkalinity from its optimal value should have only a secondary effect on decreases in welfare from lake acidification. The final range of parameter values I use are reported in Table 3.4. I solve the problem at intervals of 50 for the coefficient on pH, and at intervals of 0.5 for the coefficient on alkalinity.

3.6.2 Numerical Solution

I solve the optimal control problem using the discrete time, continuous state dynamic programming toolbox from Miranda and Fackler (Miranda & Fackler, 2002). I specify the stochastic component in the state equations for pH and alkalinity as a nine-node discretization of the bivariate normal shock with mean zero and three standard univariate nodes in each direction. I assume the variance in the stochastic component is equal to the variance in the error term from the relevant state equation estimation results. Using the solution to the optimal control problem, and starting from the average values of pH and alkalinity for sample lakes in 1981, I simulate 10,000 optimal paths for pH, alkalinity and emissions over the time period of my data (1981-2004). The mean paths from these simulations, for the lower, and upper values of the parameters A and B, are shown in the three panels of Figure 3.6.[58] As expected, as the level of damages increases, the optimal path of emissions decreases, and the pH and alkalinity levels of the lake increase more rapidly.

The optimal control rules corresponding to the simulation paths are shown in the upper and lower panels of Figure 3.7. As previously discussed, and shown in the simulation paths, for the lowest values of A and B, there is no reduction in optimal emissions below observed levels in 1981. This result stems from the fact that the state equations for pH and alkalinity are estimated for a lake recovery process that has already started. With the inclusion of the lagged dependent variable, the state equations capture the inertia of earlier recovery, and indicate that even without a further reduction in acid depositions, pH and alkalinity will continue to increase over time. When damages from acidification are low and there is less urgency to return a lake to its natural state, it is therefore not optimal to have the firm continue to invest in costly abatement.[59]

For the highest values of A and B, the optimal control rule resembles a step function. At low levels of lake quality the optimal control rule is zero emissions, and at high levels of lake quality the optimal control rule is to allow the unregulated level of emissions. It is interesting to note the pH level at which the emissions rule jumps from full to zero abatement is increasing in the alkalinity level. That is, at higher levels of alkalinity, full abatement (zero emissions) is optimal at higher levels of pH, and over a larger range of pH values. This result relates back to the interaction term in the state equation for pH. The estimation of its coefficient uses data from a relatively early portion of the recovery period, where lakes are in the lower right hand portion

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[58] The simulated paths for other combinations of parameter values for *A* and *B* fall in between the two paths given in Figure 3.6. The majority of the variation in the paths, however, is a result of changes in the value of *A*. Holding *A* constant and varying only *B* causes much smaller changes in the paths for pH, alkalinity, and optimal emissions.

[59] This result hinges on the assumption that the only damages from SO2 emissions are those related to lake acidification. There are, of course, many other SO2 externalities that make continued abatement desirable, and which should be included in a fully accounted model of SO2 abatement decisions.

of Figure 3.1. In keeping with the shape of the acidification path, the coefficient on the interaction term is negative. This suggests the effect of further decreases in acid depositions on pH will increase as alkalinity increases. As a result, the regulator has greater incentive to implement stricter emission controls when alkalinity is higher, at which point the controls are expected to have a larger positive impact on pH, and therefore generate a larger benefit in return for their cost.

The control rule approaches a step function due to the fact that under the current parameterization the social welfare function is linear in the control variable. Due to the presence of two state variables, however, the jump between zero and full abatement is not perfectly discrete, and there is instead a narrow, intermediate range of pH and alkalinity values where partial abatement is optimal.[60,61] While this range is narrow, since lake recovery is generally a slow process, it is possible that if a lake starts in this intermediate range, or enters this range after initial aggressive abatement, then partial abatement of emissions may be optimal over an extended period of time. This is the case along the optimal emissions control path for the high values of A and B , shown by the dashed line in the lower panel of Figure 3.6.

Lastly, when the control rule follows the step function, it is also the case that the optimal emissions path is always increasing over time. This result follows from my specification of the regulator's social welfare function. When the lake begins in an acidified state, and the disutility from acidification is large, the regulator has an incentive to return the lake to its natural state as quickly as possible. As there is no benefit from waiting to abate (i.e., no cost savings from abatement in later periods), the solution recommends that the firm be required to make a temporary "up front" abatement investment which will lead to a faster recovery rate.[62] Once pH and alkalinity start to increase, firms can then begin to increase emissions to a level that will maintain the recovery path, and lower their long-term abatement costs. This result is seen along the optimal emissions control path for high damages in the lower panel of Figure 3.6

3.7 Conclusion & Future Work

The acidification of freshwater lakes continues to be a significant environmental problem in many areas of the world. The problem of how to optimally implement emissions reductions that will lead to their recovery therefore remains a relevant policy question. I develop a framework for an optimal control problem that seeks to answer this question. I define a social welfare function that is maximized by a social regulator who must balance the cost of imposing emissions reductions on firms against the social disutility resulting from lake acidification. The change in water quality over time is described by state equations that measure how the pH and

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[60] The residuals for the approximation of the value function are slightly larger at the state nodes in the intermediate "step range." I expect this is because it is difficult to accurately estimate the exact location of the apparent kinks in the control rule. The residuals decrease with additional state nodes, and at 20 nodes in each dimension, is generally below 1E-04.

