THREE ESSAYS IN SUSTAINABLE OPERATIONS MANAGEMENT WITH IMPLICATIONS FOR THE TRIPLE BOTTOM LINE

BY

KARTHIK MURALI

DISSERTATION

Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in Business Administration
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2015

Urbana, Illinois

Doctoral Committee:

Professor Nicholas C. Petruzzi, Chair
Professor Michael K. Lim, Co-Chair
Professor Anupam Agrawal
Professor Dilip Chhajed

ABSTRACT

We are in a state of overshoot; the human population today consumes natural resources at a rate that exceeds what the planet can sustainably provide in the long term (Meadows et al., 2004). Two key causes of this overshoot are the overconsumption of natural resources, and the reluctance or inability of society to remedy this overconsumption through the appropriate use and deployment of technology and management practices. In this light, the work contained in this dissertation is intended to explore potential solutions that operations management can provide to mitigate the impact of these two causes of overshoot. Therefore, in the spirit of the Triple Bottom Line (3BL) framework for sustainability, we evaluate environmental and social, along with the economic implications of strategic and operational decisions in the contexts of natural resource management and green product development in this dissertation.

Freshwater is an invaluable resource to all life on earth. Groundwater reservoirs, an important source of freshwater, are drying up across the United States and the globe, creating a severe mismatch in the supply and demand of freshwater. Two new management paradigms have cropped up in recent years to remedy this mismatch: water trading and privatization. The first essay in this dissertation explores the impact of these paradigms on groundwater management and the ensuing 3BL implications.

Voluntary green product development has emerged as a viable alternative to the traditional 'command and control' approach for environmental

regulation. The second essay in this chapter addresses a producer's problem of labeling its product to communicate its environmental attributes that are otherwise invisible to consumers. The key objectives of this essay are to identify the efficacy of external ecolabeling agencies and the role of producer credibility in stimulating green product development and its resulting benefits from a 3BL perspective.

The final essay in this dissertation explores the phenomenon of pre-competitive collaboration between firms in the context of green product development. In it, we identify the motivation for and the 3BL implications of horizontal R&D collaboration between competing supply chains as well as vertical collaboration within a supply chain through cost-sharing.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude and appreciation to my co-advisors Professor Nicholas C. Petruzzi and Professor Michael K. Lim. The work contained in this dissertation could not have been made possible without their unwavering support, focused vision, and patient mentorship. Since the very first day that I made his acquaintance as an enthusiastic applicant to the doctoral program, Professor Petruzzi has guided me in my professional journey and instilled an appreciation for the rigorous, scientific pursuit of creating and disseminating new knowledge. I am deeply indebted to Professor Lim for pushing me to ask the right questions, being available to me round the clock, and for providing me with invaluable exposure to the academic community.

I would also like to thank Professor Anupam Agrawal for sharing his unique research outlook and expertise with me. Professor Dilip Chhajed's friendly feedback and thought-provoking suggestions have helped me hone and refine this dissertation. I would also like to recognize Professor Dharma Kwon, Professor Zhixi Wan, Professor Fataneh Taghaboni-Dutta, Professor Gopesh Anand, Professor Richard Engelbrecht-Wiggans, Professor Nicholas Brozovic, and Professor Dan Bernhardt whose thoughtful guidance and warm collegiality have contributed to my social and intellectual growth. I cannot thank Julie Monroe and Diana Gonzalez enough for making my progress towards the completion of this degree as smooth as possible.

Finally, I would like to thank my friends, family, and colleagues who have always stood by me through good times and bad, and exhibited a tremendous degree of tolerance and understanding while I pursued my academic goals.

Contents

Chapter 1. INTRODUCTION 1

Chapter 2. MUNICIPAL GROUNDWATER MANAGEMENT: OPTIMAL ALLOCATION AND CONTROL OF A RENEWABLE NATURAL RESOURCE 10

- 2.1. Introduction 10
- 2.2. Relation to Literature 16
- 2.3. A Model of Groundwater Management 19
- 2.4. Privatization 38
- 2.5. Conclusion 53

Chapter 3. THE IMPACT OF ECOLABELS: THE ROLE OF ECOLABELING AGENCIES AND CREDIBILITY 59

- 3.1. Introduction 59
- 3.2. Literature Review 64
- 3.3. Base Model 67
- 3.4. Producer Competition 73
- 3.5. NGO Preemption of a Private Ecolabel 83
- 3.6. Conclusion 88

Chapter 4. IS COMPETITION OR COLLABORATION THE KEY TO DRIVING SUSTAINABILITY IN SUPPLY CHAINS? 95

- 4.1. Introduction 95
- 4.2. Literature Review 100

4.3. Model 103
4.4. Impact of Competitive Intensity 115
4.5. Conclusion 118

Chapter 5. CONCLUSION 123

Bibliography 127

Appendix A (Chapter 2) 144
A1: The Centralized Management and Investment Problems 144
A2: Proofs 147

Appendix B (Chapter 3) 154
B1: Tables and Figures 154
B2: Proofs 158

Appendix C (Chapter 4) 165
C1: Proofs 165

CHAPTER 1

INTRODUCTION

"There is no more strategic issue for a company, or any organization, than its ultimate purpose. For those who think business exists to make a profit, I suggest they think again. Business makes a profit to exist. Surely it must exist for some higher, nobler purpose than that."

- Ray C. Anderson

More firms are pursuing a sustainability agenda today than at any other time in history, and they are doing so by going beyond their concern for reputation management (Bonini, 2011). But what does sustainability really mean? The most widely quoted definition of sustainability comes from the Brundtland report of 1987, "development that meets the needs of the present without compromising the ability of future generations to meet their needs" (Brundtland et al., 1987). Three decades later, while there has been some progress, including new technologies, institutions, and an awareness of environmental issues, humanity has continued to increase its ecological footprint that is now well in excess of the earth's carrying capacity (Meadows et al., 2004). John Holdren and Paul Ehrlich noted that the impact of humans on the environment can be represented by a combination of population, resource use per person (which they call affluence), and damage per unit of resource used (which they refer to as technology), i.e., the PAT formula as depicted in Figure 1 (Holdren and Ehrlich, 1974). As populations continue to rise along with affluence afforded by a growing industrial complex, we are in imminent danger of outstripping the planet of its ability to sustain us, and thus, the importance of sustainability has never been greater than it is today.

Figure 1. Holdren and Ehrlich's formula for environmental impact

Consumers demand socially and environmentally benign products, competitors carve out and take advantage of new market niches made possible by sustainable innovations, resource availability and prices remain volatile, investors and special interest groups demand a holistic focus, and regulators threaten to impose new and expensive regulation. All of the above are valid and persuasive reasons for firms to take sustainability seriously. There is considerable evidence that firms are indeed beginning to take sustainability seriously. For example, a global survey of over 1500 senior executives found that 92% of respondents said their companies were already doing something to address sustainability issues (Berns et al., 2009). More than 80% of the Global Fortune 250 companies produced annual sustainability reports to disclose their environmental performance and initiatives in 2008, and that number has since been growing (Kolk, 2008).

However, without well defined metrics and guidelines, sustainability becomes an abstract concept with little practical relevance. One framework that has emerged in recent years to measure and evaluate the impacts of management policies on multiple stakeholders; people, planet, and profit, is the Triple Bottom Line (3BL) (Elkington, 1998). Kleindorfer et al. (2005) point out that Operations Management has a significant role in measuring and reducing the impacts of firms on these stakeholders. Indeed, there is a growing literature in Operations Management that adopts a 3BL perspective which requires firms to expand their focus to consider social and environmental consequences aside from the economic objective of profit. Environmental performance measurement has been considered in a variety of contexts including supplier selection (Handfield et al., 2002; Bai and Sarkis, 2010), pollution removal and prevention (Islegen and Reichelstein, 2011; Kraft et al., 2013b,a), remanufacturing and waste minimization (Souza, 2013; Ata et al., 2012; Galbreth et al., 2013), electric vehicle deployment (Avci et al., 2014; Lim et al., 2014) etc. Social performance metrics have also been studied, for instance, in the context of supplier selection (Pagell et al., 2010; Xu et al., 2015; Guo et al., 2015), and social enterprise operations (Sodhi and Tang, 2011; Balasubramanian and Drake, 2015).

It is in light of the relevance and importance of sustainability to businesses today that I present my dissertation titled "Three essays in sustainable operations management with implications for the Triple Bottom Line". The three essays in my dissertation are drawn from developments in the fields of operations management, industrial organization, natural resource economics, and marketing. While the modeling schemes and contexts of application of these essays may vary, they are unified in their focus to obtain managerial and policy prescriptions to instruct the development and diffusion of sustainability in production and consumption.

The three essays in this thesis are characterized by two key features, the first of which is a 3BL perspective. The 3BL concept is an accounting framework for assessing the impacts of business practices using context-specific measures of environmental impact, social equity, and similar constructs with the ultimate goal of balancing *societal* and *environmental* concerns with *economic* objectives (Elkington, 1998). The 3BL concept addresses the impact of strategic and operational decisions on stakeholders not explicitly considered by standard management objectives. The three essays in this thesis contribute to the literature in Operations Management and related fields by extending the 3BL perspective beyond these contexts to the areas of natural resource management, ecolabeling and environmental quality competition, and collaboration within and across supply chains for research and development in sustainability.

The second characteristic feature of this thesis is the search for managerial and policy prescriptions to promote sustainability. The need for regulation to protect society and the environment gets widespread but grudging acceptance: widespread because everyone wants a livable planet, grudging because of the lingering belief that social and environmental regulations erode competitiveness (Porter and Van der Linde, 1995). The traditional view of sustainability in business practices assumes the existence of a trade-off between social and environmental stewardship and economic prosperity. Organizations often perceive the increased costs of production and investments required to develop more sustainable products and processes as a burden. This view pits benefits to society and the environment against the prospect of economic gains. However, there is a growing consensus among academics and practitioners that sustainable practices can add economic value by cutting operating costs, increasing revenues and market share, and by positioning a firm or organization to remain relevant in a global arena where sustainability is projected to become the norm and constraint to doing business (Vachon and Klassen, 2008; Anderson, 2009). An extensive 2009 survey of corporate executives identified the following reasons (in Figure 2) for pursuing a sustainability agenda.

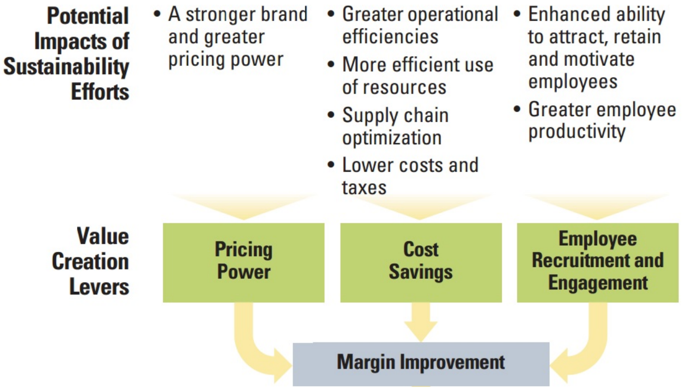


Figure 2. Source: Berns et al. (2009)

This leaves us with the following question: Can private enterprise be sustainable without external intervention or regulation? When and how is regulation or intervention by external agencies needed to ensure socially and environmentally responsible business practices? These questions are addressed in each of the three essays that follow this chapter.

The first of the three essays in this dissertation is contained in Chapter 2, and tackles a natural resource management problem. The growing scarcity of freshwater has led to a new management paradigm, two ingredients of which are market-like institutions for the reallocation of water, and the privatization of water management. The 3BL approach is particularly relevant in this context due to the importance of water from a societal and environmental perspective. Accordingly, the overarching purpose of this chapter is to assess the implications of the aforementioned management paradigms for society and the environment in the spirit of the 3BL approach for sustainable management. The specific resource in consideration is a renewable groundwater aquifer. We formulate a deterministic optimal control model to study a welfare-maximizing community's problem of managing its groundwater aquifer, and determine optimal extraction and allocation policies in the presence of market-based water transfer opportunities. We also study the impact of privatizing the management of the community's groundwater on the optimal extraction and allocation policies, and contrast the results of welfare and profit-maximizing groundwater management along societal and environmental dimensions in the spirit of the 3BL approach. To this end, we define context specific measures of environmental and societal performance in this chapter.

We find that access to water reallocation opportunities will have a detrimental (beneficial) societal and environmental impact in exporting (importing) communities. However, from a global perspective that captures impacts across trading communities, we find that water reallocation can be beneficial to society and the environment given certain hydrological characteristics. In particular, we note that water trading between communities with hydrologically similar endowments of groundwater can be beneficial from a global 3BL perspective. In contrast, trade between communities endowed with aquifers with vastly dissimilar hydrological characteristics results in detrimental global social and environmental consequences. This is particularly problematic because of the sizeable economic gains to be realized from trading between such communities. We also find that privatization of groundwater management will result in negative societal consequences in the exporting community. However, privatization can be beneficial to the environment. Moreover, privatization also results in positive societal and environmental implications from a global perspective when only the communities with specific hydrological characterestics are privatized.

The second essay in Chapter 3 studies a problem of environmental quality competition. Several studies in the literature have addressed green product design and environmental quality competition (for example, see

Chen (2001); Amacher et al. (2004)). A key characteristic of environmental product attributes is their unobservability, i.e., they cannot be searched for or experienced by consumers, and therefore need to be communicated through the use of credible ecolabels. Environmental claims can be made unilaterally by the producer, or by acquiring voluntary ecolabels from external certification agencies that stipulate labeling fees and an environmental standard that the product must meet before it can use their label. Producers consider acquiring external ecolabels because while their own environmental claims are discounted by consumers, external ecolabels enjoy full credibility and thus boost demand for a product bearing them. The primary contribution of this essay to the literature is to explore this aspect of green product development - ecolabeling by external certification agencies. We develop a Stackelberg game with the external certification agency in the role of a leader. By comparing the societal, environmental, and economic performance resulting from an environmental-benefit maximizing NGO certification agency and a profit-maximizing private certification agency, we identify conditions under which intervention by external agencies may be beneficial.

From the societal perspective, depending on the parameters in question, consumers may be better off with an NGO or private ecolabeling scheme, or neither. However, despite creating an opportunity to boost demand, external ecolabeling schemes hurt producer profits. From the environmental perspective, we find that while external ecolabeling schemes improve environmental outcomes regardless of the source, NGO's will impose a higher environmental standard while private certifiers will charge a positive labeling fee and impose lower environmental standards on producers, consequently underproviding environmental benefits. Noting that the environmental perspective is most salient given the intended purpose of ecolabeling schemes, we explore the role of NGOs in mitigating the underprovision of environmental benefits by a private ecolabeling scheme by anticipating their entry and announcing their own ecolabeling scheme in advance. We find that while such intervention has no impact in a producer monopoly, it improves environmental outcomes in the presence of producer competition. This essay also addresses the impact of credibility of environmental claims made by producers on green product development and the efficacy of external ecolabeling schemes.

The third essay in Chapter 4 was motivated by observing an interesting phenomenon: a growing number of organizations have begun to collaborate across previously inviolable boundaries to co-develop and share sustainable innovations. While the impact of supply chain coordination on sustainability has been studied (Klassen and Vachon, 2003; Swami and Shah, 2012), collaboration across supply chains is relatively unexplored. Examples of such collaborative alliances include the Sustainable Apparel Coalition with its partners including competitors Nike and New Balance, and WalMart and Target, among others, and the Climate Savers Computing Initiative with Google, Intel, Hewlett Packard, Microsoft, Apple etc. as its member organizations. This observation leads to the obvious question: why do competing firms collaborate with each other? And what impact does such collaboration have from a 3BL perspective? We address these questions in this essay by analyzing a parsimonius model of precompetitive collaboration within and across competing supply chains.

We find that vertical collaboration through cost-sharing within a supply chain can increase the level of environmental investments and improve social and environmental implications. The impacts of horizontal collaboration however depend on the competitive intensity between the collaborating supply chains: at higher (lower) levels of competitive intensity, horizontal collaboration leads to a lower (higher) investment in sustainability and consequently, in negative (positive) implications for society and the environment. However, regardless of competitive intensity, competing OEM's benefit from collaboration, which explains why we observe a growing number of such collaborative alliances.

Chapter 5 concludes this dissertation. It contains a summary of contributions, a description of the limitations, as well as potential extensions to our work here. Additional figures and tables as well as proofs are provided in Appendices.

CHAPTER 2

MUNICIPAL GROUNDWATER MANAGEMENT: OPTIMAL ALLOCATION AND CONTROL OF A RENEWABLE NATURAL RESOURCE

2.1. Introduction

As the world's supply of freshwater is burdened by the increasing demands of a growing population, the insulation and subsistence of municipal water systems on local sources of water may not be possible in the near future. Indeed, the Natural Resources Defense Council (2010) projects that by 2025, the world will experience over a 40% mismatch in the supply and demand for clean water, and over 30% of states in the continental United States are expected to experience severe water shortages by the middle of the 21st century. The growing scarcity of freshwater has led to a changing water management paradigm with an emphasis on finding or developing new sources of water supply, addressing increasing and newly realized demands, and incorporating societal and ecological considerations into water management policies (Gleick, 2000). *Groundwater* in particular is an important source of freshwater across the globe. Indeed, it accounts for 33% of the total freshwater used in the United States, and many communities, including for example, San Antonio, Texas, and 38 of Virginia's 95 counties, rely exclusively on groundwater for their needs (Kenny et al., 2009). In light of these observations, we study two important issues focused on groundwater in this chapter, namely, water transfers as a means of reallocating groundwater to address spatially differentiated demands, and privatization of groundwater-based municipal water supply systems within the context of water transfers.

The majority of arguments opposing groundwater transfers and privatization are made on the grounds of perceived deleterious impacts on the local community and the environment. In general, management objectives do not directly address the interests of these external stakeholders. Nevertheless, broader frameworks have evolved in recent years to measure and evaluate the impacts of management policies on these external stakeholders. The Triple Bottom Line (3BL) concept is one such framework for assessing the impacts of business practices using context-specific measures of environmental impact, social equity, and similar constructs with the ultimate goal of balancing *societal* and *environmental* concerns with *economic* objectives (Elkington, 1998). The 3BL concept is particularly relevant in our context of municipal water supply management. Accordingly, the overarching purpose of this chapter is to assess the implications of the aforementioned groundwater management paradigms for society and the environment in the spirit of the 3BL approach for sustainable management.

Historically, especially in the Western United States before the 1970's, the institutions that evolved to manage water scarcity were committed to increasing supply capacity with large amounts of capital invested in storage and conveyance infrastructure. However, an increase in demand, costs of capital, and water scarcity have shifted the focus to market-like institutions for the efficient reallocation of water (Vaux and Howitt, 1984). Informal markets for groundwater trading between agricultural users occur in developing regions of the world where the appropriate legal and administrative institutions to enable transactions do not exist, such as in India (Saleth, 1998) and Pakistan (Meinzen-Dick, 1998). Formal and well-developed water markets with significant volumes of trade exist in Chile, South Africa, Australia, and the Western United States (Grafton et al., 2010). Groundwater transfers may take the form of permanent sales of water rights. For example, in Texas, the city of Amarillo purchased rights to pump water and transfer it from under 72,000 acres of land in Roberts County, and the city of San Antonio has a contract with Alcoa to pump and transfer 55,000 acre-feet of groundwater from Lee and Milam counties (Kaiser, 2005). Alternatively, groundwater can also be transferred through leases in a water market, such as in the case of the Rio Grande market in Texas (Yoskowitz, 1999) and the California Emergency Drought Water Bank (Israel and Lund, 1995).

However, groundwater transfers such as these are sometimes controversial for their impacts on the environment and for their implications for affordability and accessibility to water within the exporting communities (Bakker, 2007). Depletion of local sources as a result of groundwater exports have resulted in local ordinances being passed in the state of California and the American Southwest to restrict and control the terms of these transactions (Hanak and Dyckman, 2002). There is also considerable opposition from environmentalist groups on the grounds of severe impacts on the watersheds in and around the exporting community, as is the case for example with Cadiz Inc.'s proposal to export groundwater from the Mojave Desert to suburbs in Southern California (Hart, 2008). Hence, the first objective of this study is to determine the groundwater management policy for a municipality with water reallocation opportunities and to evaluate ensuing implications for society and the environment.

A second line of inquiry is to study the effect of privatization of groundwater-based municipal water supply sytems. An increasing trend of privatization of municipal water supply systems since the 1990's has led to water being dubbed the "oil of the 21st century" (Tully, 2000). Privatization of municipal water systems can take many forms, from subcontracts for facility and distribution infrastructure operations to monopoly control, although we focus only on the latter in this chapter. Privatization may also imply the ownership of water rights by private interests such as farmer or landowner collectives. In some instances, private water rights are held with the express intent of marketing them. Two examples are Mesa Water (a landowner partnership in Roberts county, Texas) and Rio Nuevo Ltd. (a private firm) that are seeking buyers for their groundwater (Kaiser, 2005). Detractors cite overpricing, quantity rationing, and profiteering from exports as reasons to oppose privatization (Bakker, 2007). Indeed, widespread protests have been witnessed in Bolivia, India, and the Middle East in response to drastic rate hikes following privatization (Barlow and Clarke, 2005). However, proponents of privatization argue that it leads to a more judicious use of scarce water resources. Moreover, they claim that private ownership is more likely to foster rapid development and investment in creating substitutes for naturally occuring freshwater that will reduce the burden on groundwater sources (Hauter, 2012). There is some evidence to support this claim, as a vast majority of desalination projects around the globe are privately owned or operated and are expanding rapidly with installed capacity increasing at a rate of 7% annually (Gleick and Cooley, 2006). Hence, the second objective of this chapter is to determine and contrast the impacts of privatization on groundwater management and water reallocation policies and to explore ensuing implications for society and the environment.

The groundwater source we consider is a renewable and exhaustible aquifer with endogenous costs of extraction. We study the groundwater management problem for a welfare-maximizing municipality using a stylized dynamic optimization model. We consider two prominent mechanisms of water reallocation identified from an empirical analysis of water market structures in the Western United States (Hansen et al., 2008). In particular, we first model the export or import of water on a lease basis at an exogenous price that is characteristic of, and which we refer to as, a *water market*. Second, we model permanent sales of groundwater rights through an endogenously determined price-quantity agreement between two municipalities, which we refer to as a *fixed quantity contract*. In both cases, we assume that a given municipality manages its own aquifer that is hydrologically disconnected from other aquifers and the water market. We also assume that the exogenous price in the case of a water market is fixed and constant. We discuss the limitations of these assumptions and the challenges posed by relaxing them in Conclusion. Following our analysis of groundwater reallocation, we consider profit-maximization in lieu of welfare-maximization as the management objective to study and contrast the impact of privatization on groundwater management, groundwater reallocation, and investment in water production technologies. Throughout, we define surrogate measures of local and global societal and environmental impacts to evaluate the performance of these groundwater management paradigms from a 3BL perspective.

The key results and contributions of this chapter can be summarized as follows:

(1) We characterize groundwater management policies in the context of two prominent water reallocation mechanisms. We find a threshold policy that depends on the water level in the aquifer

to be optimal for governing the municipality's decision to export or import water in a water market. From a 3BL perspective, we find that exporting (importing) water leads to negative (positive) impacts on society and the environment within that municipality at steady-state. However, fixed quantity trading can lead to both positive and negative implications from a global 3BL perspective. We therefore identify the hydro-economic conditions under which these implications occur, and find that typical trading scenarios between municipalities with vastly different endowments of groundwater can be detrimental to the environment.

(2) We study the impact of privatization on groundwater management policies and their 3BL implications. We find that a municipality importing water through a water market may switch instead to exporting water following privatization. Moreover, as partial confirmation of concerns voiced by its detractors, we find that privatization results in negative implications for society at a local level. However, under export bans, privatization of a municipality can have positive implications for the environment because it mitigates the unintended overextraction of groundwater in the transition to steady-state (which is akin to the green paradox). We also find that fixed quantity trading is particularly beneficial from a global 3BL perspective if only *one* of the municipalities is privatized, but such trade leads instead to especially negative impacts from a global 3BL perspective if *both* of the municipalities are privatized. Finally, contrary to popular claims, we show that privatization does not encourage the development of water production technologies.

The remainder of this chapter is organized as follows. We provide a brief review of the relevant streams of literature in §2.2 to position and emphasize the contribution of our work. We introduce the model setting and solve the municipality's dynamic optimization problem in a water market in §2.3. Then in §2.4, we study privatization and its implications. We conclude the chapter in §2.5. Problem formulations not included in the body of the chapter are provided in Appendix A1, and technical proofs are provided in Appendix A2.

2.2. Relation to Literature

Our model and its application context are related to four streams of literature, the first of which concerns the extraction of natural resources. The modern theory of exhaustible resource extraction traces its roots to the theory of the mine (Hotelling, 1931), but it has evolved to address renewable resources and multiple spatially differentiated deposits and users, both for the case of centralized management (Shimomura, 1983; Krulce et al., 1997) and for the case of open access (Clark, 1990). Saleh et al. (2011) compare centralized groundwater management policies with open access exploitation, but they consider only a single source of groundwater. Other studies in this stream consider the related problem of exhaustible resource management with the possibility of transitioning to the importation of exogenously priced substitutes (Sethi and Sorger, 1990; Roumasset and Wada, 2012) or investing in susbtitute production capacity (Fuller and Vickson, 1987; Holland, 2003). We combine the features of multiple renewable resource deposits and demands in the context of decentralized management with exclusive user rights, and augment this literature by considering substitution through groundwater reallocation (imports as well as exports) at exogenously fixed prices in a water market or by endogenously determined prices through a fixed quantity contract.

The second stream focuses on privatization of water management. Within this domain, Bruggink (1992) provides an excellent overview of the arguments favoring privatization of groundwater. Dawande et al. (2013) study the problem of allocating surface water through various market mechanisms for a farming community to achieve an equitable distribution. In addition, a number of studies (for example, see Fractor (1988) and Holland (2003)) address privatization of groundwater management with varying modeling assumptions related to hydrology and demand functions. However, with the exception of Holland (2003, 2006) who considers investment in a capacity constrained substitute, none of these papers address alternatives for local groundwater extraction in the form of produced substitutes or reallocation mechanisms.

The third stream relates to studies of water reallocation. These focus primarily on the economic efficiency of water transfers (for example, see Vaux and Howitt (1984), Howe et al. (1986), and Calatrava and Garrido (2005)). Weinberg et al. (1993) analytically estimate the impact of water transfers on water quality. Saliba et al. (1987) discusses the impact of water transfers on social equity and cultural implications for marginalized communities. Howe and Goemans (2003) empirically estimate the socio-economic repercussions of water transfers in two different regions of Colorado. They find that low transaction costs and more frequent intra-basin transfers in economically diversified communities are likely to have positive societal and economic impacts, whereas large inter-basin transfers in highly specialized (typically agricultural) communities can have severe socio-economic consequences. However, these studies do not consider the municipality's problem of water management given a specification of hydrological and economic conditions. Rather, they take demand and supply functions of municipalities as given. Moreover, none of these studies address groundwater management or privatization.

An important contribution of our work to the literature on exhaustible resource extraction is the application of a 3BL perspective to evaluate different groundwater management paradigms. In this respect, the fourth stream of literature to which our work is related falls within the area of Operations Management, particularly the nascent domain of socially responsible operations, and addresses the impact of management policies on stakeholders not explicitly considered by standard management objectives. Kleindorfer et al. (2005) and Tang and Zhou (2012) provide two particularly relevant reviews of 3BL and related frameworks within the context of Operations Management applications and models. In a similar vein, Wang et al. (2015) consider the optimal allocation of farmland, a renewable but inexhaustible resource, for the production of biofuel crops through subsidization while taking into account environmental sustainability and the growth of the biofuel industry. In addition, there is a substantial literature studying the effectiveness of Environmental Management Systems (EMS), such as the ISO 14000 family of certifications, and Total Quality Environmental Management (TQEM), and their implications for profitability of the firm (Klassen and McLaughlin, 1996; Delmas, 2001; Melnyk et al., 2003; Corbett and Klassen, 2006). Our work differs from these studies in applying the 3BL approach for socially responsible and environmentally sustainable management outside the context of manufacturing and supply chains. Indeed, the importance of sustainable and socially responsible management practices is arguably greater in our context because they have a more direct and measurable impact on the external stakeholders, i.e., society and the environment, relative to the traditional contexts of manufacturing and supply chains that are the typical focus of this stream of literature.

2.3. A Model of Groundwater Management

We consider a groundwater reservoir with deterministic hydrodynamics that we refer to as an *aquifer*. The defining feature of the aquifer in the context of our model is its water level (i.e., the depth of the aquifer) denoted by x_t at time t. The water level in the aquifer is governed by three forces, the first of which is refill from rainfall and surface water runoff that replenishes the aquifer. The second is the leakage from the boundaries of the aquifer that tends to increase with the water level due to a greater surface area and higher hydrostatic pressure on the boundaries of the aquifer. The third is the quantity (i.e., volume) of water extracted from the aquifer at time t, q_t. To focus on the economics instead of the hydrodynamics, we do not explicitly model refill and leakage; rather, we define recharge to represent the net volume of water entering the aquifer as a result of the refill and leakage forces. Later, in the numerical analyses of §2.3.2 and §2.4.1, we will adopt a specific functional form for recharge. For now, we assume that the recharge $G(x_t)$ is such that $G'(x_t) < 0$, $G''(x_t) \leq 0$, and $G(K) = 0$, where K denotes the maximum possible water level in the aquifer, which we refer to as *capacity*. These assumptions on recharge are common in the literature (see, for example, Tsur and Graham-Tomasi (1991)) and are typically used to model porous, sandy, or coastal aquifers where losses from leakage tend to be considerable (Roumasset and Wada, 2012). Given $G(x_t)$ and q_t, the net rate of change of the water level in the aquifer can be described in principle by the differential equation $\frac{dx_t}{dt} = \rho(G(x_t) - q_t)$, where $\rho > 0$ is a factor that converts water volume to water level (Gisser and Sanchez, 1980). For analytical convenience, we set $\rho = 1$ because such a parameterization does not qualitatively affect our analysis.

The water level in the aquifer also affects the costs of extraction. We assume that the unit cost of extraction increases as the water level in the aquifer falls because the required pumping lift increases and deeper wells must be dug. In particular, consistent with the literature, we use a convex decreasing unit extraction cost function $c(x_t)$, $c'(x_t) < 0$, $c''(x_t) > 0$, and $c(K) = 0$ (see, for example, Krulce et al. (1997)). Further, we assume that the unit cost of extraction at time t is independent of the quantity extracted at that time q_t, as is the case when the quantity extracted is relatively small in comparison with the volume of the aquifer. We assume that conveyance infrastructure for transferring water between municipalities is already in place, i.e., we do not explicitly consider transportation costs in our model. Such a cost can be captured trivially and does not change our results qualitatively.

In our modeling framework, we define a *municipality* to be the basic unit of groundwater management by stipulating that a given municipality controls a single aquifer to serve a single community. A municipality may refer to a town or to a collective of farmers or landowners. Water extracted from the aquifer is either sold for consumption within the municipality or exported outside the municipality through a water market or a fixed quantity contract. We note here that the water market is hydrologically disconnected from the municipality, such that the export or import of groundwater through the market has no direct impact on the municipality's aquifer except through a change in its optimal extraction decisions.

Empirical examination of the elasticity of municipal demand for water has found that it is decreasing in the quantity of water sold for consumption (Espey et al., 1997; Harou et al., 2009). Accordingly, we define a linear demand function $p(l_t) = a - bl_t$, where $a,\ b > 0$, to characterize the price of a quantity l_t of water sold for consumption within a municipality at time t. The parameter a embodies factors including population, income, and the relative proportions of residential, agricultural, and industrial demands; b represents the aggregate price-sensitivity of demand. This demand function, which represents disparate individual demands that are aggregated across residential, industrial, and agricultural uses within a municipality, is consistent with related literature. In particular, the linear specification has been used in the empirical literature to estimate the demand for water (Espey et al., 1997; Hanemann, 1998), in analytical models of groundwater management (Gisser and Sanchez, 1980; Feinerman and Knapp, 1983), and in analytical and empirical models analyzing water transfers (Vaux and Howitt, 1984; Dinar and Letey, 1991; Weinberg et al., 1993).

We assume that the objective of the municipality is to maximize its total welfare, i.e., the economic surplus for its community, where economic surplus is the sum of consumer and producer surplus. Consumer surplus is defined as the difference between the consumers' maximum willingness to pay and the equilibrium price paid (i.e., the area under the demand curve up to the equilibrium quantity supplied). Producer surplus is the economic profit accruing to the producer (i.e., the revenue net of total costs). An example of such a welfare-maximizing municipality in the context of water supply management is the Metropolitan Water District (MWD) of Southern California (O'Connor, 1998). Later in §2.4, we model profit-maximizing water supply management to study the impact of privatization.

Given this modeling framework, we first study a single municipality's participation in a water market defined by a constant exogenous price s in §2.3.1. Following this, we study the equilibrium between two municipalities interacting through a fixed quantity contract for trading water rights at an endogenously determined price in §2.3.2. Mathematical notations are summarized in Table 1.

Variable/Parameter	**Description**
t	Time ($0 \leq t < \infty$)
x_t	Water level at time $t \geq 0$; $0 \leq x_t \leq K$
$c(x_t)$	Unit cost of water extraction at water level x_t
l_t	Total quantity of water sold locally at time t; $l_t \geq 0$
e_t	Total quantity of water exported at time t; $e_t \geq 0$
i_t	Total quantity of water imported at time t; $i_t \geq 0$
q_t	Total quantity of water extracted at time t; $q_t = l_t - i_t + e_t$
$p(l_t)$	Price of water sold within the municipality; $p(l_t) = a - bl_t$
s	Price in the water market
$G(x_t)$	Groundwater recharge at water level x_t; $G(x_t) \geq 0$
δ	Discount rate; $0 < \delta \leq 1$
K	Capacity of the aquifer; $K = G^{-1}(0)$

Table 1. Modeling notation

2.3.1. Water Markets. We begin by considering the problem faced by a municipality with the option to participate in a water market. As one example of a water market, the California Emergency Drought Water Bank of 1991 paid a fixed price of \$125/acre-foot of water to all sellers (Israel and Lund, 1995). The municipality must determine how much groundwater to sell for consumption within the municipality l_t, as well as how much water to export e_t or import i_t on the water market for all t. Water is sold within the municipality at a price $p(l_t) = a - bl_t$ and in the water market at a constant exogenous price s, as in Dinar and Letey (1991), Weinberg et al. (1993), and Calatrava and Garrido (2005). The total quantity of water extracted from the aquifer at time t is the sum of the water that is sold for local consumption net of the water imported for that purpose, and the water exported on the water market: $q_t = l_t - i_t + e_t$. The municipality's problem can be formulated as follows:

(2.3.1)

$$\underset{l_t, e_t, i_t}{\text{maximize}} \int_0^{\infty} e^{-\delta t} \left[\int_0^{l_t} (a - bu)du + s(e_t - i_t) - c(x_t)(l_t - i_t + e_t) \right] dt,$$

$$\text{Subject to} \frac{dx_t}{dt} = G(x_t) - (l_t - i_t + e_t),$$

$$l_t,\ e_t,\ i_t,\ x_t \geq 0.$$

In (2.3.1), the welfare from consumption of water within the municipality at time t is captured by the term $\int_0^{l_t}(a - bu)du - c(x_t)(l_t - i_t) - si_t$, and the profit from exporting through the water market at time t is captured by $(s - c(x_t))e_t$. The total welfare and revenue from local consumption and exports are obtained by integrating over an infinite horizon and applying a discount rate $\delta > 0$ to future streams. The first constraint represents the hydrodynamics of the aquifer, where the change in water level at time t is given by the recharge $G(x_t)$ less the total quantity of water extracted from the aquifer. The second constraint stipulates that the water level in the aquifer as well as the quantities of water consumed locally, exported, and imported must be non-negative at all times t.

The municipality's problem (2.3.1) is a deterministic optimal control problem over an infinite horizon. This problem can be solved using standard techniques by applying the maximum principle to provide the necessary conditions for optimality. These conditions are also sufficient due to the concavity of the integrand and linearity of the equation of motion in the decision variables in this problem (Mangasarian, 1966). Accordingly, the current value Hamiltonian $H^{c.v}$ (Kamien and Schwartz, 1991) for this problem is

(2.3.2)

$$H^{c.v} = al_t - \frac{b}{2}l_t^2 + s(e_t - i_t) - c(x_t)(l_t - i_t + e_t) + \lambda_t(G(x_t) - (l_t - i_t + e_t)).$$

Note that the current value Hamiltonian eliminates the discounting term $e^{-\delta t}$ from the integrand in (2.3.1), thus making the problem autonomous or time-independent. The resulting optimality conditions for (2.3.1) can be derived from (2.3.2) as follows:

$$\text{(2.3.3)} \quad \frac{\partial H^{c.v}}{\partial l_t} = a - bl_t - c(x_t) - \lambda_t \leq 0 \;\text{ and }\; l_t(a - bl_t - c(x_t) - \lambda_t) = 0,$$

$$\text{(2.3.4)} \quad \frac{\partial H^{c.v}}{\partial e_t} = s - c(x_t) - \lambda_t \leq 0 \;\text{ and }\; e_t(s - c(x_t) - \lambda_t) = 0,$$

$$\text{(2.3.5)} \quad \frac{\partial H^{c.v}}{\partial i_t} = -s + c(x_t) + \lambda_t \leq 0 \;\text{ and }\; i_t(c(x_t) + \lambda_t - s) = 0,$$

$$\text{(2.3.6)} \quad \frac{d\lambda_t}{dt} - \delta\lambda_t = -\frac{\partial H^{c.v}}{\partial x_t} = c'(x_t)(l_t - i_t + e_t) - G'(x_t)\lambda_t,$$

$$\text{(2.3.7)} \quad \frac{dx_t}{dt} = G(x_t) - (l_t - i_t + e_t),$$

$$\text{(2.3.8)} \quad l_t,\ e_t,\ i_t,\ x_t,\ \lambda_t \geq 0.$$

Therefore, the optimal solution to the municipality's problem as defined by (2.3.3)-(2.3.8) comprises a set of differential equations that uniquely characterizes the evolution of the water level in the aquifer $\frac{dx_t}{dt}$, the rate of water sold for consumption within the municipality $\frac{dl_t}{dt}$, and the rate of water either exported $\frac{de_t}{dt}$ out of or imported $\frac{di_t}{dt}$ into the municipality. At *steady-state* $t \geq T$, the evolution of the water level and quantity extracted must cease, i.e., $\frac{dx_t}{dt} = \frac{dq_t}{dt} = 0$. Thus, the hydrodynamic constraint (2.3.7) implies that the total quantity of water extracted from the aquifer $q_t = l_t - i_t + e_t$ exactly equals the recharge $G(x_t)$ at steady-state. To avoid ambiguity, we denote the variables at steady-state with the subscript "*ss*". For example, x_{ss} represents the water level of the aquifer at steady-state. Further, to distinguish it from the steady-state, we refer to $t < T$, which is such that $\frac{dx_t}{dt}, \frac{dq_t}{dt} \neq 0$, as the *transitional phase*.

Given (2.3.3)-(2.3.8), we provide the general solution to the municipality's problem in Proposition 2.1, but we first characterize the solution to a special case in which a water market does not exist, i.e., when $e_t = i_t = 0$ for all t by definition. We refer to this as the *benchmark solution* and index the variables for this special case with the superscript "*o*". Ultimately, we will use the benchmark solution to describe and contrast the effects of the water market on the municipality's optimal groundwater management policy.

LEMMA 2.1. *Suppose $e_t = i_t = 0$ for all t in (2.3.1). Then the following are true:*
(a) $l_t^o > 0$ implies that $\lambda_t^o = a - bl_t^o - c(x_t) \geq 0$.
(b) If $l_t^o > 0$, then the optimal rate of consumption and the corresponding evolution of the water level are uniquely described by the initial water level x_0 and the following system of differential equations:

$$\frac{dl_t^o}{dt} = \frac{G'(x_t) - \delta}{b}[a - bl_t^o - \kappa(x_t)],$$
$$\frac{dx_t}{dt} = G(x_t) - l_t^o,$$

where $\kappa(x) := c(x) + \frac{c'(x)G(x)}{G'(x)-\delta}$.
(c) At steady-state, $x_{ss}^o = G^{-1}(\frac{a-\kappa(x_{ss}^o)}{b})$ and $l_{ss}^o = \frac{a-\kappa(x_{ss}^o)}{b}$.

In Lemma 2.1(b), we refer to the consumption quantity l_t^o despite the lack of explicit analytical solutions to the system of differential equations. In fact, we observe that because this system of differential equations is autonomous, the benchmark consumption quantity l_t^o is time-independent and depends only on the water level x_t. Hence, we express the benchmark consumption quantity as $l^o(x_t)$. Correspondingly, given Lemma 2.1(a), we also express λ_t^o as $\lambda^o(x_t)$. We also find (as shown in the proof of Lemma 2.1) that the benchmark consumption quantity is increasing in the water level of the aquifer, i.e., $\frac{dl^o(x)}{dx} > 0$. Given $l^o(x_t)$, we define the corresponding benchmark price of water sold for consumption within the municipality as $s^o(x_t) := p(l^o(x_t)) = a - bl^o(x_t)$. Accordingly, we see from Lemma 2.1(a) that in order for any water to be sold for consumption within the municipality, the benchmark price $s^o(x_t)$ must exceed the unit extraction cost $c(x_t)$ by the mark-up amount $\lambda^o(x_t)$, i.e., $s^o(x_t) = c(x_t) + \lambda^o(x_t)$. Moreover, note from Lemma 2.1(c) that at steady-state, $s^o(x_{ss}^o) = \kappa(x_{ss}^o)$, and thus, $\lambda_{ss}^o := \lambda^o(x_{ss}^o) = \kappa(x_{ss}^o) - c(x_{ss}^o) = \frac{c'(x_{ss}^o)G(x_{ss}^o)}{G'(x_{ss}^o)-\delta}$. Finally, from the assumptions on $c(x)$ and $G(x)$, note that λ_{ss}^o increases as x_{ss}^o decreases. Thus, we refer to λ_{ss}^o as the steady-state scarcity value of groundwater when there is no access to a water market because, everything else being equal in the benchmark solution, a lower steady-state water level in the aquifer implies a higher unit mark-up λ_{ss}^o, and correspondingly, a higher benchmark price of water sold for consumption within the municipality $s^o(x_{ss}^o) = c(x_{ss}^o) + \lambda_{ss}^o$. In a similar vein, we refer to $\kappa(x)$, which is a decreasing function of x, as the effective cost of extraction (alternatively, the efficient price of water sold locally) at steady-state, and consequently, $\kappa^{-1}(s)$ is interpreted as the steady-state water level corresponding to an effective cost of water s.

