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Net Green: The Impact of Corporate Social Responsibility on the Natural Environment and Employee Satisfaction

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by

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FOREWORD

Our wills and fates do so contrary run
That our devices still are overthrown.
Our thoughts are ours, their ends none of our own.
*(*Hamlet*, 3.2, Player King)*

Our world faces unprecedented environmental challenges. Globally, economies have expanded meteorically, bringing increased affluence, quality of life, and life spans, but also vastly increased consumption and environmental impacts. The desire of people around the world to aspire to European or U.S. levels of consumption is understandable but thermodynamically untenable—the world cannot sustain 7 billion Americans. Global carbon dioxide emissions, which warm our atmosphere and acidify our oceans, have increased by a factor of three since 1970, and continue to increase each year by 1 billion tonnes (the weight of about 100,000 large cruise ships). With business-as-usual policies, climate scientists project we will see global temperatures increase 2-4°C by 2100.[a] Last month, *Science* published that the 182,000-square-kilometer Thwaites Glacier in Antarctica has begun a 200-year, irreversible slide into the ocean, which will flood and melt the entire West Antarctic Ice Sheet, raising global sea levels by more than three meters.[b] Exploitation of tar sands and shale oil has depressed energy prices, encouraging further consumption and discouraging transitions to renewable sources. Changing weather patterns and threats to habitat are causing species extinction levels estimated at several thousand times the natural extinction rate.[c]

The (more) shocking thing is that all this is set to a backdrop of seemingly increased environmental awareness and concern on the part of individuals, and increased environmental policies and actions on the part of governments and business. Recycling programs are now ubiquitous, canvas shopping bags adorn every checkstand, hybrid and electric cars are becoming more prevalent, high-efficiency lighting and appliances are spreading. Meanwhile, governments increasingly set vehicle efficiency targets and regulate toxic wastes, and companies continually assert their commitments to sustainability. It is hard to imagine that many of us actively desire to harm nature—rather, many of us express an ardent desire to help the environment—yet we damage it further every day.

Where have we gone wrong?

We have gone wrong by focusing on *programs*. Things like recycling and cap and trade are programs; plastic bag bans are programs; national parks and wildlife refuges are programs. They are seatbelts on an airplane without wings at 30,000 feet—they feel like safety but do nothing to avoid inevitable disaster. Daniel Quinn wrote in *Beyond Civilization* that if humanity is saved, “it will not be by old minds with new programs but by new minds with no programs at all.” We don’t need seatbelts; we need a new airplane. If we find one that can fly, the programs will be superfluous.

I have realized over the course of my PhD studies how true this is. I have learned troubling things, like that energy efficiency can increase impacts by encouraging increased usage, or that a canvas shopping bag must be used over 100 times before it has a lower per-use impact than a plastic bag. I have contributed to other troubling discoveries, like that

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[a] Intergovernmental Panel on Climate Change (IPCC) (2014). Fifth Assessment Report

[b] Sumner, T. (2014). No Stopping the Collapse of the West Antarctic Ice Sheet. *Science* vol. 344 p.683

[c] Kolbert, E. (2014). *The Sixth Extinction: An Unnatural History*. New York: Henry Holt & Co.

recycling can increase environmental impacts by encouraging material consumption. I have grasped the extent and nature of human impact on the natural environment, and what it will take to create change. I have discovered there are no silver bullets; none of the programs, activities, or policies that we think of as "environmental" are guaranteed to improve the environment, and some of them are guaranteed to destroy it. In this profession, one also stops to consider that all this well-meaning intellectual work requires computers, data centers, electricity, plane flights, commutes. One begins to seriously question whether one's efforts cause more impacts than they prevent. In the end, it seems there is nothing that can be done.

At least, there is nothing that can be done for our current aircraft. But can we abandon this doomed vessel and find a new one—a new way of living—that bends our trajectory away from material extraction and consumption, away from habitat destruction, away from poisoning our air and water, away from assured self-annihilation?

If we hope to realize true environmental gains—physical improvements, returns to more "natural" states—we cannot be content with superficial platitudes about what "seems green." We must instead subject our actions to the harshest criteria, forecasting the consequences of those actions and asking, "Does this action improve the environment or damage it?" As I will argue in the first chapter, only those actions that physically improve the environment can be considered environmental and should be those we embrace.

Should we be content, then, with replacing superficially green actions with superficially forecasted actions? Certainly not. We must, as scientists, policy makers, and managers, utilize the best tools at our disposal to forecast what the true environmental impact of an action will be, and continually improve those tools. In the second chapter I will demonstrate one modeling method that is a step in that direction in terms of measuring the impact of recycling activities; but it is only one step. Further work is needed to develop a true understanding of the environmental consequences of our actions.

This work represents the culmination of my past four years of study and research, and my scholarly contribution to the environmental effort thus far. However, I must admit that I am not terribly optimistic, and many of the things discussed in this document are programs themselves. And yet, as Dee Hock said, "It's far too late and things are far too desperate for pessimism." Still, the change we need is much broader, and much more fundamental. It involves news that most would rather not hear: *It is not enough to consume differently; we must live differently, and we must consume less—far less*.

This isn't about saving the world; the world will go on as it has done for millennia. But if we—*homo sapiens*, "man thinking"—hope to have a place in its future and wish our legacy not to be one of destruction and extinction, we must change our ways of thinking: our conceptions of greenness, our environmental strategies and actions, and—most importantly—our *vision of life*, so our devices no longer are overthrown, but our wills and ends align for the sake of all humanity. Time is running out.

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ABSTRACT

Net Green: The Impact of Corporate Social Responsibility on the Natural Environment and Employee Satisfaction

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Human activities continue to degrade the natural environment in myriad ways, and at the heart of the problem is industrial activity—the extraction of resources, production, transportation, and use of goods, and the eventual disposal or recycling of materials. Yet, opportunities exist to engage industrial activity in creative, strategic ways that will actively improve the natural environment and help restore it to a state that can sustain human and nonhuman life into the future. This dissertation is intended to be a step toward that future by progressing our understanding in three separate but related topics in the context of corporate social responsibility (CSR).

In the first chapter I reenvision what is meant by "green business." Although the literature on business strategy and the environment frequently discusses *whether*, *why*, and *when* companies profit from "greenness," surprisingly little has been said—and no consensus has been reached—on *what* businesses can do that counts as "green." Despite the growing importance of environmental concerns to managers, stakeholders, and policy makers, the lack of a structured and practical definition of green business leaves well-intentioned

entrepreneurs and corporate environmental managers without useful guidance on how best to make environmentally relevant business decisions. In this chapter, therefore, I propose a new definition for greenness, which states that it is the net balance of the environmental consequences caused by an activity that determines whether or not the activity is "net green." To demonstrate the usefulness of the definition, I apply it to four case studies centered on pollution control and prevention activities, which seem prima facie green. Some of these activities turn out not to be net green after all; for others, the green intuition is correct, but with caveats.

The core outcome of the first chapter is that one of the most important factors determining whether an activity results in net environmental improvement or damage centers on the concept of "displaced production." The second chapter, therefore, analyzes the displaced production mechanism in the context of recycling and develops a methodology to estimate displacement rate. The typical assumption made in environmental assessments of product systems that include recycling is that secondary materials displace primary equivalents on a one-to-one basis. However, displaced production is a complex phenomenon governed by market mechanisms, and the one-to-one displacement assumption was heretofore untested. Chapter 2 advances the understanding of displacement by presenting a displacement rate estimation methodology based on partial equilibrium market modeling. First, I develop a basic market model that explains the underlying price mechanisms of displaced production and identifies key parameters affecting displacement rate. Results from the basic model suggest that one-to-one displacement occurs only under specific parameter restrictions that are unlikely in a competitive commodity market. Next, the modeling methodology is demonstrated by developing an econometric model of the U.S. aluminum

industry. The aluminum market model corroborates the basic model and suggests that U.S. aluminum displacement rates are likely to be below 100%.

The third chapter shifts focus from *what* a business can do to be sustainable to the more common question in environmental strategy: *why* a firm would want to be socially and environmentally sustainable. One explanation posited in the literature is that corporate social responsibility leads to higher employee satisfaction, which increases worker productivity and profitability. Yet, empirical evidence for the relationship between CSR and satisfaction is scarce. Using a novel dataset, I test this relationship for 3,121 U.S. firms from 1998 to 2012 and find that a company's performance in six out of seven CSR dimensions can explain whether it is rated by its employees as one of the best places to work in the country. I disaggregate the seven CSR dimensions into forty-four individual CSR measures, and from those identify ten measures that are most likely to affect employee satisfaction—six areas in which to improve (employee ownership plans, family benefits, gay and lesbian policies, charitable giving, conscientious labor rights, and product innovation) and four areas in which to reduce negative impacts (toxic emissions, workforce reductions, poor labor rights, and deceptive marketing).

This dissertation contributes to the literature in industrial ecology and life cycle assessment by clarifying the displacement mechanism and suggesting improved ways to estimate displacement rate, as well as to the business strategy and the environment literature by crystallizing what is meant by "green business" and furthering our understanding of how CSR is likely to increase a firm's economic success.

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A NEW DEFINITION OF GREENNESS WITH FOUR CASE STUDIES

ABSTRACT

A prominent question in environmental business strategy literature is whether it "pays to be green." Much has been said on *whether*, *why*, and *when* it is profitable for firms to engage in "green" activities, but this scholarly debate has been stymied by the lack of a consensus definition of what counts as "green." A similar lack of definitional clarity exists in the practical business world, leaving managers and entrepreneurs without guidance on how to create environmental companies. In an attempt to provide structure and guidance to environmental business scholarship and strategy, in this chapter I propose a rigorous definition for "greenness" rooted in industrial ecology and consequential thinking: *A business activity is green if and only if it produces net environmental benefit*. I discuss the theoretical underpinnings of net environmental impact, and then demonstrate the usefulness and insights of the new definition in four case studies—one for each of the four categories of pollution control and prevention activities. Although pollution control and prevention activities appear, at least on the surface, to be green, by applying the net green definition I demonstrate that no pollution prevention or control activities are guaranteed to produce net environmental benefit; indeed, some are all but guaranteed to increase impacts. Several common themes emerged from the case studies: that the displacement of harmful activities is the key to generating net environmental benefit, that determining *what* counterfactual alternative is displaced by an activity has potentially large bearing on the net green determination, that determining *how much* of an alternative activity is displaced is also important and difficult to determine, and that managers have some control over how their firms' activities affect markets and create or fail to create net environmental benefit. Implications for corporate managers, entrepreneurs, and researchers are discussed. The net green definition provides rigor and clarity to what counts as a green activity that will greatly assist researchers in industrial ecology and environmental business strategy, and will also provide guidance and a proactive goal for corporate environmental managers and environmental entrepreneurs. The methodology is demanding, but applying it allows us to ensure that efforts in environmental management are not mere lip service, but result in real, measurable improvements in the quality of the natural environment. The ultimate value of the new definition of greenness is not simply to enable the labeling of some things as green and others as not, but to create a fundamental shift in our thinking, moving from things that *seem environmental* to things that *actually improve the environment*.

1 INTRODUCTION

Over the past twenty years, scholarly research has increasingly investigated how businesses interact with and impact the natural environment. This research has been conducted primarily within two distinct disciplines: industrial ecology and business strategy and the environment (BS&E). Industrial ecology stems from engineering and thermodynamics and seeks to describe the physical nature of environmental impacts from industrial activities by studying flows of materials to and from the natural environment as they pass through the industrial system (Ayers & Ayers, 2002). BS&E stems from economics and strategic management and seeks to understand why businesses might engage in environmental management, what the financial consequences of that engagement are, and how best to leverage corporate environmentalism as a source of competitive advantage (Kim & Lyon, 2011; Lyon & Shimshack, 2012; Reinhardt & Stavins, 2010).

One prominent line of inquiry within BS&E literature is whether, when, how, and why there is a financial benefit for a firm's environmental actions, which has become known as the "pays to be green" (PTBG) literature (Berchicci & King, 2007). The traditional view held that "the business of business is business"; that is, that any investment by firms to reduce negative environmental externalities stands in direct opposition to the managerial duty to maximize shareholder wealth (Friedman, 1970). Michael Porter and Claas van der Linde (1995) famously provided a competing perspective, later termed the "Porter hypothesis": namely, that well-designed environmental regulation can spur innovation and allow opportunities for companies to leverage their environmental strengths as competitive advantage. Scholars began to realize that environmental performance could be a core competency of a firm that creates value for customers, shareholders, and external stakeholders (Hart, 1995; Sharma & Henriques, 2005). Many authors later argued that environmental problems are the result of a variety of market failures, including unpriced externalities and asymmetric information (e.g., Reinhardt, 1999b), and as such provide opportunities for firms to offer profitable solutions and innovative products to capture value (Dean & McMullen, 2007).

Gradually, the PTBG debate expanded from simply asking *whether* it pays to be green to examining *when* it pays to be green (King & Lenox, 2001a). Reinhardt (1999a) argued that firms can use the environment as a source of competitive advantage by differentiating environmental products, setting private standards that raise competitors' costs, saving costs by reducing waste, reducing costly environmental risks such as spills, and opening new environmentally conscious markets, but that not all of these are viable all the time or for all companies. Ambec and Lanoie (2008) later synthesized the PTBG literature in terms of when and how it might pay to be green, outlining four opportunities to reduce costs and three opportunities to increase revenues by engaging in environmental activities.

However, what has been absent from the BS&E literature is the question, *what is meant by "green"*? Much has been said on *whether*, *why*, and *when* to be green, but surprisingly little has been said—and no consensus has been reached—on *what* a firm can do that counts as green. Montiel and Delgado-Ceballos's (2014) review of corporate sustainability yielded seventeen different definitions among scholarly and practitioner management journals. These seventeen definitions have little agreement among them, and there are yet others in the broader corporate social responsibility (CSR) literature (of which corporate environmentalism is a subset). Reinhardt and Stavins (2010), for instance, follow Elhauge (2005) in defining CSR as "sacrificing profits in the social interest." This definition was useful for their purpose, which focused on the legal and moral issues of companies sacrificing profits, but it says little about what an activity "in the social interest" truly is. A recent review of environmental entrepreneurship research (Lenox & York, 2011) suggests that the field has sidestepped the issue almost entirely, focusing on *how* and *why* environmental entrepreneurship has developed rather than *what* it aims to accomplish or *whether or not it is (environmentally) successful*. Dean and McMullen (2007) define environmental entrepreneurship only as "the process of defining, evaluating, and exploiting economic opportunities that are present in environmentally relevant market failures," but say nothing about what is required for the activities of such entrepreneurs to be considered green.

Lyon's (2009) introduction to the special issue of the *Journal of Economics and Management Strategy* on management strategy and the environment conveys the idea that environmental strategy scholars are concerned with 1) how firms can best respond to pressures from environmental consumers, activists, and regulators, 2) how to effectively differentiate "environmental" products, and 3) how environmental pressures affect supply chain management. Berchicci and King (2007), in their review of BS&E literature, suggest that the two most important topics in the field are 1) whether firms can compete more successfully by protecting the environment, and 2) whether firms can create competition whereby protecting the environment leads to financial success. What is not discussed in either of these reviews is how managers, policy makers, and stakeholders can ensure that seemingly environmental choices do, in fact, "protect the environment."

Even when authors have examined specific examples of companies engaging in seemingly green activities, the question of whether an activity is truly environmentally beneficial is largely ignored. For example, Reinhardt (1999a) illustrated how firms may profit from encouraging stricter environmental regulations by recounting how California oil refiners encouraged California legislators to require the use of methyl tertiary butyl ether (MTBE) as an additive to reduce smog. The point he made is that California refiners enjoyed a period of reduced competition from out-of-state firms once MTBE use was mandated. However, the more important question from an environmental standpoint is whether encouraging the use of MTBE is an environmentally responsible choice in the first place. Reinhardt conceded that MTBE offers a tradeoff in that it reduces air pollution but leaks into groundwater; what was missing was a discussion about whether or not the strategy by California refiners ended up being a green and profitable decision or merely a profitable one. Were the activities by California refiners green, or not green? In an example of cost savings, Reinhardt discussed the use of recycled packaging materials by hotel chains and the design-for-environment practices of Xerox. In Reinhardt's discussion, these activities are taken for granted to be environmentally beneficial; as we will see in this article, whether this is true is not straightforward.

Such untested assumptions of greenness or vague definitions of what counts as a green activity are common in BS&E literature. Berrone et al. (2013) tested the effect of regulation on environmental innovation, measuring environmental innovation as the number of patents in areas of chemistry identified by the U.S. EPA Green Chemistry program; no attempt was made to determine whether these patents are, in fact, environmentally beneficial. Kim (2013) studied the effects of deregulation on firms' greenness, measuring greenness using firm entrance into renewable energy generation. Other authors measure greenness using the Toxics Release Inventory (TRI) (e.g., Berrone & Gomez-Mejia, 2009; Kassinis & Vafeas, 2006; King & Lenox, 2001b), proprietary weighted single-score indicators such as

Trucost (e.g., Delmas & Nairn-Birch, 2011), third-party certifications such as USDA Organic (e.g., Delmas & Lessem, 2012), company disclosures and sustainability reports (e.g., Lyon & Shimshack, 2012), or simplistic assumptions about what seems intuitively "green" (e.g., York, 2008).

Unfortunately, these measures are at best related to—but do not capture—the true environmental impact of a business activity. Some, such as corporate sustainability reports and patents, are very distant from actual environmental impacts, as they merely signal the firm's intentions and self-assessment rather than physical flows of emissions. Others, such as TRI emissions, at least represent actual emissions, but only incorporate internal activities and ignore their products' life cycle impacts. As we will return to later, scholars in industrial ecology have recognized for over two decades that the majority of a firm's impacts come not from its internal activities but from the upstream supply chain and downstream use-phase impacts of its products (Finnveden et al., 2009). Management researchers, on the other hand, "have rarely looked beyond the boundaries of the firm when evaluating environmental performance" (Delmas & Nairn-Birch, 2011). Moreover, these measures are yardsticks without a benchmark, and therefore are unable to define the notion of greenness. What is a green level of TRI emissions? How many and what kind of third-party certifications must a firm obtain to be green? Such questions have not been adequately discussed, much less settled.

Admittedly, the lack of a concrete concept of greenness can be attributed to the fact that determining what is green is not strictly within the purview of environmental strategy research. However, even if such discussions have been traditionally out of the scope of BS&E, the usefulness of research in BS&E to environmentally minded entrepreneurs and sustainability managers is limited by the fact that the physical realities of corporate environmental impact—the stuff of industrial ecology—are not well understood or incorporated into strategy research. Consequently, definitions of what exactly constitutes green business are missing, misguided, or unusably vague. Rather than asking the primary question "what makes a firm's actions environmental?" many authors in the green business literature have skipped a step and assumed there is an unambiguous set of ways that a business can act in sustainable manner—that sustainability vs. non-sustainability in business is clearly delineated and well known—and the only question left to the manager is whether and when to engage in sustainable activities. As I will demonstrate throughout the course of this article, this is not the case. All business activities, even those that seem intuitively green, can cause a variety of effects with concomitant environmental consequences.

Therefore, a concise and meaningful definition of whether or not an industrial activity is green is needed so that managers and scholars can determine whether a proposed activity is actually environmentally beneficial.

I thus propose a new definition for "greenness," rooted in fundamental concepts of industrial ecology, and argue that it is the net balance of the environmental consequences caused by an activity that determines whether or not the activity is "net green." This new definition provides rigor, clarity, and direction to both BS&E and industrial ecology. Armed with this definition, managers can assess a set of alternatives based not only on their financial outcomes, but also on whether they will cause net damage or net benefit to the environment; scholars can pursue the question of whether it pays to be green with a clear definition of what is meant by "green." To demonstrate the usefulness of the definition, in this article I apply it to four different case studies focusing on industrial activities that, at least on the surface, seem intuitively green. Some of these activities turn out not to be net green after all; for others the green intuition is correct, but with caveats.

This article is organized as follows: In Section 2 I present and develop the new definition of greenness. In Section 3 I introduce the four types of pollution control and prevention (PCP) activities that serve as the basis for the four case studies in Sections 4–7. For each case study, I briefly explain the PCP activity before considering a representative case study that illustrates the key factors determining net environmental impact. In Section 8 I draw together general conclusions, lessons for improving our understanding of greenness, and general principles to help maximize the net environmental benefit of business activities.

2 NET GREEN

Progress in research on corporate greenness has been mired and its applicability to managers limited by the lack of a principled definition of a green business activity. I therefore propose a new definition of a green business activity:

> *A business activity is green if and only if it produces net environmental benefit.*

To more fully develop this definition, in this section I will discuss what is meant by environmental impact (and conversely, environmental benefit), the importance of life cycle thinking, how a business can actually create net environmental benefit, and a mathematical formulation of the definition.

2.1 Environmental impact and life cycle thinking

The condition of the environment at any given moment is the environmental status quo. Reductions from the status quo in the quality of the environment (broadly defined) represent environmental impacts or damage. Conversely, increases from the status quo in the quality of the environment represent environmental benefit. Because the current environmental status quo is one of degradation from its natural (pre-industry) state due to ongoing environmental impacts, one way to produce environmental benefit is to reduce these ongoing impacts.[4]

Environmental impacts arise from flows of physical materials to and from the natural environment at a faster rate than they are able to be regenerated or metabolized. All else equal, the higher the quantity or harmfulness of materials that flow to and from the environment, the more damage is done to the environment. Thus, when we consider the greenness of a business or business activity, we are concerned only with actual environmental impacts—physical material extraction and emission—and not "environmental policies" or "environmental practices" except to the extent that they cause or reduce physical environmental impacts.

Nearly every conceivable business activity at some point causes the extraction of raw materials from the earth or the release of substances into the environment. At the very least, any activity that uses electricity or fuel energy relies on the extraction and combustion of coal and oil, even if the electricity used is directly supplied by renewables such as solar or wind. Even the most seemingly benign activities require materials and energy and cause emissions to the environment.