[61] As A and B continue to increase, the level of pH at which optimal regulatory policy jumps from zero emissions to full emissions continues to decrease. At a high enough level of damages, the optimal policy is zero emissions at all levels of lake quality. I do not discuss these results here because the damage parameters for this result go beyond any reasonable estimates. In addition, my current specification of a constant marginal cost of abatement and no benefits from output does not accurately reflect the costs or consequences of a full reduction in emissions.

[62] In actuality, however, it is not generally reasonable to regulate firms in this fashion as it will often require costly, short-term over investments in abatement capital. An alternative specification of abatement costs that may lead to a more realistic abatement path is discussed in the conclusion.

alkalinity of lake water respond to emissions reductions. I estimate the parameters of the state equations using a fixed effects model, and the results are mostly consistent with the theoretical model of lake recovery. When I solve the optimal control problem, I find the marginal effect of decreases in emissions on lake recovery is small, and I must assume large damages from lake acidification before it is optimal to implement any emissions reductions. I also find the optimal path of emissions reductions, when implemented, is generally decreasing over time.

There are a number of limitations in my current theoretical model that contribute to the above results, and which provide opportunities for future work. First, the estimated marginal effect of emissions reductions on the pH and alkalinity of lake water is very small, making it difficult for even the largest reductions in emissions to generate any significant change in the recovery process. This stems from the result that in the estimated state equations, the recovery paths for pH and alkalinity are generated mostly by the constant term and the coefficients on the lagged dependent variables. What the equations do not capture is that the recovery paths being generated by the constant and lagged dependent variable are a result of emissions reductions of over 1700 kt of SO_2 between the early 1960s and the start of my data collection period. Also potentially contributing to the small marginal effect of emissions reductions on lake recovery is that I do not have an accurate measurement of acidic depositions at each lake site. Options for improving this estimate are to use data from SO_2 air monitoring stations to look at how ambient air concentrations of SO_2 at various distances from the smelters change in response to emissions reductions, to use lake sulphate concentrations in place of an estimate of depositions in the state transition functions, or lastly, to calibrate the state equations to match simulated scientific models of lake recovery, and not to use the measured water quality data from the lake sites.

The second limitation with the theoretical model, when comparing the results to observed emissions reductions, is that it focuses only on lake acidification, and does not account for the other benefits associated with reductions in SO_2 emissions. I currently find that at reasonable levels of lake damages, optimal emissions reductions are either small or non-existent. Observed emissions, alternatively, fell from 837 kt in 1981 to 240 kt in 2004. The reason for the observed reductions of this magnitude is that regulations are taking into account damages of SO_2 emissions in other areas including mortality and morbidity effects, corrosion of materials, soiling of property, and deterioration of landscapes (Ontario Ministry of the Environment, 1999). In many of these areas the marginal effects of emissions reductions will not be as small as those for lake recovery, and large reductions therefore become optimal. Following Nævdal (2001), I can address this limitation and account for the additional benefits of SO_2 emissions reductions by including a third term in my disutility function which is equal to the direct, “non-lake” damages from emissions.

The final limitation of my current model is that it does not accurately reflect the emissions reduction costs of firms, nor the paths they will take to achieve these reductions. The model currently assumes the marginal cost of abating each unit of emissions is constant across all units. A more likely scenario, however, is that as firms invest in different abatement technologies the marginal cost for new units of abatement will change. To capture this effect, the level of emissions can be defined as an additional state variable in the model. The initial level of emissions will be $\bar{E}$, and in each period, firms will choose how many additional units of emissions to abate, A_t. This value may be positive or negative, depending on whether firms choose to decrease or increase emissions relative to the previous period. The state transition function is then $E_t = E_{t-1} - A_t$. The abatement cost function will consist of two components; a marginal cost for the current level of abatement, ($\bar{E} - E_{t-1}$), and an adjustment cost for the change in abatement from the previous period. Previous work on the introduction of adjustment costs to dynamic models has shown they can lead to a number of interesting results including multiple equilibria and cycling towards a steady state (Feichtinger et al, 2001).

Currently the main contribution of this essay is in the development of a basic model that considers the acidification dynamics of freshwater lakes, and the role of emissions reductions in the recovery of lakes from acidification. While acidified lakes are a significant environmental concern, my main result is that if the recovery process has already begun, then the lake specific damages from current acidification often do not warrant investment in costly abatement measures to accelerate recovery. There are, however, a number of limitations in my current theoretical model that, if addressed, may provide a more accurate solution to the optimal control problem. This essay provides a starting framework for additional research that can be undertaken to understand more completely the benefits of mandating additional abatement efforts once recovery of lakes has begun.