To proceed to the solution to the municipality's problem with access to a water market where e_t, $i_t \geq 0$, we stipulate the following assumptions to eliminate trivial cases: (i) $s < a$, which ensures that the market price is not so high that it would be optimal to export all the water extracted from the aquifer and sell none of it for local consumption within the municipality, (ii) $e_t i_t = 0$ for all t, which ensures that the same unit of water is not exported and imported simultaneously on the water market[1], and (iii) $l_t^*(x_t) > 0$ for all t, which ensures that the optimal quantity of water sold for consumption within the municipality is always positive.

PROPOSITION 2.1. *The solution to the municipality's problem (2.3.1) is as follows.*

(a) For any time $t < T$ (transitional phase),

Condition	l_t^*	$e_t^*(x_t)$	$i_t^*(x_t)$
$x_t \geq \kappa^{-1}(s)$	$\frac{a-s}{b}$	$x_t - \kappa^{-1}(s) + G(x_t) - \frac{a-s}{b}$	0
$x_t < \kappa^{-1}(s)$	$\frac{a-s}{b}$	0	$\kappa^{-1}(s) - x_t - G(x_t) + \frac{a-s}{b}$

(b) For any time $t \geq T$ (steady-state),

Condition	l_{ss}^*	e_{ss}^*	i_{ss}^*	x_{ss}^*
$s \geq s^o(x_{ss}^o)$	$\frac{a-s}{b}$	$G(\kappa^{-1}(s)) - \frac{a-s}{b}$	0	$\kappa^{-1}(s)$
$s < s^o(x_{ss}^o)$	$\frac{a-s}{b}$	0	$\frac{a-s}{b} - G(\kappa^{-1}(s))$	$\kappa^{-1}(s)$

According to Proposition 2.1, the optimal quantity of water sold for consumption within the municipality, $l_t^* = \frac{a-s}{b}$ is stationary and depends only on the water market price s, i.e., it is independent of the water level in the aquifer. This is in contrast to the case when the municipality has no access to a water market (see Lemma 2.1) and is indicative of the opportunity to export or import water to close the gap between optimal groundwater extraction on the one hand and the optimal consumption quantity within the municipality on the other hand. In that spirit, note that the municipality's optimal extraction quantity at any time t is a function only of the water level in the aquifer x_t and the price in the water market s, and is independent of whether the municipality exports or imports water. In particular, $q_t^*(x_t) = x_t - \kappa^{-1}(s) + G(x_t)$ during the transitional phase, and

---

[1] This condition would always hold at the optimum, for example, if transportation costs were considered explicitly in our model.

$q_{ss}^* = G(\kappa^{-1}(s))$ at steady-state, regardless of whether the municipality exports or imports water to complement or supplement its local consumption.

Moreover, we see from Proposition 2.1(a) that the solution to the municipality's problem during the transitional phase is characterized by a threshold policy, where the threshold is defined by the steady-state water level of the aquifer $\kappa^{-1}(s)$. If the current water level exceeds this threshold, i.e., if $x_t \geq \kappa^{-1}(s)$, then it is optimal to export as much water as possible to deplete the aquifer until it reaches the steady-state water level $x_{ss}^* = \kappa^{-1}(s)$; otherwise, if $x_t < \kappa^{-1}(s)$, then it is optimal to import water instead until the aquifer recovers to the steady-state water level $x_{ss}^* = \kappa^{-1}(s)$. This policy therefore is an example of bang-bang control (Chiang, 1992), which applies here because of the linearity of e_t and i_t in the current-value Hamiltonian expression (2.3.2).

As per Proposition 2.1(b), the steady-state solution depends only on how the water market price s compares to the export/import threshold price defined by the steady-state price of water sold for consumption within the municipality when there is no access to a water market, $s^o(x_{ss}^o)$. Thus, similar to the benchmark solution in Lemma 2.1, we define $\lambda_{ss}^* := s - c(x_{ss}^*) = \frac{c'(x_{ss}^*)G(x_{ss}^*)}{G'(x_{ss}^*)-\delta}$ as the steady-state scarcity value of groundwater when there is access to a water market. Given this definition, note that as a result of the exhaustibility of the municipality's aquifer, the profit margin from exporting water must exceed the scarcity value of groundwater when there is no access to a water market, i.e., $s - c(x_{ss}^*) = \lambda_{ss}^* > \lambda_{ss}^o$ since $e_{ss}^* > 0$ implies $x_{ss}^* = \kappa^{-1}(s) < x_{ss}^o$. Similarly, the incremental cost of importing water relative to extracting it from the aquifer must be smaller than the scarcity value of groundwater when there is no access to a water market, i.e., $s - c(x_{ss}^*) = \lambda_{ss}^* < \lambda_{ss}^o$ since $i_{ss}^* > 0$ implies $x_{ss}^* = \kappa^{-1}(s) > x_{ss}^o$.

Therefore, we observe that as the market price of water increases (decreases), *ceteris paribus*, exporting (importing) water becomes more attractive to the municipality.

In the spirit of the 3BL, we now turn our attention to the societal and environmental implications of participating in a water market. We measure the *societal impact* of a municipal water supply management policy by the quantity of water sold for consumption within the municipality, i.e., the availability and affordability of water for local consumption. Due to downward sloping demand for water within the municipality $p(l_t) = a - bl_t$, an increase in the quantity of water sold for consumption within the municipality l_t also implies a decrease in the price of water sold for consumption within the municipality, and therefore we say that a higher l_t corresponds to a more positive societal impact. From the environmental perspective, lower water levels in the aquifer are associated with deleterious consequences such as land subsidence, erosion, and loss of habitat for flora and fauna (Gleick, 2000). Therefore, we capture the *environmental impact* of a management policy by the resulting water level in the aquifer, where higher water levels imply a more positive environmental impact.[2] Thus, to evaluate the impact of participating in a water market, we compare the steady-state values of l^*_{ss} and x^*_{ss} with their respective analogs l^o_{ss} and x^o_{ss} from Lemma 2.1. From Proposition 2.1, we thus observe that exporting water on a water market has negative societal and environmental impacts relative to the case when there is no access to a water market, because $e^*_{ss} > 0$ implies that $s \geq s^o(x^o_{ss}) = \kappa(x^o_{ss})$, which in turn implies that

---

[2] Note that the societal and environmental measures adopted here fit within the scope of our model. Although additional measures, such as, for example, equity or change in availability of water for consumption among different uses and users within the municipality might also be of related interest, such measures are beyond the scope of our model specification.

$l_{ss}^* = \frac{a-s}{b} \le \frac{a-s^o(x_{ss}^o)}{b} = l_{ss}^o$ and $x_{ss}^* = \kappa^{-1}(s) \le x_{ss}^o$. Conversely, the impact of importing water on a water market is positive for society and the environment, because $i_{ss}^* > 0$ implies that $s < s^o(x_{ss}^o) = \kappa(x_{ss}^o)$, which in turn implies that $l_{ss}^* = \frac{a-s}{b} > \frac{a-s^o(x_{ss}^o)}{b} = l_{ss}^o$ and $x_{ss}^* = \kappa^{-1}(s) > x_{ss}^o$. However, note from Proposition 2.1(a) that a municipality that imports (exports) at steady-state will export (import) water in the transition to steady-state if $x_t > \kappa^{-1}(s)$ ($x_t < \kappa^{-1}(s)$), thus first resulting in negative (positive) implications for the environment during the transitional phase. Therefore, as far as the environment is concerned, the overall implications of importing water will depend not only on the water level in the aquifer at steady-state but also on the severity of the consequences of the rate of depletion of water in the aquifer during the transitional phase.

2.3.2. Fixed Quantity Contracts. We now consider water transfers between two municipalities through a fixed quantity contract. Fixed quantity contracts are typically used for permanent transfers of water rights at a mutually agreeable price (Hansen et al., 2008). For example, the Santa Margarita Water District recently agreed to buy from Cadiz Inc. one-tenth of the annual quantity of water extracted from aquifers under the Mojave Desert for an indefinite period of time (Hart, 2008). Groundwater rights transfers also have been negotiated by Amarillo and San Antonio in Texas (Kaiser, 2005) and by Phoenix and Tucson in Arizona (Saliba et al., 1987).

In this subsection, we assume that each municipality has access to its own aquifer such that the aquifers in either municipality are hydrologically distinct and disconnected. Each municipality must determine how much water to extract from its aquifer and how much water to export to, or import from, the other municipality. Proposition 2.1 implies that long term trading equilibria between two municipalities are feasible only when both the exporter and the importer are at their respective steady-states. Therefore, we focus our attention on steady-state interactions. For analytical convenience, we assume that the local demand functions within the two municipalities are identical and are given by $p(l_t) = a - bl_t$. However, we assume that the two aquifers have different recharge or extraction cost characteristics or both, i.e., we assume that either $G_j(x) \neq G_k(x)$ or $c_j(x) \neq c_k(x)$ or both for municipalities j and k. Hence, each municipality has its own export/import threshold price $s_j^o(x_{jss}^o)$ or $s_k^o(x_{kss}^o)$, above (below) which either municipality is willing to export (import) water to the other municipality. Given these different export/import threshold prices, we see from Proposition 2.1(b) that the role of exporter and importer will be endogenously determined such that the municipality with the lower export/import threshold price will export water to the municipality with the higher export/import threshold price.

Fixed quantity trading between the two municipalities allows us to measure not just the local but also the global societal and environmental impacts of groundwater reallocation. We capture the *global societal impact* of trade by comparing the total quantity of water sold in the two municipalities with and without groundwater transfers. Similarly, we capture the *global environmental impact* of trade by comparing the sum of the water levels of the two aquifers with and without groundwater transfers. While it can be argued that a social planner is only concerned with impacts within his municipality, it is in the spirit of the 3BL framework that we consider the effects on all stakeholders, which includes communities and environments connected by groundwater transfers.

In the following proposition, we obtain the Nash equilibrium trading price in the fixed quantity contract denoted by $\tilde{s}$, and we perform a sensitivity analysis of the equilbrium with respect to the demand parameters a

and b. The total quantity of water sold for consumption in both municipalities is denoted by $\tilde{l}_{ss} = \tilde{l}_{jss} + \tilde{l}_{kss}$, where $\tilde{l}_{jss}$ and $\tilde{l}_{kss}$ denote the quantity of water sold for consumption following trade in municipalities j and k respectively. Similarly, the sum of water levels in both aquifers is denoted by $\tilde{x}_{ss} = \tilde{x}_{jss} + \tilde{x}_{kss}$, where $\tilde{x}_{jss}$ and $\tilde{x}_{kss}$ denote the water levels in the aquifers following trade in municipalities j and k respectively.

PROPOSITION 2.2. *(a) The equilibrium trading price at steady-state, $\tilde{s}$, uniquely solves*

$$a = s + \frac{b}{2}\left[G_j(\kappa_j^{-1}(s)) + G_k(\kappa_k^{-1}(s))\right]$$

where $\tilde{s} \in (s_j^o(x_{jss}^o) \wedge s_k^o(x_{kss}^o),\ s_j^o(x_{jss}^o) \vee s_k^o(x_{kss}^o))$. Moreover, $s_j^o(x_{jss}^o) < \tilde{s} < s_k^o(x_{kss}^o)$ implies that municipality j exports to municipality k; $s_k^o(x_{kss}^o) < \tilde{s} < s_j^o(x_{jss}^o)$ implies that municipality j imports from municipality k.
(b) The effect of the demand parameters on the equilibrium trading price $\tilde{s}$ are as follows: $\frac{\partial \tilde{s}}{\partial a} > 0$, $\frac{\partial \tilde{s}}{\partial b} < 0$.
(c) The effect of the demand parameters on the total quantity of water sold in both municipalities $\tilde{l}_{ss}$ and the total water level in both aquifers $\tilde{x}_{ss}$ are as follows: $\frac{\partial \tilde{l}_{ss}}{\partial a} > 0$, $\frac{\partial \tilde{l}_{ss}}{\partial b} < 0$; and $\frac{\partial \tilde{x}_{ss}}{\partial a} < 0$, $\frac{\partial \tilde{x}_{ss}}{\partial b} > 0$.

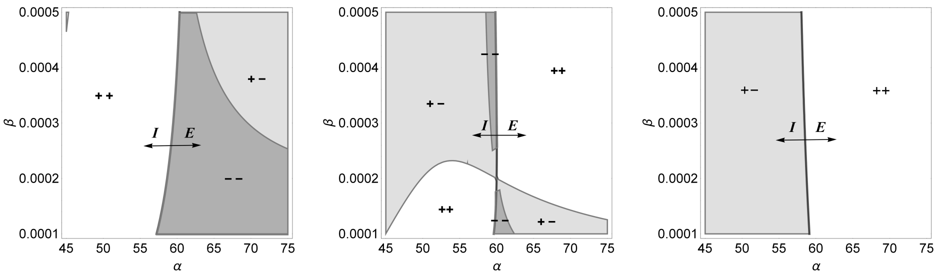
In essence, the exporter and importer agree on an equilibrium trading price between their respective threshold prices that solves the equation in Proposition 2.2(a). Note that this notion of equilibrium is consistent with the endogenous price models in Vaux and Howitt (1984) and Weinberg et al. (1993). Having obtained the trading price $\tilde{s}$, the quantity of water traded can be determined by the respective optimal export and import quantities (which are identical at the equilibrium price as shown in the proof of Proposition 2.2(a)). From Proposition 2.2(b), we observe that an increase in a through the population, or a decrease in b as a result of change in income within each municipality results in an increase in the trading price. The effect of the demand parameters on the trading price is explained by an increase in the value of selling water for consumption within each municipality, such that the exporter is more reluctant to export water and the importer is more willing to import water, resulting in a higher equilibrium trading price. To explain the results in Proposition 2.2(c), we see from Proposition 2.1(b) that the water levels in the two aquifers fall and the total quantity of water extracted from the two aquifers rises when the price of importing or exporting water increases.

Given Proposition 2.2, the societal and environmental implications of fixed quantity trading between two municipalities can be evaluated at both local and global levels. At the local level, the results from §3.1 still hold, i.e., both societal and environmental impacts of trading are negative (positive) in the exporter's (importer's) municipality at their respective steady-states. However, the global impacts of fixed quantity trading depend on the relative characteristics of the two aquifers. Therefore, we next probe deeper by performing a numerical analysis to determine the implications of differences between the aquifer recharge characteristics of the two municipalities on the global impacts of fixed quantity trading. In the analysis that follows, both the extraction volume q_t and the volume sold for consumption within the municipality l_t are measured in units of 250,000 cubic meters, and the water level x_t is measured in meters; we fix $G_j(x) = 60 - 0.0002x^2$ and $c_j(x) = c_k(x) = 300,000 - 500x^{0.75}$, while varying $G_k(x) = \alpha - \beta x^\gamma$ for $\alpha \in [45, 75]$, $\beta \in [0.0001, 0.0005]$, $\gamma \in \{1.7, 2.0, 2.3\}$; and we set the demand parameters to $a = 1,000,000$ and $b = 12,500$.

Our specification and parameterization of the recharge function $G(x_t)$ is drawn from Pongkijvorasin et al. (2010), which is one hydro-economic study in the related literature that empirically estimates the recharge characteristics of an aquifer that fits our modeling framework. Specifically, they use the functional form $G(x) = \alpha - \beta x^{\gamma}$ to estimate the recharge characteristics of the coastal Kiholo aquifer in Hawaii. Following their lead, we adopt this functional form where α represents constant refills from rainfall and runoff, β represents the leakage coefficient and γ represents the leakage rate. Fitting this curve to their data, Pongkijvorasin et al. (2010) empirically estimate the recharge parameters for the Kiholo aquifer to be $\alpha = 60$, $\beta = 0.019$, and $\gamma = 2$. These specific parameter values thus imply a capacity of $K = G^{-1}(0) = 56m$ for the Kiholo aquifer. We note, however, that although this imputed water level may be representative of coastal aquifers, it is atypical of non-coastal aquifers. For example, following decades of extraction, the water level of the Mahomet aquifer in Illinois remains at $525m$ (Burch, 2008) and the water level of the Edwards aquifer in Texas sits between $180m$ and $260m$ at different parts of the state (Slade et al., 1986). Moreover, we also note that the estimate for the leakage coefficient ($\beta = 0.019$) for the Kiholo aquifer would be atypically high for noncoastal aquifers because noncoastal aquifers are buffered from any leakage into the sea (Burnett et al., 2003). Therefore, to recalibrate and to generalize their parameterizations for our numerical analysis, we set $\alpha = 60$, $\beta = 0.0002$, and $\gamma = 2$ for municipality j to fix the capacity for that municipality's aquifer at $K_j = 548m$, but we vary α, β, and γ as specified above for municipality k (which imply capacities ranging from $K_k = 142m$ to $2857m$) to provide a broad comparative range of differences between the two municipalities' aquifer characteristics.

Consistent with these parameterizations, to further facilitate the analysis of the impact of differences in aquifer characteristics between the two municipalities, we set the demand function and extraction cost function for both municipalities j and k as $p(l) = 1,000,000 - 12,500l$ and

$c(x) = 300,000 - 500x^{0.75}$, respectively. Note that while our demand function is also identical in form to Pongkijvorasin et al. (2010), our cost function differs from theirs because they use a linearly decreasing cost function for tractability despite making the assumption of a strictly convex cost function in their theoretical model. Nevertheless, to validate our specifications for price and cost, we note first that the corresponding benchmark steady-state water level for municipality j ($x^o_{jss} = 171m$) implies a price and cost of water that is consistent with public utility rate and cost structures across the United States, and second that the corresponding price elasticity at that benchmark steady-state lies within the range of empirically estimated elasticities for water (Espey et al., 1997). We illustrate the results of our analysis in Figure 3 below.



(*a*) $\gamma = 1.7$ (*b*) $\gamma = 2.0$ (*c*) $\gamma = 2.3$

Figure 3. Global societal and environmental implications of aquifer recharge characteristics

In Figure 3, the symbols "+" and "−" indicate positive and negative global impacts, with the first and second position indicating societal and environmental impacts respectively. Moreover, "E" and "I" indicate whether municipality k is the exporter or importer respectively. Figure 3(b) represents the scenario where both aquifers have the same leakage rate γ, whereas Figure 3(a) (Figure 3(c)) represents the scenario where the aquifer in municipality k has a lower (higher) leakage rate than its counterpart in municipality j.

Notice in Figure 3(b) that as α increases for a fixed β, municipality k goes from being the importer to the exporter of water. This can be explained by the observation that, everything else being equal, a higher α implies a lower export/import threshold price at steady-state $s_k^o(x_{kss}^o)$. Correspondingly, in moving from the left to the right in Figure 3(b), the relative export/import threshold prices for the two municipalities change from $s_k^o(x_{kss}^o) > s_j^o(x_{jss}^o)$, in which case municipality k imports from municipality j, to $s_k^o(x_{kss}^o) < s_j^o(x_{jss}^o)$, in which case municipality k exports to municipality j. Here, we also point out that for the range of parameters used in our analysis, the leakage coefficient β has little impact on the threshold price and thus plays a relatively insignificant role in determining the direction and consequences of trade as compared to the refill parameter α.

Notice also from Figure 3(b) that regions of similar global impacts (as indicated by the same sign of global societal and environmental impacts) are rotationally symmetric about the point at which both aquifers have identical characteristics ($\alpha = 60$, $\beta = 0.0002$). This is a consequence of the switching of trading roles and relative magnitudes of the parameters α and β between the two municipalities about this point. For example, in the northeast corner of Figure 3(b), municipality k exports water when its aquifer receives higher refills but also has a higher leakage coefficient than its counterpart in municipality j, while in the southwest corner, municipality j exports water when its aquifer receives higher refills but has a higher leakage coefficient than its counterpart in municipality k. Naturally, this export-import symmetry results in symmetric trading consequences for society and the environment at the global level. The effect of the leakage rate γ is similar to, but stronger than, the effect of the leakage coefficient β. Therefore, in going from Figure 3(a) to (c), we find negligible change in the export/import threshold; but, in comparing Figures 3(a) and 3(c), we find apparent symmetry of the different regions of global consequences about Figure 3(b).

From this numerical analysis, we observe that trade between two municipalities is most beneficial from a global 3BL perspective when the aquifer in the exporting municipality receives higher refills but is also leakier than its counterpart in the importing municipality. Moreover, we observe that trading results in negative consequences for the environment at a global level when the aquifers in the two municipalities vary considerably in terms of their capacities. To see this, notice for example, that the difference between the aquifer capacity of municipality j ($K_j = 547m$) and the aquifer capacity of municipality k ($K_k = G_k^{-1}(0) = (\frac{\alpha}{\beta})^{1/\gamma}$) increases as we move toward the southeast or the northwest corner of Figure 3(b). The same applies as we move toward the southeast corner of Figure 3(a) or the northwest corner of Figure 3(c). These negative consequences for the environment are noteworthy because fixed quantity trading typically occurs between municipalities with vastly different endowments of groundwater.

In light of these observations from Figure 3, we next evaluate the societal and environmental implications of fixed quantity trading relative to those associated with the centralized management of the two municipalities, where we define the central planner's objective to be to maximize the total welfare across both municipalities. A detailed formulation of the central planner's problem is provided in Appendix A1. We continue to denote the local variables (i.e., the characteristics of each municipality and its aquifer) in the central planner's problem with the subscripts j and k, but to contrast the variables associated with the centralized problem with those associated with the decentralized setting, we index the variables in the central planner's problem with the superscript "cp". Thus, for example, we define the total water level in the two municipalities in the centralized setting as $x_{ss}^{cp} = x_{jss}^{cp} + x_{kss}^{cp}$, where x_{jss}^{cp} and x_{kss}^{cp} represent the water levels at steady-state in municipalities j and k respectively. We compare the solution to the central planner's problem with that of Proposition 2.2 in the following proposition.

PROPOSITION 2.3. *The centralized management of the two municipalities results in the same equilibrium outcome as that produced by the fixed quantity trading:* $x_{jss}^{cp} = \tilde{x}_{jss}$, $x_{kss}^{cp} = \tilde{x}_{kss}$, $l_{jss}^{cp} = \tilde{l}_{jss}$, *and* $l_{kss}^{cp} = \tilde{l}_{kss}$.

Proposition 2.3 essentially shows that fixed quantity trading between two municipalities is efficient in the sense that it achieves the same equilibrium outcomes as those that result from centralized management. Intuitively, this is because a municipality engaging in fixed quantity trading effectively internalizes the same steady-state scarcity value of groundwater into its threshold price as the central planner uses to determine the optimal reallocation from one municipality to the other. Therefore, the fixed quantity trading mechanism described in Proposition 2.2(a) finds an efficient allocation of groundwater extraction from the two aquifers to maximize welfare in the two municipalities. This is precisely what centralized management seeks to achieve, hence, both fixed quantity trading and centralized management produce identical societal and environmental impacts at both local and global levels.

2.4. Privatization

In this section, we study the impact of privatization by comparing the optimal groundwater management and water trading policies of §2.3, along with their implications for society and the environment, to their respective analogs that would result if a municipality operated with the objective of profit-maximization in lieu of welfare-maximization. We use these comparisons to assess the extent to which privatization would result in quantity rationing within the municipality, overexploitation of its aquifer, or profiteering from exports. Moreover, we verify if indeed privatization spurs investment in technologies that reduce reliance on groundwater.

2.4.1. The Impact of Privatization on Groundwater Management and Trading Policies.

We begin by studying the impact of privatization on the results of Proposition 2.1, the context for which is defined by access to a water market characterized by an exogenous price s. Privatization may refer to the control of a community's water supply system by a private water supplier (for example, Aquarion and American Water), or possession of water rights by private entities such as farmer or landowner collectives (for example, Mesa Water in Roberts County, Texas).

For clarity and distinction, we denote the variables in the privatization model with a "bar"; for example, $\bar{l}_t$ denotes the quantity of water sold for consumption within a privatized municipality. The municipality's problem under privatization is analogous to (2.3.1), except that the revenue term $(a - b\bar{l}_t)\bar{l}_t$ replaces the welfare term $\int_0^{l_t}(a - bu)du$ in the objective. Hence, the privatized municipality's problem when there is access to a water market is as follows:

$$\text{(2.4.1)} \quad \underset{\bar{l}_t,\, \bar{e}_t,\, \bar{i}_t}{\text{maximize}} \int_0^\infty e^{-\delta t}\Big[(a - b\bar{l}_t)\bar{l}_t + s(\bar{e}_t - \bar{i}_t) - c(x_t)(\bar{l}_t - \bar{i}_t + \bar{e}_t)\Big]dt,$$

$$\text{Subject to} \frac{dx_t}{dt} = G(x_t) - (\bar{l}_t - \bar{i}_t + \bar{e}_t),$$

$$\bar{l}_t,\ \bar{e}_t,\ \bar{i}_t,\ x_t \geq 0.$$

The total revenue in (2.4.1) comprises the revenues from selling water for consumption within the municipality, $(a - b\bar{l}_t)\bar{l}_t$, plus the revenues from exporting through the water market, $s\bar{e}_t$. The corresponding costs are $c(\bar{x}_t)(\bar{l}_t - \bar{i}_t + \bar{e}_t)$ from extraction plus $s\bar{i}_t$ from importing. Given (2.4.1), the implications of privatization for a municipality that has access to a water market are as follows:

PROPOSITION 2.4. *(a) The steady-state export/import threshold price for a privatized municipality $\bar{s}^o(\bar{x}^o_{ss})$ is lower than that of its non-privatized counterpart $s^o(x^o_{ss})$; $\bar{s}^o(\bar{x}^o_{ss}) = a - 2b\bar{l}^o_{ss} < a - bl^o_{ss} = s^o(x^o_{ss})$.*
(b) Privatization has the following effects on the optimal policies when there is access to a water market: $\bar{i}^*_t(x_t) \leq i^*_t(x_t)$, $\bar{e}^*_t(x_t) \geq e^*_t(x_t)$, and $\bar{l}^*_t = \frac{a-s}{2b} < \frac{a-s}{b} = l^*_t$ for all $t > 0$.
(c) Additionally, at steady-state, $\bar{x}^*_{ss} = x^*_{ss} = \kappa^{-1}(s)$ and $\bar{q}^*_{ss} = q^*_{ss} = G(\kappa^{-1}(s))$ for all $t > T$.

Notice from Proposition 2.4(a) that at steady-state, a privatized municipality's export/import threshold price $\bar{s}^o(\bar{x}^o_{ss}) = a - 2b\bar{l}^o_{ss}$, which represents the marginal revenue on water sold for consumption within the municipality when there is no access to a water market, is strictly less than a non-privatized municipality's export/import threshold price $s^o(x^o_{ss}) = a - bl^o_{ss}$, which, recall, represents the price of water sold for consumption within the municipality when there is no access to a water market. This difference in the export/import threshold prices means that a privatized municipality is more (less) likely to export (import) water for a given market price s. As a result, there exists a range of market prices that is such that at steady-state, a non-privatized municipality will import water, but its privatized counterpart will instead export water for the same given s. Moreover, as Proposition 2.4(b) indicates, the amount of water that a privatized municipality exports (imports) when it exports (imports) for a given s will be more (less) than the amount of water that a non-privatized municipality exports (imports) when it exports (imports) for the same s. These differences between the optimal water market policies of a privatized versus a non-privatized municipality are illustrated below in Figure 4, which we generate using the same functions and parameters that we applied to characterize the aquifer in municipality j for the numerical analysis in §2.3.2. In Figure 4, the two curves represent the quantities of water exported (negative) or imported (positive) at steady-state by a privatized and non-privatized municipality for a price s in the water market.

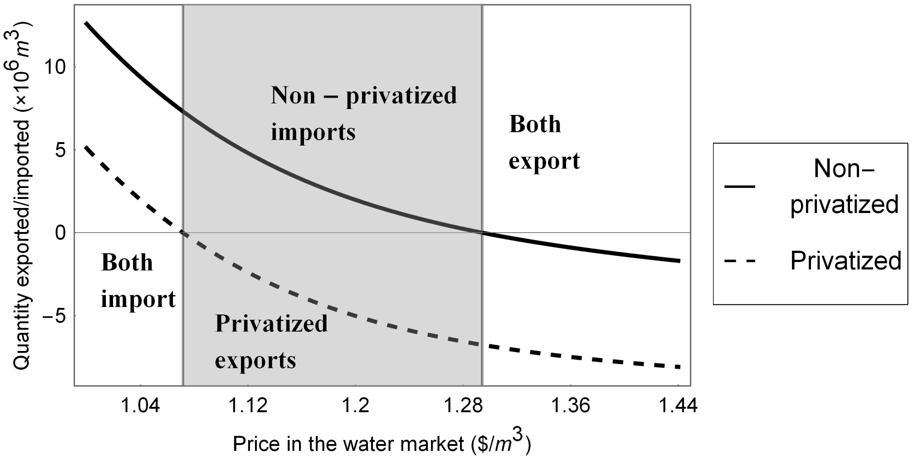


Figure 4. Optimal water market policies for a privatized and non-privatized municipality

Another implication of the difference between $\bar{s}^o(\bar{x}^o_{ss})$ and $s^o(x^o_{ss})$ is as follows. A privatized municipality could export water at water market prices that are below the price at which water would be sold for consumption within the municipality if there were no access to a water market, namely for values of s that are such that $\bar{s}^o(\bar{x}^o_{ss}) < s < \bar{s}^o(\bar{x}^o_{ss}) + b\bar{l}^o_{ss} = p(\bar{l}^o_{ss})$. However, a non-privatized municipality would not export water under analogous conditions. This controversial outcome of privatization has been cited as a major cause for concern (Barlow and Clarke, 2005). Analogously, a privatized municipality will not import at some water market prices that are below the price at which water would be sold for consumption within the municipality if there were no access to a water market, whereas a non-privatized municipality would always import water under such conditions.

The propensity of a privatized municipality to export more, but import less, relative to a non-privatized municipality has important implications for society. In particular, as Proposition 2.4(b) establishes, privatization has a negative impact on society in the sense that it results in a decrease in the affordability and availability of water sold for consumption within the municipality, i.e., $\bar{l}_t^* < l_t^*$ for all t. However, as Proposition 2.4(c) further establishes, privatization has no net impact on the environment at steady-state in the sense that the total quantity of water extracted at steady-state as well as the resulting steady-state water level of the aquifer are the same regardless of whether or not the municipality is privatized. The difference between the privatized and non-privatized municipalities lies in their respective optimal uses (local consumption vs. exports) for the water extracted. Thus, we see that only the concerns over the local societal impacts of privatization of municipal groundwater systems are justified.

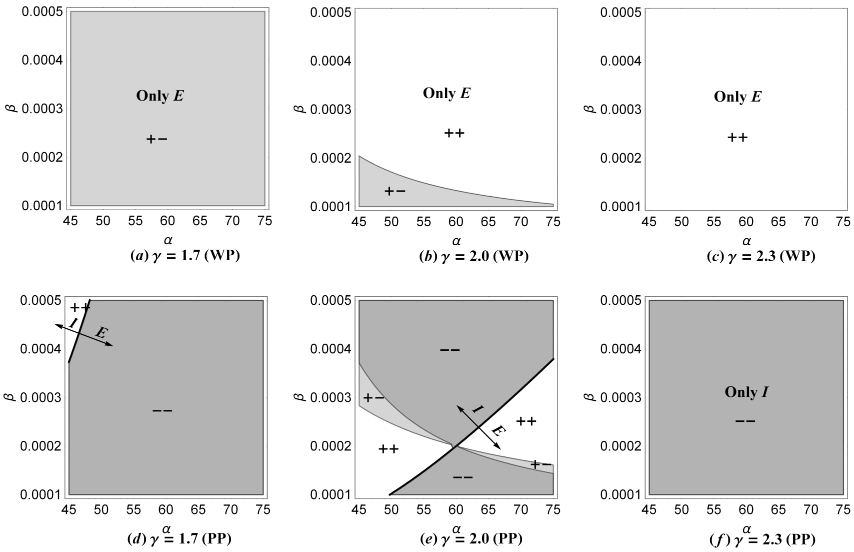
Next, we similarly address the impact of privatization on the results of Proposition 2.2, the context for which is defined by fixed quantity trading of groundwater between two municipalities at an endogenously determined price. Toward that end, we append our notation from §2.3.2 with the two letter subscript jk, where $j,\ k \in \{p,\ w\}$ now denotes whether or not a given municipality is privatized, with p and w representing privatized and non-privatized municipalities, respectively. For example, $\tilde{s}_{wp}$ denotes the equilibrium trading price between a non-privatized and a privatized municipality. Given this convention, note that Proposition 2.2 corresponds to the "WW" case.

PROPOSITION 2.5. *(a) Given two municipalities j and k that trade through a fixed quantity contract, where $j,\ k \in \{p,\ w\}$, the equilibrium trading prices are ordered as follows: $\tilde{s}_{ww} > \tilde{s}_{wp} > \tilde{s}_{pp}$. Correspondingly, the total quantity of water sold in the two municipalities and the sum of water levels in the two aquifers at equilibrium are ordered as follows: $\tilde{l}_{ww} > \tilde{l}_{wp} > \tilde{l}_{pp}$ and $\tilde{x}_{pp} > \tilde{x}_{wp} > \tilde{x}_{ww}$.*
(b) The relative effect of a change in demand parameters on the trading prices between two privatized municipalities versus two non-privatized municipalities are as follows: $\frac{\partial \tilde{s}_{ww}}{\partial a} > \frac{\partial s_{\tilde{pp}}}{\partial a}$ and $\left|\frac{\partial s_{\tilde{ww}}}{\partial b}\right| > \left|\frac{\partial s_{\tilde{pp}}}{\partial b}\right|$.

From Proposition 2.5(a), we see that the equilibrium trading price is highest when neither municipality is privatized and lowest when they both are privatized. Moreover, these trading prices follow the same ordering as the total quantity of water sold in the two municipalities. This can be explained by observing that a non-privatized municipality is willing to sell a greater quantity of water locally as compared to its privatized counterpart, which in turn results in a relatively higher trading price in the fixed quantity contract. The implication of an increase in the trading price on the total quantity of water sold and the water levels across both municipalities thus follows by analogy with Proposition 2.2. Proposition 2.5(b) further states that a change in demand parameters has a greater effect on the trading price between two non-privatized municipalities. This is because the local demand for water in a non-privatized municipality is more sensitive to changes in the demand parameters, where an increase (decrease) in the market size (a) (price sensitivity (b)) has a positive effect. This can be verified from a direct comparison between the optimal quantities of water sold within a non-privatized municipality and its privatized counterpart from Proposition 2.4. The effect of a change in demand parameters on the total quantity of water sold and the total water levels follows from Proposition 2.5(a). One implication of this result is that an increase in demand due to demographic or economic changes has a relatively smaller effect on the parameters of trade when municipal water systems are privatized.

The local impacts of privatization on society relative to the case when neither municipality is privatized are negative in both the exporting and importing municipalities. This follows from Proposition 2.5(a), since privatization in one or both municipalities results in a lower equilibrium trading price, and correspondingly, a lower quantity of water sold in the two municipalities relative to the case when neither municipality is privatized. This in turn implies a higher water level in both municipalities, hence the environmental impact of privatization in the context of fixed quantity trading is positive.

As in §2.3.2, the global impacts of privatization on society and the environment depend on the characteristics of the aquifers in the two municipalities. Thus, to facilitate the analysis of the global impacts of privatization in the context of fixed quantity trading, we perform a similar numerical analysis using the same functional specifications and parameterizations from §2.3.2, and we illustrate the results in Figure 5.



(a) γ = 1.7 (WP) (b) γ = 2.0 (WP) (c) γ = 2.3 (WP)

(d) γ = 1.7 (PP) (e) γ = 2.0 (PP) (f) γ = 2.3 (PP)

Figure 5. Global societal and environmental implications of privatization

Analogous to Figure 3, the impacts illustrated in Figure 5 are measured against the case in which the two municipalities do not have access to water reallocation opportunities. The implications of privatization for the global impacts of fixed quantity trading relative to these benchmark policies thus can be determined by observing the differences between Figures 3 and 5. In particular, relative to Figure 3 (WW case), Figures 5(a)-(c) illustrate the effect of privatizing municipality k only (WP case) and Figures 5(d)-(f) illustrate the effect of privatizing both municipalities j and k (PP case). We do not consider the case where only municipality j is privatized (PW case) as it is qualitatively similar to the WP case.

In comparison with Figure 3, Figures 5(a)-(c) indicate that the privatization of municipality k results in a trading equilibrium in which the privatized municipality is always the exporter and the non-privatized municipality is always the importer. Indeed, from Figure 5(b), we observe that the privatized municipality exports water to the non-privatized municipality even when both of their aquifers have identical characteristics

($\alpha = 60,\ \beta = 0.0002$). This is in contrast to Figure 3(b), which indicates that there is no trade between two non-privatized municipalities when their two aquifers are identical. Both of the above observations can be explained by the quantitative differences in the export/import threshold prices employed by a privatized and non-privatized municipality from Proposition 2.4, where municipality k has a lower threshold price for a given set of aquifer characteristics when it is privatized, $\bar{s}_k^o(\bar{x}_{kss}^o) < s_k^o(x_{kss}^o)$. Notice that as a result of the export of water from municipality k to municipality j, the region of positive global societal and environmental impacts expands in Figures 5(b) and (c), but contracts in Figure 5(a) relative to their counterparts in Figure 3, indicating that privatization in the municipality with a leakier (higher γ) aquifer has positive consequences for society and the environment on a global level. This can be explained as follows: As a result of the lower export/import threshold price associated with privatization, the increase in water consumption within the importing municipality j more than compensates for the decrease in water consumption within the exporting municipality k, thus leading to positive global impacts from trade for society. But, because of the steeper recharge function associated with a comparatively higher γ, trading leads to positive global impacts for the environment only when it provides a mechanism to extract additional water from the leakier aquifer in exchange for extracting less water from the less leaky aquifer.

Privatizing both municipalities does not qualitatively change our observations from §2.3.2. However, both β and γ play greater roles in determining the direction of trade between the two municipalities when they are privatized, as can be seen by observing the flatter export-import boundary curve in the PP case in Figures 5(d)-(f) relative to the WW case in Figure 3. This can be explained by noting that the roles of β and γ are more salient for higher water levels as is the case for PP relative to WW. Moreover, we see that the regions of negative global impacts on society and the environment expand in Figures 5(d)-(f) (PP case) relative to Figure 3 (WW case). This results from the concavity of the recharge functions, such that at higher water levels as in the PP case, the negative societal and environmental impacts within the exporting municipality k more than offset the positive societal and environmental impacts within the importing municipality j. In summary, we observe from these numerical studies that trade between two municipalities participating in a fixed quantity contract is particularly beneficial from a global 3BL perspective when *only* the municipality with an aquifer that is *leakier* is privatized; but trade leads instead to especially negative impacts from a global 3BL perspective when *both* of the municipalities are privatized.

2.4.2. The Green Paradox. We have observed thus far that access to a water market can produce a positive impact on the local environment if a municipality exploits that access to import water to supplement its groundwater extraction; however it can also produce a negative environmental impact if the municipality exploits that access instead to export groundwater extracted from its aquifer. Moreover, we observed from Proposition 2.1 that regardless of its eventual role as an exporter or importer at steady-state, a non-privatized municipality will initially implement a bang-bang control policy to export a positive quantity $e_t^*(x_t) > 0$ of water during the transitional phase if the water market price s and current water level in the aquifer x_t are such that $x_t \geq \kappa^{-1}(s)$. Thus, including the quantity of groundwater extracted for local consumption, a municipality with access to a water market (even a municipality that eventually imports water at steady-state) will extract a greater quantity of groundwater from its aquifer during the transitional phase relative to the case in which there is no access to a water market. We refer to this increase in the non-privatized municipality's extraction rate that is attributable to the presence of a water market, $\Delta q_t^*(x_t) := q_t^*(x_t) - q^o(x_t) \geq 0$, as the *extraction differential* and we note that, by analogy, a similar extraction differential applies to a privatized municipality ($\Delta \bar{q}_t^*(x_t)$) as well. This increase in groundwater extraction rates due to the municipality's ability to export groundwater during the transitional phase can result in severe environmental impacts such as land subsidence and desertification from rapid water level depletion (Konikow and Kendy, 2005). In response to such deleterious environmental consequences, several communities throughout the United States have enacted strict regulations banning the export of groundwater. For example, eight counties in California have imposed partial or complete bans on groundwater exports (Weber, 1994), and similar regulations have been enacted in the Groundwater Conservation Districts in Texas (Kaiser, 2005).

Consequently, in this subsection, we introduce the notion of export bans into our groundwater management model, and we study the impact of privatization accordingly. In the context of our model, banning a municipality from exporting water when it would otherwise export water on a water market means considering the case when $x_t \geq \kappa^{-1}(s)$, as well as setting $e_t = 0$ for all t in (2.3.1) and $\bar{e}_t = 0$ for all t in (2.4.1). Applying these constraints to our model thus implies the following proposition.