At the heart of this realization is "life-cycle thinking," or the idea that a company's environmental impacts arise not only from internal activities, but from the upstream and

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[4] Environmental benefits and environmental impacts can be—but are not by definition—opposites. Reducing impacts is only one way to create environmental benefit. For instance, stopping deforestation is a reduction in impacts that creates environmental benefit. On the other hand, planting trees produces environmental benefit but does not reduce ongoing environmental impact. Industrial activity rarely, if ever, takes the form of pure environmental benefit (what business exists solely to plant trees?), so I focus in this article on impact reduction with the recognition that impact reduction activities are but a subset (yet, an important subset) of activities that produce environmental benefit.

downstream activities throughout the life cycle of its products. Many companies in the developed world have low-impact internal operations only because they have largely exported dirtier stages of the supply chain—material extraction and manufacturing—to developing economies (Jackson & Clift, 1998). Yet, these dirty activities in the developing world occur as a result of companies selling products in the developed world. Life cycle assessment (LCA), a tool of industrial ecology, is a process of quantifying environmental impacts of the entire life cycle of a product system. Consequential life cycle assessment (CLCA) is an extension of LCA that recognizes that changes in products and processes—or in businesses' activities—can cause further changes that ripple throughout the global economy, meaning life cycles are effectively expanded to include environmental impacts from processes that occur as a result of the initial change (Earles & Halog, 2011).

The core of the net green definition is rooted in CLCA thinking: The net environmental effect of a business activity is the sum of the impacts from all the changes that occur as a result of the initial activity, as they ripple outward through the economy. For instance, a corn ethanol company might increase demand for corn, which raises its price and induces farmers in Brazil to deforest more Amazon rain forest land. In this case, the net impact of the corn is equal to the direct impacts as well as the downstream effects, including the carbon released by the felled rain forest trees. Only by examining the entire consequential life cycle of an activity—the consequences of that activity as they ripple through cause-effect chains in the global economy—can we grasp a complete picture of its environmental impact.

2.2 Environmental benefit through market competition: Netflix vs. Blockbuster

Given the fact that business activities necessarily involve upstream and downstream processes that cause physical environmental damage, and that net impact includes the totality of causally connected impacts, it may seem as though net green status under this definition is unattainable. How can a business activity possibly cause environmental benefit? The answer is that causally connected effects can be both environmentally harmful and environmentally beneficial. The creation of net benefit occurs when causally connected benefits outweigh causally connected impacts.

As an example, consider the rise of online and on-demand video services, and the subsequent demise of Blockbuster Entertainment Inc. Blockbuster was a runaway success in the 1980s and 1990s, defining a new industry of video and game rental. Yet, with the rise of on-demand and Internet entertainment in the late 2000s, notably from Netflix Inc., cable and satellite providers, and video piracy, Blockbuster was unable to compete and in 2010 filed for bankruptcy before liquidating its last store in November of 2013.

Blockbuster, by using brick-and-mortar retail stores and physical media for movies, had significant environmental impacts. Aside from the impacts associated with creating, maintaining, and powering more than 4,000 physical stores (at the company's peak) and causing the production of countless millions of physical VHS cassettes, DVDs, and plastic cases, the Blockbuster model also required two individual automobile trips per rental (one to pick up and one to return). By contrast, on-demand videos and online entertainment require no travel by the consumer, although they do require Internet infrastructure and large amounts of energy to power datacenters (Chang, Meza, Ranganathan, Bash, & Shah, 2010).

Some studies have attempted to quantify the tradeoff between physical stores, media, and automobile trips versus datacenter electricity and infrastructure; the emerging consensus is that digital delivery systems reduce primary energy demand and carbon dioxide emissions as compared to physical delivery systems (Weber et al., 2008; Weber, Koomey, & Matthews, 2010). A recent study has confirmed that media streaming creates lower GHG than DVD delivery (Shehabi, Walker, & Masanet, 2014). This means that the closure of Blockbuster reduced net environmental damage, and this represents a case where a company, Netflix, was able to create net environmental benefit through Schumpeterian creative destruction (Schumpeter, 1976) by competing with and eliminating a business that had higher impacts than its own.

2.3 Net environmental impact and benefit

The key to achieving net environmental benefit rests in the ability of one activity to reduce the activity level of other activities. That is, even though every business activity inevitably causes environmental damage, there are some activities that might also prevent, or "displace," even greater environmental damage by reducing the activity level of more harmful activities. The sum, or net, of all the environmental impacts caused or displaced by an activity is its net impact or benefit. Only those that result in net environmental benefit can be considered net green.[5]

To introduce more formality to the concept of net impact, we can think of a business activity (A_1) as having two environmentally relevant components. The first component is the direct environmental impacts of the activity (E_1), which are a function of the activity: $E_1 = E_1(A_1)$. Second, we can think of the business activity as being part of a chain of cause and effect, such that every business activity has consequences that ripple throughout its economic environment and influence the activity levels of other activities ($A_2, A_3, \ldots$). For instance, the activities of Netflix had impacts on the activities of Blockbuster (namely, to

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[5] Net greenness is always attainable provided there is some ongoing environmental impact that can be reduced or eliminated. If society were to achieve an environmental state that matched the pre-industrial state, net green would become unattainable because all activities would result in net impact rather than benefit. However, if we reach such a state then this distinction will, fortunately, be irrelevant.

eliminate them). These consequences then cause changes in yet other activities further down the causal chain until eventually they are drowned out by other factors. We can label these affected activities as second-order, third-order, and so on, and note that each is a function of the previous. Additionally, any given activity may have more than one consequence at each causal level; for instance, an activity might have multiple second-order consequences. Furthermore, some higher-order activities might have an effect on the original activity or other lower-order activities, creating loops. The interconnected nature of activities can, therefore, become quite complex. Figure 1.1 diagrams some of the possible connections.

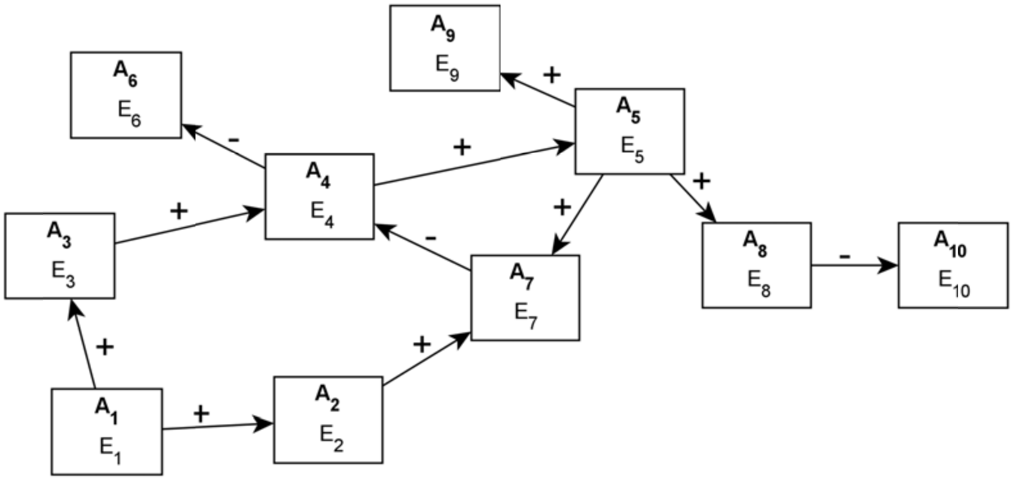

Figure 1.1: Representation of the interconnected nature of industrial activities. Signs above arrows indicate that the relationships can either be direct (+) or inverse (-).

Like the original activity, each of these higher-order activities has associated environmental impacts, $E_2(A_2), E_3(A_3), \dots, E_n(A_n)$, which are necessarily positive functions of the level of the activity (i.e., $E_i(A_i) > 0$). However, the relationships between the higher-order impacts need not be direct; increased levels of one activity may cause decreased levels of other activities; that is, it can be that $A_2(A_1) < 0$. This would mean that the associated environmental impacts of A_2 are also negative, or in other words, avoided. This is the crucial point that allows for the possibility of net environmental benefit and the realization of the net green definition. If an activity avoids more impacts than it creates, it reduces net impact.

Specifically, the net impact of activity A_1 is the sum of the direct impacts E_1 and the higher-order impacts E_i:

$$E_{net}(A_1) = \sum_{i=1}^{n} E_i \tag{2.1}$$

where $E_i = E_i(A_i)$.

Under the net green definition presented above, business activity A_1 is green if and only if $E_{net}(A_1) < 0$, which is possible because connected higher-order A_i can be negative.

2.4 Impact category tradeoffs

Thus far I have referred to "environmental impacts" as though all impacts are identical. Of course this is not the case. Environmental impacts can be classified into impact categories according to the type of environmental concern they represent: global warming impacts, water acidification impacts, human and ecotoxicity impacts, and so forth. An important theme throughout this paper will be that these impact categories occasionally conflict: An activity that reduces global warming impacts, for example, may increase toxicity impacts. How to handle these impact category tradeoffs remains a significant challenge for environmental assessment in general (Ayers & Ayers, 2002). Single-score weighting, multi-criteria decision analysis, and other methods have been proposed to assist in decision making in the face of tradeoffs (Seppälä, Basson, & Norris, 2001; Seppälä & Hämäläinen, 2001; Tuomisto, Hodge, Riordan, & Macdonald, 2012). However, it remains unequivocal that there is no scientifically objective way to compare impacts across different categories. The net green definition, therefore, cannot provide a solution to the problem of impact tradeoffs.

Nonetheless, two points are worth making regarding tradeoffs and their relevance to the net green definition. First, there are many instances in which tradeoffs exist but are less important because one impact category is clearly the impact of interest. For instance, environmental assessments of energy or transportation systems predominantly focus on greenhouse gas (GHG) emissions since global warming is the most prominent environmental impact of these systems; environmental assessments of agriculture tend to focus on eutrophication and water toxicity from runoff, since these are topics central to current debates about organic, traditional, and genetically modified farming; assessments of consumer products tend to focus on human toxicity and carcinogens, since these are topics that most concern consumers.

Second, tradeoffs are not inevitable. There are countless examples of activities in a wide range of industries that do not create impact category tradeoffs. It has been shown, for example, that light-emitting diode (LED) lightbulbs have lower life cycle impacts than incandescent lightbulbs in every impact category (except toxic landfill impacts, which are of questionable importance) (Scholand & Dillon, 2012); electric hand driers have lower impacts in all categories than paper towels (Montalbo, Gregory, & Kirchain, 2011); underground power distribution networks have higher impacts in all categories than overhead systems (Bumby et al., 2010). The fact that such cases exist suggests that the most effective environmental activities are those that are able to reduce impacts in the category of interest without tradeoffs. It may be that the presence of significant impact tradeoffs is an indication of a suboptimal environmental option; if focus-area impacts can only be reduced with higher impacts in other categories, perhaps another option exists that can avoid the tradeoff. This also suggests that the focus of environmental research should not be on interpreting or making decisions in the presence of tradeoffs, but rather on finding other solutions that avoid them entirely. One conclusion from this paper will be that some types of activities are more likely than others to avoid tradeoffs.

3 POLLUTION CONTROL AND PREVENTION ACTIVITIES

If one were to look for a set of industrial activities that would be commonly accepted—at least on the surface—to be green, one could do worse than to turn to the broad umbrella called “pollution control and prevention” (PCP) activities. These activities have arisen over the past century in response to increasing evidence of the impact humans have on the environment. From smokestack filters to complex material cycling networks, hundreds of different business activities that are meant to protect the environment can be classified as PCP activities. Under the Pollution Prevention Act, the U.S. EPA definition of pollution prevention activities includes “equipment or technology modifications, process or procedure modifications, reformulation or redesign of products, substitution of raw materials, and improvements in housekeeping, maintenance, training, or inventory control” (42 U.S.C. §13101 et seq., 1990). This list, together with traditional pollution controls, can be distilled into four categories (Jackson, 1996):

1. End-of-pipe pollution control
2. Reuse and recycling
3. Material or technology substitution
4. Dematerialization

Activities that fall into these four groups undeniably have the ring of greenness. However, simply because an activity can be classified into one of the four PCP groups does not mean that it necessarily produces net environmental benefit, and therefore—by the new definition of net greenness—it is not necessarily truly green. To demonstrate the new net green definition and to illustrate how activities that seem to be green may or may not create environmental benefit, I examine each of the four types of PCP activities through the lens of the net green definition.

In each case study, I first describe what is meant by the PCP category. I then introduce the relevant background details about the subject activity, and identify the key environmental forces that potentially decrease environmental impact and those that potentially increase environmental impact. The question in each case will then become to determine which of these forces is the strongest, or to what degree they necessarily result in tradeoffs (between different types of impacts, for instance). I identify the most important research questions one would need to answer to know how these forces are likely to manifest, and then I briefly outline the state of knowledge on the questions. To the extent that it is feasible within the scope of the article, I provide research methodologies and, where possible, answers to these key questions.

The objective of these case studies is not to conclusively determine whether any of the activities described are “net green”; such an endeavor would require deeper research into each subject. Rather, the objective is threefold: firstly, to demonstrate the usefulness and applicability of the new definition of net green; namely, that if one is interested in assessing the true greenness of an activity, the net green definition requires that one follow cause-effect chains and consider environmental impacts that arise throughout. This ensures that all possible environmental consequences of an activity are accounted for. Second, to highlight that even though all of these PCP activities may *seem* green, some of them are likely to result in net environmental benefit while others are not. In many cases, there are inherent tradeoffs that make determining the net greenness of an activity difficult or subjective. This finding will further demonstrate that the new definition gives us useful insight into best practices for corporate environmental management.

4 POLLUTION CONTROLS

Traditionally, one of the simplest environmental business activities has been to install end-of-pipe pollution control technologies such as scrubbers, filters, or purification plants. These technologies are installed at the physical end of a chain of industrial processes, for instance on smokestacks and effluent outlets, in order to reduce impacts from emissions.[6] Pollution controls can range in complexity from simple mesh or cloth filters, to chemical catalyst scrubbers, to using constructed wetlands to filter effluent and return clean water to aquifers.

Pollution controls can be mildly or extremely effective at reducing impacts and have largely solved some past environmental impact priorities, such as reducing acid rain by using coal power plant sulphur oxides (SO_x) filters. However, producing and running these end-of-pipe pollution controls requires energy and material inputs which cause environmental impacts. Additionally, captured wastes can still present a disposal problem. For instance, a chemical plant that captures end-of-pipe effluent can effectively divert pollutants away from rivers, but collected effluent must be treated and stored, which requires energy and could potentially leak to groundwater. Sometimes collected waste can be reused as an industrial input, as in the case of calcium sulfite SO_x scrubbing, which creates gypsum used for drywall. In other cases, the waste is hazardous and must be carefully stored.

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[6] Pollution controls are sometimes said to "reduce emissions." In reality, conservation of mass dictates that emissions are not reduced in mass. Rather, they are transformed to a different, less harmful state. Therefore, more precisely, pollution controls transform emissions and thereby reduce *impacts* from emissions, not emissions themselves.

The potential for pollution controls to create net environmental benefit is that the avoided impacts from the sequestered emissions may be greater than the incurred impacts of producing and running the controls and disposing of by-products. As we will see in the following case study, it is not straightforward that this will always be the case.

4.1 Case study: Coal-fired electricity with carbon capture and storage

4.1.1 Background

In 2012, U.S. electricity generation was responsible for about 2 Gt of carbon dioxide (CO_2) emissions, or roughly 39% of total U.S. energy sector emissions, with coal-fired power plants contributing 37% of total electricity generation (U.S. Energy Information Administration, 2014a). The most recent U.S. Energy Information Administration (EIA) projections predict that coal will continue to supply roughly 32% of U.S. electricity through the year 2040. However, coal produces the highest CO_2 emissions of any current electricity generation source, emitting 94.6 g CO_2/MJ electricity, as compared to 77.4 g CO_2/MJ for residual fuel oil or 56.1 g CO_2/MJ for natural gas (Intergovernmental Panel on Climate Change, 1997).[7]

Combustion of coal is therefore a major contributor of CO_2 emissions and radiative forcing that leads to global warming (Metz, Davidson, Coninck, Loos, & Meyer, 2005). In response to mounting pressures to reduce CO_2 emissions, technologies have been proposed and prototyped to capture and store carbon emissions from coal and other major combustion sources such as cement plants, a process known as carbon capture and storage (CCS)—sometimes referred to as “clean coal.” The basic idea of CCS is to capture the carbon emissions from fossil fuel—primarily coal—combustion and store the carbon underground

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[7] These figures are emissions factors from combustion only based on net calorific value; they do not account for life cycle emissions such as extraction, processing, and transportation.

for thousands or millions of years. In some instances, CCS can reduce net life cycle CO_2 emissions by 80–90%, but concerns about capture efficiency losses and safety in transport and storage have been raised (Metz et al., 2005). CCS is often touted along with natural gas as a “bridge fuel” that will enable the transition to renewable energy by providing base-load energy capacity (Haszeldine, 2009). However, some argue that allocating monetary and intellectual resources to making fossil fuels marginally cleaner reduces incentives for developing renewables and, to the extent that subsidies for cleaner fossil fuels lower energy costs, prices renewables out of the energy market (J. Farrell, 2014).

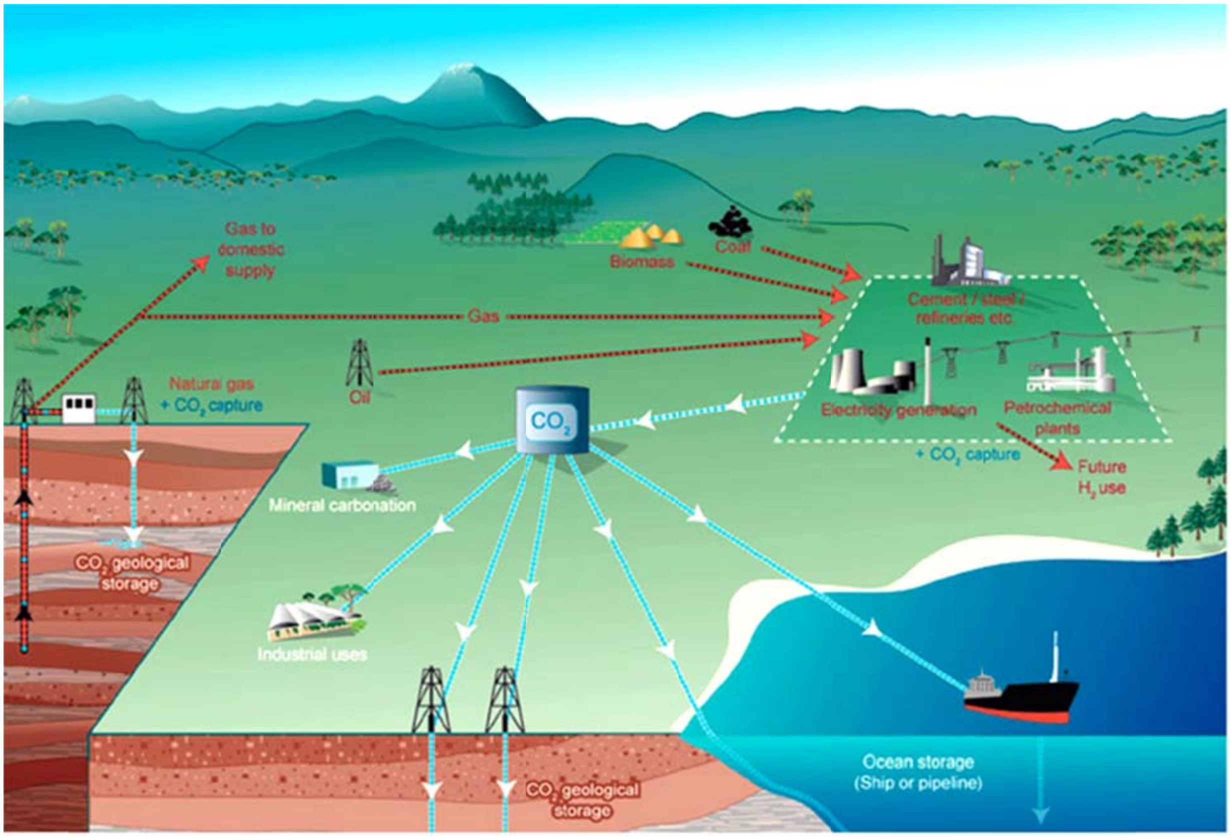

Figure 1.2: Schematic showing carbon capture and storage process (source: CO2CRC)

There are three basic steps to CCS: CO_2 capture, CO_2 transport, and CO_2 storage. Carbon dioxide capture technologies are nascent, and none have been deployed at an industrial scale, but there are currently three emergent carbon capture technology types: post-combustion, pre-combustion, and oxy-fuel capture systems.

Post-combustion technologies are most common, and operate using either absorption of CO_2 into a solvent, adsorption onto a solid surface, gas separation membranes, or cryogenic distillation (for a review of these technologies, see J. C. M. Pires, Martins, Alvim-Ferraz, & Simões, 2011). Post-combustion systems generally require large amounts of energy either for changing pressure, temperature, or for solvent regeneration. Additionally, solvent regeneration can create toxic by-products, and expired solvents present a disposal concern (Haszeldine, 2009). However, post-combustion technologies are most common because they have the advantage that they can be retrofit onto existing coal power plants. I will confine this discussion to post-combustion technologies both because they are most likely to be developed in coming years, and because they represent true end-of-pipe emission controls, which are the subject of this section.

Carbon dioxide transport is a mature technology in that similar processes are currently used to transport a variety of gases, and transport of CO_2 by pipeline occurs currently as part of enhanced oil recovery (Metz et al., 2005). To transport by pipeline, ship, or tanker truck, CO_2 is purified, dewatered, and compressed to a supercritical state (80–150 bar), requiring between 90 and 120 kWh/tonne CO_2 (Aspelund & Jordal, 2007).

Carbon dioxide can be stored in several ways: geological formations, ocean storage by injection dissolving or ocean-floor deposition, mineralization into carbonates, and, in small quantities, utilization as an industrial input (Metz et al., 2005; J. C. M. Pires et al., 2011). Mineralization involves catalyzing a reaction of CO_2 with metal oxides for permanent storage. However, this process is highly energy intensive and also problematic, because it requires intense surface mining for silicate rock and still presents a disposal challenge for the carbonate minerals. Ocean storage can either be performed by injecting gaseous or liquid CO_2 into shallow oceans, where it will dissolve and enter the global carbon cycle, or by injecting liquid CO_2 below depths of 3 km, where it will be denser than water and will sink to form "lakes" on the ocean floor. These lakes are thought to delay the dissolution of the CO_2 into the surrounding water, although only laboratory-scale tests have been conducted (J. C. M. Pires et al., 2011). Both of these methods have potential problems, because increased levels of CO_2 in ocean water increase water acidity causing death to marine life forms and potential damage to marine ecosystems, and because the storage is not permanent but will slowly reach equilibrium with atmospheric CO_2 concentration (Herzog, Caldeira, & Adams, 2001). Industrial uses of CO_2 are expected to be small and, because of the high energy costs of obtaining the CO_2, do not necessarily reduce net carbon emissions (Metz et al., 2005).