3.8 Figures & Tables

Figure 3.1: Acidification Process of Lakes

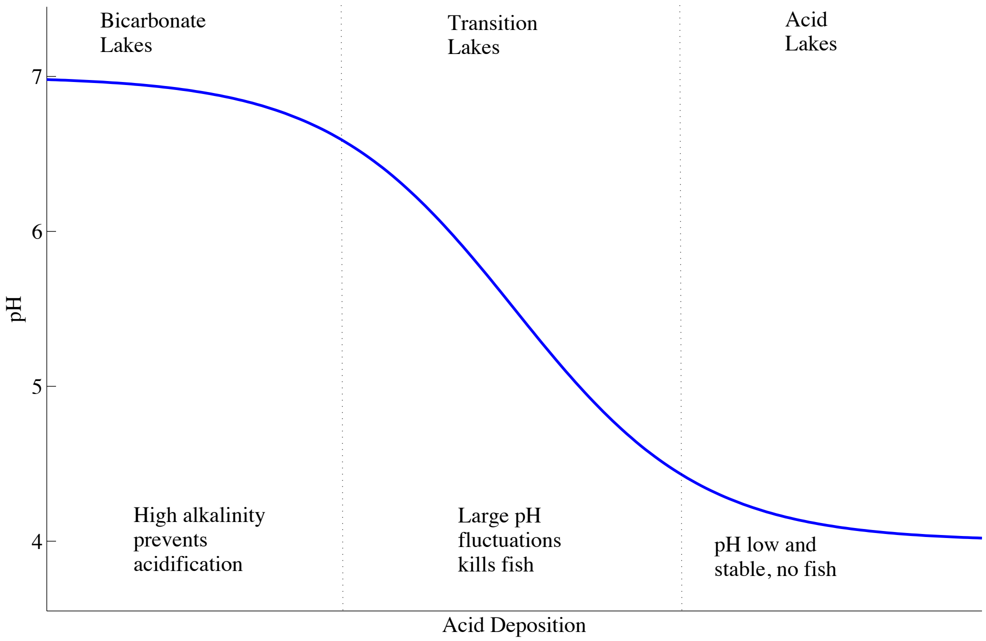


Figure 3.2: Location of SES Lakes in relation to Sudbury. The area within the dotted lines represents the zone of lakes affected by Sudbury emissions.

Figure 3.3: Regulated and Actual SO_2 Emissions for INCO and Falconbridge, 1981 – 2004