PROPOSITION 2.6. *If exports are banned such that $e_t = \bar{e}_t = 0$ for all t, then the extraction differential is non-negative for both privatized and non-privatized municipalities but it is greater in magnitude for the non-privatized municipality, i.e., $\Delta q_t^*(x_t) \geq \Delta \bar{q}_t^*(x_t) \geq 0$ for all t.*

Notice therefore, that despite the ban on exports, the mere presence of a water market results in a positive extraction differential for a municipality, regardless of whether or not the municipality is privatized. To help explain this, note that access to a water market, even if only available to import water, effectively imposes a ceiling on the price of water sold within a municipality. This in turn results in a larger quantity of water being extracted for local consumption within a municipality relative to the case when there is no access to a water market. All told, however, as noted in Proposition 2.4, a privatized municipality sells less water for local consumption than its non-privatized counterpart, thus implying a smaller extraction differential, and consequently, less damage to the local environment during the transitional phase.

The positive extraction differential in the presence of a water market when only imports are allowed can be considered an example of the 'green paradox', which is a term coined by Sinn (2008) to describe a similar phenomenon in the context of non-renewable fossil fuels, i.e., the hastening of fossil fuel extraction when greener environmental policies are anticipated. In the context of our model, the availability of groundwater substitutes through water imports can be interpreted as the greening of environmental policy. This paradox has important implications because it means, first, that importing water can produce negative environmental effects during the transitional phase despite its relative societal and environmental benefits at steady-state, and second, that privatization mitigates rather than amplifies these negative effects. Given that related literature suggests that the overall environmental consequences of groundwater extraction is a function not only of the total quantity of water extracted, but also of the rate at which it is extracted (Zektser et al., 2005), transitional phase implications like those suggested by Proposition 2.6 are important to include in any comprehensive evaluation and comparison of the environmental impacts of a groundwater management policy in a privatized and non-privatized municipality.

2.4.3. Investment in Water Production. Thus far, our exploration of the impacts of privatization of municipal groundwater management has indicated that criticisms directed at its negative consequences for society can indeed be justified. However, it has also indicated that the environmental consequences of privatization can be positive if groundwater exports are banned. In this subsection, we attempt to verify another important claim favoring the privatization of water management, namely that privatization would lead to a more rapid development of technologies to reduce reliance on exhaustible groundwater.

Although reallocation of groundwater through a water market or a fixed quantity contract has become a popular means of resolving the imbalance between the demand and supply of groundwater, there has been an emergence of newer technologies for the reclamation and production of water, such as, for example, waste water recycling and desalination. Despite high initial set-up costs, such technologies are appealing because they offer control over the timing and scale of water supply. Accordingly, in this subsection, we introduce the option of investing in water production and study its impact on groundwater management policies. We assume that the unit cost of water production is constant and we denote it by c_w, where $c_w > 0$. In addition, we assume that the capacity W for producing water is costly. Specifically, we follow the lead of Holland (2003) and assume that the fixed cost $F(W)$ of setting up a water production plant is increasing and convex in capacity, i.e., $F'(W) > 0$ and $F''(W) > 0$.

Given this construct, we study the optimal policies in a water market for the privatized and non-privatized variants of the municipality's problem. The privatized municipality's problem is stated as follows:

(2.4.2)

$$
\begin{aligned}
\underset{\bar{l}_t,\, \bar{e}_t,\, \bar{i}_t,\, \bar{w}_t,\, \bar{W},\, \bar{\tau}}{\text{maximize}} \int_0^\infty & e^{-\delta t}\Big[a\bar{l}_t - b\bar{l}_t^2 + s(\bar{e}_t - \bar{i}_t) - c(x_t)(\bar{l}_t - \bar{i}_t + \bar{e}_t - \bar{w}_t) \\
& - c_w\bar{w}_t\Big]dt - e^{-\delta\bar{\tau}}F(\bar{W}), \\
\text{Subject to } \frac{d\bar{x}_t}{dt} &= G(x_t) - (\bar{l}_t - \bar{i}_t + \bar{e}_t - \bar{w}_t), \\
& \bar{w}_t = 0 \text{ for } t < \bar{\tau}, \\
& \bar{w}_t \leq \bar{W} \text{ for } t \geq \bar{\tau}, \\
& \bar{l}_t,\ \bar{e}_t,\ \bar{i}_t,\ \bar{w}_t,\ \bar{W},\ \bar{\tau},\ x_t \geq 0,
\end{aligned}
$$

where the new variables $\bar{w}_t$, $\bar{W}$, and $\bar{\tau}$ represent the quantity of water produced at t, the capacity of water production, and the timing of the capacity investment respectively. The objective in (2.4.2) comprises two parts, the first of which is the discounted sum of profits over the infinite planning horizon, and the second of which represents the discounted cost of a one-time investment in production capacity. The constraints $\bar{w}_t = 0$ for $t < \bar{\tau}$ and $\bar{w}_t \leq \bar{W}$ for $t \geq \bar{\tau}$ stipulate that the quantity of water produced at any time be constrained by the production capacity at that time. Given the above problem specification, the total quantity of water extracted from the aquifer is defined as $\bar{q}_t = \bar{l}_t - \bar{i}_t + \bar{e}_t - \bar{w}_t$. The non-privatized variant of (2.4.2) is analogous. For convenience, we drop the time subscript in the remainder of this section. In the following proposition, we state the key implications of privatization for investment in water production.

PROPOSITION 2.7. *(a) When there is no water market, the privatized municipality invests in lower production capacity than its non-privatized counterpart;* $\bar{W}^o < W^o$.
(b) When there is access to a water market, the privatized municipality invests at the same time and in the same production capacity as its non-privatized counterpart; $\bar{\tau}^* = \tau^*$ *and* $\bar{W}^* = W^*$.

From Proposition 2.7 we observe that privatization leads to investment in a (weakly) lower capacity of water production regardless of access to a water market. To understand this result, recall that in the absence of a water market, the export/import threshold price for a privatized municipality is lower than the corresponding export/import threshold price for a non-privatized municipality, i.e., $\bar{s}^o(\bar{x}^o_{ss}) < s^o(x^o_{ss})$. This implies that the non-privatized municipality is more inclined to substitute water production for groundwater extraction, hence it invests in larger production capacity. Further, capacity investment occurs when the value of groundwater reaches an *investment threshold* (namely, the effective cost of investment $c_w + \frac{\delta F(w)}{w}$ as described in the proof of Proposition 2.7). Observe that while this investment threshold is higher for a non-privatized municipality (because $F(W)$ is convex and $\bar{W}^o < W^o$), the threshold price is also correspondingly higher. Therefore, the relationship between the timing of investments by a privatized and non-privatized municipality depends on the difference in the optimal investment levels and the convexity of the set-up cost function. When there is access to a water market, the threshold price of groundwater is defined by the water market price s, which results in a municipality investing in the same capacity regardless of whether or not it is privatized.

Moreover, this implies that both a privatized and a non-privatized municipality will either invest in a positive capacity immediately or not invest in any capacity at all.

The implications of water production along both societal and environmental dimensions at a local level are positive at steady-state, but greater for the non-privatized municipality. This follows from Proposition 2.7(a) since the non-privatized municipality substitutes groundwater extraction with water production to a greater extent than its privatized counterpart in the absence of a water market. This difference disappears when there is access to a water market as stated in Proposition 2.7(b).

2.5. Conclusion

As the first line of inquiry in this chapter, we considered the problem of municipal groundwater management in the context of water reallocation between municipalities through a water market or a fixed quantity contract. In the case of a water market, a municipality can export or import water at a constant exogenous price. In this context, we find that the decision to export or import water is guided by a threshold policy in the water level of the municipality's aquifer. At steady-state, the export/import threshold is defined by the price of water sold for local consumption in the absence of a water market, where it is optimal to export (import) water if the price in the water market exceeds (is exceeded by) this threshold. The water market essentially determines the economic value and quantity of water consumed within the municipality, and it has a beneficial (detrimental) impact on the municipality's local water consumption if the value of water within the municipality in the absence of a water market exceeds (is exceeded by) the exogenous market price. This also implies that the economic value of water is equalized across municipalities connected by a water market such that groundwater is distributed equitably regardless of initial endowments, with each municipality having to face the full opportunity cost of groundwater use as dictated by the market price. Accordingly, groundwater is only transferred from municipalities with under-stressed aquifers to those with over-stressed aquifers (that is, from municipalities with current water levels above the steady-state at the market price to municipalities with current water levels below the steady-state at the market price). As a result, importing (exporting) water through a water market leads to beneficial (detrimental) local impacts to both society and the environment. However, we find that a municipality that imports water at steady-state may export large quantities of water en-route to that steady-state, thus resulting in severe environmental impacts during the transitional phase.

In the context of fixed quantity trading between two municipalities, we have shown not only that a simultaneous-move Nash game results in the same efficient allocation of water that would result from the centralized management of the two municipalities, but also that fixed quantity trading is always economically beneficial to both municipalities when they have different export/import thresholds at steady-state. Moreover, any growth in demand through an increase in population or income, or through a change in demographic makeup (such as residential vs. industrial vs. agricultural uses) of one or both municipalities will result in more aggregate groundwater extraction and consumption, with consumption increasing more in the faster growing municipality. This observation validates the trend observed in the majority of groundwater trades in the Western United States, where small rural communities often sell groundwater extraction rights to expanding cities where the economic values and needs for water are higher. Additionally, we find that fixed quantity trading performs poorly from a global 3BL perspective when the aquifers in both municipalities vary considerably in their endowments of groundwater, especially with respect to the impact on the environment. This is particularly noteworthy because it is such trading agreements that occur most often as a result of the potential for significant economic benefits. Therefore, it is imperative that an evaluation of the benefits of fixed quantity trading must include a comprehensive analysis of societal and environmental impacts across the two municipalities.

All told, then, water markets and fixed quantity trading are examples of mechanisms that essentially reallocate groundwater from regions defined by lower water values to those defined by higher water values such that positive economic impacts are generated for the municipalities involved. In addition, fixed quantity trading in particular also can generate both positive societal and positive environmental outcomes, thus yielding a win-win-win scenario from a global 3BL perspective. However, that triple-win invariably comes at the expense of societal or environmental harm at a local level, particularly in exporting municipalities. Thus, it runs the risk of generating ill will or even contempt. This could be the case, for example, if the sustenance of indigenous communities or the environmental maintenance of water system health is a high priority for community stakeholders. Indeed, this helps explain in part why Utah Tribal Leaders filed a lawsuit against the state's agreement to export groundwater from the Snake Valley to Nevada (UTL, 2011). Thus, from a policy perspective, if municipalities with lower water values nevertheless have important socio-cultural or environmental motivations, then the negatively impacted municipalities should be adequately compensated, else appropriate restrictions to groundwater transfers should be enforced to ensure aquifer protection.

As a second line of inquiry in this chapter, we studied the impact of privatization on municipal groundwater management in the aforementioned contexts. We find that a privatized municipality employs a similar threshold policy to govern exporting or importing decisions in a water market. However, the steady-state export/import threshold price in this case is the marginal revenue on water sold within the municipality in the benchmark problem characterized by the absence of water reallocation opportunities, and as such, it is smaller in magnitude than the corresponding steady-state export/import threshold price for a non-privatized municipality. This difference implies that a privatized municipality will extract the same quantity of water as its non-privatized counterpart but allocate less for consumption within the municipality, implying negative societal impacts from privatization at a local level. This also implies that a municipality that was an importer of water prior to privatization may export water following privatization. However, the privatization of a municipality could mitigate the green paradox in under-stressed aquifers if groundwater exports are banned, thus resulting in relatively less damage to the environment. In the context of fixed quantity trading, from a global 3BL perspective, trade is most beneficial when only a single municipality, particularly one that is more likely to export water as a result of either lower local demand or a leakier aquifer, is privatized. In contrast, fixed quantity trading is most detrimental for the global 3BL when both participating municipalities are privatized.

Thus, from a policy perspective, when groundwater is not vital for local needs, such as, for example, in thinly populated regions where low value agriculture is the main source of demand for groundwater, exports can be beneficial for the global 3BL. This helps explain why instances of private interests such as Mesa Water in Texas obtaining groundwater rights with the intention of selling them to growing cities such as Amarillo and San Antonio should be encouraged (Kaiser, 2005). As discussed above, such private to public transfers are particularly beneficial on a global level to both society and the environment because they transfer the greatest quantity of water to higher valued uses without increasing the aggregate rate of exploitation of the two aquifers. Therefore, careful and restricted privatization where the aquifer is leakier or where groundwater is less vital for local needs can outperform welfare-maximizing management in the presence of groundwater reallocation opportunities. In a similar vein, although privatized municipalities will lag behind their non-privatized counterparts in investing in water production technologies in the absence of groundwater reallocation opportunities, this difference disappears with access to a water market. Therefore, policy makers seeking to incentivize investment by privatized municipalities can consider water markets as a mechanism to do so. Nevertheless, the likelihood of investment depends on the relative magnitude of the market price with respect to the fixed and variable costs of the technology, and therefore, if market prices are sufficiently low relative to the costs of the technology, water markets may dis-incentivize investments in water production technologies altogether.

In closing, we acknowledge some limitations of our model. In particular, our analysis hinges on two key modeling primitives. Firstly, we stipulate that the exogenous price in a water market is fixed and constant. If this stipulation were relaxed to consider varying market prices, then a municipality would potentially switch dynamically back and forth between exporting and importing water depending on how the water level in the municipality's aquifer compared with the steady-state water level as determined by the current market price, similar to the threshold policies implied by Proposition 2.1(a). We note however, that varying market prices will not yield a steady-state solution as described in Proposition 2.1(b). Secondly, we stipulate that the municipality's aquifer is hydrologically disconnected from other aquifers and the water market. If this stipulation were relaxed, we would have a dynamic non-cooperative extraction and reallocation game between municipalities connected through a single groundwater source, wherein the extraction and reallocation decisions of a given municipality would still be governed by a threshold policy similar to that described in Proposition 2.1. However, the threshold prices and water levels within a given municipality would depend on the actions of the other municipalities connected to the same source of groundwater. Thus, we point to considerations such as these as potentially viable extensions to our work here. Other potential extensions include optimal allocation of groundwater among different types of users with differentiated demands such as residential, commercial, and agricultural sectors, the consideration of groundwater banking wherein municipalities can import water for the purpose of artificially increasing aquifer recharge, and the conjunctive management of surface water and groundwater. Finally, in addition to the reallocation mechanisms considered here, other contract structures can be used to determine the reallocation of water between two municipalities. Knapp et al. (2003) provide an overview of some of these contract structures that are in use today.

CHAPTER 3

THE IMPACT OF ECOLABELS: THE ROLE OF ECOLABELING AGENCIES AND CREDIBILITY

3.1. Introduction

Green product development has emerged as a significant challenge to industry as a result of consumer demand, competition, and regulatory requirements. Consumer preference for green products has been identified through an increased willingness to pay for products perceived to be produced in an environmentally friendly manner (Moon et al., 2002). Increased consumer awareness of the environmental consequences of the industrial complex has pushed firms to engage in environmental quality competition to differentiate themselves from each other and attract consumers, not unlike traditional quality competition. Examples of green products include Starkists' Dolphin-safe tuna, Method's eco-friendly cleaning products, Starbucks' post-consumer recycled coffee cups and sleeves etc. However, a key differentiating feature of environmental product attributes that separates them from conventional dimensions of quality such as performance or durability is their unobservability to consumers. In particular, unlike conventional quality attributes that can be observed or experienced, it is difficult for consumers to identify the environmental quality of a product (Baksi and Bose, 2007). Consequently, ecolabels have emerged as a tool through which firms can communicate the environmental attributes of their products to consumers.

To fulfill the need for credible communication of environmental attributes embodied in products and production processes associated with them, firms may choose to affix their own self-labels on their products. As per the International Standards Organization (ISO), such self-declarations are classified as Type 2 ecolabels and do not require external validation. However, due to the lack of independent verification and the premise that firms may reveal only positive while leaving out negative environmental information, self-labels typically suffer from a lack of credibility with consumers. This results in undervaluation and decreased consumer willingness to pay for self-labeled products (Leire and Thidell, 2005; Horne, 2009). Moreover, the confusion resulting from the proliferation of self-labels has been found to depend on the credibility or environmental reputation of the firm making these claims (Teisl, 2003; Carmona, 2011). For example, standards on down procurement adopted by competing apparel manufacturers Patagonia and The North Face are perceived differently by consumers owing to the differences in their respective environmental track records; Patagonia is seen as a frontrunner of environmental stewardship and hence their claim is viewed more favorably by consumers. As our first contribution in this chapter, we identify the role of credibility in guiding the choice of environmental attribute levels in green products, and consequently, we explore the social, environmental, and economic implications of credibility.

As a recourse to this lack of credibility, firms can avail of external ecolabels for their products as provided and validated by a range of certifying organizations (Ben Youssef and Abderrazak, 2009). Such externally validated environmental standards are trusted by consumers and hence do not suffer from consumer undervaluation, resulting in improved credibility and consumer willingness to pay (Castka and Corbett, 2014). A certifying organization chooses an environmental standard and may charge a fixed labeling fee to certify the product. Firms who wish to certify their products using these ecolabels must ensure their products meet the certifier imposed environmental standard and pay the labeling fees to carry the ecolabel. Therefore, while voluntary external certification solves the credibility problem by enhancing consumer perception and willingness to pay for a green product, it imposes an exogenous environmental standard that may differ from the firm's desired level of environmental improvement, besides also collecting labeling fees.

External certification schemes differ in their objectives; governmental and NGO schemes such as the Forest Stewardship Council seek to maximize environmental benefits, while private schemes such as Ecologo are administered by profit-maximizers. Due to their differing objectives, the environmental standards chosen by these external certifying organizations for their ecolabeling schemes differ in stringency, and consequently, in their efficacy. The second contribution of this chapter is to identify the value of external ecolabeling schemes and contrast NGO and private ecolabeling schemes with respect to their impact on firms, consumers, and the environment.

While the literature on ecolabeling has primarily focused on whether it can improve environmental outcomes (Mason, 2006; Ibanez and Grolleau, 2008), our scope and focus in this study is more holistic in that we also consider the social and economic implications of ecolabeling schemes. To do so, we utilize the Triple Bottom Line (3BL) concept which is a framework for assessing the impacts of business practices using context-specific measures of environmental impact, social equity, and similar constructs with the ultimate goal of balancing *societal* and *environmental* concerns with *economic* objectives (Elkington, 1998). We define and evaluate surrogate measures of environmental, social, and economic impacts to achieve a balanced scorecard perspective of external ecolabeling schemes and the impact of firm credibility.

To address these questions, we first analyze a model with a single monopolistic producer both in the presence and absence of independent external (NGO or private) ecolabeling schemes, where the external certifying agent, when present, is a leader in a Stackelberg game. Next, to identify the impact of credibility on self-labeling competition and ensuing consequences, we study a model of duopolistic competition between two firms with asymmetric credibilities, with the firms simultaneously choosing environmental qualities in the first stage followed by price competition in the second stage. Firm credibilities are known by producers as well as consumers and ecolabeling agencies, i.e., there is no information asymmetry in our model. We then study the duopoly model with access to a single external certification scheme in a four-stage game, with the certifying agent in the role of a Stackelberg leader, followed by simultaneous ecolabel selection, environmental quality setting, and price setting by the competing firms in the following stages. Here, we contrast the NGO and private external ecolabeling schemes with respect to their impacts on firms, consumers, and the environment. Finally, we explore the ability of an NGO to mitigate the underprovision of environmental benefits by a private ecolabeling scheme. We study NGO intervention in a five-stage game with the NGO in the role of a Stackelberg leader. The key results and contributions of this chapter can be summarized as follows:

(1) As a monopolistic firm becomes more credible, its environmental quality choice and resultant 3BL implications are all impacted positively. However, in the presence of competition, a firm's environmental quality choice does not follow from its credibility vis-a-vis

its competitor. In particular, in the absence of an external ecolabel, a more credible firm will offer a product with higher environmental quality than its competitor. In contrast, the less credible firm adopts the external ecolabel, and its product bears a higher environmental quality than that of its more credible competitor when an external ecolabeling scheme from either an NGO or private agency is available. However, in the presence of both an NGO and private ecolabel, both firms will adopt an external ecolabel, and the more credible firm will revert to offering a product with higher environmental quality than its competitor.

(2) External ecolabeling schemes result in increased environmental qualities of products and result in better environmental outcomes. However, they are detrimental to the producing firms and may even hurt consumers in the presence of producer competition. Interestingly, this occurs when the credibility of the industry as a whole is low, a situation in which the greatest need for external ecolabeling programs may be perceived. While they are preferred by the industry relative to their NGO counterpart, private ecolabeling schemes underprovide environmental benefits as they set lower environmental standards relative to an NGO.

(3) An NGO cannot mitigate the underprovision of environmental benefits by a private ecolabeling scheme by preemption in a producer monopoly. In the presence of producer competition however, NGO's can mitigate the underprovision of environmental benefits by preempting a private ecolabel and steering the private ecolabel's environmental standard upwards, which also improves consumer surplus. This occurs even if the NGO's ecolabel

is not chosen in equilibrium. However, a single NGO ecolabeling scheme is most beneficial from an environmental perspective.

The rest of this chapter proceeds as follows. A brief review of the literature and our contributions are summarized in §3.2. We study two forces driving green product development in this chapter: demand-pull from consumers, and competition from producers. To focus on the role of consumer demand in stimulating green product development and the concurrent role of external certification, we begin our analysis with the case of a single-product monopolist in §3.3. Next, we jointly address the two forces by analyzing a model of duopolistic producer competition in §3.4. An analysis of NGO preemption of private ecolabeling schemes is contained in §3.5. Concluding remarks to this chapter are provided in §3.6. Appendix B1 contains additional figures and tables referenced herein and proofs are provided in Appendix B2.

3.2. Literature Review

Consumer preference for environmental attributes is well documented in the literature (Khanna, 2001; Tully and Winer, 2014). Models of product-line design first introduced by Mussa and Rosen (1978) and extended by Moorthy and Png (1992); Desai et al. (2001); Kim and Chhajed (2002) have been applied to study environmental product design choices and product-line strategies (Chen, 2001; Amacher et al., 2004). This is the first stream of literature our work is related to. The insights from traditional quality competition are applicable to the context of environmental quality competition as a result of the vertical nature of preference for the attributes in question, traditional and environmental quality, respectively. However, while Chen (2001) considers government regulation and mandatory minimum environmental quality standards, these studies do not address voluntary external certification or the specific characteristics of environmental attributes arising from their unobservability to consumers.

A second stream of literature addresses the role of voluntary certification schemes, particularly in the context of environmental preservation. Youssef and Lahmandi-Ayed (2008) and Craig et al. (2011) study a model of voluntary certification with partial information wherein consumers hold simple beliefs regarding the environmental qualities of certified and non-certified products. In a similar setting with partial information and simple beliefs, Bottega et al. (2009) and Bottega and De Freitas (2009) contrast minimum standards imposed by a regulator with public and private labeling and also consider the use of green advertisement to enhance consumer preference for ecolabels. In a model with perfect competition, Fischer and Lyon (2014) compare NGO and industry standards for ecolabels in a setting with full information and find that the coexistence of multiple standards is likely to diminish environmental benefits. Unlike our work, they do not consider self-labeling by producers and consequently, do not consider the notion of credibility. Further, these papers focus on environmental outcomes alone, while we extend our scope to consider social and economic implications of ecolabeling as well.

A few studies introduce the notion of consumer trust and credibility when environmental quality is otherwise imperceptible to consumers, which is the third stream of literature our work is related to. Castka and Corbett (2014) conduct an empirical study of the ecolabeling marketplace and identify factors such as governance, stringency, and reputation that lead to more widespread ecolabel adoption. There are few analytical studies within this stream. Craig et al. (2011) consider a single ecolabel, with consumers perceiving the unlabeled product as possessing a fraction of the environmental quality possessed by a labeled product. Brécard (2014) studies the effect of misperception of ecolabels on social surplus and the provision of environmental benefits. Harbaugh et al. (2011) consider the impact of uncertainty in exogenous quality standards (to firms and consumers) of external labels and uncertainty in exogenous product qualities (to consumers) in the presence of multiple ecolabels. In contrast, our work considers endogenously chosen producer self-labels that are known to, but discounted by consumers as a result of a lack of credibility, as well as endogenously determined environmental standards chosen by external ecolabelers.

An important contribution of our work is to extend the scope of the analysis of the impacts of ecolabeling beyond the environment. Several studies in the ecolabeling literature (see, for example, (Amacher et al., 2004; Bottega and De Freitas, 2009; Craig et al., 2011; Fischer and Lyon, 2014)) focus on its environmental implications. We consider in this study environmental, as well as the social and economic consequences of ecolabeling. In this respect, our work is related to a fourth stream of literature on Triple Bottom Line implications of operational and strategic decisions. Kleindorfer et al. (2005) and Tang and Zhou (2012) provide two particularly relevant reviews of 3BL and related frameworks within the context of Operations Management applications and models. As two examples, Guo et al. (2015) consider responsible sourcing in supply chains when consumers are socially conscious, and Xu et al. (2015) study policies that can effectively combat sourcing from suppliers utilizing child labor in developing economies. As developed in the context of groundwater management in Chapter 2, we define metrics for environmental, social, and economic implications and contrast them for different ecolabeling scenarios. Moreover, we also describe the impact of firm credibility on the 3BL implications of green product development and ecolabeling.

3.3. Base Model

We first develop a model of ecolabeling for a single-product monopolist to focus on the role of consumer demand-pull in driving green product development and ecolabeling. The role of ecolabeling in monopolistic markets is of interest given the absence of competitive forces to spur the provision of environmental attributes. In the absence of external certification, the monopolist must first choose an environmental quality $g_m \in [0,\ 1]$ for his product and subsequently set the corresponding price p_m. Note the use of the subscript m to denote a monopoly. Examples of such environmental attributes include the quantity of pasture in cattle feed, the removal of synthetic fertilizer and genetically modified ingredients from the production of food products, hazardous chemicals from cleaning products etc. Designing a product with environmental quality level g_m incurs a quadratic fixed cost of g_m^2 as in the quality and environmental product design literature (Moorthy and Png, 1992; Chen, 2001; Amacher et al., 2004). The variable costs of production are assumed to be independent of environmental quality and normalized to zero. Consumers are assumed to prefer products with higher environmental qualities to those with lower ones (see, for example, Chen (2001); Amacher et al. (2004); Bottega and De Freitas (2009)). Other product attributes such as convential quality are normalized to zero and hence do not enter the decision-making framework. The empirical literature on consumer adoption of ecolabeled products indicates that consumers respond to their awareness of the environmental track-record of a firm in evaluating their willingness to pay for a product bearing an environmental claim by that firm (Carmona, 2011; Castka and Corbett, 2014). Accordingly, we assume that a monopolist's self-label is discounted by consumers, with an environmental quality claim of g_m being perceived as μg_m, where credibility $\mu \in [0,\ 1]$. We note that the lack of full credibility of a self-label in our model does not imply the potential for firms to make fraudulent claims, a possibility we do not consider in this chapter[1]. Rather, as Horne (2009) suggests, it reflects on the nascency of the ecolabeling marketplace resulting in a lack of awareness, non-uniformity in the definitions of green marketing claims, and skepticism from consumers. Taken altogether, the monopolist faces a demand function $q_m = 1 - p_m + \beta\mu g_m$, where $\beta \in [0,\ 1]$ is the sensitivity of demand to the perceived environmental quality of the product. This specification of β implies that consumers are more sensitive to price than they are to perceived environmental quality, which reflects empirical findings in the literature (see, for example, D'Souza et al. (2006)). This linear form of demand has precedence in the literature on product design and development (Tsay and Agrawal, 2000; Savaskan et al., 2004; Gurnani and Erkoc, 2008).

Given that a key contribution of this work is to identify the social, environmental, and economic implications of ecolabeling, we now define measures for each of these categories of impacts. Social implications are measured by consumer surplus accruing from all products sold $CS = \sum_i \int_{p_i^*}^{p_i^c} q_i(g_i^*,\ p_i)dp_i$, where p_i^c is the choke price, or the price at which quantity of product sold goes to zero. Note that $i = m$ in a producer monopoly. Consumer surplus measures the difference between the maximum

---

[1] The Federal Trade Commission (FTC) issues Green Guides that outline general principles that green marketing claims must adhere to. While not enforcible, the FTC can investigate an organization believed to be violating the outlined principles. This mitigates the likelihood of rampant ecolabel fraud (FTC, 2012).

willingness to pay and the actual price paid by consumers. Environmental benefits are measured by the total diffusion of environmental quality in the market across all products sold, i.e., $E = \sum_i q_i^* g_i^*$. Finally, we measure economic implications through the total profits accruing to the producer(s) $\Pi = \sum \Pi_i^*$, i.e., the producer surplus.

We now study a monopolist's problem in the absence of external ecolabeling schemes. In the absence of an external ecolabeling scheme, the monopolist chooses his optimal environmental quality in the first stage, followed by price-setting in the second stage to maximize his profits $\Pi_m = p_m q_m - g_m^2$. In the absence of external ecolabeling schemes (i.e., when only self-labeling is possible), we denote the equilibrium outcomes with the superscript S. Solving backwards, we obtain the equilibrium choices of environmental quality and price that are described in Lemma 3.1 below.

LEMMA 3.1. *The monopolist chooses environmental quality* $g_m^S = \frac{\beta\mu}{4-\beta^2\mu^2}$, *charges price* $p_m^S = \frac{2}{4-\beta^2\mu^2}$, *and obtains profits of* $\Pi_m^S = \frac{1}{4-\beta^2\mu^2}$. *The environmental quality, price, and profits are all increasing in credibility* μ.

From Lemma 3.1, we see that an increase in the monopolist's credibility increases his product's environmental quality, price, and associated profits in the absence of external ecolabeling schemes. This follows as a result of consumers increasing their perception of environmental quality and willingness to pay as the credibility of the firm's environmental claim goes up. Naturally, we now consider the impact of ecolabeling schemes launched by external certification agencies. Regardless of their objective, i.e., environmental benefit-maximization for an NGO (G) or profit-maximization for a private agency (P), the external certification agent specifies a fixed labeling fee $\tau_m^C \geq 0$ and an environmental standard $g_m^C \in [0,\ 1]$ that must be met for a product to bear its ecolabel, where $C \in \{G,\ P\}$. We refer to this combination of labeling fee and environmental standard as an external ecolabeling scheme. Private certification agencies seek to maximize profits from labeling fees τ_m^P (we assume that a labeling agency's cost of certification is zero, hence profits equal revenues).

For the monopolist, acquiring the credible external ecolabel is beneficial as it eliminates consumer discounting due to the lack of a credible environmental claim, i.e., consumers perceive the environmental quality of a product bearing an external ecolabel of environmental standard g_m^C as g_m^C itself, whereas they perceive the environmental quality of a product bearing a self-label of environmental quality g_m^S as μg_m^S. However, to use the ecolabel, the monopolist's product must meet the ecolabeling scheme's environmental standard, and the monopolist must additionally bear the imposed labeling fees. The game with external ecolabeling schemes proceeds in four stages. In the first stage, the external certification agency announces its ecolabeling scheme $(\tau_m^C,\ g_m^C)$. The monopolist chooses whether or not to adopt the ecolabeling scheme in the second stage. In the third stage, the monopolist chooses the environmental quality of his product; if he chose to adopt the external ecolabeling scheme in the previous stage, he meets the imposed environmental standard g_m^C, else he self-labels and determines his optimal environmental quality g_m^S. He sets prices in the fourth stage. Note the use of the superscript $C \in \{G,\ P\}$ to denote the presence of an external ecolabeling scheme. The equilibrium of this four-stage game is described in Proposition 3.1 below.

PROPOSITION 3.1. *The environmental standard stipulated by the NGO ecolabeling scheme is higher than the environmental standard stipulated by the private ecolabeling scheme, which in turn exceeds the self-labeling environmental quality* *chosen by the monopolist:* $g_m^G = \frac{4\beta-\beta^3\mu^2+2\sqrt{\beta^2(1-\mu^2)(4-\beta^2\mu^2)}}{(4-\beta^2)(4-\beta^2\mu^2)} > g_m^P = \frac{\beta}{4-\beta^2} > g_m^S = \frac{\beta\mu}{4-\beta^2\mu^2}$*. Further, no labeling fees are charged under the NGO ecolabeling scheme,* $\tau_m^G = 0$*, while the private scheme charges* $\tau_m^P = \frac{\beta^2\left(1-\mu^2\right)}{(4-\beta^2)(4-\beta^2\mu^2)}$.

To induce adoption, the external ecolabeling scheme must make a tradeoff between a high environmental standard and a low labeling fee. Since the diffusion of environmental quality is increasing in the environmental quality of the product (this can be verified by substituting the optimal price such that $E(g_m) = \frac{g_m}{2}(1+\beta\kappa g_m)$, where $\kappa = \mu$ if self-labeled and $\kappa = 1$ if externally labeled), the NGO chooses to set the highest possible environmental standard that induces adoption from the monopolist (which implies that $\tau_m^G = 0$) while the private firm chooses the highest possible fee that can induce adoption from the monopolist. This results in the NGO choosing a higher environmental standard than its counterpart. Proposition 3.1 also notes that regardless of the source, the environmental standard imposed by an external ecolabeling scheme is higher than the environmental quality chosen by the monopolist when self-labeling his product. Thus, external ecolabeling schemes improve the environmental quality of the monopolist's product.

We now turn our attention to the social, environmental, and economic implications of ecolabeling. The following proposition contrasts the 3BL implications of the different ecolabeling schemes and the effect of credibility on these implications in a monopoly.

PROPOSITION 3.2. *a) Consumer surplus and environmental benefits are ordered such that* $CS_m^G > CS_m^P > CS_m^S$ *and* $E_m^G > E_m^P > E_m^S$*. Monopolist's surplus* *(profits) are independent of the type of label used, i.e.,* $\Pi_m^G = \Pi_m^P = \Pi_m^S$.

b) The impact of credibility on the 3BL implications of ecolabeling for a monopolist are such that $\frac{\partial CS_m^S}{\partial \mu}, \frac{\partial E_m^S}{\partial \mu}, \frac{\partial \Pi_m^S}{\partial \mu}, \frac{\partial \Pi_m^P}{\partial \mu}, \frac{\partial \Pi_m^G}{\partial \mu} > 0$, $\frac{\partial CS_m^G}{\partial \mu}, \frac{\partial E_m^G}{\partial \mu} < 0$, *and* $\frac{\partial CS_m^P}{\partial \mu}, \frac{\partial E_m^P}{\partial \mu} = 0$.

As noted in Proposition 3.1, the NGO scheme sets the highest environmental standard, which consequently results in the best outcomes from a 3BL perspective. It is noteworthy that regardless of the objective of the ecolabeler, consumer surplus and environmental benefits improve with external certification, i.e., ecolabeling improves not only the environmental quality designed into a product but also the 3BL outcomes in a monopoly. Proposition 3.2(b) notes that while the social and environmental impacts of the private ecolabeling scheme are independent of the monopolists' credibility (since the private scheme chooses a standard $g_m^P = \frac{\beta}{4-\beta^2}$ that is independent of μ, and indeed, a level that a monopolist with full credibility $\mu = 1$ would choose himself), the impact on the social and environmental consequences of the NGO ecolabeling scheme are negative. This occurs since an increase in credibility results in an increase in the monopolist's self-labeling profits, consequently increasing his reservation profits. Thus, the ecolabeling schemes must respond by imposing a lower environmental standard or charging a lower labeling fee. Since the NGO ecolabel already charges $\tau_m^G = 0$, it must respond by lowering its environmental standard, and consequently, the social and environmental benefits of NGO ecolabeling decline. In contrast, the private firm keeps its environmental standard intact while lowering its labeling fee, thus hurting its own profits but not impacting the social or environmental consequences of ecolabeling.

3.4. Producer Competition

To identify the role of competition in combination with consumer-demand pull in determining ecolabeling outcomes, we now study a model with competing firms (producers). The two firms H and L in our model are asymmetric in their credibilities, with environmental self-declarations from firm H being discounted by μ_H and those from firm L discounted by μ_L, such that $1 > \mu_H > \mu_L > 0$, i.e., firm H is more credible in the eyes of the consumer. Thus, a self-label claiming an environmental quality g_i from firm $i \in \{H, L\}$ is perceived by consumers as possessing environmental quality $\mu_i g_i$.

Extending the demand spefications of Banker et al. (1998) and Matsubayashi (2007) to the case of environmental quality competition, we model demand as a linear function of environmental qualities and prices, where $q_H = \frac{1}{2} - (p_H - p_L) + \beta(\mu_H g_H - \mu_L g_L)$ and $q_L = \frac{1}{2} - (p_L - p_H) + \beta(\mu_L g_L - \mu_H g_H)$, where $\beta \in [0, 1]$ is the demand sensitivity to relative perceived environmental quality $\mu_i g_i - \mu_{-i} g_{-i}$, where $i \in \{H, L\}$. Note that this demand specification is such that the two firms sell products that are otherwise identical in every respect, and moreover, $q_H + q_L = 1$, i.e., this is a market share model[2]. The firms are assumed to be identical on the supply side, i.e., designing an environmental quality of g_i costs both firms g_i^2 in fixed costs.

We now describe the setting of the self-labeling game between two duopolists in the absence of an external ecolabeling scheme. A two-stage

---

[2] This assumption can be relaxed by assuming less than perfect substitutatibility between the two products. For example, we can do so by incorporating a term $\phi \in [0,1]$ as a measure of substitutability between the two products resulting in a demand specification $q_i = \frac{1}{2} - (p_i - \phi p_{-i}) + \beta(\mu_i g_i - \phi \mu_{-i} g_{-i})$, where $i \in \{H, L\}$, such that $q_H + q_L = 1 - (1 - \phi)(p_H + p_L + \beta(\mu_H g_H + \mu_L g_L))$.

structure is widely used in the literature on quality competition as it is realistic (designing quality is a long-term activity while price-setting is relatively short-term) and also because it permits a pure-strategy equilibrium of the game. The competing firms simultaneously determine and announce thier environmental qualities (self-labels) in the first stage, followed by a simultaneous announcement of prices in the second stage after which demand for their respective products is determined. We define ν as the ratio between the credibilities of firm L and firm H, i.e., $\nu = \frac{\mu_L}{\mu_H} \in [0,\ 1]$.

We solve the game backwards by first resolving the game of price competition in the second stage following the announcement of environmental qualities by the firms in the first stage. The firms determine their optimal prices given the response of the other firm and the choices of environmental qualities in the previous stage by maximizing their profit functions $\Pi_i = q_i p_i - g_i^2$. Solving for the two optimal pricing functions simultaneously results in the price equilibrium $p_H^S(g_H^S, g_L^S) = \frac{1}{6}(2\beta\mu_H g_H^S - 2\beta\mu_H \nu g_L^S + 3)$, $p_L^S(g_H^S, g_L^S) = \frac{1}{6}(-2\beta\mu_H g_H^S + 2\beta\mu_H \nu g_L^S + 3)$. Given the price functions $p_H^S(g_H^S, g_L^S)$ and $p_L^S(g_H^S, g_L^S)$ from the second stage, we can solve for the resulting optimal environmental qualities in the first stage. The resulting equilibrium outcome is described in Lemma 3.2.

LEMMA 3.2. *The environmental qualities chosen in a self-labeling equilibrium are* $g_H^S = \frac{\beta\mu_H\left(9-2\beta^2\mu_H^2\nu^2\right)}{2\left(27-3\beta^2\mu_H^2(\nu^2+1)\right)}$ *and* $g_L^S = \frac{\beta\mu_H\nu\left(9-2\beta^2\mu_H^2\right)}{2\left(27-3\beta^2\mu_H^2(\nu^2+1)\right)}$, *where* $g_H^S > g_L^S$. *The prices chosen in equilibrium are* $p_H^S = \frac{2\beta^2\mu_H^2\nu^2-9}{2\left(\beta^2\mu_H^2(\nu^2+1)-9\right)}$ *and* $p_L^S = \frac{2\beta^2\mu_H^2-9}{2\left(\beta^2\mu_H^2(\nu^2+1)-9\right)}$, *where* $p_H^S > p_L^S$. *The resulting profits are* $\Pi_H^S = \frac{\left(9-\beta^2\mu_H^2\right)\left(9-2\beta^2\mu_H^2\nu^2\right)^2}{36\left(\beta^2\mu_H^2(\nu^2+1)-9\right)^2}$ *and* $\Pi_L^S = \frac{\left(9-2\beta^2\mu_H^2\right)^2\left(9-\beta^2\mu_H^2\nu^2\right)}{36\left(\beta^2\mu_H^2(\nu^2+1)-9\right)^2}$, *where* $\Pi_H^S > \Pi_L^S$.

We note from the equilibrium outcomes of the self-labeling game that the more credible firm H will design a higher environmental quality, charge a higher price, and obtain higher profits. This implies that in the absence of independent, external ecolabels, environmental quality choices follow from the ordering of firm credibilities. We now turn to a discussion of the 3BL implications of imperfect credibility and credibility asymmetry in the absence of independent, external ecolabels. The following proposition describes the 3BL implications of self-labeling competition between the two firms and the effect of credibility on these implications.