Geological storage is considered the most economically and environmentally viable option and can take place in depleted oil and gas reservoirs, saline aquifers, unusable coal seams, and as the primary input to enhanced oil recovery (EOR) (J. C. M. Pires et al., 2011). Geological storage is performed by compressing CO_2 and pumping it to a depth of at least 800–1,000 m, where atmospheric pressure retains it in a supercritical state (Celia & Nordbotten, 2009; Gibbins & Chalmers, 2008).

The obvious risks associated with geological storage (without EOR) are those of leakage, both above ground and to groundwater. Carbon dioxide is dangerous to humans at concentrations greater than 0.5–1.5% by volume of air, and lethal in concentrations greater than 7–10% (Metz et al., 2005; J. C. M. Pires et al., 2011). Carbon dioxide is heavier than air at sea level, so any leaks from geological storage will flow downhill and remain in valleys. In a tragic example of these risks, in Cameroon in 1984 a large quantity of CO_2 trapped at the bottom of Lake Nyos was rapidly released. The gas flowed down into nearby populated areas and killed 1,700 people (Kling et al., 1987).

Rapid leakage is most likely to occur through failed wells and would present serious health risks to any surrounding human, plant, or animal populations. Slower leaks through undetected faults or fractures pose a risk of elevated CO_2 levels in subsoil, which may be lethal to subterranean animals and plants, and may also contaminate groundwater (J. C. M. Pires et al., 2011). It has also been recognized that due to the structure of geological formations, small-scale leaks may combine to form larger releases (Celia & Nordbotten, 2009). Any CO_2 leaked from storage will reenter the atmosphere, decreasing the overall effectiveness of CCS. Additionally, it has been suggested that pressure buildup of stored CO_2 could trigger seismic events (Metz et al., 2005; J. C. M. Pires et al., 2011; Zoback & Gorelick, 2012).

Using captured CO_2 in EOR has potential benefits and risks of its own. EOR is a practice that increases recovery of oil and gas from depleted or highly viscous wells by pumping fluids into neighboring wells. The injected “drive liquid” loosens and mixes with the oil or gas, reducing viscosity and surface tension and allowing it to be pumped through an adjacent well. Since the 1970s, oil companies have used CO_2 and water as a drive liquid in EOR (Klara, 2004). Traditionally, CO_2 used in EOR has come from natural sources; recently, however, the possibility of using EOR in connection with carbon storage has been proposed. The process of EOR would remain unchanged except that the CO_2 would come from carbon capture plants as discussed above.

The primary risks of EOR using CO_2 are common to any EOR process: During the injection/recovery process, large quantities of brine are brought to the surface. Called "flowback" or "produced water," this brine often contains toxic metals, radioactive substances, and very high concentrations of salt (U.S. Environmental Protection Agency, 2012). These substances make disposal of produced water environmentally sensitive, and disposal is regulated by the U.S EPA. Typically, produced water is injected into Class II wells; however, in some areas these wells are not available or there are too few, so produced water is impounded at the surface (Vidic, Brantley, Vandenbossche, Yoxtheimer, & Abad, 2013). Class II wells are regulated in their construction, operation, monitoring, testing, reporting, and closure, and are intended to keep disposed materials from reaching drinking water aquifers. However, there are a non-trivial number of recorded cases of groundwater contamination from injection wells (Vidic et al., 2013), and it has been shown that certain characteristics of injection wells (such as the net balance in injected and withdrawn liquid) can cause them to induce seismic events. CCS in particular has been singled out as a particular concern for creating large seismic events because of the large volumes of injected fluids (Hitzman, 2013).

4.1.2 Key environmental factors and key questions

Previous authors have detailed the numerous technical, economic, and political difficulties facing the large-scale commercial viability of CCS (e.g., Haszeldine, 2009; Kirchsteiger, 2008). Some have claimed that CCS is a set of false promises that alleviates political pressure on coal energy generators while actually achieving no change (Rochon et al., 2012). It has also been pointed out that the current rate of CCS development will push the actual deployment of CCS well beyond the 2020 carbon reduction requirements to limit climate change to a 2°C rise (Haszeldine, 2009). This has led some authors (e.g., Haszeldine, 2009; Mack & Endemann, 2010) to push for streamlined regulations, institutionalized development of infrastructure, and more efficient carbon markets to incentivize the development of CCS. In response, the U.S. Department of Energy has actively encouraged research into improved carbon storage programs, particularly in connection with EOR (U.S. Department of Energy, 2013a).

However, according to the net green definition, before we begin to address the roadblocks to CCS or incentivize its development with public money, we must first determine if CCS is in fact likely to reduce net environmental damage; before we ask "Is CCS a viable technology?" we must ask "Is CCS a *net green* technology?" If it is net green, we should work to hasten the commercial rollout of CCS; if it is not net green, we should abandon the endeavor.

The preceding discussion highlighted key aspects of CCS that determine its environmental impact, summarized in Table 1.1. The table shows that the environmental impact of CCS rests on several factors: the net balance between incurred and captured emissions (including storage leakage), the extent to which stored CO_2 (whether through dissolution into seawater or leaks from geological storage) may present health risks for humans and ecosystems, and the economic consequences of increased CCS on the persistence of coal-fired energy and on the development and deployment of renewable energy technologies.

	Potential environmental benefit	Potential environmental damage
1.	CCS may capture and store CO_2 emissions that would otherwise be released to the atmosphere.	The capture, transport, and storage of CO_2 requires energy that creates emissions of its own, which may be greater or less than the emissions reduced by CCS.
2.	Geologically stored CO_2 may safely remain in storage for thousands or millions of years.	Stored CO_2 may leak through inactive wells and faults or due to seismic activity, negating the effects of capture; additionally, leaks may poison terrestrial plants and animals, contaminate groundwater, and in large-scale leaks, may be toxic to humans.
3.	CO_2 stored in oceans may safely remain out of the atmosphere for thousands of years.	CO_2 stored in oceans may equilibrate with atmospheric levels negating the effects of capture; additionally, it may increase acidity, causing mortality among aquatic organisms and damage to ecosystems.
4.	CCS may provide cleaner base-load energy that enables the transition to renewable energy technologies.	CCS may shift economic incentives from development and deployment of renewable energy technologies to that of coal-fired energy using CCS.

Table 1.1: Key factors determining the environmental impact of carbon capture and storage

We can organize these key factors into three main focus questions:

1) Does CCS increase or decrease net CO_2 emissions?
2) Does CCS lead to tradeoffs in other impact categories?
3) How does CCS affect the future role of renewable energies by changing the socio-economic-political landscape?

Next, we will address each of these questions in turn:

1) Does CCS increase or decrease net CO_2 emissions?
    a. What are the CO_2 emissions of producing CCS equipment and infrastructure?
    b. How are direct power plant CO_2 emissions affected by CCS?
    c. How are upstream fuel delivery emissions affected by CCS?

CCS requires capture equipment, extensive pipelines, and storage equipment such as drilling rigs and tanker ships. Manufacturing this equipment requires energy, which will be supplied by the marginal energy mix of the geographic region where the equipment is built, and will produce CO_2 emissions according to the type of generation technology and fuel used. Therefore, even before a CCS plant is operational it faces a significant “carbon debt,” the amount of additional carbon emissions created simply to bring the CCS equipment on-line. Because the extent and type of infrastructure required as well as the marginal generation technology and fuel are situation-specific, it is not possible to know how large the carbon debt will be in general.

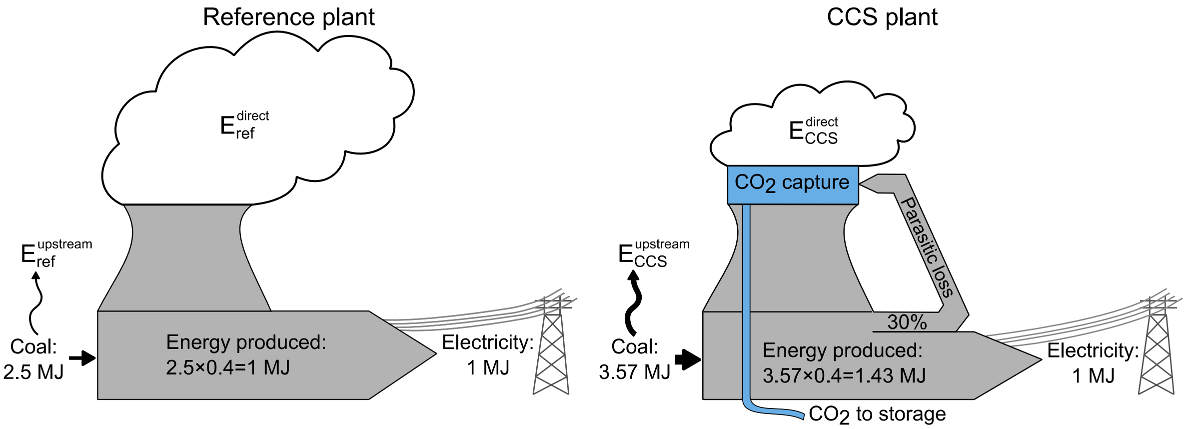

Figure 1.3: Schematic showing how direct and upstream CO_2 emissions differ between a CCS and reference plant

CCS also changes a power plant's direct CO_2 emissions per unit output, known as the emission factor (Figure 1.3). CO_2 capture equipment reduces emissions to air as a function of capture efficiency. Capture efficiency (η_{cap}) is the ratio of per-unit-output CO_2 generated to per-unit-output CO_2 captured. Generated CO_2 is equivalent to CO_2 emission factor of the reference plant (E_{ref}^{direct}):

$$\eta_{cap} = \frac{CO_{2_{cap}}}{CO_{2_{gen}}} = \frac{CO_{2_{cap}}}{E_{ref}^{direct}} \tag{4.1}$$

However, it is not the case that CO_2 emissions from a CCS plant will be lower than those of a reference plant by the amount of the capture efficiency. Rather, the actual reduction will be lower because operating capture equipment requires energy, which is provided by the output from the plant itself. The energy that is used to power capture equipment rather than produce electricity is known as parasitic loss (X) and can be expressed as one minus the ratio of energy output to energy production:

$$X = 1 - \frac{MJ_{output}}{MJ_{produced}} \tag{4.2}$$

In order for the CCS plant to overcome the parasitic loss and achieve equivalent output to the reference plant, total production must be scaled up by the inverse of one minus the parasitic loss $((1/(1-X))$. For instance, in Figure 1.3, parasitic loss is 30%, so total energy production must be increased to $(1/0.7)$ = 1.43 MJ in order to maintain 1 MJ electricity output. Scaling up total production also increases the total CO_2 generated, so that the direct CO_2 emissions per unit output for the CCS plant are equal to CO_2 emissions of the reference plant scaled by the ratio one minus capture efficiency to one minus parasitic loss:

$$E_{CCS}^{direct} = E_{ref}^{direct}\left(\frac{1-\eta_{cap}}{1-X}\right) \tag{4.3}$$

Because parasitic loss requires plant production to be scaled up, the input fuel production must also be scaled up by $1/(1-X)$. In Figure 1.3, input coal must be increased from 2.5 MJ to 2.5 × $(1/0.7)$ = 3.57 MJ. Extracting, processing, and transporting this additional fuel requires energy and resources that create increased CO_2 emissions ($E^{upstream}$). The upstream emissions factor for the CCS plant is increased over the upstream emission factor for the reference plant by the inverse of one minus parasitic loss:

$$E_{CCS}^{upstream} = E_{ref}^{upstream}\left(\frac{1}{1-X}\right) \tag{4.4}$$

Thus the total CO_2 emission factor of the CCS plant is given by combining eqs. 4.3 and 4.4:

$$\begin{aligned}
E_{CCS}^{total} &= E_{CCS}^{direct} + E_{CCS}^{upstream}\\
E_{CCS}^{total} &= E_{ref}^{direct}\left(\frac{1-\eta_{cap}}{1-X}\right) + E_{ref}^{upstream}\left(\frac{1}{1-X}\right)\\
E_{CCS}^{total} &= \frac{E_{ref}^{direct}\left(1-\eta_{cap}\right) + E_{ref}^{upstream}}{1-X}
\end{aligned} \tag{4.5}$$

To arrive at the true total additional emissions caused by CCS, one would add these increased emissions from parasitic loss to the emissions from infrastructure creation. However, because CCS infrastructure is a one-time activity and parasitic losses are in terms of unit output, they are not convenient to sum. In order to do so, one would divide the infrastructure creation emissions by an assumed lifetime plant output. For simplicity I will limit this discussion to only per-unit-output emissions. Thus, we can calculate the change in emissions due to CCS by subtracting the total CCS plant emission factor from the total reference plant emission factor:

$$E_{CCS}^{net} = E_{CCS}^{total} - E_{ref}^{total}$$
$$E_{CCS}^{net} = \left(E_{ref}^{direct} \left(\frac{1 - \eta_{cap}}{1 - X} \right) + E_{ref}^{upstream} \left(\frac{1}{1 - X} \right) \right) - \left(E_{ref}^{direct} + E_{ref}^{upstream} \right)$$
$$E_{CCS}^{net} = \frac{E_{ref}^{direct} \left(X - \eta_{cap} \right) + X E_{ref}^{upstream}}{1 - X} \qquad (4.6)$$

If $E_{CCS}^{net} < 0$, net CO$_2$ emissions from CCS are reduced as compared to a reference plant. From eq. 4.6, we can see that the net balance of CO$_2$ emissions from CCS relies on only three factors: capture efficiency, parasitic loss, and the relative sizes of direct and upstream emissions. For example, Rubin et al. (2005) calculated that a pulverized coal plant with CCS has parasitic loss of 27% and capture efficiency of 90%. From the Ecoinvent 2.2 life cycle inventory database (Ecoinvent Centre, 2012), direct CO$_2$ emissions from burning coal in a power plant in the Western Electricity Coordinating Council (WECC) region of the U.S. are 97 $\mathrm{g/MJ}$ electricity output, whereas upstream fuel supply emissions are 5.43 $\mathrm{g/MJ}$. This means a CCS plant such as the one described by Rubin et al. (2005) would result in net CO$_2$ emissions of:

$$E_{CCS}^{net} = \frac{97(0.27 - 0.9) + 0.27 \times 5.43}{1 - 0.27}$$
$$E_{CCS}^{net} = -81.7 \text{ g } \mathrm{CO_2/MJ}, \qquad (4.7)$$

or an 80% reduction in CO$_2$ emissions per MJ electricity.

It turns out that this result is typical of CCS plants. Zapp et al. (2012) conducted a review of thirteen life cycle assessments (LCAs) of coal power using post-combustion CCS. Since this review, Volkart, Bauer, and Boulet (2013) completed an additional LCA of energy generation from hard coal with and without CCS. There is a high degree of agreement among the fourteen studies that CCS can reduce life cycle CO_2 emissions by roughly 65–90%. The largest area of variation between LCA studies of CCS is assumed fuel composition and origin, which can significantly affect upstream impacts (Zapp et al., 2012).

Aside from fuel composition and origin, the second most important variable to the overall effectiveness of CCS is capture efficiency. Using eq. 4.6, and again assuming the above parasitic loss value from Rubin et al. (2005) and emission factors from Ecoinvent, a decrease in capture efficiency from 90% to 80% increases net CO_2 emissions by 13.3 g/MJ, or 16% (see Figure 1.4).

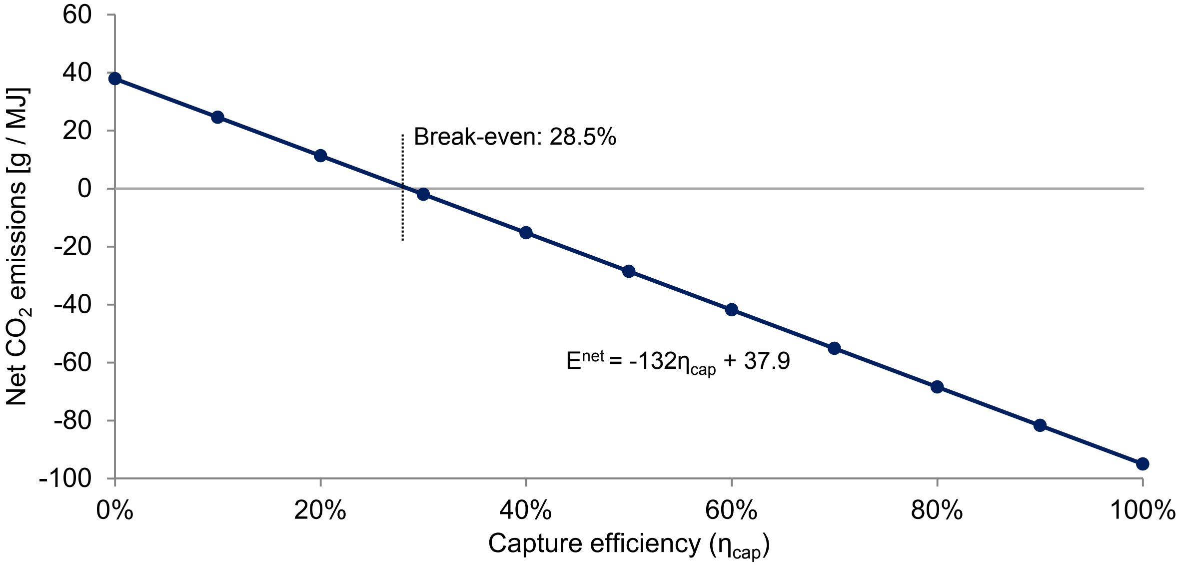

Figure 1.4: Sensitivity of net CO_2 emissions to capture efficiency showing break-even capture efficiency and linear slope

Considering the importance of capture efficiency, it is somewhat surprising that the LCA literature has paid little attention to leakage from storage. Even though leakage from storage does not happen at the time and site of energy generation, it nevertheless has the effect of reducing net capture efficiency; leaked CO_2 lowers the numerator in eq. 4.1 and thus lowers capture efficiency (Koornneef, van Keulen, Faaij, & Turkenburg, 2008). Previous authors have recognized that before proceeding with a large-scale carbon storage project a risk assessment should be completed, centering on the risk of leakage (Celia & Nordbotten, 2009). Yet, only two of the studies reviewed by Zapp et al. (2012) consider leakage from long-term storage (Khoo & Tan, 2006; Viebahn, Nitsch, & Fischedick, 2007); the rest of the studies overstate net capture efficiency to the extent that leakage may occur. Khoo & Tan (2006) assume 5% leakage over a 500-year time span, which (using the values from Figure 1.4) would increase net CO_2 emissions by ~8%. But they also acknowledge that ocean storage is likely to exhibit leakage of roughly 20% over 300–1,000 years (Herzog et al., 2001), which would increase net CO_2 emissions by ~32% relative to a scenario without leakage.

In the case of geological storage, it is thought that good site selection for qualities such as sufficient permeability of the injection medium, an impermeable "caprock" to seal the CO_2, and high enough fracture pressure, along with continuous monitoring, can mitigate these risks. However, many decades of oil exploration and drilling mean that many otherwise suitable caprocks have been compromised, and the risks of improperly sealed wells are considerable (Celia & Nordbotten, 2009). Wilson and Monea (2004) estimate that 0.005–1.3% of stored CO_2 will likely leak over 5,000 years, but this estimate depends on many geologic factors; another risk assessment suggests that in the unlikely event of a well leak, 60% of stored CO_2 could be emitted to the atmosphere (Kreft et al., 2007). Given the range of realistic on-site CO_2 capture efficiencies (i.e., without counting potential leakage) of 65–90% (Zapp et al., 2012), a leak of the magnitude suggested by Kreft et al. could reduce net CO_2 capture nearly to zero (Koornneef et al., 2008).

One way to assess the importance of leakage is to calculate break-even capture efficiency ($\eta_{cap}^{B.E.}$) by setting $E_{CCS}^{net} = 0$ and solving for η_{cap}:

$$E_{CCS}^{net} = \frac{E_{ref}^{direct}\left(X - \eta_{cap}\right) + XE_{ref}^{upstream}}{1 - X} = 0$$

$$E_{ref}^{direct}\left(X - \eta_{cap}\right) = -XE_{ref}^{upstream}$$

$$\eta_{cap}^{B.E.} = X\left(1 + \frac{E_{ref}^{upstream}}{E_{ref}^{direct}}\right) \tag{4.8}$$

The higher the ratio of upstream to direct impacts and the higher the parasitic loss, the higher capture efficiency will need to be to break even. Again using the above parasitic loss value from Rubin et al. (2005) and emission factors from Ecoinvent, we arrive at:

$$\eta_{cap}^{B.E.} = 0.27\left(1 + \frac{5.43}{97}\right) = 0.285 \tag{4.9}$$

This means for the assumed fuel and CCS efficiency penalty, net capture efficiency must be greater than 29% in order for CCS to reduce net CO_2 emissions, as depicted in Figure 1.4. CCS LCAs typically agree that capture efficiency is expected to be around 90%, not counting leakage (Zapp et al., 2012), meaning that leakage would only lead to net increased CO_2 emissions if it were over 61%. Some risk assessment studies on CCS suggest that leakage of this magnitude is unlikely (Celia & Nordbotten, 2009; Gasda, Bachu, & Celia, 2004; Kreft et al., 2007; Wilson & Monea, 2004). However, low-probability, large-scale leaks could result in significant global warming impacts as well as potentially catastrophic human casualties (a point to which we shall return). This, in combination with the fact that injecting CO_2 into geological storage sites can cause seismic instability (Metz et al., 2005), has caused some scholars to caution that CCS is an "extremely risky strategy for achieving significant reductions in greenhouse gas emissions" (Zoback & Gorelick, 2012, p. 10167).

Nonetheless, taken as a whole, the preceding evidence allows us to answer key environmental question #1: Assuming common efficiencies and reasonable leakage rates, CCS is likely to capture more CO_2 emissions than it creates, leading to a net reduction in global warming impacts. However, this result is sensitive to assumed parasitic loss rates and long-term leakage rates, indicating that these are areas of focus for further research.

2) Does CCS lead to tradeoffs in other impact categories?
    a. What are the impacts of CCS implementation in other impact categories?
    b. What is the extent of ocean acidification from oceanic CO_2 storage?
    c. What is the higher priority between global warming and other impacts?

Thus far in the discussion of CCS, we have focused on CO_2 emissions and their attendant global warming potential. However, a general shortcoming of end-of-pipe emission controls is that they tend to reduce emissions in the impact category of focus by shifting impacts to other impact categories, to other life cycle stages, or to other geographic regions (Jackson, 1996).