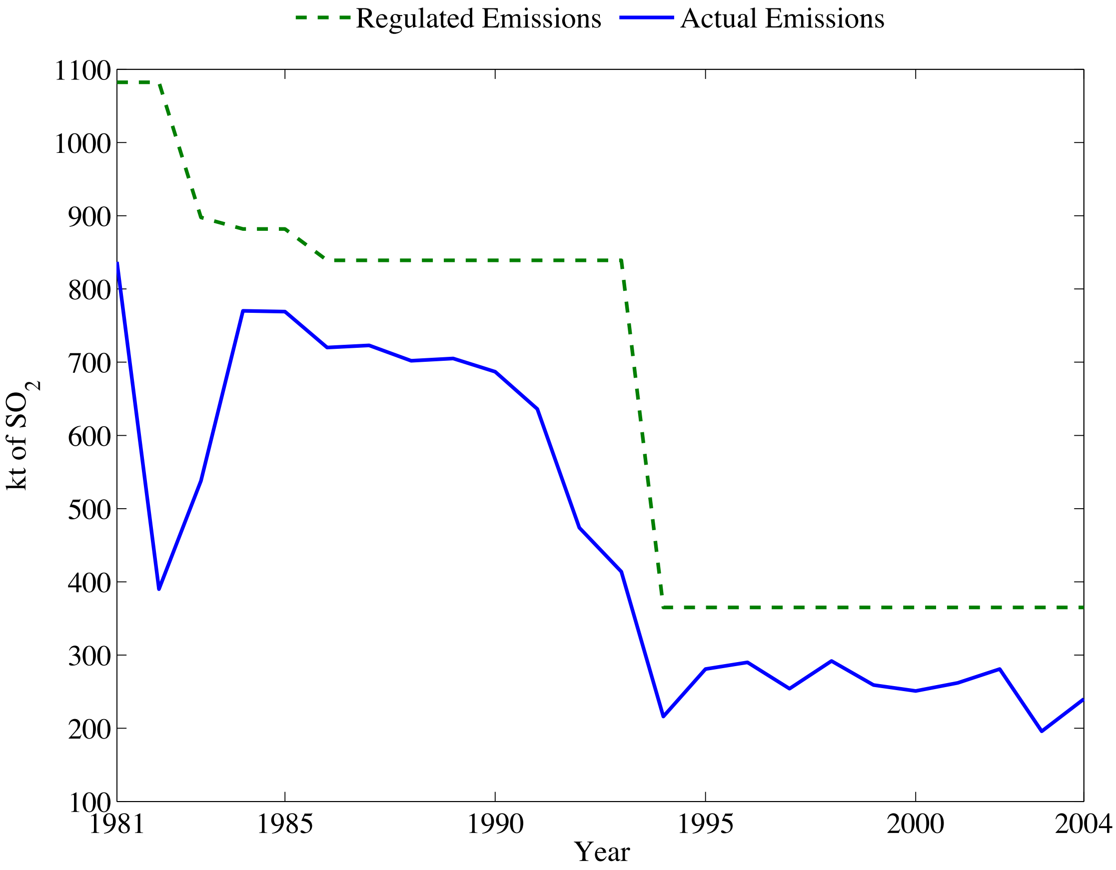


Figure 3.4: Actual & Predicted Values of pH & Alkalinity, 1981 – 2004