PROPOSITION 3.3. *a) In a self-labeling equilibrium, the consumer surplus is* $CS^S = \frac{2\beta^4\mu_H^4\left(\nu^4+1\right)-18\beta^2\mu_H^2\left(\nu^2+1\right)+81}{4\left(\beta^2\mu_H^2(\nu^2+1)-9\right)^2}$*, total diffusion of environmental quality is* $E^S = \frac{\beta\mu_H\left(4\beta^4\mu_H^4\nu^4-36\beta^2\mu_H^2\nu^2+\nu\left(9-2\beta^2\mu_H^2\right)^2+81\right)}{12\left(\beta^2\mu_H^2(\nu^2+1)-9\right)^2}$*, and total producer surplus is* $\Pi^S = \frac{1458-4\beta^6\mu_H^6\nu^2\left(\nu^2+1\right)+36\beta^4\mu_H^4\left(\nu^2+1\right)^2-405\beta^2\mu_H^2\left(\nu^2+1\right)}{36\left(\beta^2\mu_H^2(\nu^2+1)-9\right)^2}$.
b) For a fixed ν*, the impacts of a change in* μ_H *are as follows:* $\frac{\partial CS^S}{\partial \mu_H}$, $\frac{\partial E^S}{\partial \mu_H} > 0$ *and* $\frac{\partial \Pi^S}{\partial \mu_H} < 0$. *For a fixed* ν*, the impacts of a change in* ν *are as follows:* $\frac{\partial E^S}{\partial \nu} > 0$*, and* $\frac{\partial CS^S}{\partial \nu}$, $\frac{\partial \Pi^S}{\partial \nu} < 0$.

Note that given our parametrizations, ceteris paribus, an increase in μ_H to $\mu_H(1+\delta)$ results in a like increase in μ_L to $\mu_L(1+\delta)$. Thus, we interpret μ_H as industry credibility and ν as the ratio of credibilities of firm L and H. We observe from Proposition 3.3(b) that an increase in either μ_H or ν hurts industry profits. Specifically, an increase in μ_H causes a decrease in firm L's profits as the credibility gap between the two firms widens, which exceeds the resulting increase in firm H's profits. Conversely, an increase in the credibility ratio ν causes a decrease in firm H's profits due to the narrowing credibility gap resulting in increased competition between the two firms, which exceeds the resulting increase in firm L's profits. A similar explanation accounts for an increase (decrease) in consumer surplus with μ_H (ν): an increase in μ_H raises the environmental quality of both firms' products resulting in higher consumer surplus. An increase in ν results in firm H (L) lowering (raising) the environmental quality of its product. Thus, firm H (L) charges a lower (higher) price for its product, such that the increase in the price of firm L's product has a greater impact than that caused by the decrease in the price of firm H's product, thus negatively affecting consumers. However, an increase in either μ_H or ν results in an increase in total environmental benefits. Therefore, we note that, aside from the unequivocal benefit to the environment at the industry's expense, an increase in industry credibility for a fixed credibility ratio, or an increase in the credibility ratio for a fixed industry credibility may have positive or negative consequences for society under self-labeling competition.

We next turn our attention to external ecolabeling schemes in the duopoly model. We now allow for the presence of one external ecolabeling scheme (administered either by an environmental benefit-maximizing NGO or a profit-maximizing private firm), with the competing producers having the option of either choosing the external ecolabel and meeting the associated standard and incurring a labeling fee while enjoying full credibility (no consumer discounting), or using their own self-label with credibility $\mu_i < 1$. The game proceeds in four stages. In the first stage, the ecolabeling agency announces its environmental standard g_c^C and fixed labeling fee τ_c^C, where $C \in \{G, P\}$ depending on the objective of the agency and the subscript c denotes producer competition. Following the announcement, the two firms simultaneously choose whether to adopt the external ecolabel (C) or self-label (S) in the second stage. If a firm chooses to self-label, it determines its environmental quality in the third stage after having observed its competitor's label choice (S or C) in the second stage and the ecolabeling agency's announcement in the first stage. We separate the ecolabel adoption decision in the second stage and environmental quality setting in the third stage since it is realistic[3] and also permits a pure-strategy equilibrium of the game. In the fourth stage, price competition follows labeling and environmental quality choices. The matrix of the ensuing game between the two firms is described in Table 2 below.

Firm H/ Firm L	Self-label	Externally certify
Self-label	SS	SC
Externally certify	CS	CC

Table 2. Matrix form of ecolabeling game with external certification

The second stage equilibrium (choice of self-labeling S or adopting the external standard C) between the two firms is described in the following lemma.

LEMMA 3.3. *Let* $\tau_1(g_c^C)$ *and* $\tau_2(g_c^C)$ *denote thresholds for the labeling fee. The equilibria are CC iff* $\tau_c^C \leq \tau_1(g_c^C)$*, SC iff* $\tau_c^C \in [\tau_1(g_c^C),\ \tau_2(g_c^C)]$*, and SS iff* $\tau_c^C \geq \tau_2(g_c^C)$*. Further, iff* $g_c^C \geq \hat{g}$*, there exist two more ordered thresholds* $\tau_3(g_c^C) \leq \tau_4(g_c^C)$ *within the range* $[\tau_1(g_c^C),\ \tau_2(g_c^C)]$ *such that CS is an equilibrium iff* $\tau_c^C \in [\tau_3(g_c^C),\ \tau_4(g_c^C)]$.

The equilibria described in Lemma 3.3 are illustrated in Figure 6 below[4].

---

[3] For example, farms must go through a three year transition period following the adoption decision before they can sell produce labeled organic (Coleman, 2012).

[4] We only consider the case when $\tau_1(g_c^C) \leq \tau_2(g_c^C)$, which we show to be true everywhere except when $\mu_L \to 1$ from a numerical analysis illustrated in Figure 14 in Appendix B1. The case when $\tau_1(g_c^C) > \tau_2(g_c^C)$ does not admit heterogenous equilibria (SC or CS) and results in a trivial equilibrium outcome to the four-stage game.

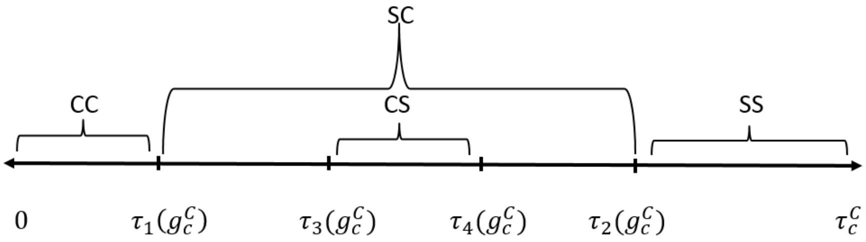


Figure 6. Equilibrium in the second-stage for a given τ_c^C as a function of g_c^C

When the two firms are differentiated only by their credibilities ($\nu < 1$), we see from Lemma 3.3 that all four equilibria described in Table 2 are feasible given the labeling fee τ_c^C and external standard g_c^C. Firm L with lower credibility has more to gain from adopting the external ecolabel (as a result of its lower self-labeling profits relative to firm H due to greater consumer discounting, and consequently, a lower reservation profit) and hence chooses action C over a wider range of labeling fees, i.e., $\tau_c^C \leq \tau_2(g_c^C)$. Firm H with higher credibility only chooses to adopt the external ecolabel C over a smaller range of labeling fees, $\tau_c^C \in [0, \tau_1(g_c^C)] \cup [\tau_3(g_c^C), \tau_4(g_c^C)]$ as it has less to gain from doing so (a higher reservation profit as a result of lower consumer discounting). Therefore, as τ_c^C increases for a given g_c^C, we first see both firms choosing C because the labeling fees are low enough to justify adoption of the external ecolabel. Thereafter, firm L continues to adopt the external ecolabel C while firm H self-labels S. As the labeling fees rise past $\tau_c^C = \tau_2(g_c^C)$, both firms choose to self-label S as the external ecolabel becomes too costly for either firm. Notice further, that the equilibrium is unique everywhere except for $\tau_c^C \in [\tau_3(g_c^C), \tau_4(g_c^C)]$ where both SC or CS equilibria may occur. This is explained by noting that at least one firm has a dominant strategy everywhere except for $\tau_c^C \in [\tau_3(g_c^C), \tau_4(g_c^C)]$. In particular, firm L will adopt the external ecolabel C regardless of what its competitor does for $\tau_c^C \leq \tau_3(g_c^C)$, and firm H will self-label S regardless of what its competitor does for $\tau_c^C \geq \tau_4(g_c^C)$. However, for $\tau_c^C \in [\tau_3(g_c^C),\ \tau_4(g_c^C)]$, neither firm has a dominant strategy, and the ensuing equilibrium (SC or CS) depends on what each firm's competitor chooses. Adopting the external ecolabel is only beneficial for a firm when its competitor does not also adopt it, i.e., differentiation drives external ecolabel adoption in this range of labeling fees. We note here that not all of the equilibrium regions depicted in Figure 6 may exist for any given g_c^C; for example, if g_c^C is too high, then $\tau_1(g_c^C) < 0$ so that the CC equilibrium disappears.

In the following proposition, we describe the equilibrium choices of $g_c^C$and τ_c^C by the external ecolabeling agencies and the ensuing equilibrium between the competing firms.

PROPOSITION 3.4. *a) Let g_c^{CA} and g_c^{CB} denote conditionally optimal environmental standards stipulated by an ecolabeling scheme $C \in \{G,\ P\}$. Similarly, let τ_c^{CA} and τ_c^{CB} denote conditionally optimal labeling fees charged by an ecolabeling scheme $C \in \{G,\ P\}$. Further, let, $\Delta E = E|_{(g_c^{GA},\ \tau_c^{GA})} - E|_{(g_c^{GB},\ \tau_c^{GB})}$ and $\Delta \Pi^{Pri} = \Pi^{Pri}|_{(g_c^{PA},\ \tau_c^{PA})} - \Pi^{Pri}|_{(g_c^{PB},\ \tau_c^{PB})}$, where Π^{Pri} denotes the private labeler's profits. Then, the equilibrium outcome of the game is described in the following table:*

	NGO scheme		***Private scheme***	
	$\Delta E \geq 0$	$\Delta E < 0$	$\Delta \Pi^{Pri} \geq 0$	$\Delta \Pi^{Pri} < 0$
Labeling fees	0	0	τ_c^{PA}	τ_c^{PB}
Environmental standard	g_c^{GA}	g_c^{GB}	g_c^{PA}	g_c^{PB}
Labeling equilibrium	GG	SG	PP	SP

b) Regardless of an NGO or private ecolabel, $g_L^* = g_c^C \geq g_H^* > g_H^S > g_L^S$, i.e., when an external ecolabel is available, firm L provides a higher environmental quality than its competitor and both firms' environmental qualities are higher than *those chosen in the absence of an external ecolabel.*

c) In a CC equilibrium, $g_c^G = g_c^{GA} > g_c^{PA} = g_c^P$*, and in an SC equilibrium,* $g_c^G = g_c^{GB} > g_c^{PB} = g_c^P$.

As noted in Proposition 3.4(a), regardless of the source of the ecolabeling scheme, firm L always chooses to adopt the external ecolabel in equilibrium, while firm H adopts the external ecolabel if and only if $\Delta E = E|_{(g_c^{GA},\, \tau_c^{GA})} - E|_{(g_c^{GB},\, \tau_c^{GB})} = E|_{(g_c^{GA},\, 0)} - E|_{(g_c^{GB},\, 0)} \geq 0$ (and in the case of the private ecolabeler, if and only if $\Delta \Pi^{Pri} = \Pi^{Pri}|_{(g_c^{PA},\, \tau_c^{PA})} - \Pi^{Pri}|_{(g_c^{PB},\, \tau_c^{PB})} \geq 0$). A numerical exploration of the switching point in firm H's ecolabel adoption decision reveals that for a given ν, this occurs when the credibility of firm H lies below some threshold value, such that an *SC* equilibrium ensues only when firm H's credibility is sufficiently high (this numerical study is described in Figure 12 in Appendix B1). This results from the larger reservation profits for firm H due to its higher credibility, making firm H more reluctant to adopt the external ecolabel when its credibility is higher than a threshold. In addition, Proposition 3.4(b) notes that in the presence of an external ecolabel, firm L, who in the absence of an external ecolabel would choose a lower environmental quality relative to its competitor, will now choose a higher environmental quality than its competitor. This implies that environmental quality choices do not follow from the ordering of firm credibilities in the presence of a single external ecolabel. Moreover, Proposition 3.4(b) states that the environmental qualities chosen in equilibrium in the presence of an external ecolabel are higher than the environmental qualities that would have been chosen in its absence. That is, the presence of an external ecolabel drives up environmental qualities of both products. In addition, we observe from Proposition 3.4(c) that conditional on a given equilibrium between the competing firms, the NGO ecolabeling scheme will stipulate a higher environmental standard than its private counterpart. A more general result on the ordering of environmental standards in an NGO and private ecolabeling scheme is obtained through a numerical exploration and illustrated in Figure 7, revealing that the NGO will stipulate a higher environmental standard than its private counterpart, who in turn will stipulate a higher environmental standard than the environmental qualities chosen in the absence of external ecolabeling schemes. We obtain this figure by plotting the self-labeling environmental qualities and environmental standards obtained in Lemma 3.2 and Proposition 3.4 respectively, conditional on the sign of ΔE and $\Delta \Pi^{Pri}$. In Figure 7, we set the parameters $\beta = 0.75$ and $\nu = 0.5$, but we note that the ordering of environmental standards and qualities does not change upon varying β and ν in increments of 0.2 over the range $\beta \in (0, 1]$ and $\nu \in [0, 1)$.

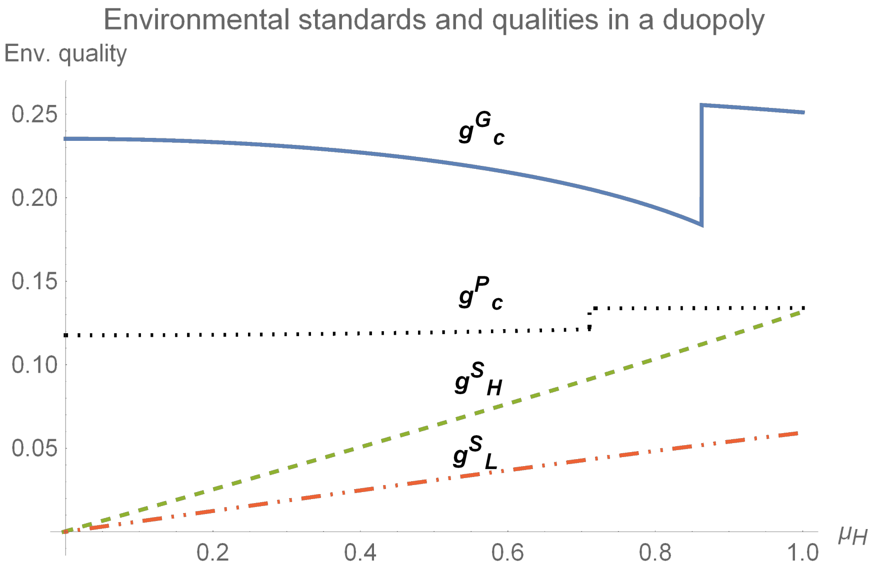


Figure 7. Environmental standards and qualities as a function of μ_H for $\beta = 0.75$, $\nu = 0.5$

We next direct our attention to the 3BL implications of the introduction of an external ecolabel. Owing to the intractability of the expressions for

3BL metrics, we perform a numerical analysis while varying the parameters $\mu_H \in [0,1]$ and $\nu \in [0,1]$. We graphically describe in Figure 8 the resulting comparisons of the 3BL implications for the cases when no external ecolabels are available, an NGO external ecolabel is available, and a private external ecolabel is available (computed from the definitions of the 3BL metrics and the equilibrium outcomes described in Lemma 3.2 and Proposition 3.4). We note here that while the results described in Figure 8 are for the case of $\beta = 0.75$, the structure of Figure 8 remains qualitatively unchanged while β is varied in increments of 0.2 in the range $\beta \in (0,\ 1]$.

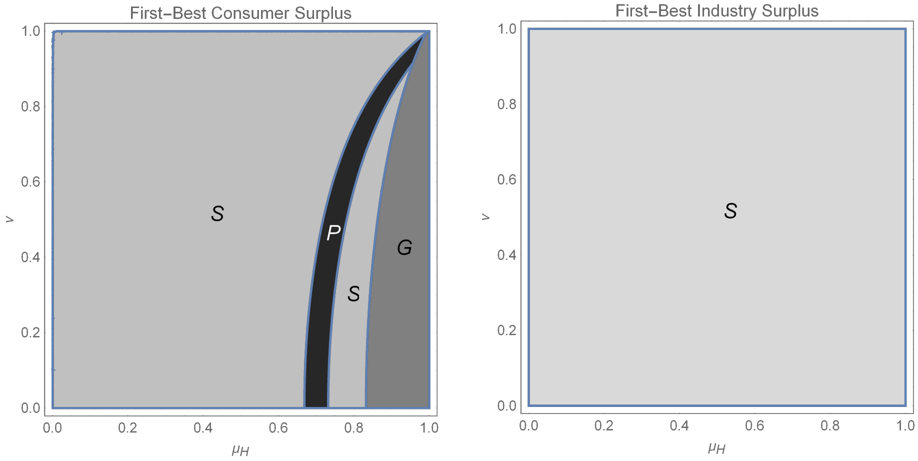


Figure 8. First-Best Consumer Surplus and Industry Surplus as a function of μ_H and ν for $\beta = 0.75$.

Figure 8 contrasts the 3BL impacts across the three scenarios: no external ecolabel, external NGO ecolabel, and external private ecolabel. Note that in Figure 8, S implies first-best implications result from self-labeling in the absence of external ecolabeling schemes, and $C \in \{G,\ P\}$ implies first-best implications result from the corresponding external ecolabeling scheme. We observe that while industry profits are higher in the absence of an external ecolabel, which occurs as a result of decreased differentiation as well as the imposed environmental standard and labeling fees in the presence of external ecolabeling schemes, consumer surplus can be maximized by either one of these three scenarios depending on the credibilities of the two firms. In particular, as μ_H increases from left to right, the first-best consumer surplus results first from the absence of an external ecolabel, then from the private ecolabel, then from the absence of an external ecolabel again, and finally from the NGO ecolabel, respectively. Note that external ecolabeling schemes result in first-best consumer surplus when industry credibility μ_H is high, a scenario wherein external ecolabeling schemes are less likely to be available or perceived as necessary. As the credibility ratio ν increases, the regions where external ecolabeling schemes result in first-best consumer surplus diminish in size. Therefore, external ecolabeling schemes may be more valuable to consumers when industry credibility is high but the credibilities of the two producers are significantly different. We note that by virtue of the NGO's objective of environmental benefit-maximization, first-best environmental impacts are achieved by the NGO ecolabeling scheme. Moreover, as in the monopoly case, we also find that the private ecolabeling scheme results in superior environmental outcomes relative to the absence of an external ecolabel. We note here that the sensitivity of demand to perceived environmental qualities, β, plays a relatively minor role in determining the ordering of 3BL implications in these three scenarios. Thus, external ecolabeling schemes improve environmental outcomes but also hurt industry profits, whereas they can leave consumers better or worse off depending on the credibilities of the two firms.

3.5. NGO Preemption of a Private Ecolabel

We noted in §3.4 that while a private ecolabel is preferred by the industry over an NGO ecolabel, it still underprovides environmental benefits by stipulating a lower environmental standard than the NGO. There is some conceptual discussion around the role of governmental and allied agencies in preempting or regulating ecolabeling in the fields of environmental and marketing law (for example, see Grabosky (1994)). We therefore explore in this section whether the NGO can remedy this underprovision of environmental benefits by a private ecolabel by anticipating its entry and choosing to preempt it.

To address this question, we analyze a Stackelberg game between the NGO and private labelers that are competing to address a firm's need for certification. We begin with an analysis of a producer monopoly as in §3.3. The NGO moves first by announcing an environmental standard g_m^{G2} and labeling fee τ_m^{G2} to maximize environmental benefits. In response to this announcement from the NGO, the private ecolabeler announces his environmental standard g_m^{P2} and labeling fee τ_m^{P2} to maximize his profits from labeling fees, where the superscript 2 indicates the presence of two external ecolabels. Next, the monopolist chooses between the two ecolabels or his own self-label, followed by implementing the environmental standard if adopting an external ecolabel or by choosing and implementing the self-labeling environmental quality instead, followed by determining a price for the product.

Resolving the game backwards, we first determine the monopolist's price function as $p_m(g, \tau) = \frac{1}{2}(\beta\kappa g + 1)$, where $\kappa = 1$ if the monopolist adopts an external ecolabel $g = g_m^{C2}$, and $\kappa = \mu$ if he self-labels instead $g = g_m^{S2}$. Note that the price function is independent of the fixed labeling fees charged. The monopolist's optimal choice of environmental quality when self-labeling is $g_m^{S2} = g_m^S = \frac{\beta\mu}{4-\beta^2\mu^2}$, and the resulting profits are $\Pi_m^{S2} = \Pi_m^S = \frac{1}{4-\beta^2\mu^2}$ as described in Lemma 3.1. Given the announcement from the NGO, the private ecolabeler maximizes his profits by choosing $g_m^{P2}(g_m^{G2}, \tau_m^{G2}, \mu)$ and $\tau_m^{P2}(g_m^{G2}, \tau_m^{G2}, \mu)$. To make a positive profit, the private ecolabeler must stipulate his scheme such that the monopolist will choose it over the self-labeling option and the NGO scheme, and hence the following constraint applies to the private ecolabeler's problem: $\Pi_m^{P2} \geq \text{Max}[\Pi_m^{G2}, \Pi_m^{S}] = \text{Max}[\Pi_m^{G2}, \frac{1}{4-\beta^2\mu^2}]$. The NGO being aware of the private labeler's response functions, chooses g_m^{G2} and τ_m^{G2} to maximize environmental benefits. The equilibrium of this Stackelberg game is described in Proposition 3.5.

PROPOSITION 3.5. *a) In equilibrium, the monopolist chooses the private ecolabel which stipulates* $g_m^{P2} = \frac{\beta}{4-\beta^2} = g_m^{P}$, *and*
$\tau_m^{P2} = Min[\frac{\beta^2(1-\mu^2)}{(4-\beta^2)(4-\beta^2\mu^2)}, \frac{\beta^2(1-4\tau_m^{G2})+16\tau_m^{G2}+(\beta^2-4)^2(g_m^{G2})^2-2(4-\beta^2)\beta g_m^{G2}}{4(4-\beta^2)}] \leq \tau_m^{P}$. *As a result, the monopolist earns profits* $\Pi_m^2 = \frac{1}{4}\left(\frac{\beta^2}{4-\beta^2} - 4\tau_m^{P2} + 1\right) \geq \Pi_m$. *The NGO does not have any impact on environmental benefits and hence chooses an environmental standard* $g_m^{G2} \geq 0$ *and labeling fee* $\tau_m^{G2} \geq 0$.
b) With two ecolabels, the 3BL implications are such that $CS_m^2 = CS_m^P$, $E_m^2 = E_m^P$, *and* $\Pi_m^2 \geq \Pi_m^P$.

Proposition 3.5(a) states that the private ecolabel is chosen in equilibrim. Despite NGO preemption, the private scheme stipulates an environmental standard of $\frac{\beta}{4-\beta^2}$ that is independent of the monopolist's credibility or the NGO's announcement. Thus, an NGO cannot improve environmental outcomes by preempting a private ecolabel in a producer monopoly. Indeed, the only change relative to the single private label case in §3.3 is a fall in the private labeler's profits resulting from lower labeling fees $\tau_m^{P2} \leq \tau_m^{P}$ so that the private label can outcompete the NGO's announcement, which results in an increase in the monopolist's profits $\Pi_m^2 \geq \Pi_m$.

However, if the private labeler's entry were assumed to be costly, in particular, if its fixed costs of entry exceeded $\tau_m^{P2}(g_m^{G2})$, the reduction in the labeler's profits from NGO intervention which occurs in equilibrium for $g_m^{G2} \in [\frac{\beta^3\mu^2 - 2\sqrt{\beta^2(\mu^2-1)(\beta^2\mu^2-4)} - 4\beta}{(4-\beta^2)(4-\beta^2\mu^2)}, \frac{\beta^3\mu^2 + 2\sqrt{\beta^2(\mu^2-1)(\beta^2\mu^2-4)} - 4\beta}{(4-\beta^2)(4-\beta^2\mu^2)}]$ can dissuade the private labeler's entry. In particular, if the NGO stipulates $g_m^{G2} = \frac{\beta}{4-\beta^2}$ and $\tau_m^{G2} = 0$, this drives the private labeler's fees and profits to zero. We also observe from Proposition 3.5(b) that while the social and environmental consequences of NGO preemption do not change in a producer monopoly as they depend only on the environmental standard and are independent of the labeling fees, the monopolist's profits go up as a result of the private ecolabeling scheme lowering its labeling fee to outcompete the NGO ecolabel. Thus, we observe from Proposition 3.5 that in a monopoly, the NGO cannot impact environmental or social outcomes but it can drive up the monopolist's profits from adopting the private ecolabel.

We next explore the NGO's preemptive role in a duopoly. The game proceeds as in the monopoly case with the NGO's announcement coming first, followed by the private labeler's announcement, after which the two producers simultaneously make ecolabel adoption, environmental quality, and pricing choices. Due to analytical intractability, we perform a full factorial numerical experiment to determine the equilibrium outcomes in a producer duopoly for the parameters $\mu_H \in \{0.2, 0.4, 0.6, 0.8\}$, $\nu \in \{0.2, 0.4, 0.5, 0.6, 0.8\}$, and $\beta \in \{0.5, 0.75\}$. The solution is obtained by backward induction as in the monopoly case. A representative snapshot of the equilibrium outcomes of this numerical analysis for $\nu = 0.5$ is provided in Tables 4 and 5 in Appendix B1.

From these tables, we observe that both firms' products are externally ecolabeled in equilibrium. Further, we see that differentiation in ecolabeling occurs when $\beta = 0.5$ but not when $\beta = 0.75$, i.e., when the sensitivity of demand to the difference in perceived environmental qualities of the two products is sufficiently low. As β increases, the profits of firm L who adopts the private ecolabel P (with a lower environmental standard than the NGO ecolabel G) are increasingly hurt as a result of differentiation, and therefore, it chooses to adopt the same ecolabel as its competitor. Since adopting the same ecolabel confers no demand benefits to either firm, both firms move downwards to adopt the private ecolabel with a lower environmental standard as it is less costly to achieve. We also observe that in the case of both NGO and private ecolabels coexisting, the more credible firm H adopts a higher environmental standard than its less credible competitor, i.e., as in the self-labeling case, environmental quality choices follow from the ordering of firm credibilities. Also note from Table 5 (in Appendix B1) that while the presence of a single external ecolabeling scheme drives the environmental qualities provided by both firms upwards relative to the absence of an external ecolabeling scheme, adding a second ecolabeling scheme does not drive the environmental qualities of both firms upward relative to the presence of a single external ecolabeling scheme.

With respect to 3BL implications in the presence of two external ecolabels, we observe from Table 4 that all entries in row 10 of Table 4 are positive. This means that the NGO can improve environmental outcomes by preempting the private ecolabel in a duopoly even when its own ecolabel is not chosen in equilibrium. This occurs as the NGO's announcement pushes the private label to increase its environmental standard and reduce labeling fees. Note that consumer surplus also improves with NGO preemption relative to the case of only a single external ecolabel being present. On the other hand, industry profits decrease (increase for $\beta = 0.5$ but decrease for $\beta = 0.75$) relative to a the scenario wherein only a single private

(NGO) ecolabeling scheme was available to the producers. It is interesting to note that NGO preemption of a private ecolabel does not improve environmental benefits relative to the scenario wherein only a single NGO ecolabel is present. We also observe that the environmental qualities chosen by the two firms are higher when a PP equilibrium ensues (when $\beta = 0.75$) relative to when a GP equilibrium ensues (when $\beta = 0.5$).

3.6. Conclusion

The two key questions addressed in this chapter are the role of external ecolabeling schemes and firm credibility in determining environmental, social, and economic outcomes from green product development. Green product development has gained momentum as a result of increased consumer awareness and impetus from competition. To distinguish the role of consumer demand for green products from the role of competitive forces, we first studied a monopolistic model wherein a single firm produces a single product with environmentally beneficial attributes. In the absence of external ecolabeling schemes, a monopolistic producer must self-label his product to declare its environmental attributes to his consumers. We observe that an increase in the credibility of the monopolist's self-labeling claims enhances the environmental quality of his product, and consequently, improves environmental, social, and economic outcomes.

External ecolabeling schemes offer the monopolist the opportunity to enhance credibility for a fixed certification fee, under the condition that his product meets the environmental standard stipulated by the external ecolabeling scheme. In comparing two possible external ecolabeling schemes from an environmental benefit-maximizing NGO and a profit-maximizing private firm, we find that the NGO ecolabel achieves the highest environmental benefits and consumer surplus by stipulating a higher environmental standard than its private counterpart and imposing no labeling fees on the monopolist. However, we also note that regardless of the source of the external ecolabeling scheme, adopting an external ecolabel results in greater environmental benefits and consumer surplus without impacting the profits of the monopolist. Thus, in a monopoly, external ecolabeling schemes offer an unequivocal benefit from a 3BL perspective.

We next study the impact of competitive forces on the efficacy of external ecolabeling schemes. Firm credibility in a duopoly of producers is captured by two notions: 1) industry credibility, and 2) a ratio between the credibilities of the firms with lower and higher credibility, respectively. In a duopoly of producers, we find that in the absence of an external ecolabel, environmental qualities go up as industry credibility rises for a fixed credibility ratio, and thus, so do the environmental benefits and consumer surplus. However, the industry as a whole becomes less profitable, as the increased differentiation caused by the rising credibility gap affects the less credible firm severely. An increase in the credibility ratio for a fixed industry credibility narrows the credibility gap between the two firms, thus intensifying competition between them. While this improves environmental benefits, it has a negative effect on industry profits, and interestingly, also on consumer surplus. We also observe that in the absence of an external ecolabeling scheme, the more credible firm provides a higher environmental quality than its competitor, i.e., environmental quality follows from the ordering of firm credibilities when firms are self-labeling.

When the duopolists have access to a single external ecolabeling scheme, environmental qualities, and consequently, environmental benefits will rise. However, a numerical exploration of the 3BL implications of a single ecolabeling scheme reveals that industry profits fall relative to the scenario where neither firm had access to an external ecolabel. This occurs as a result of the homogenezation effect of external ecolabels; only two types of equilibria occur in the presence of an external ecolabel, either both firms adopt it, or the less credible firm adopts it while its competitor self-labels. In either case, the environmental qualities are higher than in the absence of an external ecolabel, and are also closer together, reducing differentiation despite both firms bearing higher fixed costs of environmental quality. In addition, consumers may not necessarily benefit from the presence of external ecolabeling schemes. We find, in fact, that consumers benefit from external ecolabeling schemes when industry credibility is already very high, i.e., when it appears that external certification is less likely to be valuable. In comparing the two external ecolabeling schemes, we observe, as in the monopoly case, that an NGO ecolabeling scheme stipulates a higher environmental standard than its private counterpart and charges no labeling fees. Moreover, both ecolabeling schemes impose higher environmental standards than the environmental qualities chosen by the firms in the absence of the external ecolabels. In addition, when a single external ecolabeling scheme is available, the less credible firm provides a higher environmental quality than its competitor. This implies that in the presence of a single external ecolabeling scheme, environmental quality does not follow from the ordering of firm credibilities.

Observing that while the private ecolabel improves environmental benefits relative to the absence of an external ecolabel, it still underprovides them relative to an NGO ecolabeling scheme, we explore the possibility of an NGO anticipating the entry of a private ecolabeling scheme by making a preemptive announcement of its own ecolabeling scheme with the intent to boost environmental benefits. In a producer monopoly, we find that NGO preemption cannot prevent the private ecolabel from being chosen, nor can it impact the environmental benefits or consumer surplus from ecolabeling. NGO preemption can however reallocate profits from the private ecolabeler to the monopolist, and in doing so, can dissuade the private ecolabeler from entering the market should entry be costly. An alternative approach to improve environmental outcomes in the presence of a private ecolabel can be regulatory intervention by a government agency in the form of a mandatory minimum environmental quality standard.

In contrast, NGO preemption can have a positive impact on environmental benefits in a duopoly. A numerical study for a fixed set of parameters reveals that the equilibria that arise are such that both firms choose to adopt an external ecolabel; either they both adopt the private ecolabel, or the less credible firm adopts the private ecolabel while the more credible firm adopts the NGO ecolabel. Thus, within the scope of this numerical study, the private ecolabel is chosen in equilibrium by at least one firm. Despite the NGO ecolabel not always being chosen in equilibrium, we find that NGO preemption results in improved environmental benefits as it steers the environmental standard stipulated by the private ecolabeling scheme upward. However, despite the presence of two ecolabeling schemes, environmental benefits are lower relative to the scenario wherein the firms had access to only a single NGO scheme. Consumer surplus also goes up with NGO preemption, while industry profits are typically lower due to the higher average environmental standards imposed by the two ecolabeling schemes. We also note that since the environmental standard stipulated by an NGO ecolabeling scheme continues to be higher than that of its private counterpart, the more credible firm will provide a higher environmental quality when both ecolabeling schemes coexist. That is, in the presence of both ecolabeling schemes, environmental qualities follow from the ordering of firm credibilities, as in the scenario wherein no external ecolabeling schemes were available, but unlike the scenario wherein only a single external ecolabeling scheme was available.

External ecolabeling schemes are intended to stimulate the production and consumption of environmentally friendly products and services by increasing consumer awareness and trust for green products, consequently stimulating the demand for and supply of these products, thus mitigating the environmental impacts of production and consumption (Galarraga Gallastegui, 2002). The results of our study show that regardless of their source, external ecolabeling schemes can help preserve the environment. However, their impact on consumers may be negative, particularly when industry credibility is low such that the greatest need for ecolabeling is foreseen. Further, they do not necessarily boost industry profits by allowing them to target and meet consumer needs, rather, they tend to limit differentiation while simultaneously imposing costly environmental standards and labeling fees on the participating firms. The precise nature of their impact depends on industry structure; ecolabeling is unequivocally beneficial from a 3BL perspective in a producer monopoly, but not when the market is competitive. Furthermore, we find that not all ecolabeling schemes are made equal; NGO schemes are more stringent and thus provide better environmental outcomes than private ecolabeling schemes but may or may not benefit consumers depending on the industry structure and the credibilities of the producers. A preemptive NGO can remedy the underprovision of environmental quality by a private ecolabeling scheme in the presence of two competing producers even if its own scheme is not adopted. In a monopoly however, the recourse to mitigate the underprovision of environmental quality by a private ecolabeling scheme must come from either a regulatory minimum environmental quality standard or an increase in the monopolist's credibility through investments in corporate social responsibility or other forms of positive advertisement.

Credibility is the second notion we explore in this study. Our results reveal that monopolists can benefit from improving their credibility through investment or advertisement regardless of whether external ecolabeling schemes are available, while in the case of producer competition, the industry as a whole may not benefit from improving their credibility in the presence of external ecolabeling schemes. Moreover, an increase in firm credibilities can hurt consumers and the environment in the presence of an NGO ecolabeling scheme. Indeed, we find that the ordering of environmental qualities does not necessarily follow from the ordering of firm credibilities; a less credible firm will provide higher environmental quality when a single external ecolabeling scheme is available.

In closing, we acknowledge some limitations of our model and suggest potential extensions to our study. The demand form stipulated in a duopoly is such that the overall size of the market is fixed. Thus, any market share gains to one firm come from an equivalent loss in its competitor's market share. This stipulation further assumes that the two firms produce otherwise identical and perfectly substitutable products. Relaxing this stipulation by allowing for imperfect substitutability can provide insights into the role of competitive intensity on the impacts of ecolabeling. A preliminary numerical analysis described in Figure 13 in Appendix B1 suggests that the structure of the equilibria between competing firms in the presence of external ecolabeling schemes is preserved even while allowing for imperfect substitutability. We also restrict our attention to a single-product monopolist in this study. Allowing the monopolist to produce more than one product can facilitate a clearer comparison with the duopoly setting and provide greater insight into the role of market structure in determining the impact of ecolabeling schemes on green product development. One final extension we propose is to consider credibility enhancement by firms through investments in corporate social responsibility efforts and green advertisement and to identify when such a strategy might prove beneficial to the firms, consumers, and the environment, as well as its effects on the efficacy of external ecolabeling schemes.

CHAPTER 4

IS COMPETITION OR COLLABORATION THE KEY TO DRIVING SUSTAINABILITY IN SUPPLY CHAINS?

4.1. Introduction

Green product development is increasingly being undertaken by firms voluntarily and is quickly replacing the traditional 'command and control' approach to environmental regulation (Bottega and De Freitas, 2009). This has primarily resulted from the rise in consumer awareness of the environmental impacts of consumption, with a sizeable proportion of consumers now willing to pay significant premiums for sustainably produced products (Moon et al., 2002). Competitive forces and the threat of regulation have also contributed to the growing incidence of green product development. Firms have responded by offering sustainable products, for example, Starkists' Dolphin-safe tuna, Method's eco-friendly cleaning products, Starbucks' post-consumer recycled coffee cups and sleeves, among others.

However, sustainability is not created on an island. Firms are beginning to recognize that focusing on sustainability requires them to coordinate the implementation of greening strategies within their supply chains. When Walmart launched their first sustainable product – recycled paper towels in 1989, they met with immediate backlash from consumers and watchdog groups who found that only the tube was recycled, but that the towels themselves were made from 100% non-recycled paper. This event, among other such public outings of green-washing claims made firms realize the importance of transparency and visibility within their supply chains for sustainability to become a viable and winning strategy (Plambeck and Denend, 2008). Today, Walmart is driving sustainability in their product offerings and overall energy and waste reduction targets, with the primary focus on a sustainability index that covers over 200 product categories and 1000 suppliers that will be used to rate, score and bring suppliers up to acceptable environmental performance standards (Gunther, 2013b). This index is also supported by Patagonia, a firm renowned for its environmental credentials. Patagonia has a long history of coordinating its supply chain to achieve superior environmental performance (Stevenson, 2012). Similarly, the beverage giant SABMiller urged its barley suppliers to implement water conservation measures to support its goal of water-use efficiency. Data from this successful initiative is now being shared with other suppliers (Gunther, 2013a). These examples, among others, including efforts by Nike, Intel, and Coca Cola suggest that firms are increasingly learning to cooperate with other members in their supply chains when they undertake greening initiatives. This is not surprising, as much has been written in the literature about coordination within vertical supply chains for quality improvement initiatives, and as growing research suggests, the links between quality and sustainability are strong (see, for example, Corbett and Klassen (2006)). Therefore, an important question is to understand the value of and motivation for collaboration within supply chains from the perspective of sustainability.

Lately, a new paradigm has emerged within the context of sustainability: collaboration between competing firms, or horizontal collaboration (as opposed to the previously described vertical collaboration). The

Sustainable Apparel Coalition is a group of over 100 members from industry, academia and NGO's. It was convened in 2011 by Patagonia and Walmart to share research and practical tools on sustainability implementation and to develop a common index for measuring appropriate action. Today, several firms (many of whom compete with each other) such as Target, Walmart, Kohl's, H&M, Inditex, Puma, New Balance, Nike and others are members of this working group (Gunther, 2012). The Climate Saver's Computing Initiative was founded in 2007 by Google and Intel and later joined by Microsoft, HP and WWF to involve technology firms in setting joint emissions reduction targets and efficiency goals. Today, this coalition has grown into a non-profit group with 70-90% of the IT industry as its members (Clay, 2011b). Other examples include Toyota and Ford's joint venture to develop a hybrid system for SUV's, and The Sustainability Consortium which includes competitors like Unilever and P&G. These observations are particularly interesting because sustainability has historically been seen as a business opportunity and a source of competitive advantage for firms (Porter and Van der Linde, 1995). Yet, as these examples show, competing firms share research, innovations, and sourcing information. For example, Nike shared its materials sustainability index with the Sustainable Apparel Coalition, and has more recently developed an open source application known as 'Making' for use by designers outside the firm that incorporates this index (Rhodes, 2013). This leads to the natural question: Why do firms collaborate with their competitors in the context of sustainability? And under what circumstances can such collaboration be valuable? Experts and firms participating in industry consortia believe that sustainability must be a pre-competitive issue, meaning that industry needs to first come together to determine appropriate metrics and targets, shared goals and know-how, to truly take sustainability mainstream (Clay, 2011a). The benefits of precompetitive collaboration cited by firms participating in such alliances include stimulation of consumer demand, a reduction in risk of investments, and cost savings through scale economies in green technologies. However, the question remains: Does unfettered competition or implicit collusion (through horizontal collaboration) better spur sustainability?

Policy makers have also played a major role in promoting sustainability. Regulatory approaches such as mandated technologies for automobile and power plant emissions reduction, emissions standards for automakers, recycled product procurement mandates and waste take-back requirements for the electronic consumer goods industry have been widely adopted in the United States and elsewhere. In other cases, incentive-based approaches have been used to stimulate the desired behavior, such as cash subsidies for investments in pollution control technologies, and consumer subsidies such as the plug-in car and van grants in the UK (NCEE, 2004). Policy makers have also played a role in stimulating innovation and R&D through the use of incentives. There typically exists a significant gap between private and social incentives for pursuing R&D, a major cause of which has been noted to be spillover effects to rival firms, i.e., the ability of rival firms to appropriate gains from R&D investments (Bernstein and Nadiri, 1988). With collaboration, however, it would seem that these spillover effects can be appropriated by firms by making the most efficient use of their joint resources. Does under-investment in R&D occur even when competing firms collaborate? We address this question and propose as an extension to our work in this chapter, to determine the role of a policy maker in incentivizing (disincentivizing) sustainability-related

R&D collaborations through the use of subsidies (or tariffs) for collaborative alliances to achieve the environmentally and socially optimal level of investment in sustainability.