LCA evidence shows that CCS is no exception. To understand why this should be the case, consider that CCS is a system that reduces net energy efficiency of a power plant and therefore requires more fuel to be extracted, processed, transported, and combusted, and at the same time introduces new capture, transport, and storage equipment and infrastructure that must be built and operated. These processes cause considerable impacts in many categories. In the case of global warming, the extra impacts are outweighed by captured CO_2, but no such offset occurs in other impact categories. Therefore we should expect that net impacts are increased across the range of other impact categories.

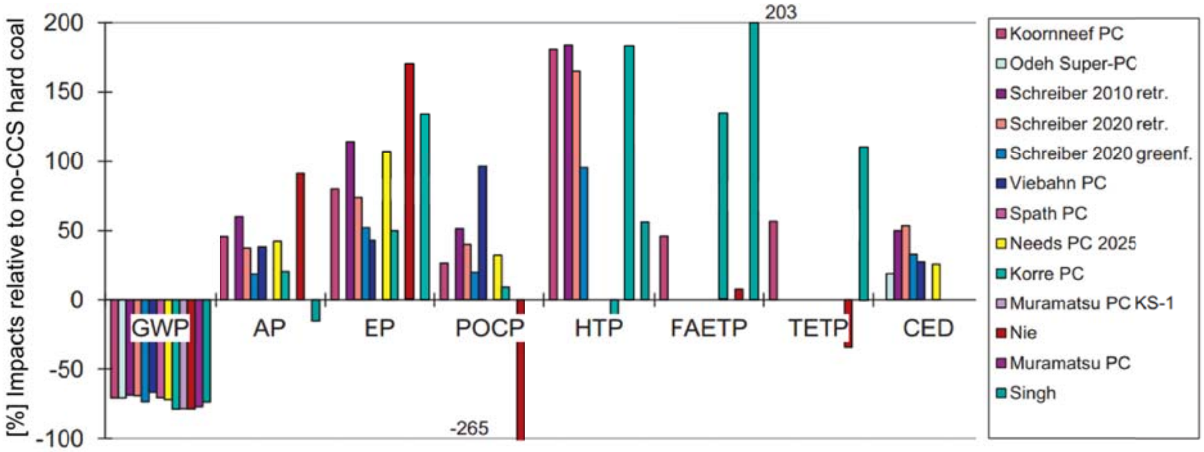

Figure 1.5: Impacts of post-combustion CCS relative to a no-CCS baseline hard coal power plant. Each bar represents an individual LCA or scenario. Modified from Zapp et al. (2012). See source for full citations.

Category	Normalization factor (world, 2000)	Average normalized impact w/o CCS	Average normalized impact w/ CCS	Change in normalized impact
GWP	4.18E+13	10.6%	2.6%	−8.0%
AP	2.39E+11	2.6%	3.2%	0.6%
EP	1.58E+11	0.4%	0.8%	0.4%
POCP	2.90E+10	1.1%	1.5%	0.4%
HTP	3.63E+12	0.5%	1.9%	1.4%
FAETP	3.47E+12	0.4%	0.7%	0.3%
TETP	1.09E+12	0.1%	0.1%	0.0%

Table 1.2: Average normalized impacts of studies presented in Zapp et al. (2012) (see Figure 1.5). Normalized impacts were calculated assuming year-2000 global hard coal power generation of 5136 TWh (normalization factors from Sleeswijk, van Oers, Guinée, Struijs, & Huijbregts, 2008).

In their review of thirteen CCS LCAs, Zapp et al. (2012) confirm this expectation. Figure 1.5 shows the summarized results of the thirteen reviewed LCAs across eight impact categories in relative terms compared to a no-CCS baseline. Aside from a few outliers, the figure shows that while CCS reduces global warming impacts, it increases impacts across all other categories. These findings are replicated in the more recent CCS LCA by Volkart et al. (2013). The additional impacts are attributable primarily to the extraction and combustion of the additional fuel needed due to parasitic loss.

Table 1.2 shows average impacts in each category, normalized by global impact levels. Normalized impacts are useful to assess whether the decrease in GWP impacts are large or small relative to the increases in other categories. Normalized global warming impacts are reduced 8% from the no-CCS baseline, while each of the other impact categories are increased less than 1.5%. Although the relative decrease of global warming impacts is larger than any one of the increases in other impacts, it is apparent that a tradeoff between GWP and other impacts is inevitable.

Additionally, the impacts in other categories, particularly eco- and human toxicity, are likely to be understated since they ignore factors such as ocean acidification and potential leakage. As discussed in the introduction to CCS, oceanic CO_2 storage increases ocean acidity (decreases pH) and may harm aquatic ecosystems. By one estimate, adding 1,300 Gt of carbon (roughly 200 years' worth at current emission rates) to the ocean would lower pH by 0.3 units; for comparison, ocean pH has decreased 0.1 units since the industrial revolution (Herzog et al., 2001). Moreover, slow leakage from geological storage can be lethal to subterranean organisms, while rapid leaks caused by well failure or seismic activities can be fatal to humans, plants, and animals (Metz et al., 2005; A. Pires & Martinho, 2012). However, our understanding of these phenomena is lacking, and thus far no LCA of CCS has incorporated these types of impacts.

In terms of determining whether the CO_2 reduction is worth the increase in other impact categories, this ultimately is a matter of subjective values that may vary across individuals, time, and geography. Climate change is a slow-burning environmental problem with global scope, whereas toxicity, smog, acidification, and eutrophication are acute, local issues, which makes prioritizing impact categories difficult. Furthermore, it has been pointed out that with a shift in impact categories and life cycle stages comes a shift in geographic location of impacts (Zapp et al., 2012). This introduces an environmental justice dimension to CCS in that global, chronic impacts (global warming) are traded for local, acute impacts (toxicity, smog). These tradeoffs introduce complexity to the net green definition that we will return to shortly.

3) How does CCS affect the future role of renewable energies by changing the socio-economic-political landscape?
    a. Is CCS actually working as a bridge technology to renewables, or does it prolong the use of fossil fuels and delay the transition to renewables?
    b. How does developing CCS technology affect the political, public, and economic landscape for coal-fired energy?
    c. How does increasing or maintaining status-quo levels of coal-fired energy production affect development and deployment of renewables relative to decreases in coal energy?
    d. How does investing in CCS affect energy prices; how do changes in energy prices affect development and deployment of renewables?

The third key question—that of determining the long-term socio-economic-political consequences of investing resources in CCS—is exceedingly complex. There are countless arguments in both directions by a range of individuals including executives, politicians, scientists, and NGO leaders. One issue at the heart of the argument is the idea that coal with CCS can be a “bridge fuel.” The bridge fuel argument is critical because, even to the extent that CCS reduces CO_2 emissions compared to coal power without CCS, it is by no means the lowest-emitting source of energy available. Renewables (wind, solar, and hydro) and nuclear energy have much lower per-MJ electricity carbon emissions than even the most advanced CCS coal plant (Raadal, Gagnon, Modahl, & Hanssen, 2011).

Thus, on one hand proponents of CCS would like to appeal to environmental values, but on the other hand, CCS competes for resources with renewables that are cleaner. One way CCS proponents thread this needle is by suggesting that CCS will provide cleaner fossil fuel base-load power in the interim, to allow time for renewables to develop to a point where they can meet most energy demand (Hansson & Bryngelsson, 2009). According to the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report, fossil fuels are expected to dominate until at least 2050 (Metz et al., 2005), and CCS is proposed as a way to reduce CO_2 emissions from fossil fuel use during this time.

Yet, detractors of CCS express concerns that CCS shifts financial, political, and social focus from renewables to what is at best an interim solution, and may contribute to "carbon lock-in" (Bäckstrand, Meadowcroft, & Oppenheimer, 2011; Rochon et al., 2012). As Christian Kirchsteiger of the European Commission summarizes the argument,

> *If the key energy issue of coming generations … is not the abundance of fossil resources but rather an unacceptably high probability of global warming due to GHG emissions, then the solution should not include any massive hiding of the emissions but entirely focus on [their] avoidance based on improved technology in power plants and other industrial installations.* (Kirchsteiger, 2008, p. 1149)

Investment in full-scale CCS installations has been slow for a variety of reasons (Bowen, 2011), but large contributors are cost and uncertainty. CCS is extremely costly to implement and operate, nearly doubling per-kWh operating costs (Rubin et al., 2005), and fluctuating energy and carbon markets lead to uncertainty and volatility (von Stechow, Watson, & Praetorius, 2011). In response, scholars have proposed and governments have experimented with a variety of financial policies to incentivize CCS development (Bäckstrand et al., 2011; Gerlagh & van der Zwaan, 2006; Kirchsteiger, 2008).

However, government resources are finite and CCS competes directly for these financial incentives with renewable energy companies. Thus, every dollar spent incentivizing investment in CCS means less investment in renewables. CCS detractors point out that CCS is unproven, uncertain, potentially risky, and—most importantly—not even the best available solution in terms of reducing GHG emissions (Kirchsteiger, 2008). Why, they ask, should we incentivize a suboptimal solution in favor of what even CCS proponents acknowledge is the long-term solution?

I will not attempt here to determine the likely counterfactual future or how CCS is likely to change it, as such an analysis is much too involved for this study. The subquestions of key question #3 above provide a starting point for such an analysis, which would be largely socioeconomic in nature. Rather than attempt to settle the argument one way or the other, my goal in summarizing these arguments is to suggest that applying the net green definition to this debate provides a useful way to frame the issues.

This brings up an important point to which we shall return in the conclusion: The determination of whether an activity is net green depends on the comparison one makes. If one compares a CCS plant to a non-CCS plant—that is, a comparison directly before and after CCS is implemented—it reduces CO_2 emissions. However, if one compares a CCS-based future to a counterfactual future without CCS—that is, forecasting the future with vs. without CCS—it may look quite different. In the latter case, the comparison depends heavily on what one assumes as the counterfactual, baseline future: If one assumes a business-as-usual, fossil-fuel-dependent future, then the deployment of CCS can be seen as reducing overall CO_2 emissions at the expense of increased impacts in other categories. But if one assumes that—in the absence of CCS—pressures against CO_2 emissions would raise the costs of fossil fuel use to a point where renewables were cost-competitive, then CCS can be seen as delaying these pressures and drawing out the dependence on fossil fuels.

4.1.3 Is carbon capture and storage net green?

In this case study, instead of asking the more common question of whether CCS is physically or financially feasible, we instead asked whether CCS is environmentally beneficial by subjecting it to the definition of net green. The discussion highlighted that answering this question is complex, but rests on three key determinations:

1) Does CCS increase or decrease net CO_2 emissions?
2) Does CCS lead to tradeoffs in other impact categories?
3) How does CCS affect the future role of renewable energies by changing the socio-economic-political landscape?

We determined that with respect to the first question, assuming current plant efficiencies and reasonable leakage rates, CCS will likely capture more CO_2 emissions than it incurs. In terms of the second question, we determined that the reductions in CO_2 emissions come at the price of increased emissions in every other impact category, with impact shifts across life cycle stage and geographic location. With respect to the third question, we summarized prominent arguments from both sides of the debate and outlined some basic questions that would be at the core of answering this piece.

The global warming results are favorable in terms of CCS being net green, but they must be weighed against the increases in other impacts. The issue of tradeoffs in category, life cycle stage, and geographic location of impacts is a complex one that the field of environmental assessment has struggled with for decades. Ultimately, to choose among such tradeoffs requires one to assign relative weights to different types of impacts; this decision is necessarily subjective and cannot be arrived at purely scientifically. As I pointed out in Section 2, the presence of tradeoffs is often a sign of a suboptimal environmental solution. Nonetheless, this discussion reveals one limitation of the net green definition: It cannot, on its own, solve the problem of impact tradeoffs without external judgments about the relative importance of different types of impacts; it can, however, bring these tradeoffs to the surface and frame them in a way that is objective in order to facilitate healthy debate.

Is coal-powered electricity with carbon capture and storage net green? At least partially, it depends on the state of technology, on one's values, and on the counterfactual future of renewable energy (i.e., without CCS). The application of the net green definition framed the discussion, helped divide the purely subjective questions from objective ones, and moved the debate a good deal closer toward specific research inquiries that will lead to a definitive answer.

CCS is representative of end-of-pipe pollution controls. A similar analysis to the one presented could be employed to determine the net green status of any number of pollution control technologies in a range of applications and industries, with results that are likely to have similar themes. Pollution controls for chemical plants, for instance, require the production of chemicals themselves, and trade water toxicity impacts for energy use and land toxicity (Jackson, 1996). It is for these reasons—efficiency losses and the inevitability of tradeoffs—that end-of-pipe pollution controls are considered the lowest on the waste management hierarchy, and starting in the 1970s started to lose favor relative to pollution prevention practices such as reuse and recycling.

5 REUSE AND RECYCLING

Reuse and recycling have been heralded as a solution to environmental problems since the 1980s, and many companies have taken up the call. Many companies exist to collect, refurbish, and resell used cell phones. Metals recycling has long been a standard practice, and plastics recycling is growing increasingly more profitable. Many businesses stress internal recycling initiatives for office pack, cardboard, and beverage containers.

Figure 1.6 shows how reuse or recycling can potentially create environmental benefit. Starting at the left of the figure, a primary product is produced and used, creating environmental damage $E_{prim} + E_{use}$. If the product is collected for reuse or recycling, it undergoes additional reprocessing, creating environmental impacts E_{rec}. To be worthwhile, reuse and recycling must therefore have some environmental benefit that exceeds these additional impacts. The potential environmental benefit of reuse and recycling is often mistakenly thought to be that these activities divert materials from landfill. This view is mistaken for two reasons: First, modern landfills are well-lined and heavily monitored for groundwater leaching. They are also well-sealed and allow for nearly zero decomposition (Borglin, Hazen, Oldenburg, & Zawislanski, 2004), and are increasingly being required to capture methane and carbon dioxide emissions for energy recovery (e.g., California Code of Regulations, 2010). In fact, modern landfills are better characterized as semi-permanent holding zones rather than releases of materials to the environment. Thus, environmental impacts from landfilling—particularly for many of the most recycled materials such as metals, glass, and aluminum—are typically negligible. Second, it is not necessarily true that recycling diverts material from landfill; as I will discuss below, recycling may also simply delay landfill of materials rather than prevent it.

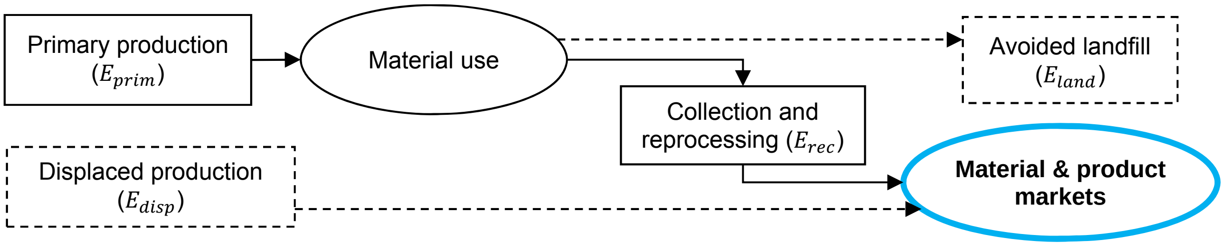

Figure 1.6: Schematic of a typical reuse or recycling system; environmental benefit is created when recycling displaces more harmful primary production

The true environmental benefit of reuse and recycling comes from the potential of secondary (recycled or reused) materials to prevent or "displace" primary material production that has higher impacts. In Figure 1.6, this "displaced production" of primary materials is shown with a dotted line, indicating that this production—and the associated impacts—would have occurred but for recycling. Displaced production of primary materials by secondary materials can create environmental benefit because most recycled materials take a fraction of the energy to collect and recycle as they do to create from raw resources. For instance, to create secondary aluminum ingot from scrap takes roughly 1/10 the energy of producing primary aluminum from bauxite (Ecoinvent Centre, 2012). However, *these impacts are only avoided to the extent that primary production is displaced* by secondary production.

Similarly, landfill is also only avoided if primary production is displaced (and therefore exists less material to eventually be disposed of). For instance, if a polyethylene terephthalate (PET) bottle is recycled into a lower-quality clamshell container and later discarded, the landfilling of the material has merely been delayed, not avoided; only if primary material is avoided does recycling the bottle prevent landfill. The quantity and type of material landfill avoided is identical to the quantity and type of primary production displaced; therefore, for the remainder of the discussion, but without loss of generality, I ignore landfill impacts.

To formalize the effect of displacement on the benefit of recycling and reuse, I refer to the fraction of primary production avoided by reusing or recycling additional material as the "displacement rate," d. Thus, the net benefit of reuse or recycling is given by:[8]

$$E_{net} = E_{rec} - d(E_{disp} - E_{land}) \tag{5.1}$$

Note that displacement rate is independent from both collection rate and recycling yield. Collection rate simply affects the relative sizes of flows from the use phase to landfill

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[8] Chapter 2 provides a much more in-depth discussion of the nature of the displacement relationship.

or recovery, while recycling yield governs the size of the outflow from recovery relative to the inflow. Displacement rate, on the other hand, is determined downstream of both of those rates and governs how changes in the flow of recovered materials affects the supply of primary material production.[9]

From Figure 1.6 and eq. 5.1, we see that reuse and recycling require processing that produces environmental impact E_{rec}. Therefore, the *only* way reuse and recycling can produce environmental benefit is if they prevent even greater impacts, E_{disp}, from displaced production of primary materials. However, it is by no means guaranteed that displacement will occur. As we will see in the following case study, determining what primary production is displaced and to what extent can be complicated.

5.1 Case study: Recycling office pack

5.1.1 Background

Companies can engage in a number of activities that fall under the category of reuse and recycling. One example is encouraging the recycling of internally created wastes by providing receptacles for recyclable materials such as aluminum, plastic, glass, and paper. Paper office pack is a nontrivial output of many office environments. Roughly 42 million tonnes of paper was collected in the U.S. in 2011 of the 64 million tonnes produced, representing a collection rate of 66% (U.S. Environmental Protection Agency, 2014). A large component of this waste and recovery stream is printer paper from office use, known as office pack. While companies may engage in office pack recycling for a variety of reasons, one of them may be that it appears to be an activity that is intrinsically good for the

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[9] See Chapter 2, Appendix A.1 for a more detailed distinction between collection rate, recycling yield, and displacement.

environment. According to the net green definition, however, office pack recycling is only green if it produces actual environmental benefit.

Production of paper consists of two stages: pulping and paper making, though nearly all paper production occurs in integrated plants (Schmidt, Holm, Merrild, & Christensen, 2007). Pulp can be produced either from virgin (primary) wood fiber or post-consumer materials (Wang, Templer, & Murphy, 2012), and virgin pulp can be created through a variety of chemical and thermo-mechanical processes (Schmidt et al., 2007). Thermo-mechanical pulping tends to have higher energy requirements for machinery and pulp drying. The paper-making phase varies in energy requirements according to the type of paper produced. Additionally, energy requirements for creating different grades of paper from virgin or recycled pulp vary according to output grade and production technology (Wang et al., 2012). For this case study, but without loss of generality in the approach, we will focus only on energy requirements (as energy requirements are very closely linked with global warming impacts) and will ignore impacts from landfilling. However, it is worth noting that impact category tradeoffs similar to those discussed in the CCS case study likely exist.

5.1.2 Key environmental factors and key questions

As discussed above, the potential for office pack recycling to create environmental benefit rests in its potential to displace the production of virgin paper. From eq. 5.1, the net energy savings of recycling depends on the energy cost of recycling, the energy cost of primary production, and the displacement rate (again, ignoring landfill impacts), with possible outcomes summarized in Table 1.3.

	Potential environmental benefit	Potential environmental damage
1.	Recycling paper may use less energy than primary production of the types of paper it might displace.	Recycling office pack may use more energy than primary production of other types of paper it might displace.
2.	Recycled office pack may displace the production of more energy-intense primary paper.	Recycled office pack may displace the production of less energy-intense primary paper. Alternatively, displacement may not occur at a high enough rate, or at all.

Table 1.3: Key factors determining the environmental impact of office pack recycling

We can organize these key factors into two main focus questions with several subquestions:

1) Are the energy requirements of recycling office pack higher or lower than those of primary products recycled office pack may displace?
2) What primary products, and how much of each, does recycled office pack actually displace?

1) Are the energy requirements of recycling office pack higher or lower than those of primary products recycled office pack may displace?
    a. What are the energy requirements of recycling office pack?
    b. What products might office pack potentially displace?
    c. What are the energy requirements for primary production of those products?

Not all pulp, whether virgin or recycled, is suitable for producing all types of paper. Office pack, for instance, is usually created from chemically produced virgin pulp due to high brightness and strength requirements. While post-consumer content does appear in some office pack, recycled pulp is more suitable to make newsprint, fine paper (also known as “woodfree paper”), cardboard, and sanitary paper (COST E48, 2010; Laurijssen, Marsidi, Westenbroek, Worrell, & Faaij, 2010; Merrild, Damgaard, & Christensen, 2008; Wang et al., 2012). Therefore paper recycling is very often an “open-loop” recycling system; that is, the product is not recycled back into another nearly identical product but into a different product. Collected office pack will most likely not be recycled back into office pack, but into newsprint, fine paper, cardboard, or sanitary paper. Thus, the relevant energy requirement comparisons are between primary and secondary production for these products.

Table 1.4 shows energy requirements for production of 1 kg of six primary material production processes from extraction of raw materials to the factory gate and four recycling processes from scrap to factory gate. From the data available, recycled office pack can be an input to the four recycling processes at the bottom of the table. Note that the data come from differing reference years. Additionally note that the type of pulping process is a larger determinant of energy requirements than final product; for instance, even though fine paper is a higher-quality product than newsprint or sanitary paper, thermo-mechanical pulping of the latter products requires more energy than chemical pulping.