State Equation Functional Form Robustness Check

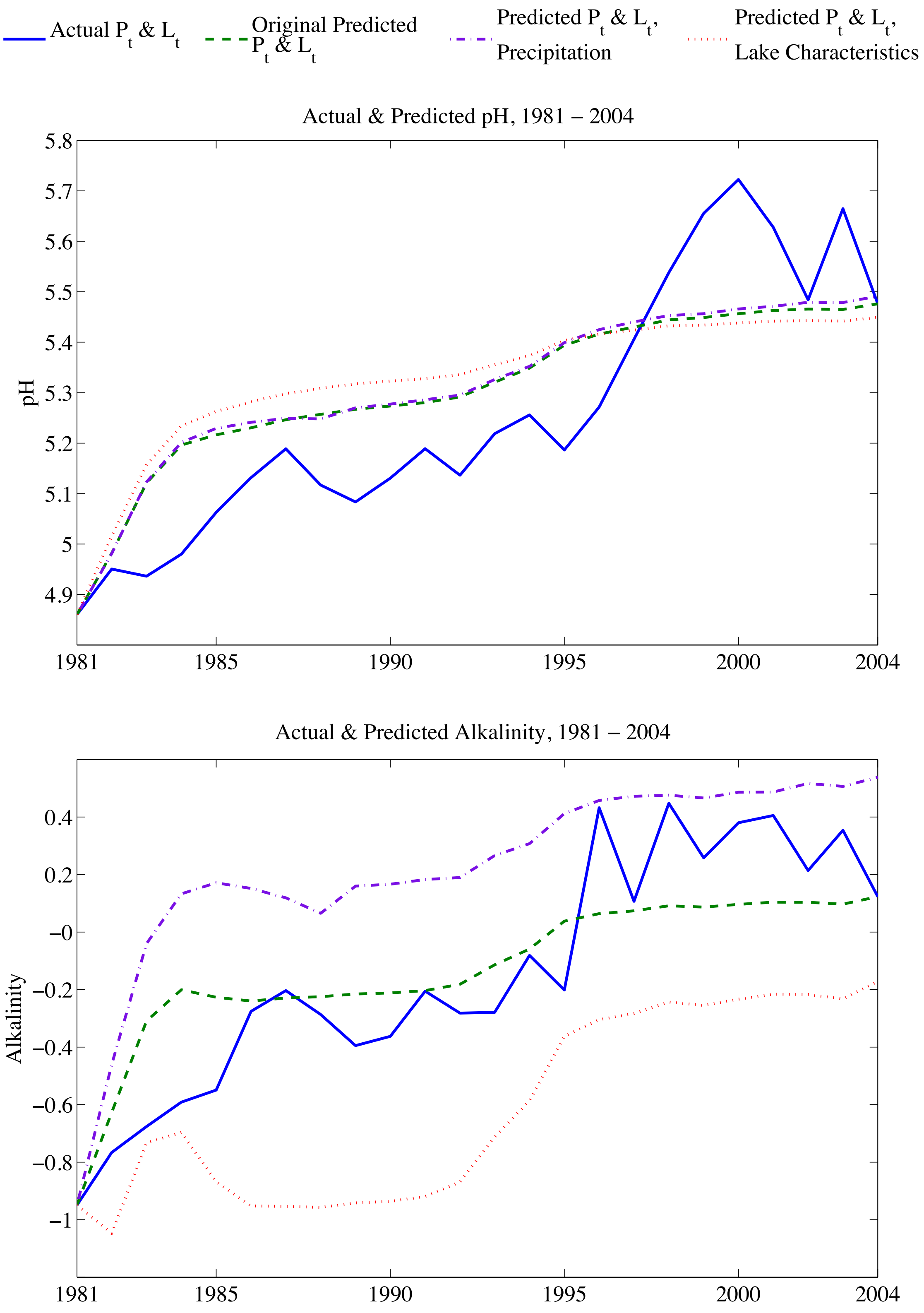
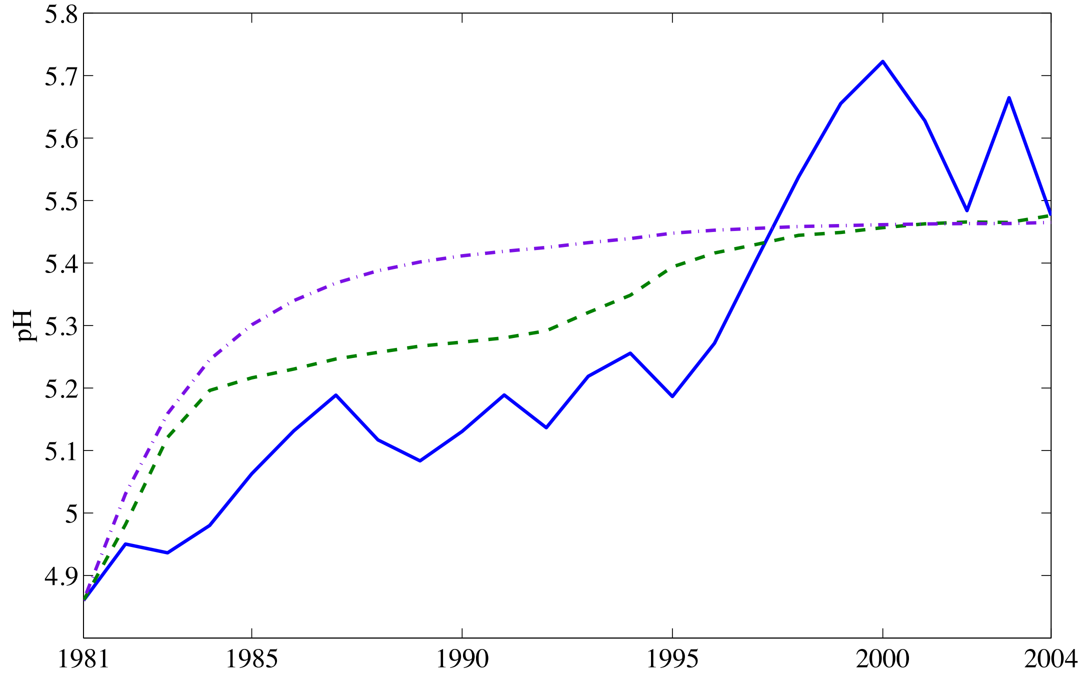