In summary, we answer two questions in this chapter: 1) In the context of sustainability-related R&D, when and why do firms (OEM's) collaborate vertically with their supply chain partners (suppliers) and horizontally with their competitors? And 2) what are the impacts of vertical and horizontal collaboration on consumers and the environment? Our focus on societal and environmental implications of collaboration stem from a Triple Bottom Line (3BL) perspective; the 3BL is a concept used to account for the impact of business practices on stakeholders not typically considered by economic objectives by using context-specific measures of environmental impact, social equity, and similar constructs with the ultimate goal of balancing *societal* and *environmental* concerns with *economic* objectives (Elkington, 1998). We find that vertical collaboration through cost-sharing between the OEM and supplier within a monopolistic supply chain can result in higher levels of sustainability-related investment and consequently, in improved social and environmental outcomes. However, at the optimal level of cost-sharing, the supply chain benefits while the social and environmental implications of vertical collaboration are negative. In a competitive setting (with perfect competition such that the two dyads produce perfectly substitutable products), we find that horizontal collaboration between OEM's reduces the level of investment in sustainability-related R&D, and consequently, results in negative social and environmental implications. Such collaborative alliances, while most beneficial to smaller OEM's, are nevertheless profitable relative to non-collaborative competition to all OEM's regardless of size. We also find that regardless of whether or not they collaborate with their competitors, larger OEM's make greater investments in sustainability. We also perform a numerical analysis to obtain insights on the role of competitive intensity between supply chains in motivating collaborative alliances and their impacts from a 3BL perspective. We find that OEM's benefits from collaboration regardless of the intensity of competition or their respective sizes. However, when similarly sized supply chains that produce complementary products and services (low degree of substitutability) collaborate, investments in sustainability-related R&D may increase, and consequently, the social and environmental implications of such collaborative alliances can be positive.

The rest of this chapter proceeds as follows. A brief review of the relevant streams of literature is summarized in §4.2. We first describe the basic setting of our model and study vertical collaboration through cost-sharing within a supply chain in a monopolistic setting in §4.3.1. Thereafter, we study horizontal collaboration between competing supply chains in §4.3.2. In §4.4, we perform a numerical study to understand the impact of competitive intensity between the two supply chains on the motivations for and implications of horizontal collaboration. Concluding remarks to this chapter are provided in §4.5.

4.2. Literature Review

Our work in this chapter is related to four main streams of literature. Firstly, we draw on the literature on supply chain coordination. One main focus of this stream is to design contracts and other mechanisms between retailers and manufacturers to achieve first-best outcomes as in a vertically integrated supply chain. As examples, Cachon and Lariviere (2005) study revenue-sharing mechanisms, while Bernstein et al. (2006) focus on two-part tariffs to coordinate a supply chain. Majumder and Srinivasan

(2008) and Agrawal et al. (2013) study coordination in upstream supplier networks. A comprehensive review of the supply chain coordination literature can be found in (Cachon, 2003). Within the context of sustainability, the coordination literature focuses on remanufacturing, with tasks such as collection effort, design effort etc., allocated among different members of the supply chain (Savaskan et al., 2004; Savaskan and Van Wassenhove, 2006). Ghosh and Shah (2012) and Swami and Shah (2012) study the impact of supply chain coordination on sustainability-related investments in a monopoly. Ghosh and Shah (2015) also study cost-sharing contracts within supply chains in the context of green product development. Our contribution to this stream is to focus on collaboration within supply chains through cost-sharing while simultaneously considering horizontal collaboration with competing supply chains in the context of sustainability-related R&D investments.

The second stream from the intersection of microeconomics and operations management studies collaboration in R&D investments between competing firms. d'Aspremont and Jacquemin (1988) study the impact of collaboration on the level of cost-reducing R&D investments made by firms engaging in Cournot competition. Sinha and Cusumano (1991) study a model of joint research ventures between asymmetric firms engaged in Cournot competition when the research outcome is uncertain. Other studies extend the work on cooperative R&D to include a wider range of game settings and cooperative scenarios (Kamien et al., 1992; Amir et al., 2003). An exception within this research stream is Atallah (2002) who studies both horizontal collaboration as well as vertical coordination with respect to cost-reducing R&D investments between dyads engaged in Cournot competition. Our focus, in contrast, is on demand-enhancing R&D investments made by OEM's engaged in Bertrand competition in the presence of vertical and horizontal collaboration.

We also draw on the literature on green product development and social responsibility in supply chains. Consumer preference for social and environmental attributes is well documented in the literature (Khanna, 2001; Tully and Winer, 2014). Chen (2001) studies a model of consumer-driven green product development and evaluates the performance of regulatory mechanisms. A few studies consider the role of external agencies in regulating the provision of environmental quality in a competitive setting (Bottega and De Freitas, 2009; Fischer and Lyon, 2014). Some studies also consider the use of contractual mechanisms to source sustainably from suppliers. Xu et al. (2015) consider mechanisms to avoid procurement from suppliers utilizing child labor. Kraft and Raz (2014) study the role of suppliers and regulators in inducing manufacturers to eliminate toxic substances from production. We focus instead on voluntary collaboration within and between supply chains to stimulate market-driven green product development.

The 3BL perspective adopted in this chapter draws on the literature in sustainable and socially responsible operations management that addresses the impact of management policies on stakeholders not explicitly considered by standard management objectives. Kleindorfer et al. (2005) and Tang and Zhou (2012) provide two extensive reviews of the 3BL and related frameworks within the context of Operations Management applications and models. In addition, there is a substantial literature studying the effectiveness of Environmental Management Systems (EMS) such as the ISO 14000 family of certifications, and Total Quality Environmental Management (TQEM) and their implications for profitability of the firm (Klassen and McLaughlin, 1996; Corbett and Klassen, 2006; Melnyk et al., 2003; Delmas, 2001). In particular, Vachon and Klassen (2008) empirically estimate the impact of vertical collaboration in the context of sustainability-related R&D on firm performance and find that profitable firms tend to be greener and coordinate investments with supply chain partners. In this chapter, we determine the value of vertical and horizontal collaboration from the firms' perspective, as well as that of society and the environment, from a parsimonius analytical model.

4.3. Model

4.3.1. Monopoly. The primary unit of analysis in our model is an OEM – Supplier dyad. We begin with an analysis of a monopolistic dyad (supply chain) to study the impact of vertical collaboration within the supply chain on sustainability-related R&D. We stipulate a demand function that is linear in price and environmental attributes $q(p, g) = (1 - p + \alpha g)$, where p and g are the final price and level of greenness designed into the product by the supplier, respectively, and $\alpha \in [0, 1]$ is the sensitivity of demand to environmental attributes in the product. The restriction on α assumes that demand is more sensitive to price than it is to environmental attributes of the product, which reflects empirical findings in the literature (see, for example, D'Souza et al. (2006)). Similar assumptions on modeling consumer demand in the context of conventional quality-type attributes have been made in the literature (Tsay and Agrawal, 2000; Savaskan et al., 2004; Gurnani and Erkoc, 2008).

Sustainability in the context of the examples alluded to in the introduction is largely driven by consumer facing organizations such as OEM's and powerful retailers. For example, Walmart is actively seeking to green its products and processes and recognizes that the real opportunity to make these changes lies not within the organization itself, but along its supply chain (Plambeck and Denend, 2008). The OEM's effort serves to identify the appropriate opportunities and methods for sustainability-related investment on behalf of the supplier. For example, Patagonia and Nike determine the least environmentally damaging fabrics for use in their clothing and footwear lines respectively (Mazzoni, 2014). Industry roundtables convened by OEM's like the Sustainable Apparel Coalition come together to determine best practices and identify 'low hanging fruit' that can be captured by making sustainability-related R&D investments. Therefore, we assume that the OEM determines the level of sustainability-related R&D investments $g \geq 0$ in the supply chain.

Typically, the costs of such investments are borne entirely by the suppliers. For instance, WalMart announced a sustainability index based on which it would score and screen suppliers who must undertake the investments themselves to retain WalMart's business (Bustillo, 2009). However, as suppliers find it increasingly expensive to adopt socially and environmentally superior processes, it is becoming common for OEM's to share the costs of making these investments with their suppliers. As an example, Unilever partners with NGO's such as Solidaridad and The Rainforest Alliance to provide financial support and training in sustainable agricultural practices to its tea suppliers (Albert, 2010). Similarly, Levi Strauss has partnered with the World Bank to help its garment suppliers become more eco-friendly and conscious of labor conditions through financial support and rewards for compliance (Donnan, 2014). Therefore, we assume that the costs of sustainability-related investments may be shared between the OEM's and suppliers. In particular, the fixed costs of pursuing and implementing sustainability-related R&D are δg^2, where $\delta \geq 0$, and a fraction $\theta \in (0, 1]$ of these costs are borne by the OEM, with the remainder borne by the supplier. There are no variable costs in our model. Later in this section, we consider and contrast the implications of not sharing investment costs within the supply chain, i.e., when $\theta = 0$. The quadratic specification of fixed costs of R&D effort are in line with the quality improvement, green product development, and R&D literature and represent diminishing returns to investment (d'Aspremont and Jacquemin, 1988; Li and Rajagopalan, 1998; Chen, 2001). We refer to this sharing of R&D costs as vertical R&D collaboration within a supply chain. Mathematical notations used in §4.3 are summarized in Table 3.

Variable/Parameter	**Description**
p	Total price to consumer $p \geq 0$
w	Wholesale price charged by supplier $w \geq 0$
m	Retail margin set by OEM $m \geq 0$
g	Level of sustainability-related investment $g \geq 0$
α	Demand sensitivity to investment $\alpha \in [0,\ 1]$
ϕ	Competitive intensity $\phi \in [0,\ 1]$
k_i	Initial market share of dyad $i \in \{A,\ B\}, k_i + k_{-i} = 1$
δ	Fixed cost coefficient $\delta \geq 0$
θ	Degree of cost-sharing within dyad $\theta \in [0,\ 1]$
λ	Degree of R&D spillovers $\lambda \in [0,\ 1]$

Table 3. Modeling notation

To focus our attention on the impact of vertical R&D collaboration within a supply chain, we first study as a benchmark, the case of a monopoly wherein the OEM and supplier share R&D investment costs. We consider a Stackelberg game with the OEM as the Stackelberg leader, as is typically the case in our context. The sequence of the game is as follows : 1) the OEM determines the optimal R&D level g, 2) The supplier responds with a wholesale price w, 3) The OEM determines its margin m. Non-negativity of decision variables and individual rationality of the two players apply as constraints to the OEM's and supplier's profit-maximization problem which is given as:

$$\text{maximize}_{m,\,g} \mathit{\Pi}_M^{OEM} = (1 - w - m + \alpha g)m - \theta\delta g^2$$

Subject to

$$\mathit{\Pi}_M^{S} \geq 0,$$

$$m,\ g \geq 0.$$

$$\text{maximize}_{w} \mathit{\Pi}_M^{S} = (1 - w - m + \alpha g)w - (1 - \theta)\delta g^2$$

Subject to

$$\mathit{\Pi}_M^{OEM} \geq 0,$$

$$w \geq 0.$$

The equilibrium outcome of this game (described by the subscript M representing a monopoly) can be obtained by backward induction and is described in Lemma 4.1. We state the following assumption on θ, $\Omega_M = 16\delta\theta - \alpha^2 > 0$, which ensures that a non-trivial, interior equilibrium is obtained. The interpretation is that the degree of cost-sharing must be sufficiently large for the OEM's objective to be concave in the level of investment. From the supplier's individual rationality constraint, we further obtain the condition $\theta > \frac{\sqrt{\alpha^4 + 128\alpha^2\delta} - \alpha^2}{64\delta} = \omega_M$ to ensure that the degree of cost-sharing is large enough to guarantee the supplier makes a positive profit. Therefore, $\theta > \text{Max}[\frac{\alpha^2}{16\delta},\ \omega_M]$ must be satisfied throughout §4.3.1 for the monopoly case.

LEMMA 4.1. *The equilibrium decisions in a monopolistic dyad are* $w_M^* = \frac{8\delta\theta}{\Omega_M}$, $m_M^* = \frac{4\delta\theta}{\Omega_M}$, *and* $g_M^* = \frac{\alpha}{\Omega_M}$ *such that* $\frac{\partial w_M^*}{\partial\theta}, \frac{\partial m_M^*}{\partial\theta}, \frac{\partial g_M^*}{\partial\theta} < 0$. *Moreover, the OEM and supplier profits are* $\mathit{\Pi}_M^{OEM*} = \frac{\delta\theta}{\Omega_M}$, *with* $\frac{\partial \mathit{\Pi}_M^{OEM*}}{\partial\theta} < 0$, *and* $\mathit{\Pi}_M^{S*} = \frac{\delta\left(32\delta\theta^2 - \alpha^2(1-\theta)\right)}{\Omega_M^2}$, *with* $\frac{\partial \mathit{\Pi}_M^{S*}}{\partial\theta} > 0$ *iff* $\theta < \frac{2}{5} - \frac{\alpha^2}{80\delta}$.

We observe from Lemma 4.1 that an increase in the degree of cost-sharing in fact lowers sustainability-related investment by a monopolistic dyad. This is explained by noting that it is the OEM that chooses the level of investment, and as θ increases, so do the fraction of R&D costs internalized by the OEM. Consequently, the OEM chooses a lower level of R&D as θ rises. Note also that while the OEM's profits are decreasing in the degree of cost-sharing, the supplier's profits are increasing (decreasing) for degrees of cost-sharing below (above) a threshold. This is explained as follows: for low degrees of cost-sharing, as θ increases, the supplier's share of R&D costs become smaller. However, as θ rises beyond a threshold, the fall in investment lowers demand to the extent that the associated loss in revenues outpaces the fall in the supplier's costs from cost-sharing with the OEM. The condition $\theta > \omega_M$ ensures that the degree of cost-sharing is large enough to guarantee the supplier makes a positive profit.

We next turn our attention to the 3BL implications of vertical collaboration in a supply chain through cost-sharing. To measure the 3BL implications, we define the following metrics for environmental, social, and economic impacts: environmental impact is captured by the following expression $E = \sum_i q_i^* g_i^*$ that measures total diffusion of environmental quality in the market; social impacts are captured via the notion of consumer surplus: i.e., $CS = \sum_i \int_{p_i^*}^{p_i^c} q_i(g_i^*, p_i) dp_i$, where $p_i = w_i + m_i$, $p_i^* = w_i^* + m_i^*$, and $p_i^c = w_i^c + m_i^c$ indicate the total price, optimal price, and choke price (price at which demand is zero), respectively; and economic impacts are measured through the total profits accruing to the industry $\Pi = \sum_i \Pi_i^{OEM*} + \Pi_i^{S*}$, where the superscripts OEM and S denote the OEM and supplier respectively. These metrics are summed across $i \geq 1$ firms, with $i = 1$ in the monopoly case. In the following proposition, we compare the equilibrium outcomes and 3BL implications of the following two scenarios: no cost-sharing in the dyad (denoted by superscript N); and strictly positive cost-sharing in the dyad. We stipulate the condition on δ, $\Omega_N = 8\delta - \alpha^2 > 0$ to ensure non-negativity and interior solutions in the no-cost sharing scenario. We also perform a sensitivity analysis of the 3BL implications in a cost-sharing monopolistic dyad with respect to the degree of cost-sharing in the supply chain.

PROPOSITION 4.1. *a) The level of investment in sustainability in a cost-sharing dyad exceeds that in a dyad without cost-sharing,* $g_M^C > g_M^N$ *iff* $\theta \in [\omega_M, \frac{\alpha}{4\sqrt{2\delta}}]$.
b) $CS_M^C > CS_M^N$ *and* $E_M^C > E_M^N$ *and* $\Pi_M^C < \Pi_M^N$ *iff* $\theta \in [\omega_M, \frac{\alpha}{4\sqrt{2\delta}}]$.
c) The degree of cost-sharing within the dyad has the following 3BL implications: $\frac{\partial E_M^C}{\partial \theta} < 0$, $\frac{\partial CS_M^C}{\partial \theta} < 0$, *and* $\frac{\partial \Pi_M^C}{\partial \theta} < 0$ *iff* $\theta > \frac{1}{3}$.

We learned from Lemma 4.1 that cost-sharing can lower the level of sustainability related investments in a monopolistic dyad. However, from Proposition 4.1(a), we see that if the degree of cost-sharing is below a threshold ($\frac{\alpha}{4\sqrt{2\delta}}$), the level of investment in a cost-sharing dyad can exceed that in a dyad without cost-sharing. The level of investment in a non-cost sharing configuration is constrained by the supplier's individual rationality condition ($\Pi_M^S \geq 0$), while the OEM's objective is convex in the investment level. In a cost-sharing configuration, this constraint is no longer binding when $\theta > \omega_M$. However, when the degree of cost-sharing increases sufficiently, the OEM lowers the level of investment below the level in a non cost-sharing configuration as a result of internalizing a greater fraction of the R&D costs. We note here that the degree of cost-sharing is discontinuous at $\theta = 0$, which coincides with the no cost-sharing case. Further, Proposition 4.1(b) reveals that if the degree of cost-sharing is sufficiently low, the social and environmental implications resulting from a cost-sharing dyad will be superior to those resulting from a non cost-sharing configuration as a result of the higher investment level. Supply chain profits however are higher in the cost-sharing configuration if and only if the degree of cost-sharing exceeds the abovementioned threshold. In comparing 3BL implications with a non cost-sharing configuration, we therefore observe that either a superior social and environmental outcome or a higher profit for the dyad may be realized depending on the degree of cost-sharing between the OEM and supplier. A graphical illustration of the comparison of the 3BL implications of cost-sharing is presented in Figure 9 below, where $\Delta X = X^C - X^N$, where $X \in \{CS,\ E,\ \Pi\}$ refers to the difference between the implications with and without vertical collaboration through cost-sharing.

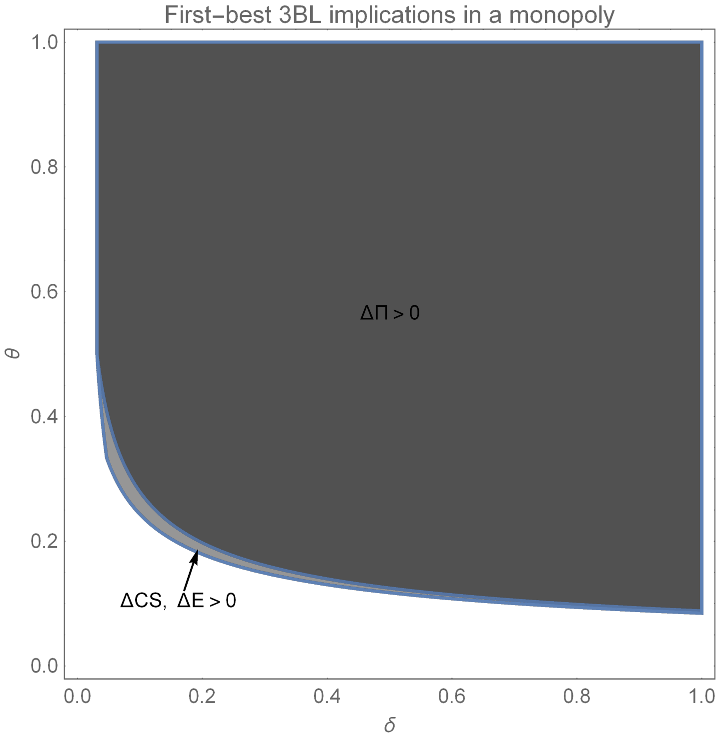


Figure 9. The 3BL impacts of cost-sharing as a function of the fixed cost coefficient δ and the degree of cost-sharing θ.

Note that the empty space in the southwest corner of Figure 9 corresponds to the infeasible region in our analysis where $\theta > \text{Max}[\frac{\alpha^2}{16\delta}, \omega_M]$ and $\delta < \frac{\alpha^2}{8}$. Further, Proposition 4.1(c) points out that consumer surplus and environmental benefits fall as the degree of cost-sharing increases. This results from a fall in the level of investment as the degree of cost-sharing rises, as observed from Lemma 4.1. The profits of the dyad on the other hand are non-monotone in the degree of cost-sharing; they increase upto a threshold as supplier profits rise, and are maximized at $\theta = \frac{1}{3}$. Thereafter, they fall as a result of tapering demand due to underinvestment in sustainability.

4.3.2. Duopoly. Having studied the value of vertical collaboration within a monopolistic supply chain in the previous subsection, we now turn our attention to horizontal collaboration across competing OEM-supplier dyads A and B. Extending the demand models of quality competition in Banker et al. (1998) and Matsubayashi (2007) to the context of environmental quality competition, we specify the demand for a dyad's product as $q_i = k_i - w_i - m_i + \phi(w_{-i} + m_{-i}) + \alpha((g_i + \lambda g_{-i}) - \phi(g_{-i} + \lambda g_i))$, where $0 \leq k_i \leq 1$ represents the initial market share of a dyad such that $k_A = k$ and $k_B = 1 - k$, i.e., $k_A + k_B = 1$, $0 \leq \phi \leq 1$ is the degree of competition between the two dyads (alternatively, the substitutability between their products), and $0 \leq \lambda \leq 1$ indicates the presence of R&D spillovers between two collaborating OEM's, where $i \in \{A, B\}$. Collaboration between OEM's takes the form of informal and non-binding arrangements where the two OEM's agree to share the results and information from their respective R&D efforts, implying an exogenous, positive degree of spillovers $\lambda > 0$. Accordingly, we stipulate that $\lambda = 0$ when the two OEM's do not collaborate. To focus on the impact of supply chain size k_i and degree of

R&D spillovers λ, we stipulate that the cost structure is identical for both firms and remains unchanged in the presence of competition and horizontal R&D collaboration.

To isolate the impact of horizontal collaboration, we study a game between two competing dyads with horizontal collaboration between the competing OEM's and vertical collaboration between the OEM's and their suppliers. The sequence of actions in the game are as follows: 1) the two OEM's simultaneously choose R&D levels g_i, 2) the two suppliers simultaneously set their wholesale prices w_i, and 3) the OEM's simultaneously choose their margins m_i. While we determine the optimal degree of vertical collaboration within each dyad (the degree of cost-sharing that maximizes a dyad's profits), we do not include this decision in the game sequence, i.e., we treat the degrees of vertical collaboration θ_i as exogenous parameters in the game. The profit-maximization problems facing the OEM's and suppliers respectively are described below.

$$\begin{aligned} \text{maximize}_{m_i,\, g_i} \Pi_i^{OEM} &= q_i(.)m_i - \theta_i \delta g_i^2 \\ &\text{Subject to} \\ &\Pi_i^S \geq 0, \\ &m_i,\ g_i \geq 0. \end{aligned}$$

$$\begin{aligned} \text{maximize}_{w_i} \Pi_i^{S} &= q_i(.)w_i - (1-\theta_i) \delta g_i^2 \\ &\text{Subject to} \\ &\Pi_i^{OEM} \geq 0, \\ &w_i \geq 0. \end{aligned}$$

This game is resolved by backward induction. In this section, we focus only on the solutions for the special case of perfect competition ($\phi = 1$)

to generate tractable analytical insights. The assumption of perfect competition makes this a market share model, where any market share gains to dyad A must come from an equivalent loss in market share to dyad B. In the following section, we thereafter relax this assumption and study the role of competitive intensity ϕ on the collaborative equilibria and ensuing 3BL implications. We stipulate the following two conditions on θ_i and δ respectively, to ensure non-trivial and interior solutions to this game: 1) the degree of cost-sharing in either dyad must be sufficiently large, $\theta_i > \frac{\alpha^2(1-\lambda)^2}{36\delta}$ and 2) $\Omega_2 = \sqrt{\delta\left(81\delta - 16\alpha^2(\lambda-1)^2\right)} + 9\delta > 9\delta$. We also define the term $\Omega_1 = 81\delta\theta_A\theta_B - \alpha^2(\lambda-1)^2(\theta_A+\theta_B)$, where $\Omega_1 > 0$ if condition 1 is satisfied. The solution of the game with horizontal and vertical collaboration for the case of perfect competition is described in Lemma 4.2 below.

LEMMA 4.2. *a) The investment levels in equilibrium are* $g_A^*(\theta) = \frac{\alpha(1-\lambda)\left(9\delta\theta_B(k+4)-\alpha^2(1-\lambda)^2\right)}{\Omega_1}$ *and* $g_B^*(\theta) = \frac{\alpha(1-\lambda)\left(9\delta\theta_A(5-k)-\alpha^2(1-\lambda)^2\right)}{\Omega_1}$.
b) The degree of cost-sharing that maximizes profits of dyads A and B is identical, $\theta_A^* = \theta_B^* = \frac{\Omega_2}{72\delta}$. *At this degree of cost-sharing, the investment levels are* $g_A^* = \frac{8\alpha(\lambda-1)\left(8\alpha^2(\lambda-1)^2-(k+4)\Omega_2\right)}{\Omega_2(9\Omega_2-16\alpha^2(\lambda-1)^2)}$ *and* $g_B^* = \frac{8\alpha(\lambda-1)\left(8\alpha^2(\lambda-1)^2+(k-5)\Omega_2\right)}{\Omega_2(9\Omega_2-16\alpha^2(\lambda-1)^2)}$.

We first note that the equilibrium outcomes described in Lemma 4.2 are continuous in the degree of R&D spillovers $\lambda \in [0,\ 1]$. Note from Lemma 4.2(b) that the degree of cost-sharing that maximizes profits of dyads A and B in equilibrium is identical in both dyads, and it is independent of the initial market shares k_i. It differs, however, from the degree of cost sharing that maximizes a dyad's profits in a monopoly ($\theta = \frac{1}{3}$) which is due to the impact of competition. Moreover, it is complementary with horizontal collaboration in the sense that it increases as the degree of R&D spillovers λ increase. In contrast, we observe from Lemma 4.2(a) that the equilibrium investment levels do indeed depend on the initial market shares of the two dyads. In the following proposition, we contrast the investment levels in the two dyads and perform sensitivity analyses of the level of investment with respect to the degree of spillovers between the two OEM's λ and the distribution of initial market shares k_i. To focus on the role of horizontal collaboration, we restrict our attention in the rest of the section to the case of identical degrees of cost-sharing within the two dyads, i.e., $\theta_A = \theta_B = \theta$.

PROPOSITION 4.2. *a) The dyad with the larger initial market share invests more in sustainability, i.e., $g_A^* > g_B^*$ iff $k > \frac{1}{2}$.*
b) The impact of R&D spillovers on investment levels is negative, i.e., $\frac{\partial g_A^*}{\partial \lambda} < 0$ and $\frac{\partial g_B^*}{\partial \lambda} < 0$. The impact of initial market share on investment levels is positive, $\frac{\partial g_A^*}{\partial k} > 0$, and $\frac{\partial g_B^*}{\partial k} < 0$.

Proposition 4.2(a) notes that dyads with a larger intrinsic market share expend greater efforts toward sustainability-related R&D. This supports observations from the field: WalMart has been more active with its sustainability agenda than its smaller partner-competitors such as Target, as has Nike, who shared their 'making' application for environmentally focused material selection with their smaller partner-competitors such as New Balance in the Sustainable Apparel Coalition (Schwartz, 2010; Rhodes, 2013). We also observe from Proposition 4.2(b) that horizontal collaboration lowers the amount of investment by a dyad. This occurs as a result of the dyads avoiding duplication and free-riding on their competitor's R&D efforts. Moreover, when the intensity of competition between the dyads is maximum ($\phi = 1$), neither dyad is inclined to invest very much in sustainability as the concomitant benefits to demand are minimal. Indeed, we observe in the following section that this may not be true at lower levels of competitive intensity between the two dyads.

Thus, at maximum competitive intensity, horizontal collaboration has a detrimental effect on the total amount of investment in sustainability-related R&D efforts. Why then do competing OEM's seek such collaborative alliances? We identify the economic motivation for horizontal collaboration in the following proposition, along with its effect on 3BL implications.

PROPOSITION 4.3. *a) Both OEM's profits are increasing in the degree of spillovers, i.e.,* $\frac{\partial \Pi_i^{OEM}}{\partial \lambda} > 0$. *Moreover, the OEM's profits are increasing in their initial market shares,* $\frac{\partial \Pi_A^{OEM}}{\partial k} > 0$ *and* $\frac{\partial \Pi_B^{OEM}}{\partial k} < 0$, *and OEM's with smaller intrinsic market shares benefit more from horizontal collaboration,* $\frac{\partial^2 \Pi_A^{OEM}}{\partial \lambda \partial k} < 0$ *and* $\frac{\partial^2 \Pi_B^{OEM}}{\partial \lambda \partial k} > 0$.
b) Environmental benefits and consumer surplus decrease with collaboration, $\frac{\partial E_C}{\partial \lambda} < 0$ *and* $\frac{\partial CS_C}{\partial \lambda} < 0$. *Environmental benefits and consumer surplus are minimized at equal initial market shares* $k = \frac{1}{2}$.

Proposition 4.3(a) notes that the two OEM's profits are increasing in the degree of R&D spillovers, and consequently, since the equilibria described in Lemma 4.2 are continuous in the degree of spillovers λ, they prefer to collaborate with their competitor. It is interesting to note that the majority of collaborative alliances in the examples we alluded to in this chapter are formed by and consist of large OEM's. Proposition 4.3(a) also points out that larger OEM's make greater profits. However, the value of horizontal collaboration (R&D spillovers) decreases as the inital market share of an OEM rises, i.e., smaller OEM's benefit most from horizontal collaboration. Despite its economic motivation, horizontal collaboration between OEM's has a detrimental impact on both consumer surplus and environmental benefits, both of which decrease with the degree of R&D spillovers as noted in Proposition 4.3(b). The reason for this detrimental impact of collaboration is tied to the lowering of investment levels as a result of an increase in the degree of R&D spillovers as described in Proposition 4.2(b). This suggests that Porter and Van der Linde (1995)'s hypothesis that competition is the most effective driver of sustainability may indeed be true. However, we also find that another competitive factor, the initial distribution of market shares, has the opposite effect on environmental benefits and consumer surplus. Both measures are minimized at equal distributions of initial market shares. To further explore the role of competitive intensity in conjunction with the degree of R&D spillovers and initial distribution of market shares, we explore the impact of competitive intensity on horizontal R&D collaboration and ensuing 3BL implications via a numerical study in the following section.

4.4. Impact of Competitive Intensity

The results described in §4.3.2 were for the special case of perfect competition ($\phi = 1$). This stipulation restricted us to a market share model, wherein any gains in market share to dyad A came from an equivalent loss in market share to dyad B. In this section, we relax this assumption and allow for the competitive intensity of the firms to vary in the range $\phi \in [0,\ 1]$. An analytical treatment of general levels of competitive intensity is cumbersome and provides limited insights, hence, we adopt a numerical approach in this section to verify if our insights from §4.3.2 continue to hold.

We obtain the equilibrium outcome for any given $\phi \in [0,\ 1]$ as in the case of $\phi = 1$ and describe the solution procedure in the proof of Lemma 4.2. We first determine the degree of cost-sharing that maximizes each dyad's profits for the two cases, namely for the case of $\lambda = 0.5$ and for the case of $\lambda = 0$, and we then compare the equilibrium level of investment across the two cases. Accordingly, let $\Delta g_i = g_i^*|_{\lambda=0.5} - g_i^*|_{\lambda=0}$ for

$i \in \{A, B\}$. The results of this comparison as a function of k_i and ϕ are described in Figure 10 for $\alpha = 0.5$ and $\delta = 1$.

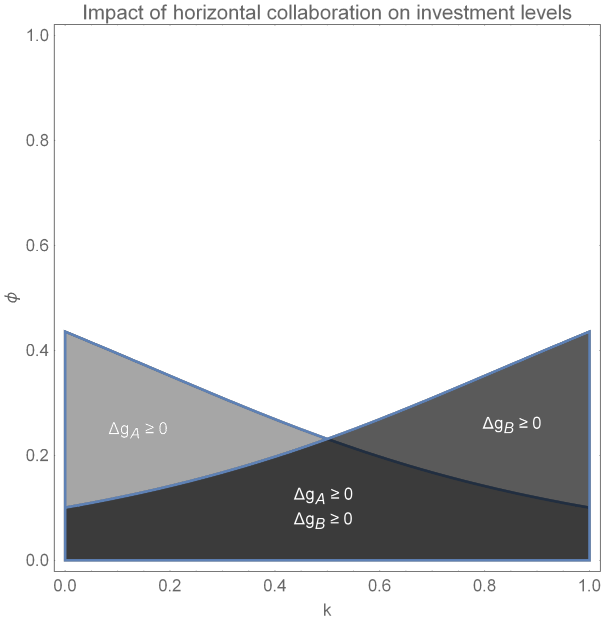


Figure 10. The effect of horizontal collaboration on investment levels in a duopoly for $\alpha = 0.5$, $\delta = 1$.

Figure 10 compares investment levels at the degrees of cost-sharing that maximizes each dyad's profits when there is ($\lambda = 0.5$) and when there is no ($\lambda = 0$) horizontal collaboration. From Figure 10, we observe that for low levels of competitive intensity between the two dyads, investment levels can increase from collaboration. In particular, investment levels increase from horizontal collaboration for a wider range of competitive intensities when the dyad has a small initial market share. Overall, investment levels of both dyads increase from horizontal collaboration at low competitive intensities when the dyads are similarly sized ($k = \frac{1}{2}$). This is explained by noting that at a lower competitive intensity, both dyads get rewarded by consumers for their investments in sustainability. In contrast, when competitive intensity is high, neither firm receives sufficient demand benefits by investing in sustainability. Rather, at higher levels of competitive intensity, the two dyads invest in sustainability to prevent a loss of market share to their competitior.

This leads us to query the role of competitive intensity on the motivation for horizontal collaboration and its 3BL implications as a counterpart to Proposition 4.3. To do so, we preform a numerical study by applying the 3BL metrics defined in §4.3 to compute the 3BL implications of the equilibrium outcomes for any given $\phi \in [0,\ 1]$. We compare the 3BL implications for each of the equilibria derived to produce Figure 10. Accordingly, to extrapolate the results illustrated in Figure 10, let $\Delta E = E|_{\lambda=0.5} - E|_{\lambda=0}$ and $\Delta CS = CS|_{\lambda=0.5} - CS|_{\lambda=0}$. We observe that $\Delta \Pi_i = \Pi_i|_{\lambda=0.5} - \Pi_i|_{\lambda=0}$, and in particular, $\Delta \Pi_i^{OEM} = \Pi_i^{OEM}|_{\lambda=0.5} - \Pi_i^{OEM}|_{\lambda=0}$ are positive throughout the range of parameters $k \in [0,\ 1]$ and $\phi \in [0,\ 1]$, i.e., horizontal collaboration results in higher OEM and dyad profits throughout the range of parameters considered in this study. Therefore, we describe only the results from the comparison of environmental benefits and consumer surplus in Figure 11.

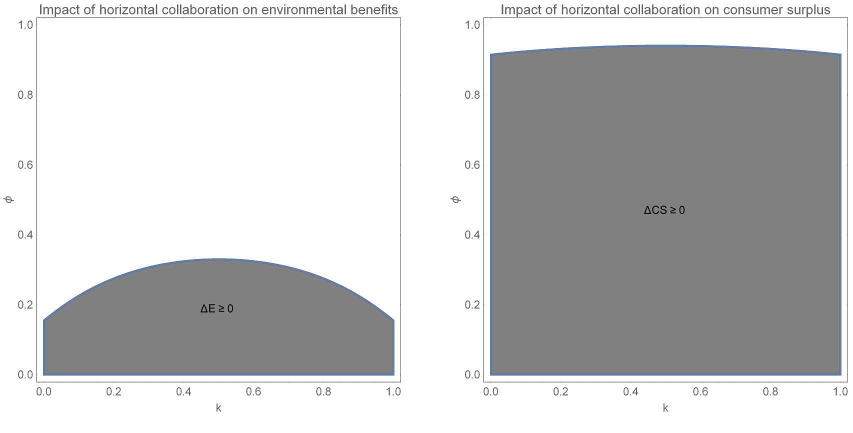


Figure 11. The impact of horizontal collaboration on environmental benefits and consumer surplus for $\alpha = 0.5$, $\delta = 1$.

While we noted in Proposition 4.3 that horizontal collaboration impacts environmental benefits and consumer surplus negatively, we observe from Figure 11 that this is not necessarily true when the competitive intensity between the firms is lower. In particular, we see that environmental benefits can increase from horizontal collaboration when competitive intensities are low and the two dyads have similar initial market shares. Note the overlap between the region of positive environmental impacts from horizontal collaboration in Figure 11 and the region where investment levels rise from horizontal collaboration from Figure 10. Consumer surplus also increases from horizontal collaboration for competitive intensities below $\phi = 1$. We also note that environmental benefits and consumer surplus are more likely (over a wider range of competitive intensities) to increase from horizontal collaboration when the two dyads are similar in size.

This suggests that horizontal collaboration can be particularly beneficial from a societal and environmental perspective when competitive intensity is low ($\phi < 1$) and the distribution of initial market shares is roughly equal ($k \to \frac{1}{2}$) as seen in Figure 11. In contrast, horizontal collaboration has negative societal and environmental consequences when the competitive intensity is high ($\phi = 1$), and moreover, these negative consequences are exacerbated at an equal distribution of initial market shares ($k = \frac{1}{2}$). Thus, competitive intensity ϕ and the initial distribution of market shares k can be viewed as substitutes in generating the best societal and environmental consequences from horizontal collaboration.

4.5. Conclusion

The objective of this chapter is to understand the motivation for collaborative alliances within and across supply chains in the context of sustainability-related R&D, and to determine the consequences of collaboration from a 3BL perspective. An important hurdle to the effective deployment of sustainable innovations has been the decentralization of decision making within supply chains; OEM's and retailers demand green or socially responsible products from their suppliers who must bear the costs of implementation. Firms are beginning to realize that creating sustainable products requires coordinating the implementation of research and development efforts throughout their supply chains. To understand the motivation behind vertical collaboration within supply chains, we first develop a model of a monopolistic OEM-supplier dyad that coordinates research and implementation of sustainable innovations through cost-sharing. Our analysis reveals that cost-sharing within a monopolistic supply chain can result in greater investment in sustainable innovation, and consequently, result in better social and environmental outcomes. However, the motivation for vertical collaboration within a supply chain is economic in nature. We find that cost sharing can either improve social and environmental outcomes, or the economic profit of the supply chain, but not both simultaneously. The impact of cost-sharing depends on the degree to which the two parties share research and development costs. At the degree of cost-sharing that maximizes supply chain profits, social and environmental outcomes are worse off than in the absence of such collaboration.

A recent development has been the formation of several industry-wide alliances to share and co-develop sustainable innovations. Examples of such collaborations include the Sustainable Apparel Coalition, The Sustainability Consortium, the Climate Saver's Computing Initiative etc. These collaborative alliances bring together customer-facing organizations (such as WalMart, Nike, Unilever, Dell etc.) that traditionally compete with their partners in the alliance along the dimension of sustainability. Therefore, we address the question of why such organizations collaborate on the back-end while they compete for customers on the front-end. Moreover, do these alliances benefit the firms, consumers, and the environment? To address these questions, we develop a model of competition between two OEM-supplier dyads, where we stipulate perfect competition, meaning that the products developed and sold by the two dyads are perfect substitutes to each other. We find that horizontal collaboration between two competing supply chains (OEM's decide whether or not to collaborate) reduces the amount of sustainability-related investment made by each supply chain as they avoid duplicating each others' efforts and pool their efforts. Consequently, the social and environmental implications of horizontal collaboration between competing supply chains is negative. However, we find that regardless of an OEM's characteristics, horizontal collaboration results in improved profits, not just for each OEM, but also for each supply chain, and thus, for the entire industry. This occurs due to a reduction in the cost of effort (since investment levels fall) and the softening of environmental quality competition between the two dyads. Moreover, we find that the dyad with the larger market share will invest more in sustainability-related R&D. This supports our observations from the aforementioned collaborative ventures; Nike shares more R&D with its smaller partner-competitors than the other way round, as does WalMart. Interestingly, despite the larger supply chains making greater R&D investments in collaborative alliances, we also find that smaller OEM's benefit more from horizontal collaboration. Therefore, the value of horizontal collaboration accrues to the participating firms at the detriment of society and the environment. We also find that the initial distribution of market shares between the two dyads impacts social and environmental implications; interestingly, these dimensions are most negatively affected when the two dyads are similarly sized.

We also perform a numerical analysis to better understand the impact of competitive intensity between dyads on the motivation for and implications of horizontal collaboration. Unlike the case of maximum competitive intensity (where the products sold by the two dyads are perfect substitutes for each other), we note that investment levels, and consequently, the social and environmental implications, can actually improve with horizontal collaboration when the intensity of compeititon between the two dyads is low. In particular, horizontal collaboration has particularly beneficial effects on the social and environmental impacts of horizontal collaboration when the two supply chains are similar in size. This is in contrast to our findings from the case of perfect competition, where horizontal collaboration between similarly sized supply chains resulted in particularly detrimental social and environmental implications. This suggests that competitive intensity and the sizes of competing supply chains are substitutes when it comes to spurring the best social and environmental implications from horizontal collaboration. We also observe that regardless of competitive intensity and the distribution of intrinsic market shares, OEM's prefer to collaborate with their competitiors. Horizontal collaboration benefits not just the OEM's but also their respective supply chains, and thus the entire industry. Thus, we find that while OEM's prefer to collaborate with their competitors, the impacts of horizontal collaboration on society and the environment depend on the competitive intensity and the initial distribution of market shares between the two dyads. The greatest benefits from such collaborative alliances are realized when the competing supply chains are similar in size and produce products that are more complements than substitutes. It is noteworthy that several of the major roundtables and sustainability-related collaborative alliances were founded by OEM's that provided complementary products and services. WalMart and Patagonia founded the Sustainable Apparel Coalition, and Intel and Google founded the Climate Savers Computing Initiative. Our analysis reveals that such alliances are more likely to have a positive impact from a 3BL perspective.