Pulp process (output: 1 kg paper)	Product	Year	Input energy [MJ][a]
Virgin production			
Chemical, total chlorine free (TCF) [b]	Fine paper	2010	1.98
Chemical, elementary chlorine free (ECF) [c]	Fine paper	2001	4.32
Chemo-thermo-mechanical [c]	Cardboard	2001	3.41
Thermo-mechanical [c]	Newsprint	2001	9.43
Thermo-mechanical [d]	Printing paper	2011	9.44
Thermo-mechanical [e]	Sanitary paper	2009	9.83
Recycling			
Waste newsprint and magazine recycling [c]	Newsprint	2001	1.13
Mixed paper and corrugated board recycling [c]	Cardboard	2001	1.77
Recycled paper pulping [e]	Sanitary paper	2009	3.26
Waste mixed paper recycling [c]	Fine paper	2001	3.84

[a] Electricity inputs only. Does not include steam or natural gas energy as these were not available for some materials.
[b] Stora (2010), cited in Wang et al. (2012)
[c] Frees et al. (2005), cited in Wang et al. (2012)
[d] Skogsindustrierna (2011), cited in Wang et al. (2012)
[e] Laurijssen, Marsidi, Westenbroek, Worrell, & Faaij (2010)

Table 1.4: Energy requirements for selected pulping and paper production processes

Table 1.4 shows that producing newsprint, cardboard, or sanitary paper from recycled office pack requires significantly less energy than primary production of these products. The comparison for recycling office pack into fine paper, however, depends on the primary production process assumed to be displaced: Recycling requires less energy than elemental chlorine-free (ECF) fine paper production, but more energy than total chlorine-free (TCF) fine paper production.[10] Therefore, even before considering the more complicated matter of displacement rate, Table 1.4 shows that the potential environmental benefit of office pack recycling depends heavily on assumptions about what product it will be recycled into and what production process it may displace. This corroborates prior research finding that the impacts of paper recycling depend heavily on the choice of virgin paper manufacturing data (Merrild et al., 2008). Given the data in Table 1.4 and for the time being assuming full displacement ($d = 1$), there are four potential scenarios for net energy savings from office pack recycling: From eq. 1, where E_{net} is the net impact per kg of recycled product (such that $E_{net} < 0$ represents environmental benefit and $E_{net} > 0$ represents environmental damage),

$$E_{net} = E_{rec} - E_{disp} = \begin{cases} 3.84 - 1.98 = 1.86 & \text{if recycled office pack displaces TCF fine paper} \\ 3.84 - 4.32 = -0.48 & \text{if recycled office pack displaces ECF fine paper} \\ 1.77 - 3.41 = -1.64 & \text{if recycled office pack displaces carboard} \\ 3.26 - 9.83 = -6.57 & \text{if recycled office pack displaces sanitary paper} \end{cases}$$

Note that the second, third, and fourth scenarios result in net environmental benefit, whereas if recycled office pack displaces TCF fine paper, net environmental damage is actually *increased* by 1.86 MJ/kg. Recycling office pack into sanitary paper requires the second-highest amount of energy, but also has the potential to avoid virgin production with the highest energy impacts. This may be counterintuitive, as it may seem that the highest and best use of used office pack is not to turn it into single-use toilet paper; however, if doing so can avoid primary sanitary paper production it can actually create the highest energy savings. This illustration highlights that knowledge about what specifically is avoided by recycling is crucial to understanding whether recycling office pack (or, indeed, anything else) is net green or not, and introduces the second key environmental question:

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[10] This may be a result of the fact that the ECF process data is almost ten years old.

2) What primary products, and how much of each, does recycled office pack actually displace?

Clearly the question of *what* is displaced by recycled office pack is an important one. Unfortunately, it is not straightforward to answer. The fate of collected post-consumer paper is largely determined by the level of contaminants in the paper, recovery and sorting technologies, acceptable levels of impurities in the finished pulp, and pulp and paper prices (Grossman, 2007). Much of these considerations are outside the control of a paper recycler, as they have to do with how consumers dispose of the paper and the collection and sorting process. Furthermore, post-consumer paper is collected, sorted, and traded on a global commodity market, such that forces of supply and demand and prevailing prices will determine where a given unit of collected end-of-life paper will go and how it will be reprocessed. Some collectors engage in more extensive sorting than others, meaning office pack is sometimes segregated and other times bundled with lower-quality scrap. After reprocessing, the finished pulp can again be traded on a global commodity market, meaning that the ultimate use of the pulp is also uncertain.

Thus, the issue is one of both technical quality and recovery processes as well as one of global economics. For instance, growth in the economies of Asian countries during the 1990s increased global demand for recovered paper, which increased prices worldwide, causing European recyclers to increase production and raising the lower bound of economically viable recovered paper quality, such that lower grades of scrap were recycled (COST E48, 2010; Grossman, 2007). Fluctuations such as this can change the fate of recycled paper as some uses become more profitable than others, depending on global supply and demand. The problem of global paper recycling is so complex that a major European industry-scientific research partnership was formed to investigate the myriad forces that govern the effectiveness and limits to paper recycling (COST E48, 2010). One outcome of this project was a determination of the average utilization of various grades of recovered paper in Confederation of European Paper Industries (CEPI) member countries, summarized in Table 1.5.

	Paper scrap source							
End utilization	Mixed grades (kt)		Corrugated & kraft (kt)		Newsprint & magazines (kt)		High grades (kt)	
Newsprint	319	3%	0	0%	8670	65%	98	2%
Graphic papers	144	1%	83	0%	2433	18%	952	18%
Cardboard & packaging papers	8600	88%	18001	93%	1205	9%	2003	39%
Household & sanitary paper	333	3%	49	0%	912	7%	1915	37%
Other	402	4%	1290	7%	113	1%	185	4%
Total (kt)	9798	100%	19423	100%	13333	100%	5153	100%

Table 1.5: End utilization of recovered paper for different paper grades in 2005 CEPI countries (source: COST E48, 2010, p. 89)

Using the nomenclature of the COST E48 report, office pack is closely aligned with "high grade" paper, and fine paper fits into "graphic papers." To determine the likely fate of office pack, then, we are interested in the final column of Table 1.5. Only 2% of recycled office pack will be recycled into newsprint, mainly because newsprint has a high tolerance for impurities, so high-quality paper is more profitable elsewhere (COST E48, 2010). Eighteen percent of recycled office pack will be utilized in making fine (graphic) paper, 39% will be utilized for cardboard, and 37% will be used in making household and sanitary papers. An additional 4% will be used for various other papers. However, caution should be used with these figures as they are nearly a decade out of date and reflect European conditions, which may be different for other, particularly developing, countries.

According to the data in Table 1.5, 76% of collected post-consumer office pack is likely to be turned into either cardboard or sanitary paper. Both of these fates at least have the potential to create environmental benefit by displacing their more energy-intensive virgin counterparts.

One question remains regarding what is likely displaced by recycled office pack: Of the 18% of recycled office pack that will be turned into fine paper, which fine paper production method is more likely to be displaced, ECF or TCF? Answering this question is considerably more straightforward, as regional and global statistics exist for production capacity of both processes, including future projections (Alliance for Environmental Technology, 2012). Figure 1.7 shows world and North American production capacity for ECF, TCF, and all other production processes. ECF is clearly the dominant technology at either scale, with less than 5% of production at the global level and less than 1% in North America; TCF is prominent only in Scandinavia (from data not shown).[11]

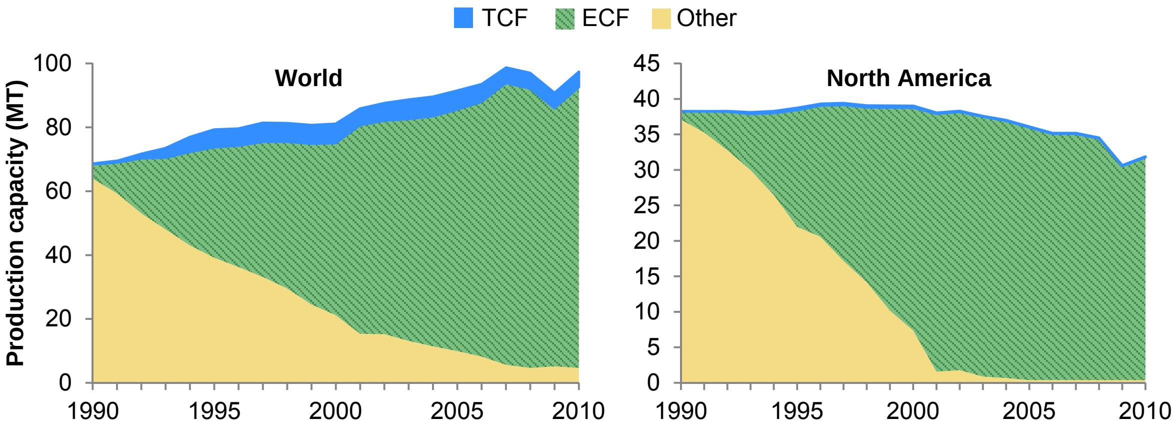

Figure 1.7: Production capacity for different pulp-making processes worldwide and in North America (Alliance for Environmental Technology, 2012)

If one were unsure about future trends, one could apply a probabilistic displacement model at this point, assuming that secondary material would displace each material according to its share of production. However, in this case we can go further and predict the future technology that is most likely to be displaced, because 10 million tonnes of new capacity is projected to come on-line by 2015 in China, Russia, Uruguay, Brazil, and Indonesia, all of

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[11] Despite the input energy savings shown in Table 1.4 (which, as mentioned in footnote 10, may simply be a matter of reference dates), ECF dominates due to a lower chemical input cost and higher production yield than TCF (Alliance for Environmental Technology, 2012).

which will be ECF (Alliance for Environmental Technology, 2012). Future trends are important to consider because increases in recycling will only displace *marginal* production, not average production (Weidema, 2003). That is, increases in recycling will prevent the next unit of virgin production that would have occurred had the increase in recycling not taken place. Given the current and projected pulp-making technologies, we can safely assert that to the extent that recycled office pack displaces fine paper, it will displace ECF production.

From the discussion so far, we can conclude that recycled office pack at least has the *potential* to create net environmental benefit, at least in terms of energy consumption. However, simply knowing *what* products and production technologies are most likely to be avoided by increased office pack recycling is not enough to determine whether office pack recycling is a net green activity. Earlier we made the naïve simplification of full displacement—that every kilogram of office pack that is recycled avoids the production of one kilogram of production from virgin pulp. In reality, there is no reason why this should always be the case. The next relevant question therefore is *how much* primary production of each type of product is displaced; what is the displacement rate for each product?

The key insight of Figure 1.6 is that the relationship between the supply of recycled paper and the supply of primary paper is not determined by engineering relationships but by market forces of supply and demand. These forces are explained in detail in Chapter 2 of this dissertation; for the time being, I will simply state that the actual displacement rate—the amount of primary production avoided by producing an additional unit of recycled material—is complex and by no means guaranteed to equal unity.

For this discussion, I leave the displacement rate as an open parameter, d, and recognize that E_{net} as calculated in eq. 5.1 depends on this parameter. For instance, imagine that market forces are such that in order to sell recycled fine paper it is necessary to offer a steep discount relative to primary fine paper. This may increase overall demand for fine paper by drawing away demand from competing materials or by creating entirely new uses and markets for fine paper. These effects may ultimately increase fine paper demand in general, such that the increased recycling affects primary production very little. In this case, d will be small, and therefore the net benefit will be reduced or even reversed. For example, using the figures above, if $d = 0.25$, then net impact assuming ECF fine paper is $E_{net} = 1.77 - 0.25(3.41) = 0.92$, an increase in net impacts. This means that even if recycled office pack competes with ECF fine paper, if the *amount* of displacement is small, recycling office pack *increases* net energy consumption by 0.92 MJ/kg.

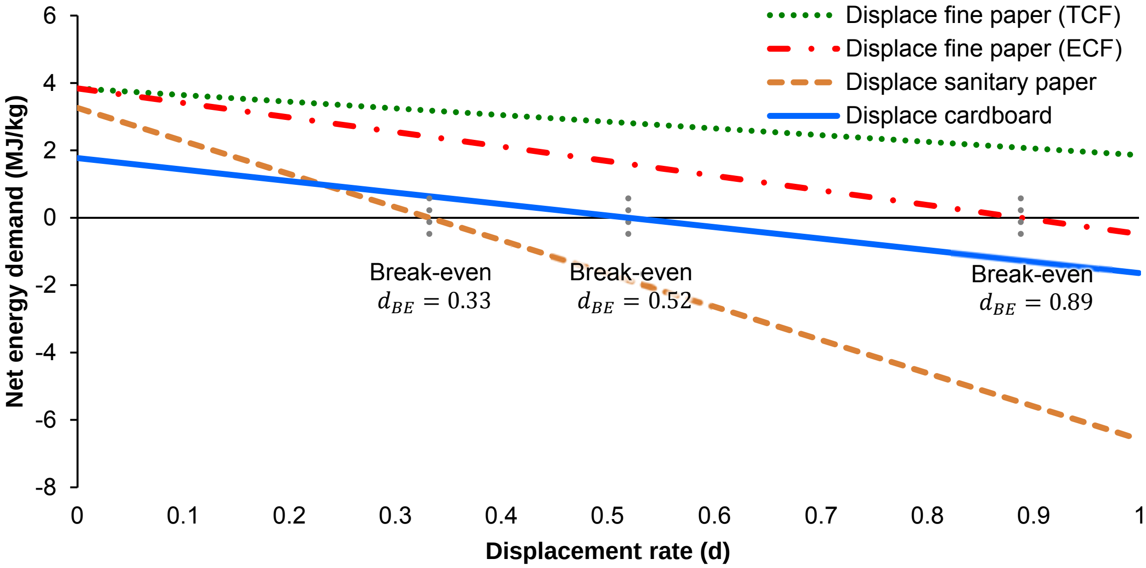

Figure 1.8: Net energy impact of office pack recycling assuming different displaced products across displacement rates

When $d = 1$ recycling office pack into ECF fine paper results in net environmental benefit, but when $d = 0.25$ it results in net environmental damage. This implies that there is some crossover or break-even point where lower values of d lead to damage and higher values lead to benefit. I refer to this point as the "break-even displacement rate," illustrated in

Figure 1.8 for all four potentially displaced products. Given the impacts of recycling and the impacts of avoided production, the break-even displacement (d_{BE}) rate can easily be calculated by setting the equation for $E_{net} = 0$ and solving for d:

$$E_{net} = E_{rec} - d_{BE}\left(E_{disp}\right) = 0$$
$$d_{BE} = \frac{E_{rec}}{E_{disp}} \tag{5.2}$$

Using eq. 5.2, we can see that the break-even displacement rate is different for all four products because they have different primary production and recycling impacts. If recycled office pack is recycled into and displaces sanitary paper, the break-even displacement rate is $d_{BE}^{sanitary} = \frac{3.26}{9.83} = 0.33$; if it is recycled into cardboard the displacement rate is $d_{BE}^{cardboard} = \frac{1.77}{3.41} = 0.52$; if it is recycled into fine paper and displaces ECF production, the displacement rate is $d_{BE}^{fine\ paper\ (ECF)} = \frac{3.84}{4.32} = 0.89$; if it is assumed to displace fine paper from TCF production, the displacement rate is $d_{BE}^{fine\ paper\ (TCF)} = \frac{3.84}{1.98} = 1.94$. A break-even rate greater than one indicates that recycling in this scenario will never result in net environmental benefit, even under full displacement, as illustrated in Figure 1.8 by the fact that TCF net energy demand is positive across all levels of displacement.

5.1.3 Is office pack recycling net green?

In this case study, I started from the idea that the environmental benefit of reuse and recycling comes from the potential for secondary materials to displace production of primary materials. I stated that in order for office pack recycling to be net green, it must prevent greater impacts than it creates. By applying the net green definition to the issue, I determined that the answer rests with several key questions:

1) Are the environmental impacts of recycling less than the environmental impacts of a displaced primary alternative?

2) What kind of and to what extent primary production is actually displaced by recycled office pack?

Limiting the discussion to energy demand, I answered the first question using preexisting life cycle assessment studies of paper recycling and primary paper production. I determined that whether recycling requires more or less energy than a primary alternative depends on what primary product is compared. I answered the second question in part by determining what production is most likely to be displaced by looking at first average utilization of recycled office pack and then at marginal fine paper production technologies. I determined that recycled office pack at least has the potential to create environmental benefit as it is most likely to compete with primary materials that have higher production impacts. To fully answer the second question would require one to determine the actual displacement rate of sanitary paper, primary cardboard, and ECF fine paper. This analysis would be more involved and is out of the scope of this case study, though I develop and demonstrate a methodology for doing so in Chapter 2. Nonetheless, we were able to place lower bounds on the displacement rate required for office pack recycling to be net green by calculating break-even displacement rates for each of the potentially displaced products.

From this discussion we learned that the environmental impacts of reuse and recycling depend on assumptions about *what* products will be displaced. This not only highlights the need to understand the relevant materials markets, it also suggests that the net environmental benefit of reuse and recycling could be increased if secondary materials were recycled in a way that was more likely to displace products with higher impacts. For instance, from Table 1.4 we can see that if office pack could be recycled back into printer paper, which requires 10.3 MJ/kg for primary production, the potential environmental savings might be even greater (depending, of course, on the energy demand of the waste paper-to-printing paper process). Improved sorting and processing could improve the quality of recycled pulp and allow it to compete more directly with primary pulp for printer paper, increasing the net environmental benefit. Additionally, the fact that currently 42% of American recovered paper is processed in China, where environmental controls are lower (U.S. Environmental Protection Agency, 2014), suggests that even factors such as *where* a product is reprocessed—or where a displaced product would have been produced—can have significant implications for the net greenness of reuse and recycling activities.

Office pack is not unique among recycled materials. These same principles apply to reuse and recycling in general. It is not a given that these activities result in net environmental benefit; their status as net green activities depends on the impacts of reprocessing, the impacts of displaced production, and how much primary production is actually displaced. Overall, the lessons of this case study show that designing a collection, sorting, and reprocessing system in a way that maximizes the displacement potential of recycled or reused products can drastically increase the net environmental benefit of reuse and recycling activities.

6 MATERIAL OR TECHNOLOGY SUBSTITUTION

Material or technology substitution refers to the practice of identifying problematic materials or processes and replacing them with different, ideally cleaner, safer, or more efficient alternatives. Technological development and increasing understanding of toxic impacts drive these changes, often pushed by entrepreneurs and firms with cutting-edge research and development. A classic example of material substitution is the replacement of lead with methyl tertiary butyl ether (MTBE, which was later found to contaminate groundwater) as an antiknock agent in gasoline, while an example of technology substitution is the phase-out of carbureted engines in favor of direct injection engines.

The new replacement material or technology has impacts of its own; in order for material or technology substitution to create net environmental benefit, the new impacts from the substitute must be lower than those of the old alternative. There are two complications in determining whether a new alternative is cleaner or dirtier. First, if impacts are merely shifted from one life cycle stage to another (e.g., from the use phase to disposal), or if one type of impacts are traded for another (e.g., ozone depletion for toxicity), then it is not clear that any environmental benefit occurs. We will see in the following case study that these tradeoffs can be difficult to predict because they often involve complex social and macroeconomic forces, a theme that will be further explored and quantified in Chapter 2. Second, as we will also see in the case study, determining the most appropriate baseline against which to compare a new alternative is not always obvious. For instance, when studying energy from natural gas, is the most appropriate comparison against coal, or against renewables? Additionally, the baseline changes over time—for instance, at one time petroleum was seen as a clearly superior option to coal for powering machinery; now petroleum is being challenged by a variety of renewable energy sources.

6.1 Case study: Corn ethanol

6.1.1 Background

Biofuels are increasingly being produced in response to a need for low-carbon fuels (and for other reasons, such as national energy security). They are intended as a direct competitor to liquid fuels and as such they represent an ideal case study for material substitution activities.[12] Biofuels can be produced from sugar or starch plants through fermentation to produce ethanol, while oily plants can be directly burned or processed to produce biodiesel. Nearly all fuel ethanol is produced from starch- and sugar-based feedstocks, the majority of which comes from corn (U.S. Department of Energy, 2013b). In 2012, 4.5 billion bushels of corn representing 40% of U.S. corn production were used for ethanol production in the U.S. (US Department of Agriculture, 2013). Therefore, I will focus this discussion on ethanol from corn. However, I would be remiss not to point out that a wide variety of alternative biofuels and production methods are currently in use and under development, some of which show greater promise to meet GHG reduction goals (see Fargione, Plevin, & Hill, 2010; Tilman, Hill, & Lehman, 2006).

A range of problems with corn ethanol have been discussed, including that it reengages degraded and environmentally sensitive land that was previously taken out of production under the Conservation Reserve Program and Soil Conservation Act (Gelfand et al., 2011), that it reduces biodiversity both in the U.S. and abroad (Fargione et al., 2010), and that it presents several socioeconomic issues. Most common among the latter is that diverting food crops to biofuels raises the price of food commodities that form a substantial nutritional basis for many poorer people (BBC News, 2007; de Gorter, Drabik, & Just, 2013; Fortenbery & Park, 2008; Maxwell & Davison, 2014; McPhail & Babcock, 2012). Despite these issues, the environmental argument for corn ethanol rests on the claim that it reduces GHG emissions, so for the present discussion I will focus solely on net GHG emissions of corn ethanol as compared to gasoline.

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[12] Bioethanol is most commonly blended with fossil fuels; however, because biofuels replace fossil fuels in the blend, they can be seen to directly compete.

The environmental argument for biofuels is that they are less carbon intensive than fossil fuels, or are even carbon neutral (Baker, Ochsner, Venterea, & Griffis, 2007; Blanco-Canqui & Lal, 2008; Verma et al., 2005). Biofuel is derived from plants that sequester carbon from the air through photosynthesis during growth, such that the amount of carbon released to the atmosphere upon combustion is equal to the amount of carbon removed from the atmosphere during growth. In principle, therefore, combustion of biofuels is carbon neutral. However, two drawbacks have been proposed and discussed at some length, both related to land use change (LUC). The first is direct land use change (DLUC), which refers to changes to land from a previous use to corn-planted agricultural use. Such changes require the operation of equipment, can release carbon stored in soil during tillage, and can remove highly carbon-retaining plants (Fargione, Hill, Tilman, Polasky, & Hawthorne, 2008). The second is indirect land use change (ILUC), which refers to changes to physically distant lands—principally deforestation of native rain forests—caused by changes in global commodity prices (Searchinger et al., 2008). Diverting corn from food to fuel uses increases demand and raises prices, inducing farmers worldwide to bring previously native forests under cultivation, releasing vast carbon stores.

Furthermore, comparing internal combustion vehicles (ICVs) using corn ethanol to ICVs using fossil fuel may not be the most appropriate comparison. Similar to the case of coal-fired electricity with carbon capture and storage, how one defines the baseline comparison technology can change the net green assessment, and with biofuels it may be that the more appropriate comparison is against other emerging technologies. For instance, corn ethanol could be seen to directly compete with fossil fuels, but in order to be competitive it also requires land and government subsidies (Maxwell & Davison, 2014) that could alternatively be allocated to development and deployment of photovoltaic (PV) solar energy coupled with battery electric vehicles (BEVs) (Geyer, Stoms, & Kallaos, 2013). Therefore, whether such competition occurs and how it affects net GHG emissions is also a consideration.