Figure 3.5: Actual and Predicted Values of pH and Alkalinity, 1981 – 2004
Acid Depositions Robustness Check

Actual & Predicted pH, 1981 – 2004



Actual & Predicted Alkalinity, 1981 – 2004

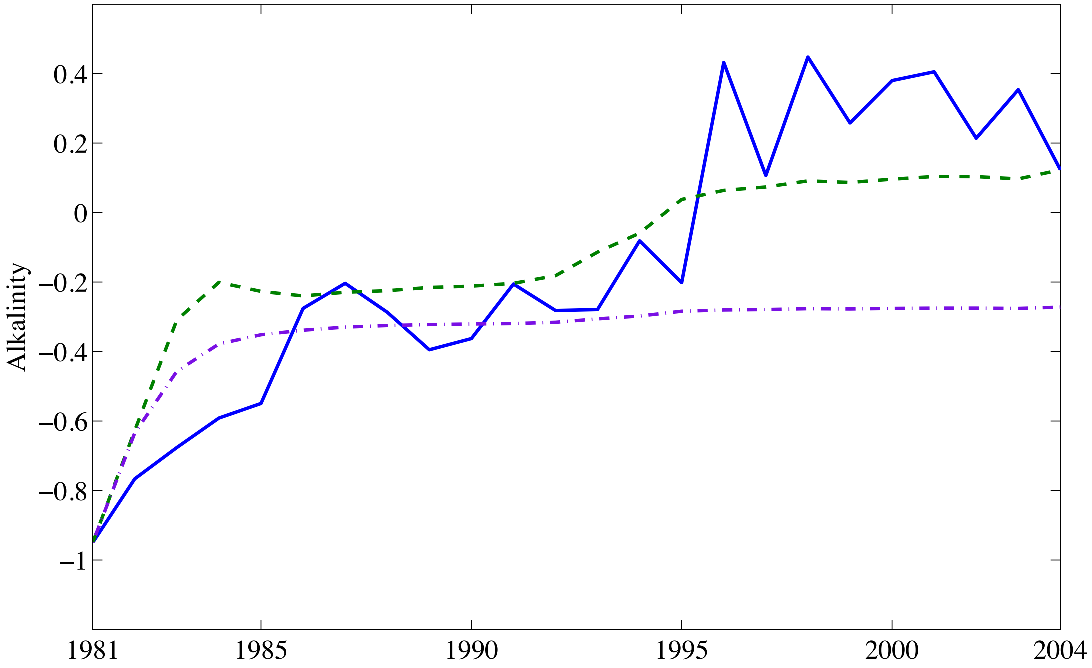
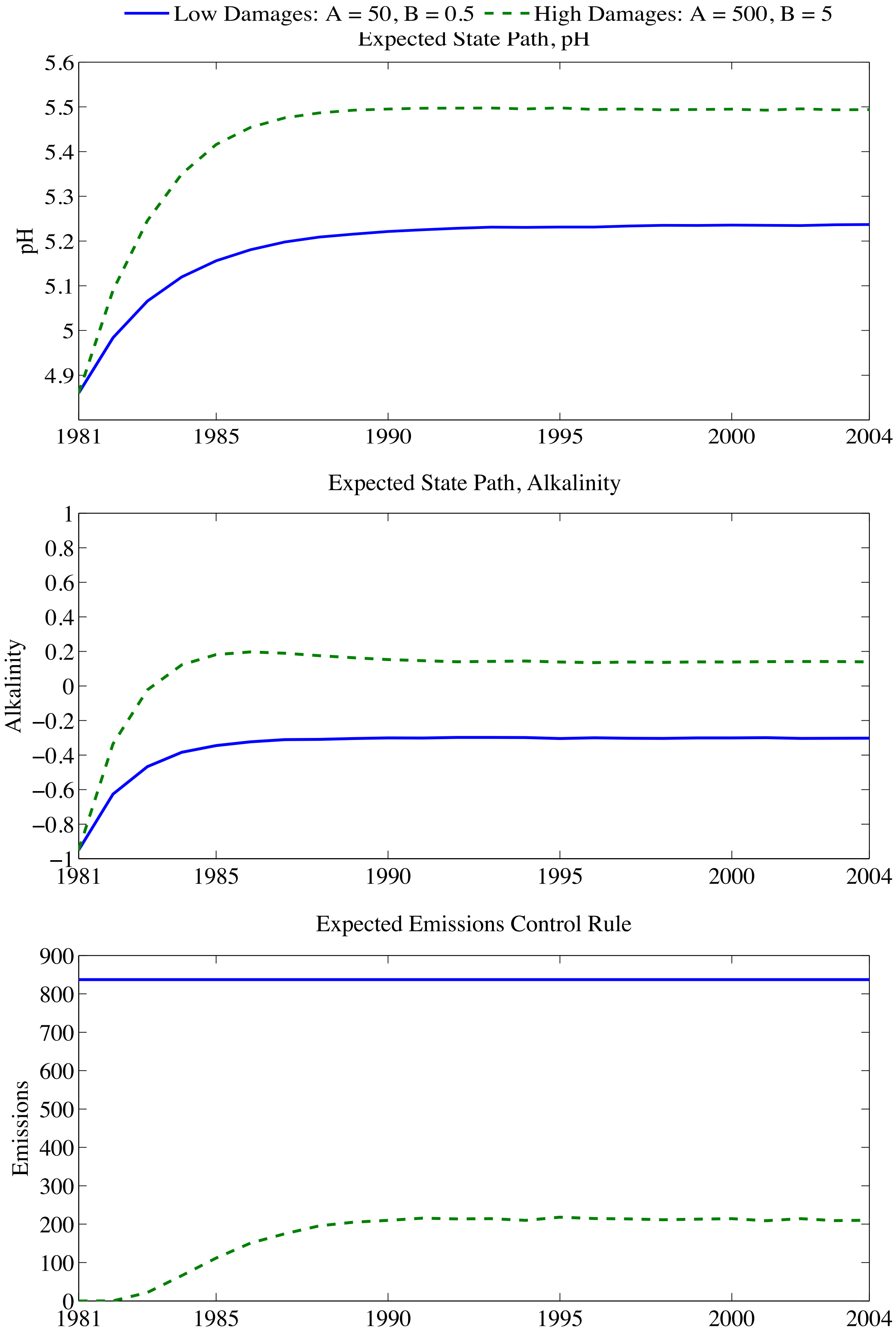