In closing, we acknowledge some limitations of our model and suggest potential extensions to our study. The demand form stipulated in the duopoly model is such that the overall size of the market is fixed, such that any market share gains to one firm come from an equivalent loss in its competitor's market share. This stipulation further assumes that the two firms produce otherwise identical and perfectly substitutable products. We relax this stipulation in a numerical section to gain insight into the role of competitive intensity on the motivations for and the implications of R&D collaboration. An analytical treatment of the same in a more parsimonius modeling framework could facilitate clearer insights. Secondly, we consider only non-collusive R&D collaboration between competing OEM's, where collaboration occurs through a spillover of R&D efforts between the two dyads. While we believe that joint non-competitive determination of R&D efforts by the two OEM's is not appropriate given our context of study, it could be a valuable extension to our model here. Similarly, it would be valuable to allow horizontally collaborating firms to determine their optimal levels of spillovers. One final extension we propose to pursue is to explore the role of regulatory bodies in incentivizing (disincentivizing) collaborative alliances through the use of subsidies (tariffs) so as to achieve the socially and environmentally optimal level of investment in sustainability-related R&D.

CHAPTER 5

CONCLUSION

For centuries, the finiteness of the earth's natural resources did not appear to place a binding constraint on the needs and aspirations of a small but growing human population. In the last few decades however, several fish stocks have been depleted beyond commercial viability, droughts and famines have rendered vast tracts of land unarable, global temperatures and instances of extreme weather events have been on the rise, and the availability and prices of minerals and other natural resources have become increasingly uncertain. Each of these environmental problems stem from four fundamental factors: 1) the earth and its resources that we depend on are finite, renewable or otherwise; 2) human population is increasing; 3) per-capita incomes are increasing; and 4) we have exerted little effort to mitigate this risk.

The combination of these four factors, as noted by Holdren and Ehrlich (1974) and described in Figure 1, is pushing us rapidly towards collapse. While factors 1-3 are virtually beyond our control, Holdren and Ehrlich (1974) identify the appropriate use of technology and markets as the manifestation of factor 4 that will allow us to mitigate this risk of collapse. However, technology and markets are merely tools to serve the goals of society as a whole. If society's implicit goals are to exploit nature and ignore the long term, then society will develop technologies and markets that destroy the environment, widen the gap between rich and poor, and optimize for short-term gain (Meadows et al., 2004).

Nevertheless, there are several steps being taken in the right direction by society today. Demand from a growing segment of conscious consumers has led firms to innovate and produce socially and environmentally benign products and adopt responsible business models, examples of which include recycling and remanufacturing, developing ethical and environmental criteria for supplier selection, a focus on cleaner and more efficient water, energy, and transportation etc. These changes would not have been possible if the traditional view of business as a tool to maximize profits, return on investments, and shareholder value had persisted. Several firms have now embraced a more holistic view, one that encompasses the needs and considerations of multiple stakeholders - the people, the planet, as well as profit. This framework, coined the 3BL (Elkington, 1998), has allowed firms like Interface, Patagonia, Nike, and WalMart to maintain a sustainable competitive advantage (Scott, 2012). This perspective is becoming mainstream and does not necessarily conflict with, but rather, complements the traditional economic interests of the firm (Kiron et al., 2012).

Firms' operational decisions determine the choice of production and distribution technologies, which in turn determine the efficiency of material, water, and energy use and disposal. From a more strategic perspective, business models and product-line decisions of firms impact patterns of consumption in society. Therefore, Operations Management can offer a vital sustainability perspective (Drake and Spinler, 2013). The current literature in Operations Management and related areas tackles sustainability in contexts ranging from reuse and remanufacturing (see Souza (2013) for a review of the literature on closed-loop supply chains) to socially and environmentally responsible products and business models (see, for example, Chen (2001); Agrawal et al. (2012); Lim et al. (2014)). This thesis contributes to this stream of literature by extending the application of a 3BL perspective to consider the role of technology, markets and regulation in the contexts of natural resource management, environmental quality competition, and pre-competitive collaboration for sustainability-related R&D.

The first essay considers the impact of markets on groundwater management from a societal, environmental, and economic perspective. Markets can have beneficial or detrimental impacts along these dimensions depending on the hydro-economic parameters of the system. This essay also explores the impact of privatizing the management of groundwater reservoirs and identifies conditions under which privatization can prove beneficial from a 3BL perspective. The second essay contributes to the literature on environmental quality competition by considering the role of external certification agencies in providing credible environmental labeling services for products with otherwise unobservable environmental characteristics. The key contribution of this essay is to contrast private and non-governmental ecolabeling schemes with respect to their impacts on producers, society, and the environment when producers are not fully credible and are asymmetric in their credibilities. In the third essay, I identify the motivation for pre-competitive collaboration for sustainability-related R&D within and across competing supply chains, as well as its impacts from a 3BL perspective.

There are several viable extensions to our work here. In the context of groundwater management, one stipulation made in the model is that the municipality's aquifer is hydrologically disconnected from other aquifers and water markets. If this stipulation were relaxed, a dynamic non-cooperative extraction and reallocation game would ensue between communities connected through a single groundwater source. Another potential extension to this essay and to the literature on closed-loop supply chains is to consider a community's problem of water recycling in conjunction with ground and surface water management, a new consideration in arid parts of the world (Monks, 2014).

The single-period model of ecolabeling in Chapter 3 can be extended to consider a multi-period game of credibility building by competing producers, wherein consumers update their information about a firm's credibility after observing a firm's environmental quality choice in previous stages. This model also assumes that producers only make truthful environmental quality claims. Therefore, a potential extension to this model is to consider information asymmetry where the producers signal their product's environmental qualities through prices or by acquiring costly external certification. This essay also focuses on the case of perfect competition between producers, i.e., when their products are perfect substitutes for each other, restricting the model to a zero-sum market share game. Relaxing this stipulation can provide insights into the role of competitive intensity in determining the consequences of ecolabeling and environmental quality competition.

The essay on pre-competitive R&D collaboration in Chapter 4 specifies exogenous levels of knowledge spillover from collaboration. Endogenizing the extent of R&D spillovers from horizontal collaboration is a natural extension to this model. The model of horizontal collaboration in Chapter 4 assumes that environmental investment levels are chosen competitively, with collaboration resulting from the creation of a pathway for transmission and spillover of R&D from one OEM to the other. While this modeling stipulation is appropriate to our context of study, the model can be extended by considering non-competitive joint-setting of environmental investment levels by collaborating OEM's.

Bibliography

Agrawal, Anupam, Luk N Van Wassenhove, Arnoud De Meyer. 2013. The sourcing hub and upstream supplier networks. *Manufacturing & Service Operations Management* **16**(2) 238–250.

Agrawal, Vishal V, Mark Ferguson, L Beril Toktay, Valerie M Thomas. 2012. Is leasing greener than selling? *Management Science* **58**(3) 523–533.

Albert, Angeline. 2010. Unilever sets sustainable sourcing target. URL `www.supplymanagement.com/news/2010/unilever-sets-sustainable-sourcing-target`.

Amacher, Gregory S, Erkki Koskela, Markku Ollikainen. 2004. Environmental quality competition and eco-labeling. *Journal of Environmental Economics and Management* **47**(2) 284–306.

Amir, Rabah, Igor Evstigneev, John Wooders. 2003. Noncooperative versus cooperative R&D with endogenous spillover rates. *Games and Economic Behavior* **42**(2) 183–207.

Anderson, R.C. 2009. *Confessions of a Radical Industrialist: Profits, People, Purpose - Doing Business by Respecting the Earth*. McClelland & Stewart, Toronto, Canada.

Ata, Baris, Deishin Lee, Mustafa H Tongarlak. 2012. Optimizing organic waste to energy operations. *Manufacturing & Service Operations Management* **14**(2) 231–244.

Atallah, Gamal. 2002. Vertical R&D spillovers, cooperation, market structure, and innovation. *Economics of Innovation and New Technology* **11**(3)

179–209.

Avci, Buket, Karan Girotra, Serguei Netessine. 2014. Electric vehicles with a battery switching station: Adoption and environmental impact. *Management Science* **61**(4) 772–794.

Bai, Chunguang, Joseph Sarkis. 2010. Integrating sustainability into supplier selection with grey system and rough set methodologies. *International Journal of Production Economics* **124**(1) 252–264.

Bakker, Karen. 2007. The commons versus the commodity: Alter-globalization, anti-privatization and the human right to water in the global south. *Antipode* **39** 430–455.

Baksi, Soham, Pinaki Bose. 2007. Credence goods, efficient labelling policies, and regulatory enforcement. *Environmental and Resource Economics* **37**(2) 411–430.

Balasubramanian, Karthik, David Drake. 2015. Mobile money: The effect of service quality and competition on demand. Working paper, Harvard Business School, Boston, MA.

Banker, Rajiv D, Inder Khosla, Kingshuk K Sinha. 1998. Quality and competition. *Management Science* **44**(9) 1179–1192.

Barlow, Maude, Tony Clarke. 2005. *Blue Gold: The Fight to Stop the Corporate Theft of the World's Water*. The New Press, New York, NY.

Ben Youssef, Adel, Chema Abderrazak. 2009. Multiplicity of eco-labels, competition, and the environment. *Journal of Agricultural & Food Industrial Organization* **7**(2) 1–24.

Berns, Maurice, Zayna Khayat, Balu Balagopal, Martin Reeves. 2009. The business of sustainability: what it means to managers now. Tech. rep.

Bernstein, Fernando, Fangruo Chen, Awi Federgruen. 2006. Coordinating supply chains with simple pricing schemes: the role of vendor-managed inventories. *Management Science* **52**(10) 1483–1492.

Bernstein, Jeffrey I, M Ishaq Nadiri. 1988. Interindustry R&D spillovers, rates of return, and production in high-tech industries. Tech. rep., National Bureau of Economic Research.

Bonini, Sheila. 2011. The business of sustainability. URL `www.mckinsey.com/insights/energy_resources_materials/the_business_of_sustainability_mckinsey_global_survey_results`.

Bottega, Lucie, Jenny De Freitas. 2009. Public, private and nonprofit regulation for environmental quality. *Journal of Economics & Management Strategy* **18**(1) 105–123.

Bottega, Lucie, Philippe Delacote, Lisette Ibanez. 2009. Labeling policies and market behavior: Quality standard and voluntary label adoption. *Journal of Agricultural & Food Industrial Organization* **7**(2) 1–18.

Boyce, W.E., R.C. DiPrima. 2001. *Elementary Differential Equations and Boundary Value Problems*. Wiley, New York, NY.

Brécard, Dorothée. 2014. Consumer confusion over the profusion of eco-labels: Lessons from a double differentiation model. *Resource and Energy Economics* **37** 64–84.

Bruggink, T. H. 1992. Privatization versus groundwater central management. *American Journal of Economics and Sociology* **51** 205–222.

Brundtland, Gru, Mansour Khalid, Susanna Agnelli, Sali Al-Athel, Bernard Chidzero, Lamina Fadika, Volker Hauff, Istvan Lang, Ma Shijun, Margarita Morino de Botero, et al. 1987. Our common future. Oxford University Press, Oxford, United Kingdom.

Burch, Stephen L. 2008. Development of an observation well network in the Mahomet aquifer of East Central Illinois. Tech. rep.

Burnett, William C, Henry Bokuniewicz, Markus Huettel, Willard S Moore, Makoto Taniguchi. 2003. Groundwater and pore water inputs to the coastal zone. *Biogeochemistry* **66**(1-2) 3–33.

Bustillo, Miguel. 2009. Wal-Mart to assign new 'green' ratings. URL `www.wsj.com/articles/SB124766892562645475`.

Cachon, Gérard P. 2003. Supply chain coordination with contracts. *Handbooks in operations research and management science* **11** 227–339.

Cachon, Gérard P, Martin A Lariviere. 2005. Supply chain coordination with revenue-sharing contracts: strengths and limitations. *Management science* **51**(1) 30–44.

Calatrava, Javier, Alberto Garrido. 2005. Spot water markets and risk in water supply. *Agricultural Economics* **33** 131–143.

Carmona, M. 2011. Eco-labels as signals: the role of credibility and reputation. *Innovative Marketing* **7** 116–124.

Castka, Pavel, Charles J Corbett. 2014. Governance of eco-labels: Expert opinion and media coverage. *Forthcoming in Journal of Business Ethics* .

Chen, Chialin. 2001. Design for the environment: a quality-based model for green product development. *Management Science* **47**(2) 250–263.

Chiang, A.C. 1992. *Elements of Dynamic Optimization*. McGraw-Hill, New York, NY.

Clark, Colin. 1990. *Mathematical Bioeconomics*. Wiley Interscience, New York, NY.

Clay, Jason. 2011a. Roundtables help solve problems on a global scale. URL `www.theguardian.com/sustainable-business/problem-solving-global-scale-roundtables-collaboration`.

Clay, Jason. 2011b. Smart companies see the imporance of collaboration. URL `www.theguardian.com/sustainable-business/smart-companies-collaboration-productivity-efficiency`.

Coleman, Pamela. 2012. Guide for organic crop producers. URL `www.ams.usda.gov/AMSv1.0/getfile?dDocName=STELPRDC5101542`.

Corbett, Charles J, Robert D Klassen. 2006. Extending the horizons: Environmental excellence as key to improving operations. *Manufacturing & Service Operations Management* **8** 5–22.

Craig, Anthony J, Edgar E Blanco, Yossi Sheffi. 2011. Competing on environmental quality: A model of product carbon labels. Working paper, MIT, Cambridge, MA.

d'Aspremont, Claude, Alexis Jacquemin. 1988. Cooperative and noncooperative R & D in duopoly with spillovers. *The American Economic Review* **80(3)** 1133–1137.

Dawande, Milind, Srinagesh Gavirneni, Mili Mehrotra, Vijay Mookerjee. 2013. Efficient distribution of water between head-reach and tail-end farms in developing countries. *Manufacturing & Service Operations Management* **15** 221–238.

Delmas, Magali. 2001. Stakeholders and competitive advantage: The case of ISO 14001. *Production and Operations Management* **10** 343–358.

Desai, Preyas, Sunder Kekre, Suresh Radhakrishnan, Kannan Srinivasan. 2001. Product differentiation and commonality in design: Balancing revenue and cost drivers. *Management Science* **47**(1) 37–51.

Dinar, Ariel, J Letey. 1991. Agricultural water marketing, allocative efficiency, and drainage reduction. *Journal of Environmental Economics and Management* **20** 210–223.

Donnan, Shawn. 2014. Jeans maker launches cheap financing for more ethical factories. URL `www.ft.com/intl/cms/s/0/a541bcb4-6417-11e4-8ade-00144feabdc0.html#axzz3clVX8flN`.

Drake, David F, Stefan Spinler. 2013. Sustainable operations management: An enduring stream or a passing fancy? *Manufacturing & Service Operations Management* **15**(4) 689–700.

D'Souza, Clare, Mehdi Taghian, Peter Lamb. 2006. An empirical study on the influence of environmental labels on consumers. *Corporate Communications: An International Journal* **11**(2) 162–173.

Elkington, John. 1998. Partnerships from cannibals with forks: The triple bottom line of 21st-century business. *Environmental Quality Management* **8** 37–51.

Espey, Molly, James Espey, W Douglass Shaw. 1997. Price elasticity of residential demand for water: A meta-analysis. *Water Resources Research* **33** 1369–1374.

Feinerman, Eli, Keith C Knapp. 1983. Benefits from groundwater management: Magnitude, sensitivity, and distribution. *American Journal of Agricultural Economics.* **65** 703–710.

Fischer, Carolyn, Thomas P Lyon. 2014. Competing environmental labels. *Journal of Economics & Management Strategy* **23**(3) 692–716.

Fractor, David T. 1988. Privatizing the groundwater resource. *Journal of the American Water Resources Association* **24** 405–412.

FTC. 2012. Guides for the use of environmental marketing claims ("green guides"). URL `www.ftc.gov/policy/federal-register-notices/guides-use-environmental-marketing-claims-green-guides`.

Fuller, JD, RG Vickson. 1987. The optimal timing of new plants for oil from the Alberta tar sands. *Operations Research* **35** 704–715.

Galarraga Gallastegui, Ibon. 2002. The use of eco-labels: A review of the literature. *European Environment* **12**(6) 316–331.

Galbreth, Michael R, Tamer Boyacı, Vedat Verter. 2013. Product reuse in innovative industries. *Production and Operations Management* **22**(4) 1011–1033.

Ghosh, Debabrata, Janat Shah. 2012. A comparative analysis of greening policies across supply chain structures. *International Journal of Production*

Economics **135**(2) 568–583.

Ghosh, Debabrata, Janat Shah. 2015. Supply chain analysis under green sensitive consumer demand and cost sharing contract. *International Journal of Production Economics* **164** 319–329.

Gisser, Micha, David A Sanchez. 1980. Competition versus optimal control in groundwater pumping. *Water Resources Research* **16** 638–642.

Gleick, Peter H. 2000. A look at twenty-first century water resources development. *Water International* **25** 127–138.

Gleick, Peter H, Heather Cooley. 2006. *The World's Water, 2006-2007*. Island Press, Washington, D.C.

Grabosky, Peter N. 1994. Green markets: Environmental regulation by the private sector. *Law & Policy* **16**(4) 419–448.

Grafton, R Quentin, Clay Landry, Gary D Libecap, Sam McGlennon, Robert O'Brien. 2010. An integrated assessment of water markets: Australia, chile, china, south africa and the usa. Tech. rep., National Bureau of Economic Research.

Gunther, M. 2012. Behind the scenes at the sustainable apparel coalition. URL `www.greenbiz.com/blog/2012/07/26/behind-scenes-sustainable-apparel-coalition`.

Gunther, M. 2013a. Millercoors: A trickle-down theory of corporate sustainability. URL `www.marcgunther.com/millercoors-a-trickle-down-theory-of-corporate-sustainability/`.

Gunther, Marc. 2013b. Walmart's index: This is big. really big. URL `www.marcgunther.com/walmarts-index-this-is-big-really-big/`.

Guo, Ruixie, H. L. Lee, Robert Swinney. 2015. Responsible sourcing in supply chains. *Forthcoming in Management Science* .

Gurnani, Haresh, Murat Erkoc. 2008. Supply contracts in manufacturer-retailer interactions with manufacturer-quality and retailer effort-induced demand. *Naval Research Logistics* **55**(3) 200–217.

Hanak, Ellen, Caitlin Dyckman. 2002. Counties wresting control: Local responses to California's statewide water market. *University of Denver Water Law Review* **6** 490–520.

Handfield, Robert, Steven V Walton, Robert Sroufe, Steven A Melnyk. 2002. Applying environmental criteria to supplier assessment: A study in the application of the analytical hierarchy process. *European Journal of Operational Research* **141**(1) 70–87.

Hanemann, W Michael. 1998. Determinants of Urban Water Use. *Urban Water Demand Management and Planning*. McGraw-Hill, New York, 31–75.

Hansen, Kristiana, Richard Howitt, Jeffrey Williams. 2008. Short-term leases or long-term transfers? An econometric test of water market structure in the Western United States. Working Paper, University of California, Davis.

Harbaugh, Rick, John W Maxwell, Beatrice Roussillon. 2011. Label confusion: The groucho effect of uncertain standards. *Management Science* **57**(9) 1512–1527.

Harou, Julien J, Manuel Pulido-Velazquez, David E Rosenberg, Josué Medellín-Azuara, Jay R Lund, Richard E Howitt. 2009. Hydro-economic models: Concepts, design, applications, and future prospects. *Journal of Hydrology* **375** 627–643.

Hart, Kelley J. 2008. The Mojave Desert as grounds for change: Clarifying property rights in California's groundwater to make extraction sustainable statewide. *West-Northwest Journal of Environmental Law Policy* **14** 1213–1703.

Hauter, W. 2012. Are we better off privatizing water? URL `online.wsj.com/article/SB10000872396390443816804578002280926253750.html`.

Holdren, John P, Paul R Ehrlich. 1974. Human population and the global environment: Population growth, rising per capita material consumption, and disruptive technologies have made civilization a global ecological force. *American Scientist* **62**(3) 282–292.

Holland, Stephen P. 2003. Set-up costs and the existence of competitive equilibrium when extraction capacity is limited. *Journal of Environmental Economics and Management* **46** 539–556.

Holland, Stephen P. 2006. Privatization of water-resource development. *Environmental and Resource Economics* **34** 291–315.

Horne, Ralph E. 2009. Limits to labels: The role of eco-labels in the assessment of product sustainability and routes to sustainable consumption. *International Journal of Consumer Studies* **33**(2) 175–182.

Hotelling, Harold. 1931. The economics of exhaustible resources. *Journal of Political Economy* **39** 137–175.

Howe, Charles W, Christopher Goemans. 2003. Water transfers and their impacts: Lessons from three Colorado water markets. *Journal of the American Water Resources Association* **39** 1055–1065.

Howe, Charles W, Dennis R Schurmeier, W Douglas Shaw. 1986. Innovative approaches to water allocation: The potential for water markets. *Water Resources Research* **22** 439–445.

Ibanez, Lisette, Gilles Grolleau. 2008. Can ecolabeling schemes preserve the environment? *Environmental and Resource Economics* **40**(2) 233–249.

Islegen, Özge, Stefan Reichelstein. 2011. Carbon capture by fossil fuel power plants: An economic analysis. *Management Science* **57**(1) 21–39.

Israel, Morris, Jay R Lund. 1995. Recent California water transfers: Implications for water management. *Natural Resources Journal* **35** 1–32.

Kaiser, Ronald A. 2005. *Solving the Texas Water Puzzle: Market-Based Allocation of Water*. Texas Public Policy Foundation, Austin, TX.

Kamien, M.I., N.L. Schwartz. 1991. *Dynamic Optimization: The Calculus of Variations and Optimal Control in Economics and Management*. Advanced Textbooks in Economics, North Holland, Amsterdam, Netherlands.

Kamien, Morton I, Eitan Muller, Israel Zang. 1992. Research joint ventures and R&D cartels. *The American Economic Review* 1293–1306.

Kenny, Joan F, Nancy L Barber, Susan S Hutson, Kristin S Linsey, John K Lovelace, Molly A Maupin. 2009. *Estimated use of water in the United States in 2005*. US Geological Survey Reston, VA.

Khanna, Madhu. 2001. Non-mandatory approaches to environmental protection. *Journal of economic surveys* **15**(3) 291–324.

Kim, Kilsun, Dilip Chhajed. 2002. Product design with multiple quality-type attributes. *Management Science* **48**(11) 1502–1511.

Kiron, David, Nina Kruschwitz, Knut Haanaes, Ingrid von Streng Velken. 2012. Sustainability nears a tipping point. *MIT Sloan Management Review* **53**(2) 69–74.

Klassen, Robert D, Curtis P McLaughlin. 1996. The impact of environmental management on firm performance. *Management Science* **42** 1199–1214.

Klassen, Robert D, Stephan Vachon. 2003. Collaboration and evaluation in the supply chain: The impact on plant-level environmental investment. *Production and Operations Management* **12**(3) 336–352.

Kleindorfer, Paul R, Kalyan Singhal, Luk N Wassenhove. 2005. Sustainable operations management. *Production and Operations Management* **14** 482–492.

Knapp, Keith C, Marca Weinberg, Richard Howitt, Judith F Posnikoff. 2003. Water transfers, agriculture, and groundwater management: A dynamic economic analysis. *Journal of Environmental Management* **67** 291–301.

Kolk, Ans. 2008. Sustainability, accountability and corporate governance: exploring multinationals' reporting practices. *Business Strategy and the Environment* **17**(1) 1–15.

Konikow, Leonard F, Eloise Kendy. 2005. Groundwater depletion: A global problem. *Hydrogeology Journal* **13**(1) 317–320.

Kraft, Tim, Feryal Erhun, Robert C Carlson, Dariush Rafinejad. 2013a. Replacement decisions for potentially hazardous substances. *Production and Operations Management* **22**(4) 958–975.

Kraft, Tim, Gal Raz. 2014. Competing on toxicity: The impact of supplier prices and regulation on manufacturers' substance replacement strategies. Working Paper, Darden Business School, Charlottesville, VA.

Kraft, Tim, Yanchong Zheng, Feryal Erhun. 2013b. The ngo's dilemma: how to influence firms to replace a potentially hazardous substance. *Manufacturing & Service Operations Management* **15**(4) 649–669.

Krulce, Darrell, James A. Roumasset, Tom Wilson. 1997. Optimal management of a renewable and replaceable resource: The case of coastal groundwater. *American Journal of Agricultural Economics* **79** 1218–1228.

Leire, Charlotte, Åke Thidell. 2005. Product-related environmental information to guide consumer purchases–a review and analysis of research on perceptions, understanding and use among nordic consumers. *Journal of Cleaner Production* **13**(10) 1061–1070.

Li, George, Sampath Rajagopalan. 1998. Process improvement, quality, and learning effects. *Management Science* **44**(11) 1517–1532.

Lim, Michael K, Ho-Yin Mak, Ying Rong. 2014. Toward mass adoption of electric vehicles: Impact of the range and resale anxieties. *Manufacturing & Service Operations Management* **17**(1) 101–119.

Majumder, Pranab, Ashok Srinivasan. 2008. Leadership and competition in network supply chains. *Management Science* **54**(6) 1189–1204.

Mangasarian, O. 1966. Sufficient conditions for the optimal control of nonlinear systems. *SIAM Journal on Control* **4** 139–152.

Mason, Charles F. 2006. An economic model of ecolabeling. *Environmental Modeling & Assessment* **11**(2) 131–143.

Matsubayashi, Nobuo. 2007. Price and quality competition: The effect of differentiation and vertical integration. *European Journal of Operational Research* **180**(2) 907–921.

Mazzoni, Mary. 2014. The higg 2.0 index and the journey to an industry-wide sustainable apparel standard. URL `http://www.triplepundit.com/special/sustainable-fashion-2014/higg-2-0-index`.

Meadows, D.H., J. Randers, D.L. Meadows. 2004. *The Limits to Growth: The 30-Year Update*. Chelsea Green Publishers, Burlington, VT.

Meinzen-Dick, Ruth S. 1998. Groundwater markets in Pakistan: Institutional development and productivity impacts. *Markets for Water*. Springer, 207–222.

Melnyk, Steven A, Robert P Sroufe, Roger Calantone. 2003. Assessing the impact of environmental management systems on corporate and environmental performance. *Journal of Operations Management* **21** 329–351.

Monks, Kieron. 2014. From toilet to tap: Getting a taste for drinking recycled water. URL `www.cnn.com/2014/05/01/world/from-toilet-to-tap-water/`.

Moon, Wanki, Wojciech J Florkowski, Bernhard Brückner, Ilona Schonhof. 2002. Willingness to pay for environmental practices: implications for eco-labeling. *Land Economics* **78**(1) 88–102.

Moorthy, K Sridhar, Ivan PL Png. 1992. Market segmentation, cannibalization, and the timing of product introductions. *Management Science* **38**(3) 345–359.

Mussa, Michael, Sherwin Rosen. 1978. Monopoly and product quality. *Journal of Economic theory* **18**(2) 301–317.

Natural Resources Defense Council. 2010. Climate change, water, and risk. URL `www.nrdc.org/globalwarming/watersustainability/files/WaterRisk.pdf`.

NCEE. 2004. International experiences with economic incentives for protecting the environment. Tech. rep., US EPA.

O'Connor, Dennis. 1998. *Governance of the Metropolitan Water District of Southern California: Options for Change*. California Research Bureau, California State Library.

Pagell, Mark, Zhaohui Wu, Michael E Wasserman. 2010. Thinking differently about purchasing portfolios: an assessment of sustainable sourcing. *Journal of Supply Chain Management* **46**(1) 57–73.

Plambeck, Erica L, L Denend. 2008. Wal-mart. *Stanford Social Innovation Review* **6**(2) 53–59.

Pongkijvorasin, Sittidaj, James Roumasset, Thomas Kaeo Duarte, Kimberly Burnett. 2010. Renewable resource management with stock externalities: Coastal aquifers and submarine groundwater discharge. *Resource and Energy Economics* **32** 277–291.

Porter, Michael E, Claas Van der Linde. 1995. Green and competitive: ending the stalemate. *Harvard business review* **73**(5) 120–134.

Rhodes, Margaret. 2013. Nike launches a new app to help designers choose green materials. URL `www.fastcodesign.com/1672949/`.

Roumasset, James A, Christopher A Wada. 2012. Ordering the extraction of renewable resources: The case of multiple aquifers. *Resource and Energy Economics* **34**(1) 112–128.

Saleh, Yahya, Ülkü Gürler, Emre Berk. 2011. Centralized and decentralized management of groundwater with multiple users. *European Journal of*

Operational Research **215** 244–256.

Saleth, R Maria. 1998. Water markets in India: Economic and institutional aspects. *Markets for Water*. Springer, 187–205.

Saliba, Bonnie Colby, David B Bush, William E Martin, Thomas C Brown. 1987. Do water market prices appropriately measure water values. *Journal of Natural Resources* **27** 617–651.

Savaskan, R Canan, Shantanu Bhattacharya, Luk N Van Wassenhove. 2004. Closed-loop supply chain models with product remanufacturing. *Management science* **50**(2) 239–252.

Savaskan, R Canan, Luk N Van Wassenhove. 2006. Reverse channel design: the case of competing retailers. *Management Science* **52**(1) 1–14.

Schwartz, Ariel. 2010. Sustanability faceoff: Walmart vs. target. URL `www.fastcompany.com/1634995/sustainability-faceoff-walmart-vs-target`.

Scott, Ryan. 2012. The bottom line of corporate good. URL `www.forbes.com/sites/causeintegration/2012/09/14/the-bottom-line-of-corporate-good/`.

Sethi, Suresh, Gerhard Sorger. 1990. An exercise in modelling of consumption, import and export of an exhaustible resource. *Optimal Control Applications and Methods* **11** 191–196.

Shimomura, K. 1983. On the optimal order of exploitation of deposits of a renewable resource. *Journal of Institutional and Theoretical Economics* **139** 319–322.

Sinha, Deepak K, Michael A Cusumano. 1991. Complementary resources and cooperative research: a model of research joint ventures among competitors. *Management Science* **37**(9) 1091–1106.

Sinn, Hans-Werner. 2008. Public policies against global warming: A supply side approach. *International Tax and Public Finance* **15** 360–394.

Slade, Raymond M, Michael E Dorsey, Sheree L Stewart. 1986. *Hydrology and water quality of the Edwards Aquifer associated with Barton Springs in the Austin area, Texas*. US Department of the Interior, Geological Survey.

Sodhi, ManMohan S, Christopher S Tang. 2011. Social enterprises as supply-chain enablers for the poor. *Socio-Economic Planning Sciences* **45**(4) 146–153.

Souza, Gilvan C. 2013. Closed-loop supply chains: A critical review, and future research*. *Decision Sciences* **44**(1) 7–38.

Stevenson, Seth. 2012. Patagonia's founder is america's most unlikely business guru. URL `www.wsj.com/articles/SB10001424052702303513404577352221465986612`.

Swami, Sanjeev, Janat Shah. 2012. Channel coordination in green supply chain management. *Journal of the Operational Research Society* **64**(3) 336–351.

Tang, Christopher S., Sean Zhou. 2012. Research advances in environmentally and socially sustainable operations. *European Journal of Operational Research* **223** 585 – 594.

Teisl, Mario F. 2003. What we may have is a failure to communicate: Labeling environmentally certified forest products. *Forest Science* **49**(5) 668–680.

Tsay, Andy A, Narendra Agrawal. 2000. Channel dynamics under price and service competition. *Manufacturing & Service Operations Management* **2**(4) 372–391.

Tsur, Yacov, Theodore Graham-Tomasi. 1991. The buffer value of groundwater with stochastic surface water supplies. *Journal of Environmental Economics and Management* **21** 201–224.

Tully, Shawn. 2000. Water, water everywhere. URL `money.cnn.com/magazines/fortune/fortune_archive/2000/05/15/279789/`.

Tully, Stephanie M, Russell S Winer. 2014. The role of the beneficiary in willingness to pay for socially responsible products: a meta-analysis. *Journal of Retailing* **90**(2) 255–274.

UTL. 2011. Opposing the signing of the Utah-Nevada agreement on the Snake Valley groundwater management system. URL `www.goshutewater.org/index.php/june-utl-resolution.html`.

Vachon, Stephan, Robert D Klassen. 2008. Environmental management and manufacturing performance: the role of collaboration in the supply chain. *International journal of production economics* **111**(2) 299–315.

Vaux, Henry J, Richard E Howitt. 1984. Managing water scarcity: An evaluation of interregional transfers. *Water Resources Research* **20** 785–792.

Wang, X., M. K. Lim, Y. Ouyang. 2015. Food, energy, and environment trilemma: Sustainable farmland use and biofuel industry development. Working paper, University of Illinois - Urbana Champaign, Champaign, IL.

Weber, Gregory S. 1994. Twenty years of local groundwater export legislation in california: Lessons from a patchwork quilt. *Natural Resources Journal* **34** 657–750.

Weinberg, Marca, Catherine L Kling, James E Wilen. 1993. Water markets and water quality. *American Journal of Agricultural Economics* **75** 278–291.

Xu, Ying, Soo-Haeng Cho, Sridhar R Tayur. 2015. Combating child labor: Incentives and information transparency in global supply chains. Working Paper, Tepper School of Business, Carnegie Mellon University, Pittsburgh, PA.

Yoskowitz, David W. 1999. Spot market for water along the Texas Rio Grande: Opportunities for water management. *Natural Resources Journal* **39** 345–355.

Youssef, Adel Ben, Rim Lahmandi-Ayed. 2008. Eco-labelling, competition and environment: Endogenization of labelling criteria. *Environmental and Resource Economics* **41**(2) 133–154.

Zektser, S, HA Loaiciga, JT Wolf. 2005. Environmental impacts of groundwater overdraft: Selected case studies in the Southwestern United States. *Environmental Geology* **47** 396–404.

Appendix A (Chapter 2)

A1: The Centralized Management and Investment Problems

The centralized planner's problem

A centralized planner determines how much water to sell in each of the municipalities, l_j^{cp} and l_k^{cp}, and how much to extract from the aquifer in either municipality, q_j^{cp} and q_k^{cp}. The objective of the central planner is to maximize total welfare across both municipalities. We drop the time subscript for convenience. The formulation is as follows:

$$\begin{aligned}
(5.0.1) \qquad & \underset{l_j^{cp},\, l_k^{cp},\, q_j^{cp},\, q_k^{cp}}{\text{maximize}} \int_0^\infty e^{-\delta t}\Big[\int_0^{l_j^{cp}} (a-bu)du + \int_0^{l_k^{cp}} (a-bu)du \\
& \qquad - c_j(x_j)q_j^{cp} - c_k(x_k)q_k^{cp}\Big]dt, \\
& \text{Subject to} \frac{dx_j}{dt} = G_j(x_j) - q_j^{cp}, \\
& \frac{dx_k}{dt} = G_k(x_k) - q_k^{cp}, \\
& l_j^{cp},\, l_k^{cp},\, q_j^{cp},\, q_k^{cp},\, x_j,\, x_k \geq 0, \\
& l_j^{cp} + l_k^{cp} = q_j^{cp} + q_k^{cp}.
\end{aligned}$$

The constraint $l_j^{cp} + l_k^{cp} = q_j^{cp} + q_k^{cp}$ stipulates that all water extracted must be sold in the two municipalities. We apply the maximum principle to solve (5.0.1). The Hamiltonian is $H^{c.v} = al_j^{cp} - \frac{b}{2}l_j^{cp2} + al_k^{cp} - \frac{b}{2}l_k^{cp2} - c_j(x_j)q_j^{cp} - c_k(x_k)q_k^{cp} + \lambda_j^{cp}(G_j(x_j) - q_j^{cp}) + \lambda_k^{cp}(G_k(x_k) - q_k^{cp}) + \mu(q_j^{cp} + q_k^{cp} -$

$l_j^{cp} - l_k^{cp}$), where μ is a Lagrange multiplier associated with the aforementioned constraint. The unique solution is described by the following optimality conditions:

$$\frac{\partial H^{c.v}}{\partial l_j^{cp}} = a - b l_j^{cp} - \mu \leq 0 \text{ and } l_j^{cp}(a - b l_j^{cp} - \mu) = 0, \tag{5.0.2}$$

$$\frac{\partial H^{c.v}}{\partial l_k^{cp}} = a - b l_k^{cp} - \mu \leq 0 \text{ and } l_k^{cp}(a - b l_k^{cp} - \mu) = 0, \tag{5.0.3}$$

$$\frac{\partial H^{c.v}}{\partial q_j^{cp}} = \mu - c_j(x_j) - \lambda_j^{cp} \leq 0 \text{ and } q_j^{cp}(\mu - c_j(x_j) - \lambda_j^{cp}) = 0, \tag{5.0.4}$$

$$\frac{\partial H^{c.v}}{\partial q_k^{cp}} = \mu - c_k(x_k) - \lambda_k^{cp} \leq 0 \text{ and } q_k^{cp}(\mu - c_k(x_k) - \lambda_k^{cp}) = 0, \tag{5.0.5}$$

$$\frac{d\lambda_j^{cp}}{dt} - \delta\lambda_j^{cp} = -\frac{\partial H^{c.v}}{\partial x_j} = c'(x_j) q_j^{cp} - G'(x_j)\lambda_j^{cp}, \tag{5.0.6}$$

$$\frac{d\lambda_k^{cp}}{dt} - \delta\lambda_k^{cp} = -\frac{\partial H^{c.v}}{\partial x_k} = c'(x_k) q_k^{cp} - G'(x_k)\lambda_k^{cp}, \tag{5.0.7}$$

$$\frac{dx_j}{dt} = G_j(x_j) - q_j^{cp}, \tag{5.0.8}$$

$$\frac{dx_k}{dt} = G_k(x_k) - q_k^{cp}, \tag{5.0.9}$$

$$l_j^{cp} + l_k^{cp} = q_j^{cp} + q_k^{cp}, \tag{5.0.10}$$

$$l_j^{cp},\ l_k^{cp},\ q_j^{cp},\ q_k^{cp},\ x_j,\ x_k,\ \lambda_j^{cp},\ \lambda_k^{cp} \geq 0. \tag{5.0.11}$$

The investment problem

We consider the investment problem in (2.4.2) for a privatized municipality. The non-privatized variant of this problem follows by analogy and is hence omitted. The current-value Hamiltonian and optimality conditions follow as in the other problem formulations. For analytical convenience, we substitute $\bar{q}_t$ for $\bar{l}_t$ throughout. We state three new optimality conditions associated with the three decision variables unique to this problem:

$$\frac{\partial H^{c.v}}{\partial \bar{w}_t} = a - 2b(\bar{q}_t + \bar{w}_t + \bar{i}_t - \bar{e}_t) - c_w - \bar{\sigma}_t \leq 0 \text{ and} \tag{5.0.12}$$

$$\bar{w}_t(a - 2b(\bar{q}_t + \bar{w}_t + \bar{i}_t - \bar{e}_t) - c_w - \bar{\sigma}_t) = 0,$$

$$\frac{\partial H^{c.v}}{\partial \bar{W}} = 0 \Rightarrow F'(\bar{W}) = \int_0^{\infty} e^{-\delta t} \bar{\sigma}_{t+\bar{\tau}} dt, \tag{5.0.13}$$

where $\bar{\sigma}_t$ is a Lagrange multiplier associated with the capacity constraint. To compute the optimal time of investment, we note that while the price path and hence the path of the total quantity of water sold within the municipality is continuous, the extraction path may not be continuous when the capacity investment is made and water production begins (Holland, 2006). Therefore, we define $\bar{q}_{\bar{\tau}-}$ and $\bar{q}_{\bar{\tau}+}$ as the limits of the extraction path just before and after water production begins. The optimality condition for investment timing can now be stated as:

$$\begin{aligned} & a(\bar{q}_{\bar{\tau}-} + \bar{w}_t + \bar{i}_t - \bar{e}_t) - b(\bar{q}_{\bar{\tau}-} + \bar{w}_t + \bar{i}_t - \bar{e}_t)^2 + s(\bar{e}_t - \bar{i}_t) \\ & - (c(\bar{x}_t) + \bar{\lambda}_t)\bar{q}_{\bar{\tau}-} + \delta F(\bar{W}) = a(\bar{q}_{\bar{\tau}+} + \bar{w}_t + \bar{i}_t - \bar{e}_t) \\ & - b(\bar{q}_{\bar{\tau}+} + \bar{w}_t + \bar{i}_t - \bar{e}_t)^2 + s(\bar{e}_t - \bar{i}_t) - (c(\bar{x}_t) + \bar{\lambda}_t)\bar{q}_{\bar{\tau}+} - c_w \bar{w}_t. \end{aligned} \tag{5.0.14}$$

A2: Proofs

PROOF. **Lemma 2.1:** For part (a), from (2.3.3) and (2.3.8), $l_t^o > 0 \Rightarrow \lambda_t^o = a - bl_t^o - c(x_t) \geq 0$. For part (b), substituting for λ_t^o in (2.3.6), we get $\frac{dl_t^o}{dt} = \frac{(G'(x_t)-\delta)}{b}[a - bl_t^o - c(x_t) - \frac{c'(x_t)G(x_t)}{G'(x_t)-\delta}]$, where $\kappa(x) := c(x) + \frac{c'(x)G(x)}{G'(x)-\delta}$. From (2.3.7), $\frac{dx_t}{dt} = G(x_t) - l_t^o - e_t^o$ where $e_t^o = 0$ for all t by definition in the benchmark solution. The system of differential equations $\frac{dl_t^o}{dt}$ and $\frac{dx_t}{dt}$ along with the initial condition x_0 have a unique solution (Boyce and DiPrima, 2001). For part (c), applying steady-state conditions to this system, $\frac{dl_t^o}{dt} = \frac{dx_t}{dt} = 0$, we have $l_{ss}^o = \frac{(a-\kappa(x_{ss}^o))}{b}$ and $x_{ss}^o = G^{-1}(\frac{(a-\kappa(x_{ss}^o))}{b})$. To show that $\frac{ds^o(x)}{dx} < 0$, we first claim that $\frac{dl^o(x)}{dx} > 0$. We see that $\frac{dl^o(x)}{dx} = \frac{\frac{(G'(x_t)-\delta)}{b}[a-bl_t^o-\kappa(x_t)]}{G(x_t)-l_t^o}$, where $a - bl_t^o - \kappa(x_t)$ and $G(x_t) - l_t^o$ must move in opposite directions to approach steady-state (this system has a saddle-point steady-state which can be approached only along one separatrix (Boyce and DiPrima, 2001)). Therefore, $\frac{ds^o(x)}{dx} = -b\frac{dl^o(x)}{dx} < 0$.