6.1.2 Key environmental factors and key questions

From the above discussion, three forces emerge that determine the net green status of corn ethanol, summarized in Table 1.6.

	Potential environmental benefit	Potential environmental damage
1.	Corn ethanol can cause lower fuel cycle GHG emissions than gasoline.	Corn ethanol can cause higher fuel cycle GHG emissions than gasoline.
2.	Corn ethanol direct and indirect land use change impacts may be outweighed by fuel cycle GHG emission reductions.	Corn ethanol requires conversion of land to corn production, and also diverts food and feed corn to fuel uses; the production of food and feed corn may be displaced elsewhere with higher land use change impacts.
3.	Corn ethanol may reduce dependence on fossil fuels and contribute to a transition toward renewable energy.	Corn ethanol may directly compete for resources and land with photovoltaic solar energy; if solar energy offers lower life cycle GHG emissions, this competition leads to net GHG increases over widespread solar deployment.

Table 1.6: Key factors determining the environmental impact of corn ethanol

We can organize these key factors into three main focus questions:

1) Does corn ethanol have lower fuel cycle impacts as compared to gasoline?
2) How large are potential impacts from direct and indirect land use change?
3) Does corn ethanol investment and development compete with development of other, more environmentally benign energy alternatives?

1) Does corn ethanol have lower fuel cycle impacts as compared to gasoline?

Fuel cycle emissions, sometimes referred to as well- or field-to-wheels emissions, include all upstream energy inputs required to extract (or in the case of bioethanol, grow), refine, and deliver fuel to a combustion source, in addition to emissions from combustion of the fuel. Significant research has been conducted in the past decade to quantify the fuel cycle emissions of corn ethanol. Table 1.7 presents a selection of GHG emissions for corn ethanol as well as gasoline for reference.

Fuel	Qty	Units	Source
Gasoline	96.9	g CO_2-eq/MJ	Hill, Nelson, Tilman, Polasky, & Tiffany (2006)
Gasoline	96	g CO_2-eq/MJ	Fargione et al. (2010)
Gasoline	94	g CO_2-eq/MJ	Geyer, Stoms, & Kallaos (2013)
Corn ethanol	77–94	g CO_2-eq/MJ	Coelho, Goldemberg, Lucon, & Guardabassi (2006)
Corn ethanol	84.9	g CO_2-eq/MJ	Hill et al. (2006)
Corn ethanol	76	g CO_2-eq/MJ	A. E. Farrell et al. (2006)[a]
Corn ethanol	30.6–76	g CO_2-eq/MJ	Liska et al. (2009)[b]
Corn ethanol	70	g CO_2-eq/MJ	ANL (2009)[c]
Corn ethanol	66–69	g CO_2-eq/MJ	Fargione et al. (2010)
Corn ethanol	74	g CO_2-eq/MJ	Geyer et al. (2013)

[a] EBAMM model ("ethanol today" scenario)

[b] Lower range is based on a hypothetical closed-loop anaerobic digestion plant

[c] GREET model

Table 1.7: Representative fuel-cycle GHG emissions for gasoline and corn ethanol

Variation between studies in Table 1.7 is primarily due to differing assumptions about corn production yields, refining fuel sources, and refinery technology. Some studies have developed future scenario projections to determine lower bounds for corn ethanol fuel cycle emissions (Liska et al., 2009), while a recent study has incorporated spatially explicit life cycle assessment methods to account for differing crop yields across the U.S. (Geyer et al., 2013). Despite the variability in the figures, the data indicate that corn ethanol can reduce fuel cycle emissions by roughly 20 g CO_2-eq/MJ as compared to gasoline.

2) How large are potential impacts from direct and indirect land use change?

Growing corn for ethanol requires additional land to be planted, converting that land from its prior use to agricultural use (Wicke et al., 2012). The effects of this direct land use change are typically discussed in terms of the effect on biodiversity and ecosystems (e.g., Fargione et al., 2010; Fthenakis & Kim, 2009; Geyer et al., 2013), but the conversion of certain types of land to agriculture can also have large GHG impacts. Plow tillage farming reduces soil organic carbon storage in the upper soil layers, and agricultural use changes methane (CH_4) fluxes, requires nitrogen inputs that release the potent GHG dinitrous oxide

(N_2O), and foregoes future soil carbon sequestration (Blanco-Canqui & Lal, 2008; Crutzen, Mosier, Smith, & Winiwarter, 2008; Gelfand et al., 2011).

This means that land conversion to biofuel production creates initial releases of carbon to begin biofuels production, called a "carbon debt," which according to a recent estimate can range from 68 to 222 Mg CO_2-eq/ha (for soybean-corn rotation without tillage and corn-only with tillage, respectively) (Gelfand et al., 2011). This debt can eventually be repaid by the lower fuel cycle GHG emissions discussed above, but the repayment periods for the above debt figures range from 29 to 123 years, respectively (Gelfand et al., 2011). Thus, converting land to biofuel production today essentially locks U.S. energy policy into a commitment to biofuels until the middle of the twenty-first century at best or the beginning of the twenty-second century at worst. We will return to this point in addressing the third key question.

Emissions from direct land use change are an important consideration, but biofuels research increasingly demonstrates that a potentially greater concern is that of indirect land use change (ILUC) (Searchinger et al., 2008). ILUC refers to a phenomenon where land use changes in one region can affect land development decisions in another region, with the original use being displaced to the second region. The primary mechanism for this effect is price changes in the global commodity market (Sanchez et al., 2012). As corn is diverted from food uses to fuel, food corn prices rise, inducing farmers around the world—but particularly in developing regions in South America—to increase food corn production. This often means clearing old-growth forests or converting pasture land which is itself displaced to old-growth forests. When these native forests are cleared, the amounts of carbon they store are released to the environment, creating an even larger carbon debt.

Figure 1.9 diagrams the mechanism of ILUC, considerably simplified. The left-hand side represents the land use equilibrium prior to introduction of biofuels. In the developed region (top), land is either used for agriculture, pasture and other arable uses, or is protected or unsuitable for planting. In the developing region (bottom), land use equilibrium is similar except that old-growth native forests still exist and governmental protections on land development are weaker or lacking. Food grown in both agricultural areas is traded internationally to meet global food demand.

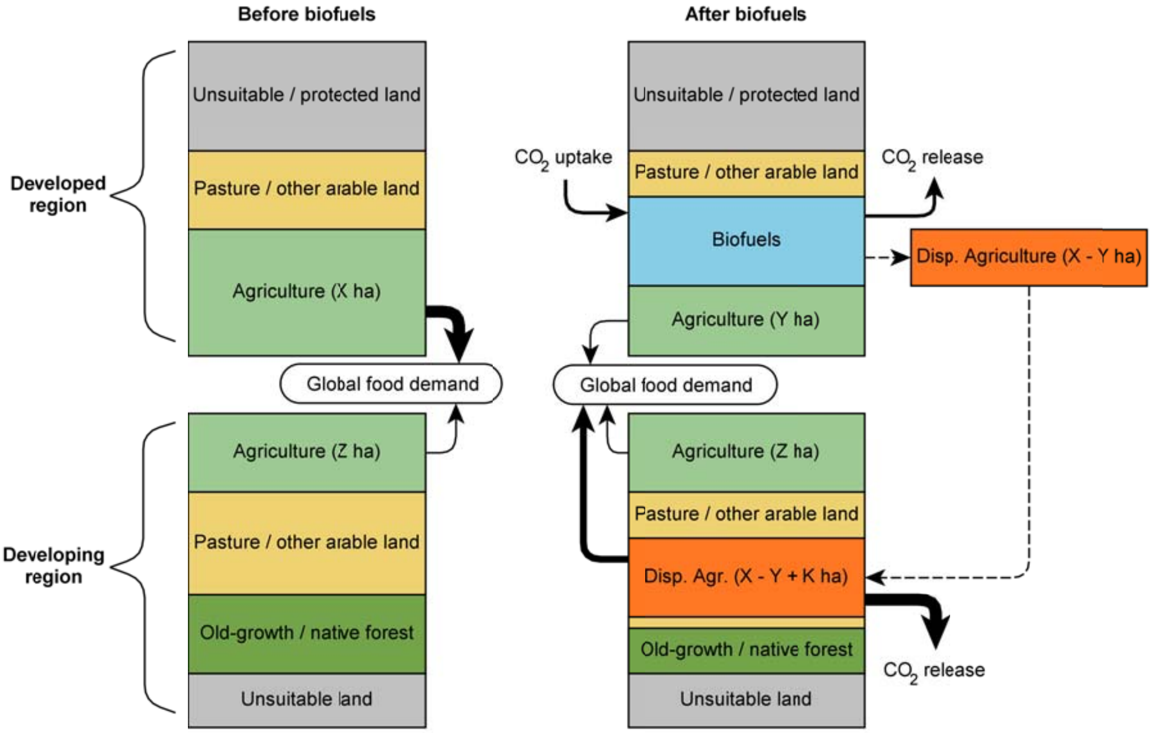

Figure 1.9: Mechanism of indirect land use change (ILUC). Introduction of biofuels in the developed world displaces agricultural activities to the developing world. Land conversion in the developing world releases large carbon stocks into the atmosphere.

The right-hand side of Figure 1.9 represents the situation after the introduction of biofuels in the developed region. Existing agricultural and pasture land is converted to biomass production, each proportional to its land rental rates (van Meijl, van Rheenen, Tabeau, & Eickhout, 2006). Land rental rate is the economic cost of marginal land for conversion; as more productive lands are exhausted, land supply becomes less elastic and rents rise. This ensures that biomass production will not displace only agricultural or only pasture land, but some combination of the two. As shown in the diagram, the non-biofuels agricultural area decreases from X hectares to Y hectares.

Indirect land use change occurs as a result of the displaced non-biofuel agriculture. Introducing biofuels diverts crops from food to fuel, which raises food commodity prices (Serra, Zilberman, Gil, & Goodwin, 2011) and induces more food production either through increasing yields (termed "intensification") or planting more land elsewhere ("extensification"). Tilman et al. (2002) have demonstrated that the ability to further intensify crop yields in the developed world is extremely limited. Instead, a likely consequence of increased prices from unmet food demand is that pasture and old-growth forest in the developing world will be converted to agriculture. This effect is shown in the lower-right portion of Figure 1.9. Land is converted according to its rent; the most productive and cheapest land is converted first. Because yields are lower in the developing region than in the developed region (Tilman et al., 2002), it is very likely that a greater area of land will be converted in the developing world than was displaced in the developed world (the added area is shown in the diagram as K hectares).

The effects of ILUC are both economic and biophysical. Food exports from the developing region will increase while food exports from the developed region decrease (Searchinger et al., 2008). Land-conversion activities in the developing region are poorly regulated, and therefore likely more environmentally harmful than those in the developed region. Much more importantly, when old-growth forests are clear-cut and burned or left to decompose they release their stored carbon, which can be fifteen times greater per hectare than that of grassland (Searchinger et al., 2008). For corn ethanol grown in the U.S., these indirect releases have been estimated between 30 and 100 g CO_2-eq/MJ electricity (Sanchez et al., 2012; Searchinger et al., 2008). Like direct land use changes, these GHG emissions represent one-time releases; however, they add considerably to the carbon debt repayment period, potentially pushing it well into the twenty-first or twenty-second centuries.

ILUC is a particularly difficult problem to manage, for two reasons. First, it is difficult to quantify. Complex computable general equilibrium (CGE) or partial equilibrium (PE) models (Wicke et al., 2012) including spatially explicit components (Lapola et al., 2010) have been developed to attempt to model the global effects of changing economic incentives. The state of the art in these models is such that they require expert users, and the results are increasingly opaque to laypeople such as policy makers. ILUC is even more complicated to show empirically, although a recent article has provided statistical evidence for ILUC in the case of soybeans (Arima, Richards, Walker, & Caldas, 2011). According to this study, a 10% increase in U.S. soybean expansion into pasture lands results in a 40% increase in deforestation in the Brazilian Amazon.

3) Does corn ethanol investment and development compete with development of other, more environmentally benign energy alternatives? How does this change net GHG emissions?

Comparing corn ethanol to gasoline is reasonable because both are liquid fuels used in ICVs. However, corn ethanol also represents a sun-to-wheels energy conversion pathway; that is, corn ethanol is a method of harvesting energy from the sun through photosynthesis and converting it to drivetrain power. Therefore it is also reasonable to compare corn ethanol to another viable sun-to-wheels conversion pathway: photovoltaic energy to power battery electric vehicles. Both pathways require land, and since they are nascent technologies, both may benefit from government subsidy support to spur investment and innovation. To the extent that they compete for land and financial resources, government support for one technology could be seen to hamper development of the other. Additionally, to the extent that there are carbon payback periods associated with each, investment in one pathway today may lock society in to that pathway for many years to come.

To determine whether corn ethanol slows the development of PV-powered BEVs—and, if so, whether that makes it more or less green—we need to know three things: first, which sun-to-wheels pathway creates lower GHG emissions; second, whether biofuels receive and grow because of subsidies or tax breaks; third, whether this money could have otherwise been used to increase PV and BEV investment, development, and deployment.

With respect to the first item, a recent study compared five different sun-to-wheels conversion pathways including corn ethanol for ICVs and PV to BEVs (Geyer et al., 2013). Using spatially explicit county-level data on crop yields and solar insolation, the study quantified the life cycle land use and GHG emissions resulting from driving 100 km, including vehicle production. Corn ethanol burned in an ICV was found to create between 20.9 and 32.5 kg CO_2/100 km (where the range is due to varying corn yield) including only direct impacts, and could be as high as 55.2 kg CO_2/100 km assuming upper-end ILUC impacts. The PV-BEV pathway, on the other hand, was found to create only 5.9 kg CO_2/100 km. Additionally, the corn ethanol ICV pathway required between 26.1 and 68.9 m^2/100 km of land use (up to 55.2 m^2/100 km including ILUC), as compared to only 0.12–0.18 m^2/100 km for PV BEV (where the range is due to varying insolation). To meet the entirety of U.S. transportation energy needs, 1.1 million ha of cadmium-telluride PV would be required; by contrast, if 100% of 2009 U.S. corn production were converted to ethanol it would displace only 15.7% of U.S. gasoline consumption. These results are in line with nonspatially explicit results from prior studies (Jacobson, 2009; McDonald, Fargione, Kiesecker, Miller, & Powell, 2009). Furthermore, the PV-BEV pathway has the additional advantage that it does not divert food crops to fuel, so it does not cause the aforementioned socioeconomic difficulties associated with raising food prices. Therefore, the evidence strongly favors the PV-BEV pathway to the corn ethanol ICV pathway.

For the second item—whether biofuels received and benefited from subsidies—the answer is fairly clearly affirmative. Biofuels production was heavily subsidized from 1978 to the end of 2011 through the Volumetric Ethanol Excise Tax Credit (VEETC), with tax credits ranging from $0.10 to 0.60 per gallon of ethanol (Maxwell & Davison, 2014). Tax credits were reduced with the passage of the 2008 Farm Bill and ended entirely in December 2011. The tax credit amounted to $5.4 billion in 2010, and cost an estimated $20 billion over its lifetime (NPR, 2012; U.S. Government Accountability Office, 2011). Considerable evidence suggests that the rapid expansion of the ethanol market had much to do with this subsidy. The Renewable Fuels Association, an ethanol industry group, reported that ending the subsidy would result in a 38% reduction in U.S. biofuels production (Urbanchuk, 2010). Economic models predict that the subsidy has allowed more firms to remain competitive in the industry than would have been possible without it (Schmit, Luo, & Conrad, 2011), that more firms entered the industry and face less risk because of the subsidy, and that firms would exit the industry if the subsidy were removed (Maxwell & Davison, 2014). Indeed, the production of fuel ethanol peaked at an average 890,000 barrels per day in 2011, with production declining for the first time in 2012 to an average 860,000 barrels per day (U.S. Energy Information Administration, 2014c). Whether this trend continues in the absence of the subsidy remains to be seen; thus far production has been buoyed by stable and high corn prices (U.S. Energy Information Administration, 2014b). Overall, we can safely conclude that the VEETC subsidy bolstered the corn ethanol industry over what it would have done naturally.

The third item—whether governmental support for biofuels was mutually exclusive to support for PV and BEV development—is more difficult to determine with certainty, since it relies on counterfactual reasoning. Namely, we must answer the question, where would PV BEV technology be today if we had focused governmental support on it instead of corn ethanol? PV and BEV demand has been bolstered by subsidies in the form of consumer tax credits for plug-in electric, plug-in hybrid, and (until 2010) hybrid vehicles (U.S. Department of Energy, 2014). Given that increased demand increases prices and therefore investment and R&D incentives, and given that government funds are finite, it is at least plausible that if funds had been allocated to PV and BEVs instead of corn ethanol, the PV and BEV industries would be further developed than they are today. It could be possible to test this theory using an econometric model of the renewable energy industry, but such an endeavor is well beyond the scope of this article.

6.1.3 *Is corn ethanol net green?*

This case study collected much of the most prominent scientific research on corn ethanol and organized it by applying the definition of a net green activity. Three questions emerged that determine whether corn ethanol is net green:

1. Does corn ethanol have lower fuel cycle impacts as compared to gasoline?
2. How large are potential impacts from direct and indirect land use change?
3. Does corn ethanol investment and development compete with development of other, more environmentally benign energy alternatives?

The scientific evidence shows that while corn ethanol does indeed have lower fuel cycle GHG emissions, these gains are overwhelmed by increased GHG emissions from land use change, both directly at the site of production and worldwide by raising commodity corn prices. We determined that photovoltaic energy to drive battery electric vehicles represents a vastly superior option to internal combustion vehicles powered by corn ethanol, and prima facie reasoning suggests that investment in corn ethanol comes at least partially at the expense of investment in PV and BEV technology, though to determine this with certainty would require more extensive study.

One thing that is relatively certain is that the long carbon debt repayment period of corn ethanol has already locked society in to a future of biofuel production if we ever hope to make prior investments in corn ethanol net carbon negative. However, to continue to invest in corn ethanol simply to repay this debt may not be the best environmental decision according to the net green definition: The carbon debt of already-produced corn ethanol represents a sunk cost; what we must decide now is where to focus efforts in order to maximize marginal carbon reductions. This very well may mean taking a net loss on existing corn ethanol in order to reallocate funds, resources, and intellectual capital to other, greener options.

7 DEMATERIALIZATION

Dematerialization is the practice of fulfilling human needs and desires with reduced production and disposal of material products. One aspect of dematerialization is simply increased material efficiency. If improved materials can reduce the amount needed to create a product, or if products can be made more durable or easily repairable, less material needs to be produced to perform the same function. Another, perhaps more powerful aspect of dematerialization, however, is the concept of “servicizing.” Servicizing leverages the idea that people are not usually interested in material products themselves, but rather the function they provide. If these functions can be met with a service rather than a dedicated product, there are opportunities for material reduction.

For instance, very few people are actually interested in owning carpeting for its own sake; rather, they value the service it provides: floor covering that is soft, warm, and attractive. Interface Inc. has recognized this fact, and rather than selling carpeting, it sells floor-covering services on a contractual basis. Customers purchase several years of floor covering services, selecting quality, color, and other preferences, and Interface then provides carpet. When the carpet wears out, Interface replaces it and recycles the old carpet into new product. Because there is a large financial incentive for Interface to make the carpet easily and efficiently recyclable, there is very little waste in this system. The consequence is that virtually no carpeting is landfilled, and less carpeting is needed to fulfill customers' needs—a classic example of dematerialization.

The potential net environmental benefit of dematerialization is that material production and disposal can be reduced, usually with few additional impacts. However, dematerialization can sometimes require new infrastructure or reverse logistics, and often requires an underlying shift in consumer behavior. These can be difficult to achieve, or in some cases perhaps impossible. Additionally, there is risk of a "rebound effect" if material cost savings lead to reduced purchase prices and therefore increased demand. As we will see in the following case study, these are complex considerations. When it works, however, the benefits of dematerialization can be dramatic.

7.1 Case study: Car sharing

7.1.1 Background

A car sharing service provides cars for hire around a city. Members of the service can use the cars at any time, paying for usage time, mileage, and in some cases a monthly fee. Car sharing represents one way to servicize personal transportation, with the user paying only for the service of driving, not for the car itself. Car sharing services typically offer a flat rate for time and/or mileage, and gas is often included in the price. Shared cars can be found in public parking lots, specially designated street-side parking stalls, and in the parking lots of participating businesses. Car sharing members typically reserve a car online for a specified period of time. They pick up the car from its indicated location, use the car for the duration of the rental period, and are usually required to return the car to its original location at the end of the rental period.

Car sharing companies specifically market to a broad customer base including people who would like to shed their personal cars, people who are “carless” and currently use public transportation, people who occasionally need a second car, travelers, and small business owners. Car sharing companies often tout their services based on a number of benefits including “car-ownership freedom,” lower cost, and flexibility, but often a significant part of the marketing effort is focused on car sharing as an environmental transportation solution (e.g., Zipcar Inc., 2014b). Under the net green definition, in order for the environmental claim to be true, car sharing must result in a net environmental benefit. As in the previous case studies, I will limit the discussion here to energy or global warming impacts, as these are important impacts in the automotive sector.

7.1.2 *Key environmental factors and key questions*

Car sharing can potentially reduce net environmental global warming impacts in four ways: 1) decreasing total vehicle miles traveled (VMT); 2) shifting travel from less efficient to more efficient vehicles; 3) shifting travel from personal vehicles to public transportation; and 4) preventing future production and disposal of personal vehicles. However, car sharing may also *increase* net environmental impacts by: 1) increasing total miles driven; 2) shifting travel from more efficient vehicles to less efficient vehicles; 3) shifting travel from public transportation to car travel; or 4) stimulating demand for personal vehicles. These key factors are summarized in Table 1.8.

	Potential environmental benefit	Potential environmental damage
1.	Car sharing may shift travel from less efficient to more efficient vehicles	Car sharing may shift travel from more efficient to less efficient vehicles
2.	Car sharing may decrease total vehicle-miles traveled	Car sharing may increase total vehicle-miles driven
3.	Car sharing may reduce public transportation usage	Car sharing may increase public transportation usage
4.	Car sharing may reduce production and disposal of vehicles	Car sharing may stimulate production and disposal of vehicles

Table 1.8: Key factors determining the environmental impact of car sharing

I will investigate these key environmental factors by asking four focus questions:

1) Are shared cars likely to be more or less efficient than the personal cars with which they compete?
2) What effect does car sharing have on total vehicle-miles traveled?
3) What is the effect of car sharing on public transportation use, and how does that affect vehicle miles traveled?
4) What is the total effect of car sharing on the production of new cars?