Figure 3.6: Simulated Paths for pH, Alkalinity and Optimal Emissions

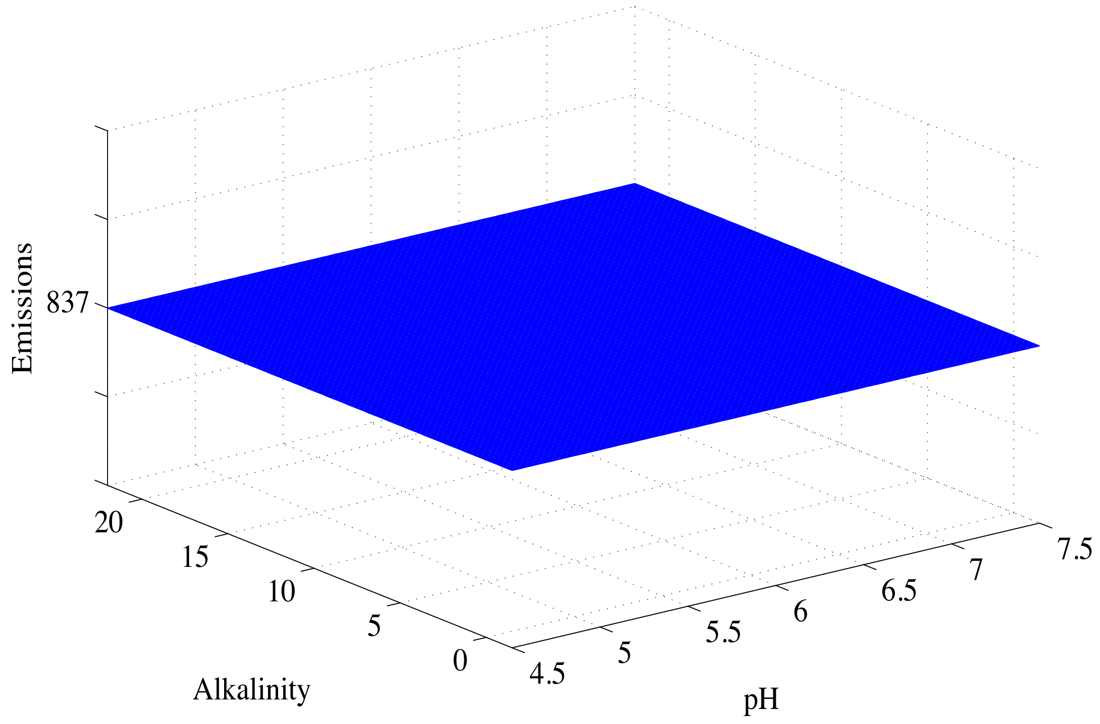

Expected State Path, pH

Expected State Path, Alkalinity

Expected Emissions Control Rule

Figure 3.7: Control Rule for Regulated Emissions

Low Damages: A = 50, B = 0.5



High Damages: A = 500, B = 5

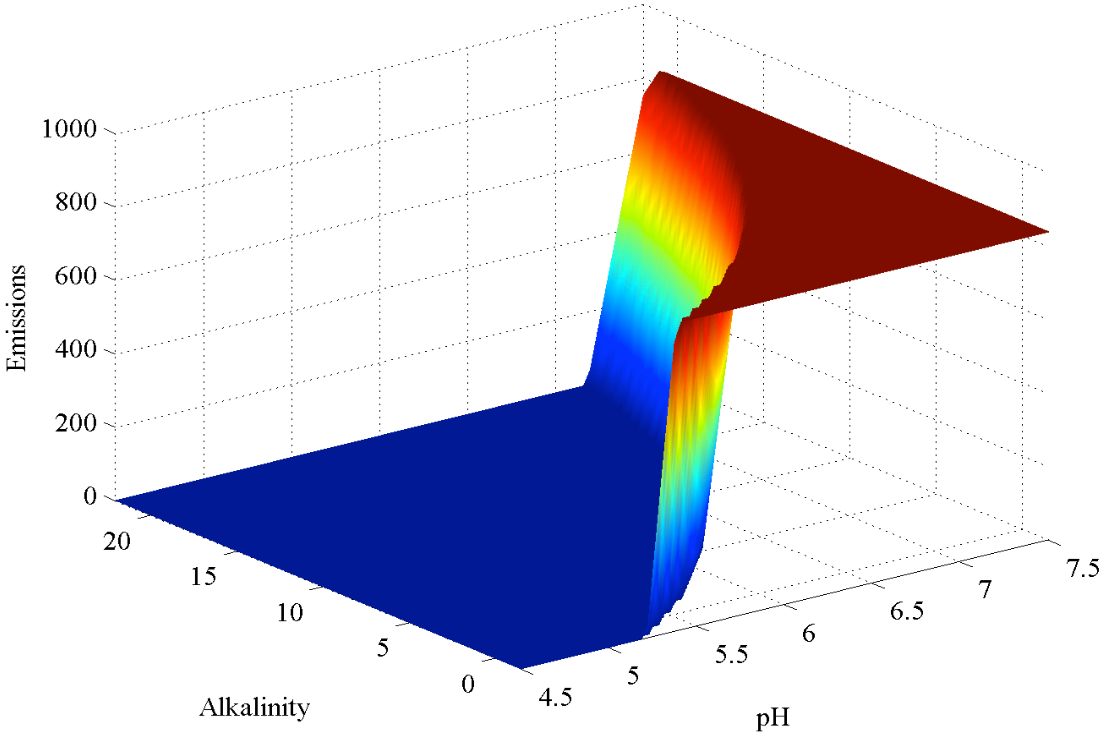


Table 3.1: Summary Statistics

	Mean	Std Dev	Min	Max	N
Water Quality Variables: 1981					
pH	4.86	0.33	4.13	5.49	40
Alkalinity	-0.95	0.90	-4.40	0.23	40
Water Quality Variables: 2004					
pH	5.57	0.52	4.66	6.47	43
Alkalinity	0.29	0.75	-1.06	2.14	43
Environmental Variables: 1981					
Current Regulatory Cap (kt of SO^2)	1082.23	-	-	-	-
Future Regulatory Cap (kt of SO^2)	882	-	-	-	-
Total Emissions (kt of SO^2)	837	-	-	-	-
Lake Site Acid Deposition	21.81	21.05	6.54	104.63	40
Environmental Variables: 2004					
Current Regulatory Cap (kt of SO^2)	365	-	-	-	-
Future Regulatory Cap (kt of SO^2)	241	-	-	-	-
Total Emissions (kt of SO^2)	240	-	-	-	-
Lake Site Acid Deposition	6.11	5.85	1.88	30.0	43
Lake Characteristics					
Distance from Sudbury (km)	59.6	30	8	128	43
Direction from Sudbury (=1 Downwind)	0.58	0.5	0	1	43
Lake Area (hectares)	273.7	305.8	14.54	1316.45	43
Elevation (m)	300.4	73.5	189	486	43
Shoreline Length (km)	19.8	20.8	2.6	89.3	43
Maximum Depth (m)	31.1	17.4	8.0	90.3	40
Mean Depth (m)	9.3	4.8	3.8	24.1	39
Volume (x 10^4 m^3)	3125.3	4032.4	83.0	17,621.0	36
Road Access (=1 Access)	0.35	0.48	0	1	43
Number of Observation	1019				

Table 3.2: State Equation for pH, Estimation Results

	(1)	(2)	(3)	(4)
$P_{i,t-1}$	0.6840	0.6806	0.6451	0.6984
	(12.64)***	(12.71)***	(11.02)***	(12.79)***
$D_{i,t-1}$	-0.0080	-0.0126	-0.0249	-0.0737
	(4.92)***	(5.17)***	(3.69)***	(2.65)**
$D_{i,t-1} \cdot L_{i,t-1}$	-3.93E-04	-4.0E-04	-7.42E-05	-0.0062
	(2.10)*	(2.27)**	-0.36	-1.53
$D_{i,t-1} \cdot Precipitation_{i,t-1}$		5.13E-06		