$\square$

PROOF. **Proposition 2.1:** For part (a), first note from assumption (iii) and (2.3.3) that $a - bl_t^*(x_t) = c(x_t) + \lambda_t^*(x_t)$. By substituting $z_t = e_t - i_t$ in (2.3.1), note that conditions (2.3.4) and (2.3.5) can be replaced by $s - c(x_t) - \lambda_t = 0$ and $z_t(s - c(x_t) - \lambda_t) = 0$. For optimality, $a - bl_t^*(x_t) = c(x_t) + \lambda_t^*(x_t) = s$, i.e., $l_t^*(x_t) = \frac{a-s}{b}$. Additionally, substituting for $\lambda_t^*(x_t) = s - c(x_t)$ in (2.3.6), we get $x_t^* = \kappa^{-1}(s)$. Therefore, the unique z_t^* that solves the optimality conditions (2.3.3)-(2.3.8) must satisfy the hydrodynamic constraint at time t, $z_t^*(x_t) = x_t^* - x_t - G(x_t) - l_t^*(x_t)$, i.e., $z_t^*(x_t) = \kappa^{-1}(s) - x_t - G(x_t) - \frac{a-s}{b}$. From the constraint $e_t i_t = 0$, we thus have $e_t^*(x_t) = \text{Max}[z_t^*, 0] = x_t - \kappa^{-1}(s) + G(x_t) - \frac{a-s}{b} \geq 0$ when

$x_t \geq \kappa^{-1}(s)$ and $i_t^*(x_t) = |\text{Min}[z_t^*, 0]| = \kappa^{-1}(s) - x_t - G(x_t) + \frac{a-s}{b} > 0$ when $x_t < \kappa^{-1}(s)$.

For part (b), note that setting (2.3.7) to zero for steady-state gives $z_{ss}^* = G(x_{ss}^*) - l_{ss}^* = G(\kappa^{-1}(s)) - \frac{a-s}{b}$, where $e_{ss}^* = \text{Max}[z_{ss}^*, 0] = G(\kappa^{-1}(s)) - \frac{a-s}{b}$ when $x_{ss}^o \geq x_{ss}^* = \kappa^{-1}(s)$, i.e., $s^o(x_{ss}^o) \leq s$, and $i_{ss}^* = |\text{Min}[z_{ss}^*, 0]| = \frac{a-s}{b} - G(\kappa^{-1}(s))$ when $x_{ss}^o < x_{ss}^* = \kappa^{-1}(s)$, i.e., $s^o(x_{ss}^o) > s$.

□

PROOF. **Proposition 2.2:** (a) Without loss of generality, assume that j is the exporter. The Nash equilibrium is obtained by equating the supply and demand curves $q_{jss}(s) = \frac{a-s}{b} - G_j(\kappa_j^{-1}(s))$ to $q_{kss}(s) = G_k(\kappa_k^{-1}(s)) - \frac{a-s}{b} \Rightarrow a = s + \frac{b}{2}\left[G_j(\kappa_j^{-1}(s)) + G_k(\kappa_k^{-1}(s))\right]$. This admits a unique solution $\tilde{s} \in (s_j^o(x_{jss}^o) \wedge s_k^o(x_{kss}^o),\ s_j^o(x_{jss}^o) \vee s_k^o(x_{kss}^o))$. To prove that this is indeed the Nash equilibrium, we show that it is not optimal for either the importer or exporter to deviate unilaterally from this price. Dividing the range of prices into $s < \tilde{s}$ and $s > \tilde{s}$, we first show that it is never optimal for the exporter to deviate. For all prices s, the traded quantity is given by $\min[q_{jss}(s),\ q_{kss}(s)]$. When $s < \tilde{s}$, from Proposition 2.1(b), the traded quantity is $q_{jss}(s) = G_j(\kappa_j^{-1}(s)) - \frac{a-s}{b} < q_{kss}(s)$ since $\frac{dq_{jss}(s)}{ds} > 0$ and $\frac{dq_{kss}(s)}{ds} < 0$. Therefore, the equilibrium welfare of the exporter is $\Pi_{jss} = (\frac{a-s}{b})(s + \frac{b}{2}(\frac{a-s}{b})) + s(G_j(\kappa_j^{-1}(s)) - \frac{a-s}{b}) - c(\kappa_j^{-1}(s))G_j(\kappa_j^{-1}(s))$. Taking the derivative, we get $\frac{\partial \Pi_{jss}}{\partial s} = \frac{\partial \kappa_j^{-1}(s)}{\partial s}(s - c_j(\kappa_j^{-1}(s)) - \frac{c_j'(\kappa_j^{-1}(s))G_j(\kappa_j^{-1}(s))}{G_j'(\kappa_j^{-1}(s))})G_j'(\kappa_j^{-1}(s)) + G_j(\kappa_j^{-1}(s)) - \frac{a-s}{b} > 0$, where the sign of the derivative can be verified from Proposition 2.1. When $s > \tilde{s}$, from Proposition 2.1(b), the traded quantity is $q_{kss}(s) = \frac{a-s}{b} - G_k(\kappa_k^{-1}(s)) < q_{jss}(s)$. It can be shown that the steady-state condition $\tilde{x}_{jss}$ for the constrained export problem solves $\kappa_j(x) = a - b(G_k(\kappa_k^{-1}(s)) + G_j(x)) - s$, such that $\frac{\partial \tilde{x}_{jss}}{\partial s} > 0$. The equilibrium welfare of the exporter is given by $\Pi_{jss} = (\frac{a-\kappa_j(\tilde{x}_{jss})}{b})(\kappa_j(\tilde{x}_{jss}) + \frac{b}{2}(\frac{a-\kappa_j(\tilde{x}_{jss})}{b})) +$

$s(\frac{a-s}{b} - G_k(\kappa_k^{-1}(s))) - c_j(\tilde{x}_{jss})G_j(\tilde{x}_{jss})$. The derivative with respect to s is $\frac{\partial \Pi_{jss}}{\partial s} = \frac{a-2s-\kappa_j(\tilde{x}_{jss})\kappa_j'(\tilde{x}_{jss})\frac{\partial \tilde{x}_{jss}}{\partial s}}{b} - G_k(\kappa_k^{-1}(s)) - \frac{\partial \tilde{x}_{jss}}{\partial s}(c_j'(\tilde{x}_{jss})G_j(\tilde{x}_{jss}) + c_j(\tilde{x}_{jss})G_j'(\tilde{x}_{jss})) - s\frac{\partial G_k(\kappa_k^{-1}(s))}{\partial s} < 0$. Therefore, since $\frac{\partial \Pi_{jss}}{\partial s} > 0$ when $s < \tilde{s}$ and $\frac{\partial \Pi_{jss}}{\partial s} < 0$ when $s > \tilde{s}$, it is never optimal for the exporter to deviate from $\tilde{s}$. Repeating a similar analysis for the importer reveals that it is not optimal for the importer to deviate from $\tilde{s}$. For part (b), observe that $\frac{\partial \tilde{s}}{\partial a} = -\frac{\frac{\partial \Psi}{\partial a}}{\frac{\partial \Psi}{\partial s}} = \frac{2/b}{(2/b)+G_j'x_j'(s)+G_k'x_k'(s)} > 0$ where $\Psi = a - s - \frac{b}{2}\left[G_j(\kappa_j^{-1}(s)) + G_k(\kappa_k^{-1}(s))\right]$. Similarly, $\frac{\partial \tilde{s}}{\partial b} = -\frac{\frac{\partial \Psi}{\partial b}}{\frac{\partial \Psi}{\partial s}} = \frac{-2(a-s)/b^2}{(2/b)+G_j'x_j'(s)+G_k'x_k'(s)} < 0$. Part (c) follows from the proof of part (b) and Proposition 2.1(b).

□

PROOF. **Proposition 2.3:** We now characterize the solution described by (5.0.2)-(5.0.11). We extend assumption (iii) to the central planner's problem by imposing the condition l_j^{cp}, $l_k^{cp} > 0$ for all t. From (5.0.2) and (5.0.3), this implies that $l_j^{cp} = l_k^{cp}$ for all t. Moreover, from our modeling assumptions that $c(K) = G(K) = 0$ for both aquifers, $l_j^{cp} + l_k^{cp} > 0 \Rightarrow q_j^{cp}$, $q_k^{cp} > 0$ for all t by (5.0.10). From (5.0.4) and (5.0.5), this implies that $c_j(x_j) + \lambda_j^{cp} = c_k(x_k) + \lambda_k^{cp}$ for all t. Substituting for $\lambda_j^{cp}$and λ_k^{cp} into (5.0.6) and (5.0.7) respectively gives us differential equations that describe the evolution of l_j^{cp} and l_k^{cp}. Setting $\frac{dl_j^{cp}}{dt} = \frac{dl_k^{cp}}{dt} = 0$ gives us the steady-state quantities $l_{jss}^{cp} = l_{kss}^{cp} = l_{ss}^{cp} = \frac{a-\kappa_j(x_{jss}^{cp})}{b} = \frac{a-\kappa_k(x_{kss}^{cp})}{b}$, where we define $s^{cp} = \kappa_j(x_{jss}^{cp}) = \kappa_k(x_{kss}^{cp})$. Setting (5.0.8) and (5.0.9) equal to zero at steady-state and adding them, along with (5.0.10), gives us the following equation that is uniquely solved by s^{cp}: $G_j(x_j(s)) + G_k(x_k(s)) = \frac{2(a-s)}{b}$. Note that this equation is identical to the equation whose unique solution $\tilde{s}$ solves the fixed quantity trading equilibrium in Proposition 2.2(a). This equation has a unique solution, therefore, $s^{cp} = \tilde{s}$. From the monotonicity of $\kappa_j(x)$,

$\kappa_k(x)$, $G_j(x)$ and $G_k(x)$, it follows that $x^{cp}_{jss} = \tilde{x}_{jss}$, $x^{cp}_{kss} = \tilde{x}_{kss}$, $l^{cp}_{jss} = \tilde{l}_{jss}$ and $l^{cp}_{kss} = \tilde{l}_{kss}$.

$\square$

PROOF. **Proposition 2.4:** For the profit-maximizing exporter, $H^{c.v} = a\bar{l}_t - b\bar{l}^2_t + s(\bar{e}_t - \bar{i}_t) - c(\bar{x}_t)(\bar{l}_t + \bar{e}_t - \bar{i}_t) + \bar{\lambda}_t(G(\bar{x}_t) - (\bar{l}_t + \bar{e}_t - \bar{i}_t))$. The rest of the proof follows by analogy with the proof of Proposition 2.1, with $2b$ replacing b in the solution.

For part (a), we begin by showing that $\bar{s}^o(\bar{x}^o_{ss}) < s^o(x^o_{ss})$. It can be shown that if $l^o(\bar{x}^o_{ss}) < 2\bar{l}^o_{ss}$; then it is also true for all t (Boyce and DiPrima, 2001). From the optimal paths $l^o(x_t)$ and $\bar{l}^o(x_t)$ from Lemma 2.1 and its counterpart for the privatized municipality, note that at $\bar{x}^o_{ss}$, $l^o(\bar{x}^o_{ss}) < 2\bar{l}^o_{ss} = \frac{a-\kappa(\bar{x}^o_{ss})}{2b}$, which implies that $l^o(x_t) < 2\bar{l}^o(x_t)$ must be true for all t. Therefore, $\bar{s}^o(x_t) = a - 2b\bar{l}^o(x_t) < a - bl^o(x_t) = s^o(x_t)$ for all t, and hence $\bar{s}^o(\bar{x}^o_{ss}) < s^o(x^o_{ss})$ for $t \geq T$. For part (b), from Proposition 2.1 and its analog for the privatized municipality, we have $\bar{l}^*_t = \frac{a-s}{2b} < \frac{a-s}{b} = l^*_t$ for all t and any price s in the water market. For the rest of part (b) and part (c), note that from part (a), Proposition 2.1 and its analog for the privatized municipality, it follows that $\bar{e}^*_t(x_t) \geq e^*_t(x_t)$ and $\bar{i}^*_t(x_t) \leq i^*_t(x_t)$. In addition, $\bar{x}^*_{ss} = x^*_{ss} = \kappa^{-1}(s)$, and $\bar{q}^*(\bar{x}^*_{ss}) = q^*(x^*_{ss})$.

$\square$

PROOF. **Proposition 2.5:** Part (a) follows by analogy with the proof of Proposition 2.2(a) after noting that when a privatized municipality trades with a non-privatized municipality, the corresponding equation uniquely solved by $\tilde{s}_{wp}$ is $a = s + \frac{2b}{3}\left[G_j(\kappa_j^{-1}(s)) + G_k(\kappa_k^{-1}(s))\right]$, and when two privatized municipalities trade, $\tilde{s}_{pp}$ solves $a = s + b\left[G_j(\kappa_j^{-1}(s)) + G_k(\kappa_k^{-1}(s))\right]$.

We define the expression $\theta(\omega,\ s,\ a,\ b)$: $= s + \omega b \left[G_j(\kappa_j^{-1}(s)) + G_k(\kappa_k^{-1}(s)) \right] - a$, whose root $\tilde{s}$ is decreasing in ω from our assumptions on $G_j(x)$ and $G_k(x)$, therefore, $\tilde{s}_{ww} > \tilde{s}_{wp} > \tilde{s}_{pp}$. The effects on $\tilde{l}$ and $\tilde{x}$ follow from Proposition 2.1(b) and its counterpart for the privatized municipality. The proof of 5(b) follows directly from the proof of 2(b).

$\square$

PROOF. **Proposition 2.6:** To see the impact of export bans on Proposition 2.1, let $e_t = 0$ for all t in (2.3.1). There are two cases to consider for a given $x_t \geq \kappa^{-1}(s)$. If $s \geq s^o(x_t)$, assume that $i_t^*(x_t) = 0$ solves (2.3.1). Plugging $i_t^*(x_t) = 0$ in the optimality conditions returns the benchmark solution from Lemma 2.1 which admits a unique solution $q_t^*(x_t) = q^o(x_t)$. Therefore, insomuch as $c(x_t) + \lambda_t^*(x_t) = c(x_t) + \lambda^o(x_t) = s^o(x_t) \leq s$ satisfies the inequality in (2.3.5) when $s \geq s^o(x_t)$, $q_t^*(x_t) = q^o(x_t)$, $i_t^*(x_t) = 0$ solve the problem when $e_t = 0$ for all t. Alternatively, if $s < s^o(x_t)$, we have $a - bl_t^*(x_t) = c(x_t) + \lambda_t^*(x_t)$ from (2.3.3) since $l_t^*(x_t) > 0$ from assumption (iii). Now assume that $c(x_t) + \lambda_t^*(x_t) < s$, which implies from (2.3.5) that $i_t^*(x_t) = 0$. However, these two conditions together (from the $s \geq s^o(x_t)$ condition and the uniqueness of its solution) imply that $q_t^*(x_t) = q^o(x_t)$, which along with (2.3.3) ($c(x_t) + \lambda_t^*(x_t) = a - bl_t^*(x_t) = a - bl^o(x_t) = s^o(x_t) < s$) violates $s < s^o(x_t)$, therefore $c(x_t) + \lambda_t^*(x_t) < s$ is infeasible if $s < s^o(x_t)$, and hence $c(x_t) + \lambda_t^*(x_t) = s$. Therefore, $c(x_t) + \lambda_t^*(x_t) \geq s$ for all t, which, taken together with (2.3.3) and $i_t^*(x_t) = 0$ if $x_t \geq \kappa^{-1}(s)$ from Proposition 2.1(a), imply that $q_t^*(x_t) \geq \frac{a-s}{b}$. More specifically, $q_t^*(x_t) = q^o(x_t)$ if $s \geq s^o(x_t)$ and $q_t^*(x_t) = \frac{a-s}{b}$ if $s < s^o(x_t)$, i.e., $q_t^*(x_t) = \text{Max}[\frac{a-s}{b},\ q^o(x_t)]$. Analogously, for the privatized municipality, $\bar{q}_t^*(x_t) = \bar{q}^o(x_t)$ if $s \geq \bar{s}^o(x_t)$ and $\bar{q}_t^*(x_t) = \frac{a-s}{2b}$ if $s < \bar{s}^o(x_t)$, i.e.,

$\bar{q}_t^*(x_t) = \text{Max}[\frac{a-s}{2b}, \bar{q}^o(x_t)]$.

Given the solutions to (2.3.1) and (2.4.1) when $e_t = \bar{e}_t = 0$ for all t, we see that $0 \leq \Delta\bar{q}_t^*(x_t) = \bar{q}_t^*(x_t) - \bar{q}^o(x_t) = \text{Max}[\frac{a-s}{2b}, \bar{q}^o(x_t)] - \bar{q}^o(x_t) \leq \text{Max}[\frac{a-s}{b}, q^o(x_t)] - q^o(x_t) = \Delta q_t^*(x_t) = q_t^*(x_t) - q^o(x_t)$ since we have shown that $q^o(x_t) < 2\bar{q}^o(x_t)$ must be true for all t in the proof of Proposition 2.4.

□

PROOF. **Proposition 2.7:** (a) We first characterize the solution for a privatized municipality with no access to a water market, i.e., $\bar{e}_t = \bar{i}_t = 0$ for all t. First, notice from (5.0.12) that $\bar{w}_t^o > 0 \Rightarrow \bar{\sigma}_t^o(x_t) = a - 2b(\bar{q}_t^o(x_t) + \bar{w}_t^o) - c_w = a - 2b\bar{l}^o(x_t) - c_w$, and correspondingly, for the non-privatized analog, $w_t^o > 0 \Rightarrow \sigma_t^o(x_t) = a - b(q_t^o(x_t) + w_t^o) - c_w = a - bl^o(x_t) - c_w$, where $\bar{l}^o(x_t)$ and $l^o(x_t)$ are the quantities of water sold in the investment problem when there is no access to a water market. The result from Proposition 2.4(b) still applies due to the continuity of the price paths (Holland, 2006) before and after water production begins, such that $\sigma_t^o(x_t) > \bar{\sigma}_t^o(x_t)$ for all x_t. Therefore, from (5.0.13), $\bar{W}^o < W^o$. Moreover, notice that $\bar{\sigma}_t^o(x_t) > 0$ for $t \geq \bar{\tau}$ since $a - 2b(\bar{q}_t^o(x_t) + \bar{w}_t^o)$ is increasing from Lemma 2.1's counterpart for the non-privatized municipality, hence $\sigma_t^o(x_t) > 0$. Therefore, from the corresponding complementary slackness condition (and similarly for the non-privatized analog), this implies that $\sigma_t^o(x_t) > \bar{\sigma}_t^o(x_t) > 0 \Rightarrow w_t^* = W^*$, $\bar{w}_t^* = \bar{W}^*$. Further, note that $\bar{q}^o(x_{\bar{\tau}-}) - \bar{w}_{\tau+} = \bar{q}^o(x_{\bar{\tau}^+})$ for the continuity of the price paths. Substituting for $\bar{q}^o(x_{\bar{\tau}-})$ and $\bar{q}^o(x_{\bar{\tau}^+})$ in (5.0.14) gives the investment threshold criterion $c(x_{\bar{\tau}}) + \bar{\lambda}(x_{\bar{\tau}}) = c_w + \frac{\delta F(\bar{W})}{\bar{W}}$ and the analogous condition for the non-privatized municipality. From the convexity of $F(W)$, note that this threshold is higher for the non-privatized municipality. For part (b), note from Proposition 2.4(b) that

$a - bl_t^*(x_t) = a - 2b\bar{l}_t^*(x_t) = s$ when there is access to a water market. Therefore, from (5.0.12), $\sigma_t^*(x_t) = \bar{\sigma}_t^*(x_t) = s - c_w$, which implies from (5.0.13) that $\bar{W}^* = W^*$. Moreover, $c(x_t) + \bar{\lambda}^*(x_t) = c(x_t) + \lambda^*(x_t) = s$ for all t, implying from the investment threshold criterion that both municipalities invest simultaneously (immediately or never). $\square$

Appendix B (Chapter 3)

B1: Tables and Figures

Figure 12 was obtained by plotting $\Delta E = E|_{(g_c^{GA},\ \tau_c^{GA})} - E|_{(g_c^{GB},\ \tau_c^{GB})}$ and $\Delta \mathit{\Pi}^{Pri} = \mathit{\Pi}^{Pri}|_{(g_c^{PA},\ \tau_c^{PA})} - \mathit{\Pi}^{Pri}|_{(g_c^{PB},\ \tau_c^{PB})}$ as defined in the proof of Proposition 3.4. We observe from the figure that for the chosen parameters ($\beta = 0.75$, $\nu = 0.5$), ΔE and $\Delta \mathit{\Pi}^{Pri}$ are decreasing in μ_H and are negative when μ_H rises above a threshold value that is different for the NGO and private ecolabeling scheme. Varying $\beta \in (0,\ 1]$ and $\nu \in [0,\ 1)$ in increments of 0.2 does not affect the monotonicities of ΔE and $\Delta \mathit{\Pi}^{Pri}$. Thus, from Proposition 3.4(a), we infer that for sufficiently high (low) μ_H, the NGO and private ecolabeling schemes are optimally stipulated such that the ensuing equilibrium between the two firms is *SC* (*CC*).

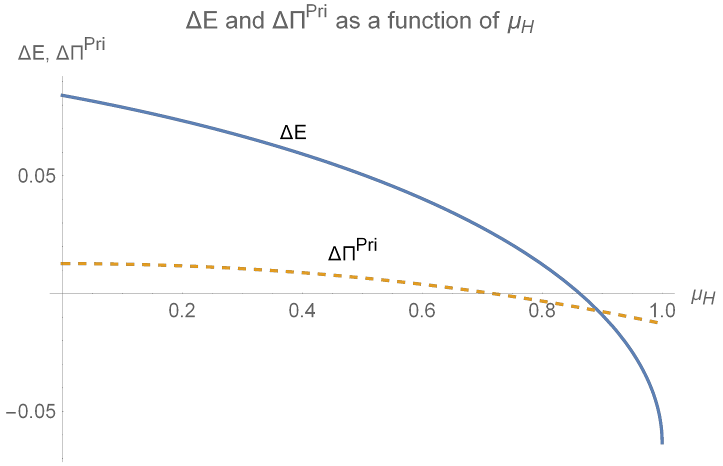


Figure 12. The effect of credibility on the equilibrium choices of NGO and private ecolabeling schemes for $\beta = 0.75$ and $\nu = 0.5$

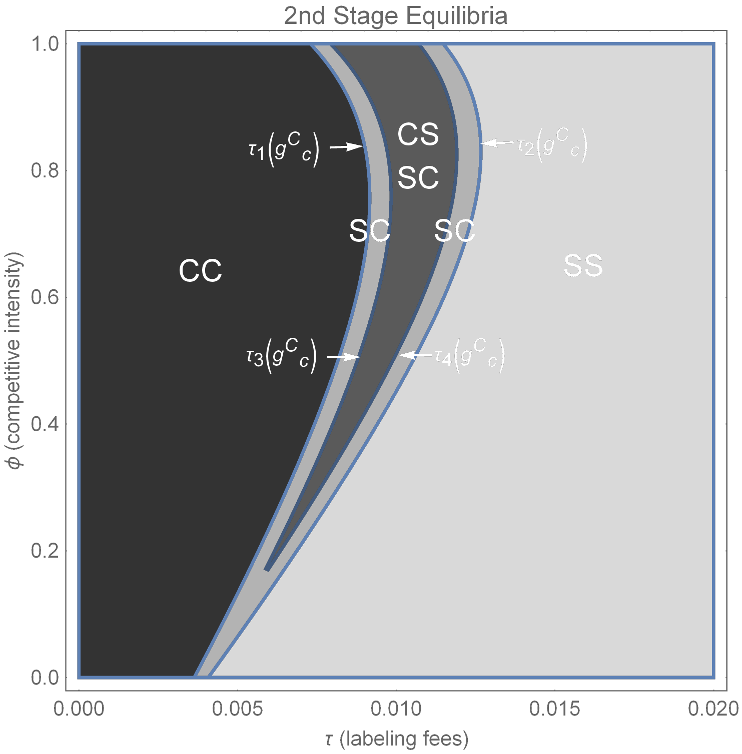


Figure 13. The effect of credibility on 3BL measures when *SC* equilibria ensue for $\beta = 0.75$, $\mu_H = 0.75$, and $\nu = 0.9$

Figure 13 illustrates the second-stage equilibria between competing producers in the presence of a single external ecolabeling scheme for a general level of substitutability between the two firms' products, which is captured by $\phi \in [0,\ 1]$ in the demand functions $q_i = \frac{1}{2} - (p_i - \phi p_{-i}) + \beta(\mu_i g_i - \phi\mu_{-i}g_{-i})$, where $i \in \{H,\ L\}$. The analysis in §3.4 assumes $\phi = 1$, i.e., the two firms' products are perfectly substitutable. Note that the equilibrium structure in Figure 13 preserves the structure in Figure 6 for $\phi = 1$. Figure 13 was obtained for $\beta = 0.75$, $\mu_H = 0.75$, and $\nu = 0.9$, by comparing each firm's profits for each of the equilibria described in Table 2 with its profits from unilateral deviation as in the proof of Lemma 3.3.

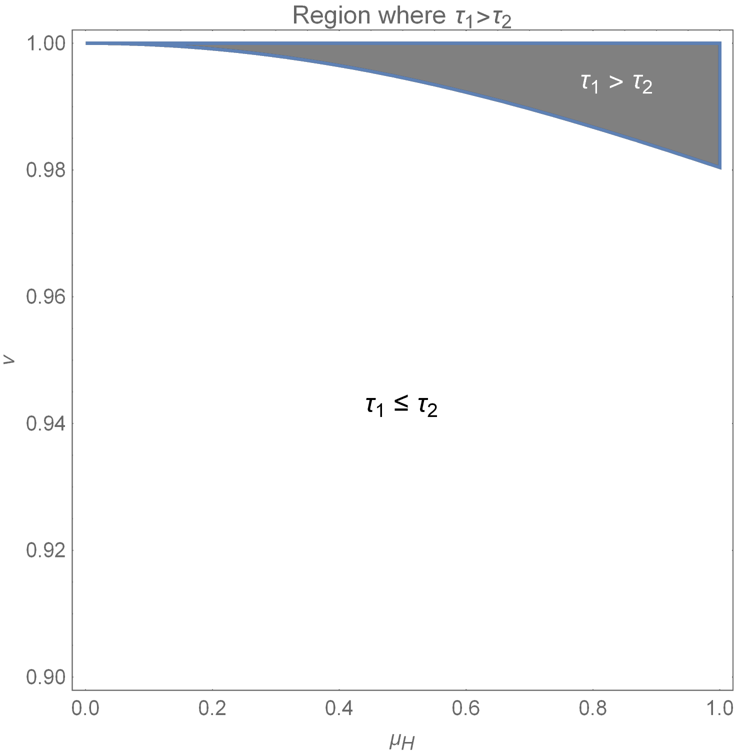


Figure 14. Region where $\tau_1(g_c^C) > \tau_2(g_c^C)$ for $\beta = 0.9$

To show that $\tau_1(g_c^C) \leq \tau_2(g_c^C)$, we solve $\tau_2(g_c^C) - \tau_1(g_c^C) = 0$ for g_c^C and obtain the two roots $g_c^C = \frac{162\beta^3\mu_H^4\left(\nu^2+1\right)-9\beta^5\mu_H^6\left(\nu^2+1\right)^2-729\beta\mu_H^2\mp\sqrt{A}}{6\left(\beta^2\mu_H^2-18\right)\left(\beta^2\mu_H^2(\nu^2+1)-9\right)^2}$, where $A = \mu_H^2\left(\beta^2\mu_H^2-9\right)^2\left(\beta^2\mu_H^2\left(\nu^2+1\right)-9\right)^2\left(4\beta^6\mu_H^6\nu^2+9\beta^4\mu_H^4\left(3\nu^4-6\nu^2-1\right)\right.$ $\left.-81\beta^2\mu_H^2\left(2\nu^4+\nu^2-4\right) + 1458\left(\nu^2-1\right)\right)$ such that $\frac{\partial^2(\tau_2(g_c^C)-\tau_1(g_c^C))}{\partial(g_c^C)^2} = \frac{2\beta^2\left(18-\beta^2\mu_H^2\right)}{\left(\beta^2\mu_H^2-9\right)^2} > 0$, implying that $\tau_2(g_c^C) - \tau_1(g_c^C) < 0$ between the two roots. This region is feasible only when the expression $\psi(\beta,\, \mu_H,\, \nu) = \left(4\beta^6\mu_H^6\nu^2+9\beta^4\mu_H^4\left(3\nu^4-6\nu^2-1\right)-81\beta^2\mu_H^2\left(2\nu^4+\nu^2-4\right)+1458\left(\nu^2-1\right)\right) > 0$. We plot this region as a function of μ_H and ν in Figure 14 for $\beta = 0.9$, and observe that it exists only for $\nu,\ \mu_H \rightarrow 1$, i.e., for $\mu_L \rightarrow 1$. Varying β in increments of 0.05 within the range $\beta \in [0.05,\ 0.95]$ does not qualitatively change the result illustrated in Figure 14, however, we note that the size of the region where $\tau_1(g_c^C) > \tau_2(g_c^C)$ shrinks as β decreases.

`Eqm characteristics`/μ_H	0.2	0.4	0.6	0.8	0.2	0.4	0.6	0.8
β	0.5	0.5	0.5	0.5	0.75	0.75	0.75	0.75
`Equilibrium`	*GP*	*GP*	*GP*	*GP*	*PP*	*PP*	*PP*	*PP*
$(g_H^*,\ g_L^*)$	(0.16, 0.06)	(0.16, 0.04)	(0.11, 0.07)	(0.11, 0.07)	(0.19, 0.19)	(0.19, 0.19)	(0.19, 0.19)	(0.19, 0.19)
$(g_c^{G2},\ \tau_c^{G2})$	(0.16, 0.00)	(0.16, 0.00)	(0.11, 0.00)	(0.11, 0.00)	(0.21, 0.00)	(0.21, 0.00)	(0.21, 0.00)	(0.20, 0.00)
$(g_c^{P2},\ \tau_c^{P2})$	(0.06, 0.01)	(0.04, 0.01)	(0.07, 0.00)	(0.07, 0.00)	(0.19, 0.03)	(0.19, 0.03)	(0.19 0.03)	(0.19, 0.00)
$E_c^2 - E_c^G$	−0.05	−0.05	−0.06	−0.04	−0.04	−0.04	−0.03	0.00
$(CS_c^2 - CS_c^G) \times 10^{-2}$	0.03	0.04	0.00	0.00	0.00	0.00	0.00	0.00
$\Pi_c^2 - \Pi_c^G$	0.01	0.01	0.03	0.02	−0.02	−0.03	−0.04	0.00
$E_c^2 - E_c^P$	0.03	0.02	0.01	0.01	0.07	0.07	0.07	0.07
$(CS_c^2 - CS_c^P) \times 10^{-2}$	0.03	0.04	0.00	0.00	0.00	0.00	0.00	0.00
$\Pi_c^2 - \Pi_c^P$	−0.03	−0.02	0.00	0.00	−0.07	−0.08	−0.08	−0.04

Table 4. Equilibrium outcomes and 3BL implications with NGO preemption when $\nu = 0.5$

The entries in Tables 4 and 5 are obtained by fixing $\nu = 0.5$ and varying μ_H in increments of 0.2 in the range $\mu_H \in [0.2,\ 0.8]$ for $\beta = 0.5$ and for $\beta = 0.75$. Repeating this procedure by varying ν in the range $\nu \in [0.2,\ 0.8]$ in increments of 0.2 does not impact the equilibria between the competing firms or the 3BL implications. The equilibrium outcomes are obtained by backward induction as in the monopoly case described in the proof of Proposition 3.5.

Environmental qualities/μ_H	0.2	0.4	0.6	0.8
Self-labeling	(0.017, 0.008)	(0.033, 0.017)	(0.050, 0.025)	(0.068, 0.033)
1 NGO ecolabel	(0.160, 0.160)	(0.156, 0.156)	(0.147, 0.147)	(0.132, 0.132)
1 Private ecolabel	(0.081, 0.081)	(0.081, 0.081)	(0.082, 0.082)	(0.066, 0.086)
NGO and private ecolabels	(0.162, 0.058)	(0.159, 0.044)	(0.108, 0.070)	(0.108, 0.070)

Table 5. Equilibrium environmental qualities $(g_H^*,\ g_L^*)$ when $\beta = \nu = 0.5$

B2: Proofs

PROOF. **Lemma 3.1:** The monopolist's objective is $\text{maximize}_{p_m, g_m} \mathit{\Pi}_m = p_m q_m - g_m^2$. First solving for price in the second stage by setting $\frac{\partial \mathit{\Pi}_m}{\partial p_m} = 0$ ($\frac{\partial^2 \mathit{\Pi}_m}{\partial p_m^2} = -2$, i.e., objective is concave in p_m) with $\tau = 0$ for a self-labeling monopolist gives $p_m(g_m) = \frac{1}{2}(\beta \mu g_m + 1)$. Substituting for $p_m(g_m)$ in $\mathit{\Pi}_m$ and solving for g_m in the second stage by setting $\frac{\partial \mathit{\Pi}_m(g_m)}{\partial g_m} = 0$ ($\frac{\partial^2 \mathit{\Pi}_m(g_m)}{\partial g_m^2} = \frac{\beta^2 \mu^2}{2} - 2 < 0$, i.e., objective is concave in g_m), we get $g_m^S = \frac{\beta \mu}{4 - \beta^2 \mu^2}$. Substituting for g_m^S in $p_m(g_m)$ and $\mathit{\Pi}_m(g_m)$, we obtain $p_m^S = \frac{2}{4 - \beta^2 \mu^2}$ and $\mathit{\Pi}_m^S = \frac{1}{4 - \beta^2 \mu^2}$. It is readily verified that $\frac{\partial g_m^S}{\partial \mu} > 0$, $\frac{\partial p_m^S}{\partial \mu} > 0$, and $\frac{\partial \mathit{\Pi}_m^S}{\partial \mu} > 0$.

$\square$

PROOF. **Proposition 3.1:** The NGO ecolabelers problem is $\text{maximize}_{g_m, \tau_m}(1 - p_m(g_m) + \beta g_m) g_m$, subject to the monopolist's individual rationality criterion: $\mathit{\Pi}_m^G \geq \mathit{\Pi}_m^S = \frac{1}{4 - \beta^2 \mu^2}$, where $p_m(g_m) = \frac{1}{2}(\beta \kappa g_m + 1)$ where $\kappa = 1$ if C, else $\kappa = \mu$, from the proof of Lemma 3.1. Similarly, the private ecolabeler solves $\text{maximize}_{g_m, \tau_m} \tau_m$ subject to the monopolist's individual rationality criterion $\mathit{\Pi}_m^P \geq \mathit{\Pi}_m^S = \frac{1}{4 - \beta^2 \mu^2}$. The monopolist's individual rationality constraint must hold with equality at the optimum, thus, substituting for g_m from the equation $\mathit{\Pi}_m^C = \frac{1}{4 - \beta^2 \mu^2}$ into the respective objective functions for the two external ecolabelers and solving simultaneously for g_m and τ_m, we obtain $g_m^G = \frac{4\beta - \beta^3 \mu^2 + 2\sqrt{\beta^2(1 - \mu^2)(4 - \beta^2 \mu^2)}}{(4 - \beta^2)(4 - \beta^2 \mu^2)}$, $\tau_m^G = 0$, $g_m^P = \frac{\beta}{4 - \beta^2}$, and $\tau_m^P = \frac{\beta^2(1 - \mu^2)}{(4 - \beta^2)(4 - \beta^2 \mu^2)}$. It is readily verified from the definitions of $\beta \in [0, 1]$ and $\mu \in [0, 1]$ that $g_m^G > g_m^P > g_m^S$.