Throughout the discussion, I will periodically cite findings from three articles based on a large survey-based car sharing study by Martin, Shaheen, and Lidicker (Martin, Shaheen, & Lidicker, 2010; Martin & Shaheen, 2011a, 2011b). Martin and his colleagues conducted a survey of 6,281 active car sharing households to assess their pre- and post-membership driving behavior, their car ownership changes, what they would have done otherwise in the absence of car sharing, and a host of demographic information. This survey is extremely helpful in determining the impact of car sharing, but several key aspects were not included in the study. Therefore, rather than simply repeat the results of the survey, for each question I will first present theoretical arguments before turning to Martin et al.'s car sharing survey for empirical support, where it exists.

1) Are shared cars likely to be more or less efficient than the personal cars with which they compete?

Because car sharing companies include gas in the price of the rental, they have an incentive to maximize the efficiency of their rental fleet. Additionally, shared cars must be comfortable, clean, and mechanically sound in order to entice users. Therefore, we should expect shared car fleets to be new and fuel efficient. Car owners also have an incentive to minimize fuel costs, but for many people the long payback times of most hybrid or electric vehicles make them a poor investment at this point. Car sharing firms, on the other hand, put many times as many miles on each vehicle in a year, which shortens the payback period for fuel-efficient vehicles substantially. We therefore would expect car sharing fleets to be more efficient than personal vehicles.

These expectations are confirmed by Martin, Shaheen, and Lidicker (2010). As part of their car sharing survey, they collected data on the year, make, and model of each household's vehicles before joining a car sharing service as well as that of the shared car model they used most often. Matching survey responses with the U.S. Environmental Protection Agency's fuel economy database, they found that the average fuel efficiency of participants' owned cars before joining car sharing was 23.3 miles per gallon (MPG) (median = 23 MPG), whereas the average fuel efficiency of shared cars was 32.8 MPG (median = 31 MPG), an increase of over 10 MPG, or 41%. Additionally, over 25% of shared cars feature ultra-high fuel efficiency (46 MPG and above), in contrast to only 1% in the case of owned cars. Therefore, with respect to key question #1, we can conclude that car sharing is very likely to shift travel from less-efficient to more-efficient vehicles.

2) What effect does car sharing have on personal vehicle-miles traveled (not counting shifts in public transportation use)?
    a. If both car sharing and personal car ownership are possibilities, under what circumstances will people choose to share rather than purchase a vehicle?
    b. Once people have selected to use car sharing or to buy a personal car, will they drive more or less as a result?

This question is complex, as it is inherently behavioral-economic in nature. As indicated by the subquestions above, this question rests on two behavioral decisions: First, when will people use car sharing instead of purchasing a car, and second, will they drive more or less as a result of their decision? I will explore this question in two ways: By developing a discrete choice model utility maximization model, and then by using data provided by Martin et al.

The behavioral model assumes people have the option to either purchase a personal car or join a car sharing service. The two options have inherently different cost structures, and based on relative costs and individual preferences, will yield different optimal amounts of travel. The general approach I take is to derive a general utility function and budget constraints for both vehicle scenarios. I find the level of utility that derives from the optimal amount of travel under each scenario, and stipulate that individuals will choose the option that yields the highest utility for a given set of prices and preferences. Then, once the method of travel has been selected, I determine the optimal amount of travel under the selected option and determine whether more or less miles are traveled under the selected option than under the competing option.

Specifically, in this model people seek to maximize their utility, which they achieve by traveling in cars and consuming all other goods (more easily thought of as money spent on goods other than trips):

$$\begin{aligned} &\max_{T,Y} U = z\log(T_s) + \log(Y_s) \text{ for the shared car scenario} \\ &\max_{T,Y} U = x\log(T_o) + \log(Y_o) \text{ for the owned car scenario} \end{aligned} \tag{7.1}$$

where T_s and T_o are the number of miles driven in a shared car and owned car, respectively, and Y is the amount of all other consumption (the subscripts Y_s and Y_o are simply to distinguish Y under the shared car and owned car scenarios, respectively, but Y still represents the same kind of consumption in either case). $z \in [0,\infty)$ and $x \in [0,\infty)$ are the individual's preferences for shared car travel and owned car travel, respectively, normalized to his preference for all other goods (i.e., the coefficient on consumption of Y is 1). Logarithmic utility is used to ensure concave preferences, declining marginal utility, and increasing marginal rates of substitution, properties which are not only useful mathematically but have a long tradition in economic theories of decision making: Concave preferences arise from the theory of expected utility maximization (Bernoulli, 1954; von Neumann & Morgenstern, 1953), which explains people's tendency toward risk-aversion (see Varian, 2009).

Individuals choose the optimum level of trips and other consumption subject to their budget constraint, which is different based on whether they choose to take shared car trips (T_s) or purchase a car and take owned car trips (T_o). The budget constraint is:

$$\begin{aligned} &N = P_sT_s + Y_s \qquad \text{for the shared car scenario} \\ &N = P_oT_o + P_f + Y_o \quad \text{for the owned car scenario} \end{aligned} \tag{7.2}$$

where N is the individual's income/endowment during a modeling period of interest (year, month, etc.), P_s and P_o are the marginal price per mile of driving in a shared car or owned car, respectively, P_f is the fixed cost per period associated with purchasing a car, and the price of Y is one.

Maximizing the utility function subject to the budget constraint leads to optimal levels of T and Y for both scenarios. For the shared car scenario, maximizing eq. 7.1 subject to eq. 7.2, the optimal values are as follows:

$$\begin{aligned} T_s^* &= \frac{zN}{P_s(z+1)} \\ Y_s^* &= \frac{N}{z+1} \end{aligned} \tag{7.3}$$

For the owned car scenario, the optimal values are:

$$\begin{aligned} T_o^* &= \frac{x(N-P_f)}{P_o(x+1)} \\ Y_o^* &= \frac{N-P_f}{x+1} \end{aligned} \tag{7.4}$$

Comparing eq. 7.3 to eq. 7.4, individuals drive less and have lower consumption of other goods by the amount of P_f, all else equal. Individuals with higher income drive more miles and consume more of other goods under either scenario. Plugging these optimal values into the objective function in eq. 7.1, we can see that the two scenarios result in different levels of utility (again, to distinguish the cases, I use U_s and U_o for utility under the shared car case and owned car case, respectively):

$$\begin{aligned} U_s^* &= z\log\left(\frac{zN}{P_s(z+1)}\right) + \log\left(\frac{N}{z+1}\right) \\ U_o^* &= x\log\left(\frac{x\left(N-P_f\right)}{P_o(x+1)}\right) + \log\left(\frac{N-P_f}{x+1}\right) \end{aligned} \tag{7.5}$$

From eq. 7.5, the optimal choice between shared car travel and owned car travel is a function of the ratio of mileage prices (P_s/P_o), the ratio of trip type preferences (x/z), and the owned car fixed costs relative to income. Based on these values, individuals will choose the vehicle option that delivers the highest level of utility. Once the decision about method of travel has been made for that set of prices and preferences, we can return to eqs. 7.3 and 7.4 to determine the number of miles that will be driven under the chosen and alternative travel method. From this, we can determine whether vehicle miles traveled increased or decreased as a result of the chosen travel method.

To demonstrate, we will model one year of behavior for a person who has an annual net income of \$50,000 and has the option to purchase a car for an annualized fixed cost of \$6,000, which is the American Automobile Association (AAA) average annual ownership cost including financing, insurance, license, registration, and depreciation (American Automobile Association, 2012). Let us remain agnostic about her preferences for personal car travel vs. shared car travel, allowing the trip type preference ratio x/z to vary between 0 and 2.5, with $z = 0.05$ (i.e., the person values traveling a mile in a shared car 1/20 as much as "other" consumption). Let us also explore a range of potential price ratios, letting P_s/P_o range from 0.5 (shared car miles are half as expensive as personal car miles) to 5 (shared car miles are 5 times more expensive than owned car miles), with the own car mileage price set at the (AAA) estimate for operating costs of \$0.167 per mile (American Automobile Association, 2012).

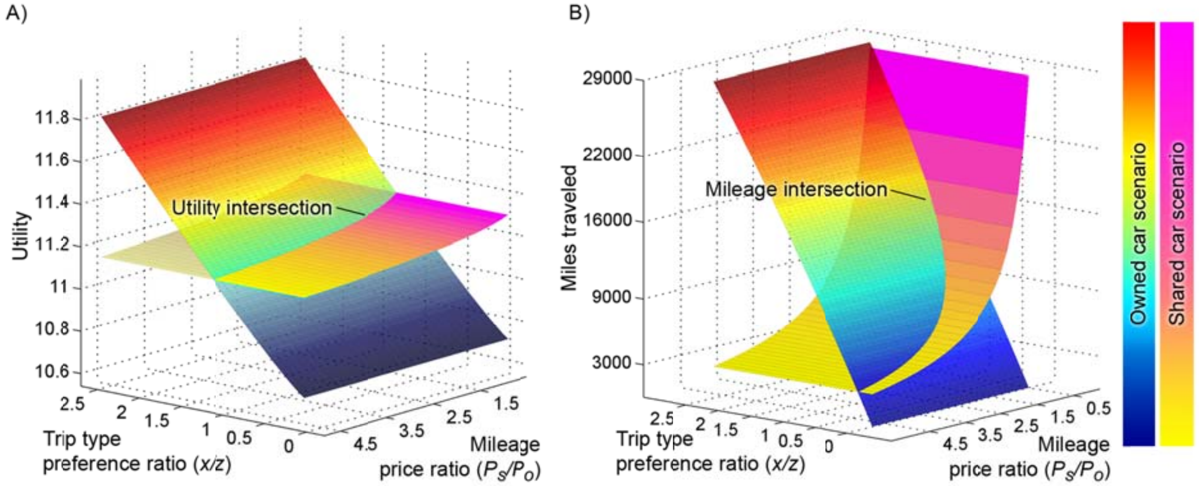

Figure 1.10: Set of optimal utility values (panel A) and associated number of trips (panel B) under the shared car scenario (yellow-pink) and owned car scenario (rainbow).

The universe of solutions for T_s, T_o, U_s, and U_o with this parameter set is shown in Figure 1.10. In panel A, the range of values of trip type preference ratio and mileage price ratio are plotted on the horizontal x-y axis. The maximized utility for each of the x-y pairs is plotted on the z axis, resulting in two planes of possible solutions, one for each scenario. The shared car results are plotted using a gradient from yellow (low) to pink (high); the owned car results are plotted as a rainbow gradient from blue (low) to red (high). Maximum utility from the shared car scenario decreases as the price of shared car mileage increases relative to the price of owned car mileage. As explained, the trip type preference ratio is normalized to shared car preferences (z), so utility of the shared car scenario is constant along this axis. Maximum utility from the owned car scenario increases in the trip type preference ratio as the value of a personal trip relative to a shared trip and other consumption increases, but is constant in the mileage price ratio since this ratio is normalized to the price of owned car mileage.

The portion of each plane that is “above” the other plane (i.e., higher on the z axis) in panel A makes up the consideration set:[13] to maximize utility, the individual making the travel mode decision would evaluate her preferences and the actual prices of shared car and owned car travel, then choose the option corresponding to whatever plane is higher (i.e., that leads to more utility) at that point. For instance, for a price ratio of 3 and trip preference ratio of 2, owning a car provides more utility than a shared car; but for a price ratio of 3 and a trip value ratio of 0.5, a shared car provides more utility. The curve where the two utility planes intersect (marked on the figure) is the set of price and preference values for which the individual is indifferent between taking shared car trips and purchasing a car. This line is infinitesimally thin, however, so the probability of a price ratio–preference ratio combination leading to true indifference is zero. The indifference line can thus better be thought of as the set of decision cutoff points.

Once the travel mode decision has been made, we can turn to panel B of Figure 1.10, which shows the optimal number of trips under each scenario, using an x-y axis and coloring identical to panel A. From panel B we can see that there are some price ratio–preference ratio combinations that result in more trips under the shared car scenario (where the yellow-pink plane is higher on the z axis than the rainbow plane), and some that result in more trips under the owned car scenario (the reverse). Similarly to panel A, the curve where the two trip planes intersect is the set of price ratio/preference ratio points where the two scenarios result in an equal number of trips (also marked on the figure).

Combining Figure 1.10 panels A and B, there are four possible outcomes. Depending on the actual price ratio of owned vs. shared mileage and on individual trip type preferences, individuals can:

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[13] The portions of the planes not in the consideration set are slightly grayed-out in panel A.

- Choose a personal car and drive more as a result
- Choose a personal car and drive less as a result
- Choose a shared car and drive more as a result
- Choose a shared car and drive less as a result

We can use the two intersection curves from both panels of Figure 1.10 to determine the range of parameter values that will result in each of these outcomes. Figure 1.11 shows the intersection curves projected onto the x-y plane. The area above the utility intersection curve denotes points where the individual will choose a personal car, while the area below it denotes points where she will choose a shared car. The area above the mileage intersection curve denotes points where choosing an owned car will result in more mileage, while the area below this curve denotes points where choosing a shared car will result in more mileage. Thus, the figure is divided into four quadrants corresponding to the four outcomes listed above. For points in the upper left quadrant (white solid), the individual will choose to own a personal car and will consequently drive fewer miles than she would have if she were forced to car share. On the upper right (dotted), she will choose a personal car and will drive more than she would under car sharing. On the lower left (gray solid), the individual will choose a shared car and will drive more than she would have if she were forced to purchase a car; on the lower right (diagonal hash), she will choose a shared car but drive less as a result.

There are several interesting general outcomes of Figure 1.11. One is to note that for the modeled parameters (income of \$50k, fixed costs of \$6k or 12% of income), individuals who are indifferent between shared cars and owned cars (i.e., the line at $x/z = 1$) will never opt to purchase a car, even if shared car mileage costs five times as much as owned car mileage. This is because buying a car effectively reduces total consumption by the amount of the fixed cost, lowering utility.

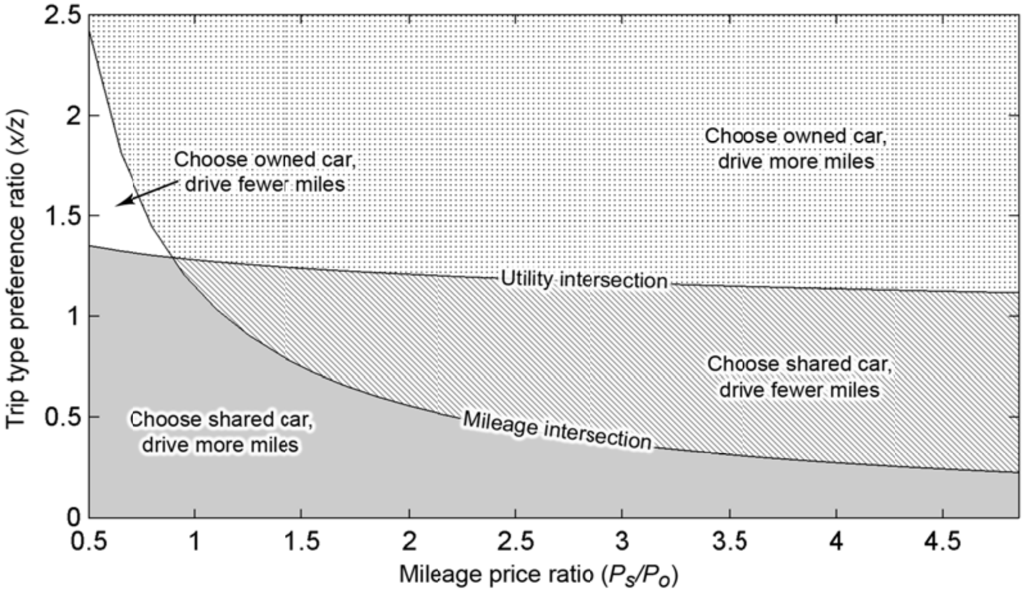

Figure 1.11: Intersection curves from the utility and mileage planes showing the sets of parameter values that result in four different behavioral outcomes. Parameters: $N = \$50\text{k}$, $P_f = \$6\text{k}$, $z = 0.05$, $P_o = 0.167$.

Additionally, people who prefer owned car travel over shared car travel (for convenience, status, etc.) may end up above the utility intersection depending on the shared vs. owned mileage price ratio. With the modeled input parameters, people who prefer owned car travel 1.5 times as much as shared car travel will never opt for a shared car even if the per-mile price of shared cars is half that of owned cars. For people on the fringe, however, the price ratio is the primary determinant of which travel mode a person chooses and whether she drives more or less. If the shared car price is too high, people will choose to buy a car and will drive more as a result. If the price is too low, people will choose a shared car but will drive more as a result.

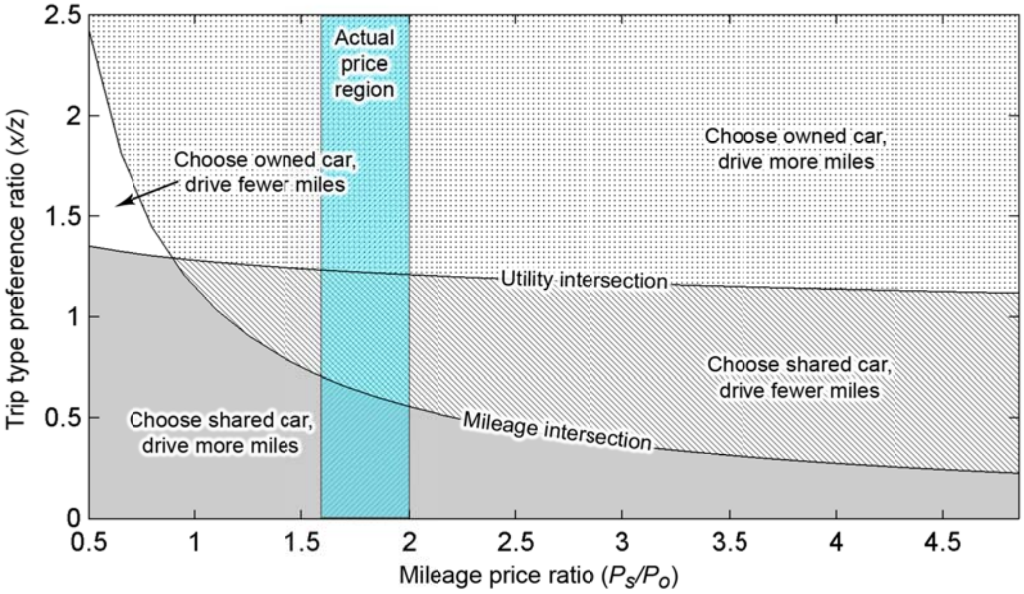

Figure 1.12: Figure 1.11 with overlay region showing range of real-life shared-to-owned mileage price ratios

What does the model suggest about real-life outcomes? To answer this, we can look at a range of actual mileage price ratios in Figure 1.11. At the time of writing, Zipcar Inc. charged \$8–10 per hour (after a \$6 monthly fee) (Zipcar Inc., 2014a). Assuming an average urban speed of 30 miles per hour,[14] this equates to \$0.27-0.33 per mile. As stated, AAA estimates that operating a small sedan costs \$0.167 per mile. This results in a shared-to-owned car mileage price ratio between 1.6 and 2.

This means that the real-world set of points in Figure 1.11 that we are interested in are those in the region between $P_S/P_o = 1.6$ and $P_S/P_o = 2$. Figure 1.12 replicates Figure 1.11, highlighting this region (blue crosshatch). The utility intersection curve intersects this region at about $x/z = 1.25$, meaning that people facing owned car fixed costs of 12% of income who prefer owned car travel 1.25 times more than shared car travel will choose an owned car and will drive more miles as a result (the segment where owned car travel leads to

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[14] Average of fifty largest U.S. cities using Google Maps speed data, not including traffic (Google, 2012; InfiniteMonkeyCorps.net, 2014)

fewer miles is infeasible within the actual price region for this set of parameters). People with the assumed parameters who do not have a preference for owning a car ($x/z = 1$) will choose to share a car within this price region. Whether they choose to drive more or less with a shared car than they would have if car sharing were not an option depends on how much they value car travel in general and how much they value personal car travel to shared car travel. The general shape of these curves and results of the model are robust to variation in the parameters N, P_f, and z (see the Appendix for more details).

The behavioral model is useful because it shows how different relative mileage prices, fixed costs, and preferences can affect the decision of whether or not to use car sharing and how VMT can be affected as a result. From the range of real-life price ratios, we were able to see the set of feasible outcomes. However, this feasible set includes three of the four original possibilities: choose an owned car and drive more, choose a shared car and drive more, and choose a shared car and drive less. Therefore, without further information on car travel preferences (both relative to other consumption and each type relative to the other), the model was unable to determine with certainty which outcome will be realized. In principal, one could measure an individual's preferences to determine where he or she falls in Figure 1.11. With enough individual observations, one could also establish a probability distribution of preferences, from which one could determine the various probabilities of each of the three feasible outcomes occurring.

Following this approach, one could determine what proportion of a city's population is likely to use car sharing if it were introduced, and the number of miles those people would drive as a result. From this information, the net green status of car sharing, with respect to net VMT, could be established. Suppose, for example, one discovered that in a city of 100,000 people, 40% would be likely to use car sharing instead of buying a car, and of those, half would drive an additional 1,000 miles each year while the other half would drive 1,500 less each year, on average. Then the net change in VMT would be $100{,}000 \times 0.4(0.5 \times 1000 - 0.5 \times 1500) = 20 \times 10^6 - 30 \times 10^6 = -10\text{M}$ vehicle miles.

The model only describes the own-or-share decision.[15] This, of course, is one of many possible decisions facing urban travelers. Nonetheless, the model demonstrates how, with more complexity, these kinds of behavioral decisions could be modeled in order to determine the net effect car sharing has on vehicle miles traveled and, in general, the net green status of a dematerialization activity (of course recognizing the inherent limitations and simplifications of model-based approaches).

Another possibility to answer focus question #2 is to survey car sharing users and ask them about their current driving behavior, their past driving behavior (before car sharing), as well as their projections of what they would have done if car sharing had not been available, which was the approach taken by Martin and Shaheen (2011b). These authors divide VMT changes into two categories: "observed" and "full." Observed impacts are observable changes in VMT—simply the difference between VMT before and after a person joins car sharing. Full impacts are observed impacts minus any avoided impacts of foregone travel. Avoided impacts are impacts from mileage that a person would have traveled if he or she had purchased a car instead of joining car sharing. To estimate avoided VMT, Martin and

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[15] Although the discussion centered on the decision to buy or share a car, the model can equally be used to model the decision to continue to use an owned car or sell it to use a shared car. In this case, the decision would involve whether to eliminate the fixed cost associated with car ownership as well as increase income in the form of cash for the sold car. However, I will not derive the results of using the model in this way in this chapter.