		(3.79)***		
$D_{i,t-1} \cdot Lake\ Area_{i,t-1}$			-2.37E-05	
			-1.58	
$D_{i,t-1} \cdot Direction_{i,t-1}$			-0.0085	
			(2.58)**	
$D_{i,t-1} \cdot Elevation_{i,t-1}$			8.84E-05	
			(3.90)***	
$D_{i,t-1} \cdot Shoreline\ Length_{i,t-1}$			2.89E-04	
			1.26	
$D_{i,t-1} \cdot Road\ Access_{i,t-1}$			-0.0063	
			(2.23)**	
Constant	1.7644	1.7885	1.9565	1.6536
	(5.92)***	(6.10)***	(5.88)***	(5.53)***
Year Dummy	Yes	Yes	Yes	Yes
Emissions Weighting Factor				
Observations	964	964	964	964
Number of Lakes	43	43	43	43
R^2	0.85	0.85	0.85	0.85

Table 3.3: State Equation for Alkalinity, Estimation Results

	(1)	(2)	(3)	(4)
$L_{i,t-1}$	0.5037	0.4936	0.4953	0.4885
	(5.15)***	(5.12)***	(4.81)***	(5.09)***
$D_{i,t-1}$	-0.0208	-0.0480	-0.0485	-0.1831
	(7.06)***	(6.82)***	(1.89)*	(5.76)***
$D_{i,t-1} \cdot Precipitation_{i,t-1}$		3.00E-05		
		(6.16)***		
$D_{i,t-1} \cdot Lake\ Area_{i,t-1}$			-3.86E-05	
			-0.71	
$D_{i,t-1} \cdot Direction_{i,t-1}$			-0.0091	
			-0.56	
$D_{i,t-1} \cdot Elevation_{i,t-1}$			1.28E-04	
			1.43	
$D_{i,t-1} \cdot Shoreline\ Length_{i,t-1}$			5.60E-04	
			0.68	
$D_{i,t-1} \cdot Road\ Access_{i,t-1}$			-0.0070	
			-1.32	
Constant	0.1428	0.3522	0.1034	-0.1271
	(2.21)**	(4.51)***	0.57	(1.90)*
Year Dummy	Yes	Yes	Yes	Yes
Emissions Weighting Factor				
Observations	964	964	964	964
Number of Lakes	43	43	43	43
R^2	0.76	0.76	0.76	0.76

Table 3.4: Parameter Estimates for Social Welfare Function

Parameter	Value	Unit of Measurement
ψ_1	6.67	million \$
ψ_2	0.362	million \$ per SO_2 kt abated
ψ_3	0	million \$ per (SO_2 kt abated)^2
$\bar{E}$	837	kt of SO_2
A	50 – 500	Marginal increase in damages (million \$) per one unit deviation from P^*
P^*	7.0	Optimal pH
B	0.5 – 5.0	Marginal increase in damages (million \$) per one unit deviation from L^*
L^*	3.0	Optimal Alkalinity
δ	0.95	Discount factor

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