$\square$

PROOF. **Proposition 3.2:** (a): $CS_m^S = \int_{\frac{2}{4-\beta^2\mu^2}}^{\frac{4}{4-\beta^2\mu^2}} (\frac{4}{4-\beta^2\mu^2} - p)dp = \frac{2}{(\beta^2\mu^2-4)^2}$, $CS_m^P = \int_{\frac{2}{4-\beta^2}}^{\frac{4}{4-\beta^2}} (\frac{4}{4-\beta^2} - p)dp = \frac{2}{(\beta^2-4)^2}$, and $CS_m^G = \int_{\frac{-2\beta^2\mu^2+\beta\sqrt{\beta^2(\mu^2-1)(\beta^2\mu^2-4)}+8}{(\beta^2-4)(\beta^2\mu^2-4)}}^{\frac{-4\beta^2\mu^2+2\beta\sqrt{\beta^2(\mu^2-1)(\beta^2\mu^2-4)}+16}{(\beta^2-4)(\beta^2\mu^2-4)}} (\frac{-4\beta^2\mu^2+2\beta\sqrt{\beta^2(\mu^2-1)(\beta^2\mu^2-4)}+16}{(\beta^2-4)(\beta^2\mu^2-4)} - p)dp$ $= \frac{\beta^4(\mu^2-1)+4\beta^2\mu^2-4\beta\sqrt{\beta^2(\mu^2-1)(\beta^2\mu^2-4)}-16}{2(\beta^2-4)^2(\beta^2\mu^2-4)}$. The ordering $CS_m^G > CS_m^P > CS_m^S$ can be determined by noting that CS_m^S, CS_m^P, CS_m^G are monotonic in μ such that $\frac{\partial(CS_m^G - CS_m^P)}{\partial\mu} < 0$ and $(CS_m^G - CS_m^P)|_{\mu=1} = 0$; $\frac{\partial(CS_m^P - CS_m^S)}{\partial\mu} < 0$, and $(CS_m^P - CS_m^S)|_{\mu=1} = 0$. Similarly, environmental benefits are $E_m^S = \frac{2\beta\mu}{(\beta^2\mu^2-4)^2}$, $E_m^P = \frac{2\beta}{(\beta^2-4)^2}$, and $E_m^G = \frac{\left(\beta^3(-\mu^2)+2\sqrt{\beta^2(\mu^2-1)(\beta^2\mu^2-4)}+4\beta\right)\left(-2\beta^2\mu^2+\beta\sqrt{\beta^2(\mu^2-1)(\beta^2\mu^2-4)}+8\right)}{(\beta^2-4)^2(\beta^2\mu^2-4)^2}$, which are ordered as $E_m^G > E_m^P > E_m^S$ by similarly noting that E_m^G, E_m^P, E_m^S are monotonic in μ such that $\frac{\partial(E_m^G - E_m^P)}{\partial\mu} < 0$ and $(E_m^G - E_m^P)|_{\mu=1} = 0$; and $\frac{\partial(E_m^P - E_m^S)}{\partial\mu} < 0$ and $(E_m^P - E_m^S)|_{\mu=1} = 0$. Producer surplus under the three ecolabeling regimes are equal as follows from the proof of Proposition 3.1 as the monopolist's individual rationality constraint must hold with equality at the optimal choices of both external ecolabeling schemes.

b) The sensitivity of the measures from part a) follows directly by taking their first derivative w.r.t μ. ☐

PROOF. **Lemma 3.2:** The optimal environmental qualities are chosen by simultaneously solving $\frac{\partial \Pi_H^S(p_H^S(g_H^S))}{\partial g_H^S} = \frac{\partial \Pi_L^S(p_L^S(g_L^S))}{\partial g_L^S} = 0$. Optimal prices are obtained by substituting for g_H^S and g_L^S in the price functions $p_H^S(g_H^S)$ and $p_L^S(g_L^S)$ which in turn are obtained by solving $\frac{\partial \Pi_H^S(p_H^S, g_H^S)}{\partial p_H^S} = \frac{\partial \Pi_L^S(p_L^S, g_L^S)}{\partial p_L^S} = 0$. Concavity of the objective functions in p_i^S and g_i^S is readily verified. Finally, substituting for g_H^S, g_L^S, p_H^S, and p_L^S, we obtain Π_H^S and Π_L^S. The ordering of the two firms optimal decisions and profits follow directly. ☐

PROOF. **Proposition 3.3:** a) $CS^S = \int_{\frac{2\beta^2\mu_H^2\nu^2-9}{2\left(\beta^2\mu_H^2(\nu^2+1)-9\right)}}^{\frac{2\beta^2\mu_H^2\nu^2-9}{\beta^2\mu_H^2(\nu^2+1)-9}} (\frac{2\beta^2\mu_H^2\nu^2-p_H^S\left(\beta^2\mu_H^2\left(\nu^2+1\right)-9\right)-9}{\beta^2\mu_H^2(\nu^2+1)-9})dp_H^S$
$+\int_{\frac{2\beta^2\mu_H^2-9}{2\left(\beta^2\mu_H^2(\nu^2+1)-9\right)}}^{\frac{2\beta^2\mu_H^2-9}{\beta^2\mu_H^2(\nu^2+1)-9}} (\frac{2\beta^2\mu_H^2-p_L^S\left(\beta^2\mu_H^2\left(\nu^2+1\right)-9\right)-9}{\beta^2\mu_H^2(\nu^2+1)-9})dp_L^S =$
$\frac{2\beta^4\mu_H^4\left(\nu^4+1\right)-18\beta^2\mu_H^2\left(\nu^2+1\right)+81}{4\left(\beta^2\mu_H^2(\nu^2+1)-9\right)^2}$, $E^S = \frac{\beta\mu_H\left(4\beta^4\mu_H^4\nu^4-36\beta^2\mu_H^2\nu^2+\nu\left(9-2\beta^2\mu_H^2\right)^2+81\right)}{12\left(\beta^2\mu_H^2(\nu^2+1)-9\right)^2}$,
and $\Pi^S = \Pi_H^S + \Pi_L^S$
$= \frac{1458-4\beta^6\mu_H^6\nu^2\left(\nu^2+1\right)+36\beta^4\mu_H^4\left(\nu^2+1\right)^2-405\beta^2\mu_H^2\left(\nu^2+1\right)}{36\left(\beta^2\mu_H^2(\nu^2+1)-9\right)^2}$.
b) Sensitivities of the three measures w.r.t. credibility μ_H and credibility ratio ν follow directly by taking their first derivatives and from the definitions of β, μ_H, and ν. □

PROOF. **Lemma 3.3:** Given g_c^C and τ_c^C, we compute firm H and firm L's profits for each strategy pair SS, SC, CS, and CC. We then solve for τ_c^C such that neither firm prefers to deviate from an action given its competitors action. For example, CC is an equilibrium iff $\Pi_H^{CC} \geq \Pi_H^{SC}$ and $\Pi_L^{CC} \geq \Pi_L^{CS}$, where the first and second letters in the superscripts denote firm H and firm L's actions, respectively. Solving $\Pi_H^{CC} - \Pi_H^{SC} \geq 0$ and $\Pi_L^{CC} - \Pi_L^{CS} \geq 0$ for τ_c^C, we obtain the condition $\tau_c^C \leq \tau_1(g_c^C) = \mathrm{Min}[\frac{\beta^2\mu_H^2+4(g_c^C)^2\left(9-\beta^2\left(\mu_H^2-1\right)\right)-12\beta g_c^C}{4\left(\beta^2\mu_H^2-9\right)}, \frac{1}{4}\left(-4(g_c^C)^2+\frac{(3-2\beta g_c^C)^2}{\beta^2\mu_H^2\nu^2-9}+1\right)] = \frac{\beta^2\mu_H^2+4(g_c^C)^2\left(9-\beta^2\left(\mu_H^2-1\right)\right)-12\beta g_c^C}{4\left(\beta^2\mu_H^2-9\right)}$. Similarly, solving $\Pi_H^{SC} - \Pi_H^{CC} \geq 0$ and $\Pi_L^{SC} - \Pi_L^{SS} \geq 0$ for τ_c^C, we obtain $\frac{\beta^2\mu_H^2+4(g_c^C)^2\left(9-\beta^2\left(\mu_H^2-1\right)\right)-12\beta g_c^C}{4\left(\beta^2\mu_H^2-9\right)} = \tau_1(g_c^C) \leq \tau_c^C \leq \tau_2(g_c^C) = \frac{\frac{\beta^2\mu_H^2\nu^2\left(9-2\beta^2\mu_H^2\right)^2\left(\beta^4\mu_H^4+9\beta^2\mu_H^2\nu^2-81\right)}{\left(\beta^2\mu_H^2(\nu^2+1)-9\right)^2}-36(g_c^C)^2\left(\beta^4\mu_H^4-9\beta^2\left(2\mu_H^2+1\right)+81\right)+108\beta g_c^C\left(9-2\beta^2\mu_H^2\right)}{36\left(\beta^2\mu_H^2-9\right)^2}$.
Solving $\Pi_H^{SS} - \Pi_H^{CS} \geq 0$ and $\Pi_L^{SS} - \Pi_L^{SC} \geq 0$ for τ_c^C, we get $\tau_c^C \geq \tau_2(g_c^C) =$

$$\text{Max}[\frac{\beta^2\mu_H^2\left(\beta^4\mu_H^4\nu^4+9\beta^2\mu_H^2-81\right)\left(9-2\beta^2\mu_H^2\nu^2\right)^2-108\beta g_c^C\left(2\beta^2\mu_H^2\nu^2-9\right)\left(\beta^2\mu_H^2\left(\nu^2+1\right)-9\right)^2}{36\left(\beta^2\mu_H^2\nu^2-9\right)^2\left(\beta^2\mu_H^2(\nu^2+1)-9\right)^2}$$

$$\frac{-36(g_c^C)^2\left(\beta^2\mu_H^2\left(\nu^2+1\right)-9\right)^2\left(\beta^4\mu_H^4\nu^4-9\beta^2\left(2\mu_H^2\nu^2+1\right)+81\right)}{36\left(\beta^2\mu_H^2\nu^2-9\right)^2\left(\beta^2\mu_H^2(\nu^2+1)-9\right)^2},$$

$$\frac{\frac{\beta^2\mu_H^2\nu^2\left(9-2\beta^2\mu_H^2\right)^2\left(\beta^4\mu_H^4+9\beta^2\mu_H^2\nu^2-81\right)}{\left(\beta^2\mu_H^2(\nu^2+1)-9\right)^2}-36(g_c^C)^2\left(\beta^4\mu_H^4-9\beta^2\left(2\mu_H^2+1\right)+81\right)+108\beta g_c^C\left(9-2\beta^2\mu_H^2\right)}{36\left(\beta^2\mu_H^2-9\right)^2}]$$

$$= \frac{\frac{\beta^2\mu_H^2\nu^2\left(9-2\beta^2\mu_H^2\right)^2\left(\beta^4\mu_H^4+9\beta^2\mu_H^2\nu^2-81\right)}{\left(\beta^2\mu_H^2(\nu^2+1)-9\right)^2}-36(g_c^C)^2\left(\beta^4\mu_H^4-9\beta^2\left(2\mu_H^2+1\right)+81\right)+108\beta g_c^C\left(9-2\beta^2\mu_H^2\right)}{36\left(\beta^2\mu_H^2-9\right)^2}.$$

Solving $\mathit{\Pi}_H^{CS} - \mathit{\Pi}_H^{SS} \geq 0$ and $\mathit{\Pi}_L^{CS} - \mathit{\Pi}_L^{CC} \geq 0$ for τ_c^C, we obtain $\frac{1}{4}\left(-4(g_c^C)^2 + \frac{(3-2\beta g_c^C)^2}{\beta^2\mu_H^2\nu^2-9} + 1\right) = \tau_3(g_c^C) \leq \tau_c^C \leq \tau_4(g_c^C) =$

$$\frac{\beta^2\mu_H^2\left(\beta^4\mu_H^4\nu^4+9\beta^2\mu_H^2-81\right)\left(9-2\beta^2\mu_H^2\nu^2\right)^2-36(g_c^C)^2\left(\beta^2\mu_H^2\left(\nu^2+1\right)-9\right)^2}{36\left(\beta^2\mu_H^2\nu^2-9\right)^2\left(\beta^2\mu_H^2(\nu^2+1)-9\right)^2}$$

$$\frac{\left(\beta^4\mu_H^4\nu^4-9\beta^2\left(2\mu_H^2\nu^2+1\right)+81\right)-108\beta g_c^C\left(2\beta^2\mu_H^2\nu^2-9\right)\left(\beta^2\mu_H^2\left(\nu^2+1\right)-9\right)^2}{36\left(\beta^2\mu_H^2\nu^2-9\right)^2\left(\beta^2\mu_H^2(\nu^2+1)-9\right)^2}.$$

Note that $\tau_3(g_c^C) \leq \tau_4(g_c^C)$ iff $g_c^C \geq \hat{g} = \frac{9\beta^5\mu_H^6\left(\nu^3+\nu\right)^2-162\beta^3\mu_H^4\nu^2\left(\nu^2+1\right)+729\beta\mu_H^2\nu^2+\sqrt{B}}{6\left(18-\beta^2\mu_H^2\nu^2\right)\left(\beta^2\mu_H^2(\nu^2+1)-9\right)^2}$ where $B = \mu_H^2\left(\beta^4\mu_H^4\nu^2\left(\nu^2+1\right) - 9\beta^2\mu_H^2\left(2\nu^2+1\right) + 81\right)^2$
$(4\beta^6\mu_H^6\nu^6 - 9\beta^4\mu_H^4\left(\nu^4+6\nu^2-3\right)\nu^2 + 81\beta^2\mu_H^2\left(4\nu^4-\nu^2-2\right)$
$+1458\left(1-\nu^2\right))$. ☐

PROOF. **Proposition 3.4:** a) For the NGO's problem; maximize$_{g_c^G,\tau_c^G} q_H g_H + q_L g_L$ subject to the firms' individual rationality and incentive compatibility constraints, we first rewrite the thresholds in Lemma 3.3 in terms of $g_i(\tau_c^G)$. We note that all thresholds are such that $\frac{\partial g_i(\tau_c^G)}{\partial \tau_c^G} < 0$. Further, within each region, the NGO's objective is increasing in g_c^G, implying that $\tau_c^G = 0$ is optimal and the optimal environmental standard must be at an equilibrium region's upper threshold. Thus, rewriting $g_1(0)$, we obtain $g_c^{GA} = \frac{\sqrt{\beta^2\left(\mu_H^2-1\right)\left(\beta^2\mu_H^2-9\right)}+3\beta}{-2\beta^2\mu_H^2+2\beta^2+18}$ as the environmental benefit maximizing environmental standard for region GG, and

$$g_c^{GB} = \frac{-18\beta^7\mu_H^6\left(\nu^2+1\right)^2+81\beta^5\mu_H^4\left(\nu^4+6\nu^2+5\right)-1458\beta^3\mu_H^2\left(\nu^2+2\right)+6561\beta}{6\left(\beta^4\mu_H^4-9\beta^2\left(2\mu_H^2+1\right)+81\right)\left(\beta^2\mu_H^2(\nu^2+1)-9\right)^2}$$
$$\frac{+\sqrt{\beta^2\left(2\beta^4\mu_H^4-27\beta^2\mu_H^2+81\right)^2\left(\beta^4\mu_H^6\nu^2+9\beta^2\mu_H^4\nu^4-9(\beta^2+9)\mu_H^2\nu^2+81\right)\left(\beta^2\mu_H^2(\nu^2+1)-9\right)^2}}{6\left(\beta^4\mu_H^4-9\beta^2\left(2\mu_H^2+1\right)+81\right)\left(\beta^2\mu_H^2(\nu^2+1)-9\right)^2}$$

as the environmental benefit maximizing environmental standard for region SG. We claim that GS can never occur in equilibrium. Environmental benefits from a GS equilibrium will exceed environmental benefits from an SG equilibrium iff $g_c^G > \frac{3\left(81+18\beta^2\mu_H^2\nu-\beta^4\mu_H^4\nu\left(\nu^2+\nu+1\right)\right)}{2\beta\left(\beta^4\mu_H^5\nu^2(\nu+1)-\beta^4\mu_H^4\nu(\nu^2+\nu+1)-9\beta^2\mu_H^3(\nu^3+\nu^2+\nu+1)+18\beta^2\mu_H^2\nu+81\mu_H(\nu+1)+81\right)}$ $> \text{Max}[(g_c^G)^{-1}(\tau_2(0))]$, where the second inequality can be verified by noting that the minimum value of the central term exceeds the maximum value of $(g_c^G)^{-1}(\tau_2(0))$ by evaluating them at the boundary of the parametric regions of $\beta,\ \mu_H,\ \nu \in [0,\ 1]$ due to their monotonicities in each of these parameters: the central term is decreasing in β, μ_H, ν, and $\text{Max}[(g_c^G)^{-1}(\tau_2(0))]$ is decreasing in ν but increasing in β and μ_H). However, an SS equilibrium would ensue for $g_c^G > (g_c^G)^{-1}(\tau_2(0))$. SS can never be an equilibrium outcome since it does not maximize environmental benefits; $E|_{(g_c^{GA},\ \tau_c^G)} > E^{SS}$. Therefore the NGO chooses environmental standard g_c^{GA} iff environmental benefits from the ensuing GG equilibrium exceed those from an SG equilibrium, i.e., iff $\Delta E = E|_{(g_c^{GA},\ \tau_c^G)} - E|_{(g_c^{GB},\ \tau_c^G)} \geq 0$, else he chooses standard g_c^{GB}.

For the private ecolabeler's problem, $\text{maximize}_{g_c^P, \tau_c^P} \tau_c^P(I[Eqm = P*] + I[Eqm = *P])$ subject to the firms' individual rationality and incentive compatibility constraints, where $I[..] = 1$ if true, else 0. If PP, then τ_c^P is maximized at $g_c^{PA} = \frac{3\beta}{2\left(9+\beta^2\left(1-\mu_H^2\right)\right)}$ (by solving $\frac{\partial \tau_1(g_c^P)}{\partial g_c^P} = 0$, where $\frac{\partial^2 \tau_1(g_c^P)}{\partial (g_c^P)^2} < 0$) and $\tau_c^{PA} = \tau_1(g_c^{PA}) = \frac{\beta^2\left(\mu_H^2-1\right)}{4\left(\beta^2\left(\mu_H^2-1\right)-9\right)}$, the threshold for PP, giving total labeling profits $\Pi^{Pri}|_{(g_c^{PA},\ \tau_c^{PA})} = \frac{2\beta^2\left(\mu_H^2-1\right)}{4\left(\beta^2\left(\mu_H^2-1\right)-9\right)}$. If SP, then τ_c^P is maximized at $g_c^{PB} = \frac{27\beta-6\beta^3\mu_H^2}{2\left(\beta^4\mu_H^4-9\beta^2\left(2\mu_H^2+1\right)+81\right)}$ (by solving $\frac{\partial \tau_2(g_c^P)}{\partial g_c^P} = 0$, where $\frac{\partial^2 \tau_2(g_c^P)}{\partial (g_c^P)^2} < 0$) and

$\tau_c^{PB} = \tau_2(g_c^{PB}) = \frac{\beta^2\left(9-2\beta^2\mu_H^2\right)^2\left(\beta^4\mu_H^6\nu^2+9\beta^2\mu_H^4\nu^4-9\left(\beta^2+9\right)\mu_H^2\nu^2+81\right)}{36\left(\beta^4\mu_H^4-9\beta^2\left(2\mu_H^2+1\right)+81\right)\left(\beta^2\mu_H^2(\nu^2+1)-9\right)^2}$, giving total labeling profits $\Pi^{Pri}|_{(g_c^{PB},\ \tau_c^{PB})} = \frac{\beta^2\left(9-2\beta^2\mu_H^2\right)^2\left(\beta^4\mu_H^6\nu^2+9\beta^2\mu_H^4\nu^4-9\left(\beta^2+9\right)\mu_H^2\nu^2+81\right)}{36\left(\beta^4\mu_H^4-9\beta^2\left(2\mu_H^2+1\right)+81\right)\left(\beta^2\mu_H^2(\nu^2+1)-9\right)^2}$. The equilibrium choice is determined by whichever obtains higher labeling profits, i.e., the private ecolabeler stipulates g_c^{PA} and τ_c^{PA} iff $\Delta\Pi^{Pri} = \Pi^{Pri}|_{(g_c^{PA},\ \tau_c^{PA})} - \Pi^{Pri}|_{(g_c^{PB},\ \tau_c^{PB})} = \frac{2\beta^2\left(\mu_H^2-1\right)}{4\left(\beta^2\left(\mu_H^2-1\right)-9\right)} - \frac{\beta^2\left(9-2\beta^2\mu_H^2\right)^2\left(\beta^4\mu_H^6\nu^2+9\beta^2\mu_H^4\nu^4-9\left(\beta^2+9\right)\mu_H^2\nu^2+81\right)}{36\left(\beta^4\mu_H^4-9\beta^2\left(2\mu_H^2+1\right)+81\right)\left(\beta^2\mu_H^2(\nu^2+1)-9\right)^2} \geq 0$, else he stipulates g_c^{PB} and τ_c^{PB}. Note that since $\tau_3(g_c^P)$, $\tau_4(g_c^P) \leq \tau_2(g_c^P)$, PS can never earn maximum labeling profits, and hence, never occur in equilibrium.

b) From the proof of Proposition 3.4(a), note that ensuing equilibria are always CC or SC, i.e., firm L always adopts the external ecolabel in equilibrium. It remains to show that when firm H chooses S, that its self-labeling environmental quality is lower than the environmental standard adopted by firm L. Note that firm H's best response to firm L when firm L adopts an external standard g_c^C (obtained by solving for g_H^S in $\frac{\partial \Pi_H^S(g_L=g_c^C)}{\partial g_H^S} = 0$) is $g_H^S(g_L = g_c^C) = \frac{\beta\mu_H(2\beta g_c^C-3)}{2\left(\beta^2\mu_H^2-9\right)}$. This self-labeling environmental quality exceeds the external environmental standard adopted by L iff $g_c^C < \frac{3\beta\mu_H}{2(9-\beta^2(\mu_H-1)\mu_H)}$. But from Proposition 3.4(a), Lemma 3.3, and the definitions of β, μ_H, and ν, $\frac{3\beta\mu_H}{2(9-\beta^2(\mu_H-1)\mu_H)} < g_c^{PA} < g_c^{PB}$ and $\frac{3\beta\mu_H}{2(9-\beta^2(\mu_H-1)\mu_H)} < g_c^{GA} < g_c^{GB}$, thus, $g_L^* = g_c^C \geq g_H^*$.

c) Within each of the possible equilibrium regions CC and SC, the NGO chooses $g_c^G = g_c^{GA} = g_1(\tau_c^{GA} = 0)$ and $g_c^G = g_c^{GB} = g_2(\tau_c^{GB} = 0)$. From Proposition 3.4(a), within these equilibrium regions, the private labeler chooses τ_c^{PA}, $\tau_c^{PB} > 0$. Noting that $\frac{\partial g_i(\tau_c^G)}{\partial \tau_c^G} < 0$, this implies $g_c^{GA} = g_1(\tau_c^{GA} = 0) > g_1^c(\tau_c^{PA} > 0) = g_c^{PA}$, and $g_c^{GB} = g_2(\tau_c^{GB} = 0) > g_2(\tau_c^{PB} > 0) = g_c^{PB}$. $\square$

PROOF. **Proposition 3.5:** a) From Lemma 3.1, we have the monopolist's reservation profits as $\frac{1}{4-\beta^2\mu^2}$. We start first by solving the private ecolabeler's problem in the second stage. The private ecolabeler maximizes his revenues τ_m^{P2}, leaving a profit of $\frac{1}{4}\left(\left(\beta^2-4\right)(g_m^{P2})^2+2\beta g_m^{P2}-4\tau_m^{P2}+1\right)$ to the monopolist, subject to two constraints: 1) monopolist's profits from adopting the private label exceed the monopolist's reservation profits $\frac{1}{4-\beta^2\mu^2}$, and 2) monopolist's profits from adopting the private label exceed the monopolist's profits from adopting the NGO's ecolabel $\frac{1}{4}\left(\left(\beta^2-4\right)(g_m^{G2})^2+2\beta g_m^{G2}-4\tau_m^{G2}+1\right)$. The maximum labeling fee the private label can charge (when the monopolist's profits meet these two constraints with equality) is thus $\tau_m^{P2}=\text{Min}[\frac{1}{4}\left(\frac{4}{\beta^2\mu^2-4}+\left(\beta^2-4\right)(g_m^{P2})^2+2\beta g_m^{P2}+1\right)$, $\frac{1}{4}\left(-\left(\beta^2-4\right)(g_m^{G2})^2-2\beta g_m^{G2}+4\tau_m^{G2}+g_m^{P2}\left(2\beta+\left(\beta^2-4\right)g_m^{P2}\right)\right)] \leq \frac{1}{4}\left(\frac{4}{\beta^2\mu^2-4}+\left(\beta^2-4\right)(g_m^{P2})^2+2\beta g_m^{P2}+1\right)=\tau_m^P$. Note that both expressions $\frac{1}{4}\left(\frac{4}{\beta^2\mu^2-4}+\left(\beta^2-4\right)(g_m^{P2})^2+2\beta g_m^{P2}+1\right)$, and $\frac{1}{4}\left(-\left(\beta^2-4\right)(g_m^{G2})^2-2\beta g_m^{G2}+4\tau_m^{G2}+g_m^{P2}\left(2\beta+\left(\beta^2-4\right)g_m^{P2}\right)\right)$ are maximized at $g_m^{P2}=\frac{\beta}{4-\beta^2}$. b) The environmental benefits $E_m^{C2}=\frac{1}{2}g_m^{C2}(\beta g_m^{C2}\kappa+1)$ and consumer surplus $CS_m^{C2}=\frac{1}{8}(\beta g_m^{C2}\kappa+1)^2$ depend only on g_m^{C2} and are independent of τ_m^{C2}. Therefore, since $g_m^{P2}=g_m^P$, $E_m^2=E_m^P$ and $CS_m^2=CS_m^P$. Monopolists profits $\Pi_m^2=\frac{1}{4}\left(\frac{\beta^2}{4-\beta^2}-4\tau_m+1\right)$are decreasing in labeling fees τ_m and since $\tau_m^{P2}\leq\tau_m^P$ and $g_m^{P2}=g_m^P=\frac{\beta}{4-\beta^2}$, $\Pi_m^2=\Pi_m^{P2}\geq\Pi_m^P$. □

Appendix C (Chapter 4)

C1: Proofs

PROOF. **Lemma 4.1:** Resolving by backward induction, in the third stage, OEM chooses $m^*(w,\, g) = \frac{1-w+\alpha g}{2}$ by solving $\frac{\partial \Pi_M^{OEM}(m,w,g)}{\partial m} = 0$ ($\frac{\partial^2 \Pi_M^{OEM}(m,w,g)}{\partial m^2} < 0$). Anticipating this choice in the second stage, the supplier chooses $w^*(g) = \frac{1+\alpha g}{2}$ by solving $\frac{\partial \Pi_M^S(w,g)}{\partial w} = 0$ ($\frac{\partial^2 \Pi_M^S(w,g)}{\partial w^2} < 0$). In the first stage, the OEM chooses $g_M^* = \frac{\alpha}{16\delta\theta - \alpha^2}$ by solving $\frac{\partial \Pi_M^{OEM}(g)}{\partial g} = 0$ ($\frac{\partial^2 \Pi_M^{OEM}(g)}{\partial g^2} < 0$ iff $16\delta\theta - \alpha^2 = \Omega_M > 0$). Substituting for $g_M^* = \frac{\alpha}{\Omega_M}$ in the price functions, we get $m_M^* = \frac{4\delta\theta}{\Omega_M}$ and $w_M^* = \frac{8\delta\theta}{\Omega_M}$. Note that $\frac{\partial m_M^*}{\partial \theta}, \frac{\partial w_M^*}{\partial \theta}, \frac{\partial g_M^*}{\partial \theta} < 0$. For this solution to meet the supplier's individual rationality constraint, $\Pi_M^S = \frac{\delta\left(\alpha^2(\theta-1)+32\delta\theta^2\right)}{\left(\alpha^2-16\delta\theta\right)^2} \geq 0$, i.e., $\theta > \frac{\sqrt{\alpha^4+128\alpha^2\delta}-\alpha^2}{64\delta} = \omega_M$ must hold. □

PROOF. **Proposition 4.1:** a) In a cost-sharing dyad, $E_M = q_M^* g_M^* = (1 - w_M^* - m_M^* + \alpha g_M^*) g_M^* = \frac{4\alpha\delta\theta}{\Omega_M^2}$, $CS_M = \int_{\frac{12\delta\theta}{\Omega}}^{\frac{16\delta\theta}{\Omega}} (1 - p + \alpha g_M^*) dp = \frac{8\delta^2\theta^2}{\Omega_M^2}$, and $\Pi_M = \Pi_M^{OEM*} + \Pi_M^{S*} = \frac{\delta(48\delta\theta^2 - \alpha^2)}{\Omega_M^2}$. For a dyad without cost-sharing, the solution proceeds as in the proof of Lemma 4.1 except in the final stage of backward induction where the OEM's objective $\Pi_M^{OEM}(g) = \frac{1}{16}(\alpha g + 1)^2$ is convex in g. Invoking the supplier's individual rationality constraint restricts $g_M^N \leq \frac{\alpha + 2\sqrt{2\delta}}{\Omega_N}$. Note that the condition $\Omega_N = 8\delta - \alpha^2 > 0$ must hold for a non-negative solution. These solutions along with 3BL implications are compiled in the following table.

Eqm characteristics	No cost-sharing dyad	Cost-sharing dyad
g_M^*	$\frac{\alpha+2\sqrt{2\delta}}{\Omega_N}$	$\frac{\alpha}{\Omega_M}$
E_M	$\frac{\left(\alpha+2\sqrt{2\delta}\right)\left(\alpha\sqrt{2\delta}+4\delta\right)}{2\Omega_N^2}$	$\frac{4\alpha\delta\theta}{\Omega_M^2}$
CS_M	$\frac{\delta\left(\alpha^2+4\alpha\sqrt{2\delta}+8\delta\right)}{4\Omega_N^2}$	$\frac{8\delta^2\theta^2}{\Omega_M^2}$
$\mathit{\Pi}_M$	$\frac{\delta\left(\alpha^2+4\alpha\sqrt{2\delta}+8\delta\right)}{2\Omega_N^2}$	$\frac{\delta\left(48\delta\theta^2-\alpha^2\right)}{\Omega_M^2}$

Table 6. Comparison of equilibria and 3BL outcomes in a monopoly with and without cost-sharing

The results in Proposition 4.1(a) and (b) follow from Table 6.

c) It is readily verified that $\frac{\partial E_M^C}{\partial\theta}$, $\frac{\partial CS_M^C}{\partial\theta} < 0$, and $\frac{\partial \mathit{\Pi}_M^C}{\partial\theta} = \frac{32\alpha^2\delta^2(1-3\theta)}{\Omega_M^3}$, such that $\mathit{\Pi}_M^C$ is unimodal achieving its maximum at $\theta = \frac{1}{3}$ ($\frac{\partial \mathit{\Pi}_M^C}{\partial\theta} < (>)0$ for $\theta > (<)\frac{1}{3}$). □

PROOF. **Lemma 4.2:** Setting $\phi = 1$, we simultaneously solve $\frac{\partial \mathit{\Pi}_A^{OEM}(w,m,g,\theta)}{\partial m_A} = \frac{\partial \mathit{\Pi}_B^{OEM}(w,m,g,\theta)}{\partial m_B} = 0$ to obtain $m_A(w,\ g,\ \theta)$ and $m_B(w,\ g,\ \theta)$ in the fourth stage. Substituting the OEM margin functions in the supplier's objectives, we next simultaneously solve $\frac{\partial \mathit{\Pi}_A^S(w,g,\theta)}{\partial w_A} = \frac{\partial \mathit{\Pi}_B^S(w,g,\theta)}{\partial w_B} = 0$ to obtain $w_A(g,\ \theta)$ and $w_B(g,\ \theta)$ in the third stage. Concavity of the objective functions is readily verified. In the second stage, simultaneously solving $\frac{\partial \mathit{\Pi}_A^{OEM}(g,\theta)}{\partial g_A} = \frac{\partial \mathit{\Pi}_B^{OEM}(g,\theta)}{\partial g_B} = 0$ gives $g_A^*(\theta) = \frac{\alpha(\lambda-1)\left(\alpha^2(\lambda-1)^2-9\delta\theta_B(k+4)\right)}{9\delta\Omega_1}$ and $g_B^*(\theta) = \frac{\alpha(\lambda-1)\left(\alpha^2(\lambda-1)^2+9\delta\theta_A(k-5)\right)}{9\delta\Omega_1}$, where $\Omega_1 = 81\delta\theta_A\theta_B - \alpha^2(\lambda-1)^2(\theta_A+\theta_B)$ with $\delta > \mathrm{Max}[\frac{\alpha^2(1-\lambda)^2}{81\theta_A},\ \frac{\alpha^2(1-\lambda)^2}{81\theta_B}]$ as the concavity condition which is satisfied given conditions 1 and 2. To obtain the degrees of cost-sharing that maximize supply chain profits, simultaneously solving $\frac{\partial(\mathit{\Pi}_A^{OEM}(\theta)+\mathit{\Pi}_A^S(\theta))}{\partial\theta_A} = \frac{\partial(\mathit{\Pi}_B^{OEM}(\theta)+\mathit{\Pi}_B^S(\theta))}{\partial\theta_B} = 0$ gives $\theta_A^* = \theta_B^* = \frac{\Omega_2}{72\delta}$ ($\frac{\partial^2(\mathit{\Pi}_i^{OEM}(\theta)+\mathit{\Pi}_i^S(\theta))}{\partial\theta_i^2} < 0$), where $\Omega_2 = \sqrt{\delta\left(81\delta - 16\alpha^2(\lambda-1)^2\right)} + 9\delta$. Substituting θ_i^* in $g_i(\theta)$ returns the investment levels at the optimum level of cost-sharing.

Equilibrium outcomes for general ϕ are obtained similarly with the condition $\delta > \mathrm{Max}[\frac{\alpha^2\left(\phi^2-2\right)^2\left(\lambda\left(\phi^2-2\right)\phi+2\phi^4-9\phi^2+8\right)^2}{\theta_B(-4\phi^6+33\phi^4-84\phi^2+64)^2}, \frac{\alpha^2\left(\phi^2-2\right)^2\left(\lambda\left(\phi^2-2\right)\phi+2\phi^4-9\phi^2+8\right)^2}{\theta_A(-4\phi^6+33\phi^4-84\phi^2+64)^2}]$ ensuring concavity of the objectives in g_i and non-trivialty of solutions. Supply-chain optimal degrees of cost-sharing are obtained by solving $\frac{\partial(\Pi_A^{OEM}(\theta,\phi)+\Pi_A^S(\theta,\phi))}{\partial\theta_A} = \frac{\partial(\Pi_B^{OEM}(\theta,\phi)+\Pi_B^S(\theta,\phi))}{\partial\theta_B} = 0$ to obtain $\theta_A^* = \theta_B^* = \frac{2\alpha^2\left(\lambda^2-1\right)\left(4\phi^{10}-49\phi^8+228\phi^6-499\phi^4+508\phi^2-192\right)\left(\phi^2-2\right)^2-16\delta\phi^{14}}{4\delta(3-\phi^2)(-4\phi^6+33\phi^4-84\phi^2+64)^2}$ $\frac{+296\delta\phi^{12}-2289\delta\phi^{10}+9578\delta\phi^8-23392\delta\phi^6+33312\delta\phi^4-25600\delta\phi^2+8192\delta+\sqrt{A}}{4\delta(3-\phi^2)(-4\phi^6+33\phi^4-84\phi^2+64)^2}$, where $A^2 = \left(4\phi^8-41\phi^6+150\phi^4-232\phi^2+128\right)^2\left(4\alpha^4\left(\lambda^2-1\right)^2\left(\phi^6-6\phi^4+11\phi^2-6\right)^2\right.$ $+\delta^2\left(-4\phi^6+33\phi^4-84\phi^2+64\right)^2-4\alpha^2\delta\left(\phi^4-5\phi^2+6\right)$ $\left(\lambda^2\left(4\phi^8-35\phi^6+109\phi^4-140\phi^2+64\right)+4\lambda\left(2\phi^6-13\phi^4+26\phi^2-16\right)\phi\right.$ $\left.\left.+4\phi^8-35\phi^6+109\phi^4-140\phi^2+64\right)\right)$.

$\square$

PROOF. **Proposition 4.2:** a) From Lemma 4.2, and given the assumption $\theta_A = \theta_B = \theta$, $g_A^*(\theta) = \frac{\alpha(\lambda-1)\left(\alpha^2(\lambda-1)^2-9\delta\theta(k+4)\right)}{9\delta\Omega_1}$ and $g_B^*(\theta) = \frac{\alpha(\lambda-1)\left(\alpha^2(\lambda-1)^2+9\delta\theta(k-5)\right)}{9\delta\Omega_1}$. Given condition 1 which ensures $\Omega_1 > 0$, the difference $\Delta g(\theta) = g_A^*(\theta) - g_B^*(\theta) = \frac{\alpha(2k-1)(1-\lambda)}{\Omega_1} > 0$ iff $k > \frac{1}{2}$.
b) Taking the derivative of the investment levels w.r.t λ gives $\frac{\partial g_A^*(\theta)}{\partial\lambda} = \frac{-\alpha\left(2\alpha^4(\lambda-1)^4+9\alpha^2\delta\theta(2k-19)(\lambda-1)^2+729\delta^2\theta^2(k+4)\right)}{9\delta\theta\Omega_1^2} < 0$ from condition 2 ($\Omega_2 > 9\delta$). Taking the derivative of $g_B^*(\theta)$ w.r.t λ gives $\frac{\partial g_B^*(\theta)}{\partial\lambda} = \frac{-2\alpha^5(\lambda-1)^4+9\alpha^3\delta\theta(2k+17)(\lambda-1)^2+729\alpha\delta^2\theta^2(k-5)}{9\delta\theta\Omega_1^2} < 0$ from condition 2 ($\Omega_2 > 9\delta$). Taking the derivatives of $g_A^*(\theta)$ and $g_B^*(\theta)$ w.r.t k gives $\frac{\partial g_A^*(\theta)}{\partial k} = \frac{\alpha(1-\lambda)}{\Omega_1} > 0$ and $\frac{\partial g_B^*(\theta)}{\partial k} = \frac{\alpha(\lambda-1)}{\Omega_1} < 0$ from condition 1 which ensures $\Omega_1 > 0$. $\square$

PROOF. **Proposition 4.3:** a) OEM A's profits evaluated at the equilibrium described in Lemma 4.2 (along with the assumption $\theta_A = \theta_B = \theta$) are $\Pi_A^{OEM} = \frac{\left(81\delta\theta-\alpha^2(\lambda-1)^2\right)\left(\alpha^2(\lambda-1)^2-9\delta\theta(k+4)\right)^2}{81\delta\theta\Omega_1^2}$. The derivative of OEM A's profits w.r.t λ is evaluated as $\frac{\partial\Pi_A^{OEM}}{\partial\lambda} = \frac{2\alpha^2(\lambda-1)\left(\alpha^2(\lambda-1)^2-9\delta\theta(k+4)\right)\left(2\alpha^4(\lambda-1)^4+9\alpha^2\delta\theta(2k-19)(\lambda-1)^2-2187\delta^2\theta^2(k-2)\right)}{81\delta\theta\Omega_1^3}$.
Solving $\frac{\partial\Pi_A^{OEM}}{\partial\lambda} = 0$ for k gives $k_{A1} = \frac{\alpha^2(\lambda-1)^2-36\delta\theta}{9\delta\theta} < 0$ and $k_{A2} = \frac{2\alpha^4(\lambda-1)^4-171\alpha^2\delta\theta(\lambda-1)^2+4374\delta^2\theta^2}{9\delta\theta(243\delta\theta-2\alpha^2(\lambda-1)^2)} > 1$, and $\frac{\partial^2\frac{\partial\Pi_A^{OEM}}{\partial\lambda}}{\partial k^2} = \frac{4\alpha^2\delta\theta(\lambda-1)\left(2\alpha^2(\lambda-1)^2-243\delta\theta\right)}{-\Omega_1^3} < 0$, where the inequalities follow from

condition 1. This implies that $\frac{\partial \Pi_A^{OEM}}{\partial \lambda} > 0 \,\forall\, k \in [0, 1]$. Similarly, OEM B's profits are evaluated as $\frac{\left(81\delta\theta - \alpha^2(\lambda-1)^2\right)\left(\alpha^2(\lambda-1)^2 + 9\delta\theta(k-5)\right)^2}{81\delta\theta\Omega_1^2}$, and $\frac{\partial \Pi_B^{OEM}}{\partial \lambda} = \frac{2\alpha^2(\lambda-1)\left(\alpha^2(\lambda-1)^2+9\delta\theta(k-5)\right)\left(2\alpha^4(\lambda-1)^4 - 9\alpha^2\delta\theta(2k+17)(\lambda-1)^2 + 2187\delta^2\theta^2(k+1)\right)}{81\delta\theta\Omega_1^3}$. Solving $\frac{\partial \Pi_B^{OEM}}{\partial \lambda} = 0$ for k gives $k_{B1} = \frac{-2\alpha^4(\lambda-1)^4 + 153\alpha^2\delta\theta(\lambda-1)^2 - 2187\delta^2\theta^2}{9\delta\theta(243\delta\theta - 2\alpha^2(\lambda-1)^2)} < 0$ and $k_{B2} = \frac{45\delta\theta - \alpha^2(\lambda-1)^2}{9\delta\theta} > 1$, and $\frac{\partial^2 \frac{\partial \Pi_B^{OEM}}{\partial \lambda}}{\partial k^2} = \frac{4\alpha^2\delta\theta(\lambda-1)\left(2\alpha^2(\lambda-1)^2 - 243\delta\theta\right)}{-\Omega_1^3} < 0$, where the inequalities follow from condition 1. This implies that $\frac{\partial \Pi_B^{OEM}}{\partial \lambda} > 0 \,\forall\, k \in [0, 1]$. Taking the derivative of OEM A's profits w.r.t k, $\frac{\partial \Pi_A^{OEM}}{\partial k} = \frac{2\left(\alpha^2(\lambda-1)^2 - 81\delta\theta\right)\left(\alpha^2(\lambda-1)^2 - 9\delta\theta(k+4)\right)}{9(81\delta\theta - 2\alpha^2(\lambda-1)^2)^2} > 0$ from condition 1 and similarly, for OEM B, $\frac{\partial \Pi_B^{OEM}}{\partial k} = \frac{2\left(81\delta\theta - \alpha^2(\lambda-1)^2\right)\left(\alpha^2(\lambda-1)^2 + 9\delta\theta(k-5)\right)}{9(81\delta\theta - 2\alpha^2(\lambda-1)^2)^2} < 0$ from condition 1. Taking the derivative of $\frac{\partial \Pi_A^{OEM}}{\partial \lambda}$ and $\frac{\partial \Pi_B^{OEM}}{\partial \lambda}$ w.r.t k, $\frac{\partial^2 \Pi_A^{OEM}}{\partial \lambda \partial k} = \frac{4\alpha^2\delta\theta(\lambda-1)\left(2\alpha^2(k+4)(\lambda-1)^2 - 243\delta\theta(k+1)\right)}{(2\alpha^2(\lambda-1)^2 - 81\delta\theta)^3} < 0$ and $\frac{\partial^2 \Pi_B^{OEM}}{\partial \lambda \partial k} = \frac{4\alpha^2\delta\theta(\lambda-1)\left(2\alpha^2(k-5)(\lambda-1)^2 - 243\delta\theta(k-2)\right)}{(2\alpha^2(\lambda-1)^2 - 81\delta\theta)^3} > 0$ from condition 1.

b) Environmental benefits at equilibrium (along with the assumption $\theta_A = \theta_B = \theta$) are evaluated as $E_C = \frac{\alpha(1-\lambda)\left(2\alpha^4(\lambda-1)^4 - 162\alpha^2\delta\theta(\lambda-1)^2 + 81\delta^2\theta^2\left(2k^2-2k+41\right)\right)}{9\delta\theta\Omega_1^2}$. Taking the derivative w.r.t λ and solving $\frac{\partial E_C}{\partial \lambda} = \frac{\alpha\left(4\alpha^6(\lambda-1)^6 - 486\alpha^4\delta\theta(\lambda-1)^4 - 972\alpha^2\delta^2\theta^2\left(k^2-k-20\right)(\lambda-1)^2 - 6561\delta^3\theta^3\left(2k^2-2k+41\right)\right)}{9\delta\theta\Omega_1^3} = 0$ which gives complex roots $k_{E1} = k_E + \imath r_E$ and $k_{E2} = k_E - \imath r_E$, and $\frac{\partial^2 (\frac{\partial E_C}{\partial \lambda})}{\partial k^2} = \frac{108\alpha\delta\theta\left(2\alpha^2(\lambda-1)^2 + 27\delta\theta\right)}{-\Omega_1^3} < 0$, implying that $\frac{\partial E_C}{\partial \lambda} < 0 \,\forall\, k \in [0, 1]$. Taking the derivative w.r.t k, $\frac{\partial E_C}{\partial k} = \frac{9\alpha\delta\theta(4k-2)(1-\lambda)}{\Omega_1^2}$ which goes to zero at $k = \frac{1}{2}$, and $\frac{\partial^2 E_C}{\partial k^2} = \frac{36\alpha\delta\theta(1-\lambda)}{\Omega_1^2} > 0$, implying E_C is minimized at $k = \frac{1}{2}$. Consumer surplus at equilibrium (along with the assumption $\theta_A = \theta_B = \theta$) is evaluated as $CS_C = \frac{2\alpha^4(\lambda-1)^4 - 162\alpha^2\delta\theta(\lambda-1)^2 + 81\delta^2\theta^2\left(2k^2-2k+41\right)}{2\Omega_1^2}$. The derivative w.r.t λ is evaluated as $\frac{\partial CS_C}{\partial \lambda} = \frac{162\alpha^2\delta^2\theta^2(1-2k)^2(1-\lambda)}{-\Omega_1^3} < 0$. Taking the derivative w.r.t k, $\frac{\partial CS_C}{\partial k} = \frac{81\delta^2\theta^2(2k-1)}{\Omega_1^2}$ which goes to zero at $k = \frac{1}{2}$, and $\frac{\partial^2 CS_C}{\partial k^2} = \frac{162\delta^2\theta^2}{\Omega_1^2} > 0$, implying CS_C is minimized at $k = \frac{1}{2}$. $\square$