Shaheen asked respondents how many cars they would have bought in the absence of car sharing, and how many miles they would have traveled with each.[16]

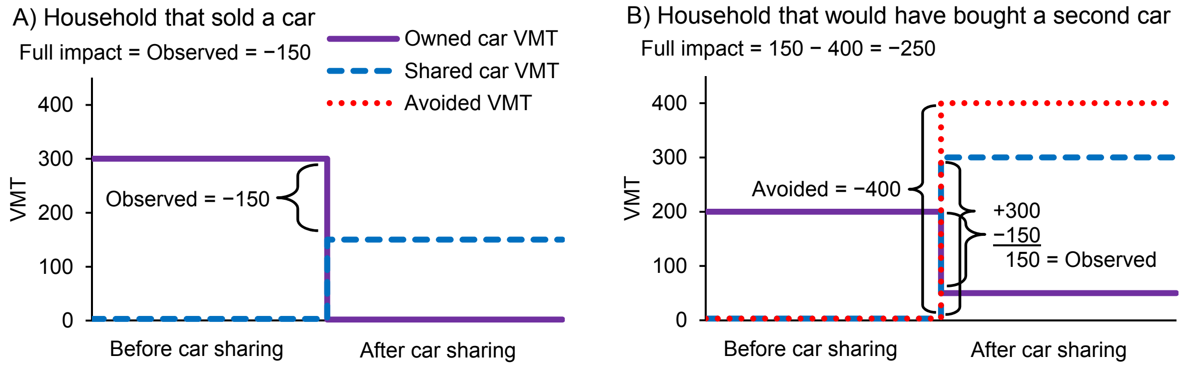

Figure 1.13: How "observed" and avoided impacts are combined to calculate "full" impacts. Observed impacts are measurable changes in VMT before and after car sharing; avoided impacts are miles not traveled in vehicles not purchased as a result of car sharing. Full impacts are the sum of observed and avoided impacts.

The two categories of impacts are illustrated in two hypothetical situations in Figure 1.13. Panel A illustrates a household that sells a car upon joining car sharing. Since there is no avoided vehicle purchase, there are no avoided VMT and "full" impact is equal to "observed" impact, which is simply the difference between VMT before and after joining car sharing. Panel B illustrates a case of a household that would have bought a second car in the absence of car sharing. Before joining car sharing, they drove their owned car 200 VMT; after joining car sharing, they drive their owned car 150 VMT less, and drive a shared car 300 VMT, for a net increase of 150 VMT. Additionally, because they joined car sharing, they decided not to buy a second vehicle, which they estimate they would have driven 400 VMT. Since they do not purchase the car, these 400 VMT are avoided.

However, the situation in panel B is more complex than it may appear. A complicating factor—not discussed by Martin et al. but nonetheless crucial—is that the

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[16] Asking individuals to forecast their own counterfactual travel introduces considerable uncertainty; however, Martin and Shaheen conduct sensitivity analysis and determine that even significant (100%) overestimation of counterfactual travel would not change the overall results of the survey.

calculation of avoided impacts depends on the household's assumed future behavior with respect to their owned car in the absence of car sharing (i.e., the counterfactual). As it is illustrated, there is an implicit assumption that the 150 VMT decrease in owned car usage was due to the household joining car sharing, and without car sharing the household would have continued to drive their owned car 200 VMT in addition to the 400 VMT of the second car. However, if the household would have decreased this car's usage by 150 VMT even in the absence of car sharing, perhaps because they favor their new second car, then the full impact calculated as shown in the figure is overstated by 150 VMT. Instead, the 150 VMT decrease of the owned car must also be counted in the "buy a second car" counterfactual.

"Full" impact is "what happened" minus "what would have happened"; if the owned car would have been driven less in either case it must be included in both parts of the equation. Thus, the true avoided impacts in this case are the 400 VMT of the foregone car less the 150 VMT of the decrease in the owned car. Therefore, the "full" impacts are the sum of the additional 300 VMT of the shared car, less the decreased 150 VMT of the first owned car, less the avoided VMT: 300 – 150 – (400 – 150) = –100 VMT. In other words, the effect of the decrease in the first owned car is canceled out of the net impact calculation since it occurs either with or without car sharing. This highlights a general point about the importance of the forecasted counterfactual future. In this case, different assumptions about the counterfactual can significantly change the "full" impact calculation. I will return to this important concept in the conclusion.

Based on the survey data from Martin and Shaheen (2011b), 58% of car sharing households were previously carless and joined a car sharing service to gain access to a vehicle. Among these previously carless households, 100% reported increases in their vehicle miles traveled by car (by definition). By comparison, 17% of the survey respondents shed at least one owned vehicle after joining car sharing, and an additional 8% decided to join car sharing instead of replacing or repairing a nonoperational vehicle. Among these households, 88–93% reported reducing their vehicle travel, with the size of reductions depending on the number of vehicles shed (reductions were greater among households going from one car to none). The travel reductions in this group were much larger (often an order of magnitude) than the increases of those in the previously carless group. Thus, the increases of carless households driving shared cars was offset by the reductions of households driving less after shedding cars. The average direct VMT change after joining car sharing was $-1{,}081$ miles per year (27% decrease), and the average full VMT change—including miles that would have been driven in the absence of car sharing—was $-1{,}728$ miles per year (43% decrease).

Considering these changes in vehicle miles traveled as well as changes in fuel economy from owned to shared vehicles, Martin and Shaheen calculate the average household "full" GHG impact according to the formula

$$GHG_{full} = EF(VMT_{new} \times FE_{new} - VMT_{old} \times FE_{old} - VMT_{avoid} \times FE_{avoid}) \tag{7.6}$$

where EF is the EPA emission factor for combustion of gasoline, VMT_{old} and VMT_{new} are vehicle miles traveled before and after joining car sharing, respectively, FE_{old} and FE_{new} are the fuel efficiencies of vehicles used before and after joining car sharing, respectively, and VMT_{avoid} and FE_{avoid} are the number of miles and fuel efficiency not driven on foregone vehicles (i.e., the avoided "full impact" emissions). Direct GHG emissions are identical except they omit the avoided emissions. Not included in the GHG calculation were vehicle production and disposal emissions and emissions from public transportation use. The GHG formula was applied to each survey respondent, and the results were binned into a histogram showing how many respondents increased or decreased their GHG emissions by different amounts, both for only direct impacts and for full impacts, replicated in Figure 1.14.

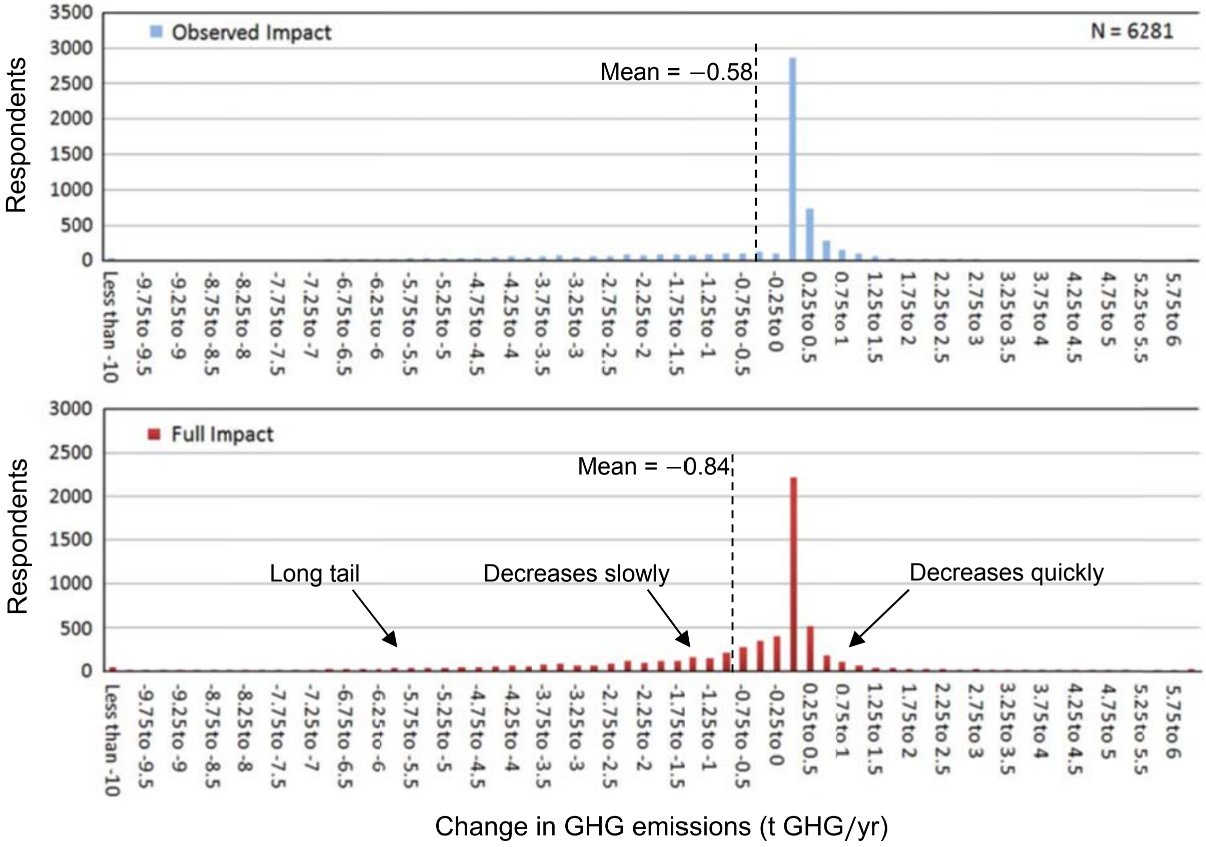

Figure 1.14: Number of car sharing users reporting different levels of GHG emissions changes (modified from Martin & Shaheen, 2011b)

According to the figure, the majority of respondents increase their GHG emissions; 71% increase direct emissions and 53% increase full emissions. Yet, as indicated on the figure, the mean direct emissions change is −580 kg GHG/year per user and the mean full emissions change is −840 kg GHG/year per user. This seemingly counterintuitive result can be explained by the asymmetry of the distribution of emissions changes: Most of these increases are small in magnitude, whereas the long tail on the left of both histograms indicates that although there are fewer people who decrease emissions, they do so by a larger amount (bars further from zero have a larger impact on the cumulative GHG emissions because they represent larger increases or decreases). Thus, the survey results of Martin and Shaheen (2011b) show that, in aggregate, car sharing reduces VMT in personal vehicles and associated GHG emissions, but this decrease is not uniform across all car sharing users: A minority of users who exhibit large VMT reductions compensate for the majority of users who increase VMT.

3) What is the effect of car sharing on mileage shifts to and from public transportation?

Answering key question #2 focused on VMT changes resulting from the decision to buy a personal car or use a shared car, and how much to drive a personal car versus a shared car. However, also at issue is the effect that car sharing can have on various modes of public and alternative transportation. Changes in public transportation usage are important because they reduce the size of the VMT changes discussed in the previous section, as illustrated in Figure 1.15.

In panel A of the figure, the increases in car VMT from previously carless households gaining access to shared vehicles are partially offset by reductions in public transport VMT. Conversely, for households that shed cars, reductions in car VMT are partially offset by increases in public transport VMT (panel B). This effect is important to keep in mind while answering focus question #3: Because we have already evaluated changes in car VMT in focus question #2, changes in public transportation usage discussed in this section are separate and in addition to the changes in car VMT discussed earlier. Somewhat counterintuitively, therefore, increases in public transportation usage represent increases—not decreases—in GHG emissions.

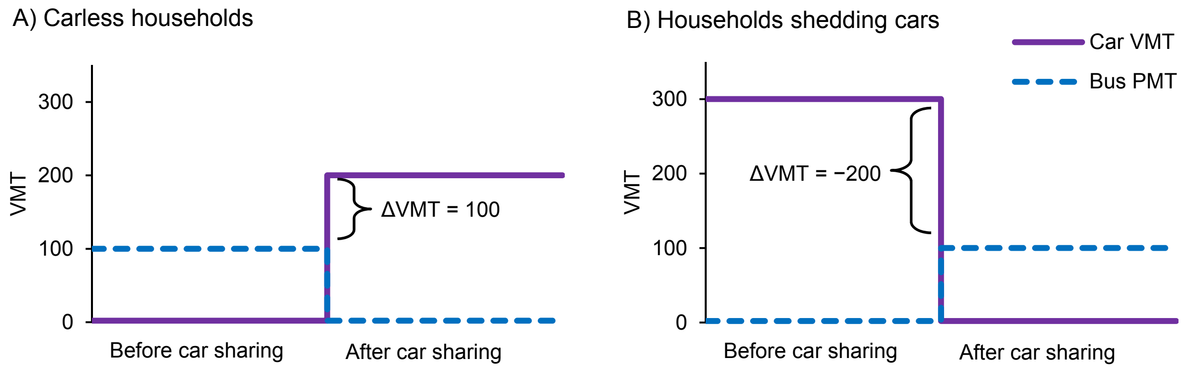

Figure 1.15: How shifts toward and away from public transportation usage compensate for shifts in car VMT. The net change in total travel is the difference between travel before and after car sharing, which is less than the change in car VMT if public transport is used instead. PMT stands for passenger miles traveled, since a public transportation user only adds an additional passenger—rather than additional vehicle—for each additional mile traveled.

As reported by Martin and Shaheen (2011b), the majority of car sharing users are people who did not own a car before joining car sharing. This means that, outside of occasional rental cars, they had no access to car travel and thus used public or alternative transportation (motor scooter, walking, biking, etc.). Traveling by car can be more convenient than traveling by public or alternative transportation due to increased freedom and flexibility. Thus, because car sharing gives carless households access to car travel, it may shift their travel from public or alternative transportation to car travel. Previously carless people who used public transportation for errands may find a shared car more convenient and use public transportation less. This shift increases these households' car VMT, but decreases their public transportation travel, which partially offsets the emissions increase. However, alternative transportation typically has low or no emissions, and public transportation has very low emissions per passenger mile traveled (PMT) due to high vehicle capacity; thus, the public transportation decrease will not fully offset increases in car VMT, even if it is an even shift in terms of mileage.

On the other hand, in many urban environments driving a car is less convenient than taking public or alternative transportation due to high vehicle congestion and limited parking. It is conceivable that some people own a car only because they occasionally need to use it for abnormal trips for which public or alternative transportation would be impractical. Yet, because they own the car, they may take more trips (on weekends, or occasional commuting) simply because it is easy to do so. With car sharing as an option, these people may decide that occasionally using a shared car fills the need for occasional abnormal trips, and may choose to sell their owned car. Without the availability of an owned car, not only will these people drive less in total, they may increase their usage of public or alternative transportation. This increase will offset the emissions reductions from car VMT, but due to the lower emissions per PMT of public transportation this offset will not be full.

In their third car sharing article, Martin and Shaheen (2011a) report results from the car sharing survey on members' transportation mode shifts after joining a car sharing service. Portions of these results are reproduced in Tables 1.9 and 1.10.

Transportation mode	Number of people increased	Number of people decreased	Increase ratio
Rail	494	589	0.84
Bus	732	828	0.88
Walk	756	568	1.33
Bike	628	235	2.67
Carpool	289	99	2.92
Ferry	6	13	0.46

Table 1.9: Summary of transportation mode shifts (source: Martin & Shaheen, 2011a). Increase ratio is calculated as the number of people increasing the mode divided by the number of people decreasing the mode. An increase ratio greater than one indicates that more people increased than decreased the transportation mode.

Table 1.9 shows the number of people who increased and decreased different alternative and public transportation modes, along with the ratio of people increasing to people decreasing each mode. From the table, the effect of car sharing on public and alternative transportation usage appears to be mixed. Some car sharing members increased their public transportation use, but more decreased it. For every six people who decreased rail use, only five people increased it; for every eight people who rode the bus less, only seven people rode the bus more. More people increased rather than decreased their travel by bicycle, carpool, and walking.

Martin and Shaheen attribute these findings to the large proportion of carless households in the sample. They suggest that whether people use public transportation more or less after having access to car sharing is a result of differences in travel circumstances. Those who previously had a car and are adapting to a carless lifestyle will ride public transportation more; those previously without cars will ride public transportation less. Since 60% of the sample was carless before car sharing, the results are pushed toward an overall decrease in public transportation usage.

People can appear in Table 1.9 more than once (for instance, the six people who increased ferry use may have also increased usage of the other modes), making it difficult to draw conclusions about overall transportation shifts. Table 1.10 presents similar information but groups the transportation modes into car travel vs. public and alternative transportation, and places each respondent into only one category based on whether he or she increased, decreased, both increased and decreased, or had no change in their public and alternative transport modes. This split makes it clearer that more people increased their usage of public and alternative transportation than decreased it. Additionally shown is the average VMT in personal cars for respondents in each group, which shows that the personal car VMT decrease from people who increased their usage of alternative and public transportation far outweighs the personal car VMT increase from people who decreased their usage of these transport modes. Even people who stated both an increase and a decrease in public and alternative transportation tended to drive less as a result.

Measurement	Direction of change after joining car sharing	Respondent count	Average observed personal VMT change (VMT/yr/hh)
Average hours using transit	Increased public and alternative transport only	1,046 (17%)	-5,040
	Both increased and decreased public and alternative transport	755 (12%)	-1,711
	Decreased public and alternative transport only	901 (14%)	438
	No stated change in and alternative transport	3,579 (57%)	-181

Table 1.10: Change in nonmotorized/public transit travel (source: Martin & Shaheen, 2011a)

Interestingly, there were differences in the mode-change and driving distance behavior of users among the eleven car sharing companies represented in the sample, indicating that there may be differences in the companies' marketing or target consumers that encourage either increased or decreased public transportation usage, a point to which we shall return in the conclusions.

Mode	Passenger-miles per gallon	Source	Notes
Car	23.3	Martin, Shaheen, & Lidicker (2010)	Owned-car average
Rail	52.6	DOT NTS Table 4-27[a]	pMPG-equivalent, assuming U.S. EPA standard 33.7 kWh/gal
Bus	48.6	DOT NTS Table 4-24[a]	
Walk	0		Excludes food energy
Bike	0		Excludes food energy
Carpool	46.6	Calculated	Double car MPG; assumes two occupants
Ferry	13.6	Cottrell (2011)	Vessel count-weighted average of all U.S. ferry operators reporting to National Transit Database

[a] U.S. Department of Transportation (2012) National Transportation Statistics; 2011 values

Table 1.11: Average fuel efficiency used to compute GHG change from transportation mode shifts

In order to calculate the net GHG change from transportation mode shifts, more information would be needed. First, representative fuel efficiencies for each transportation mode would be required, such as those shown in Table 1.11. Second, data on each individual car sharing member's VMT for each transportation mode would be needed. These data could be combined to calculate a net change in fuel consumption and, with a fuel emission factor, a net change in GHG emissions. Unfortunately, the survey authors have not made the individual-level data available to conduct this analysis. Aggregated information such as shown in Tables 1.9 and 1.10 is insufficient because it is impossible to determine the source and destination of the mode shifts.

Even without this calculation, however, we have come a good deal closer to answering key question #3. Basically, the answer is that car sharing does draw some people away from public and alternative transportation, but it draws more people toward them. Due to the lifestyles of formerly carless people (short commute distances, urban settings, etc.), the increase in car VMT from those decreasing their use of public and alternative transportation is outweighed by the VMT decrease of people shedding cars; however, this decrease is partially offset by these people using more public and alternative transportation. In summary, car sharing appears to create a net transportation mode shift that lowers overall VMT and likely (but not assuredly) lowers net GHG emissions.

4) What is the total effect of car sharing on the production and disposal of new cars?

The discussion of the net green status of car sharing thus far has focused exclusively on use-phase emissions. GHG emissions from use are an important part of a transportation system's overall impact, but they are not the only impacts. According to a life cycle assessment by Hawkins, Singh, Majeau-Bettez, and Strømman (2013), fuel combustion makes up 65% of total GHG emissions, but production and end-of-life (EOL) are the second-largest category at 15% of GHG emissions; production and EOL also represent the largest life cycle phase in terms of human and ecotoxicity impacts. Production and EOL impacts are relevant for car sharing because car sharing has the potential to change net vehicle production. This aspect of car sharing is often highlighted in car sharing marketing materials.

Zipcar Inc., for instance, claims that “each and every Zipcar takes fifteen personally owned vehicles off the road” (Zipcar Inc., 2014b), which they derive from data and statements made by Martin et al. (2010). Whether this claim is true has a potentially large bearing on the net green status of car sharing.

To evaluate the effect of car sharing on vehicle production, let us first make several simplifying assumptions that should be uncontroversial. First, assume that on average, each vehicle produced is driven for a lifetime of M miles before being scrapped. M represents the point at which the vehicle has been fully “consumed” and is more valuable as scrap than as a vehicle, and therefore depends on a number of factors that we will discuss. Note that this first assumption does not require every vehicle to be driven for the same number of miles, merely that the average lifetime over the entire vehicle fleet is equal to M, around which we expect there to exist a distribution of actual vehicle lifetimes. Second, assume that there is a total “demand” for vehicle-miles by all consumers each year (or other time period t), equal to VMT_t. This number is simply the sum of all miles traveled by all vehicles over the period t, estimates of which are readily available from many transportation statistics agencies. Third, assume that new vehicles are produced as old vehicles are scrapped to the extent that they are needed to fulfill VMT_t. Therefore, in the steady state where VMT is constant, the number of vehicles produced equals the number of vehicles scrapped, which is equivalent to the number of vehicles fully consumed in the period.[17] We can then express the total number of vehicles scrapped and produced in the period (V_t) by dividing period VMT by vehicle lifetime:

$$V_t = \frac{VMT_t}{M} \tag{7.7}$$

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[17] Because the number of vehicles produced equals the number disposed of, for the remainder of the discussion I refer only to vehicle production rather than vehicle production and disposal.

We can confirm the validity of this approach by plugging actual values for VMT and vehicle production into eq. 7.7 and ensuring this produces a sensible vehicle lifetime estimate. For instance, total U.S. VMT for cars in 2010 was 1.56×10^{12} miles (Davis, Diegel, & Bundy, 2013); total U.S. car sales and leases in 2010 were 7.53×10^{6} (U.S. Bureau of Transportation Statistics, 2013), which results in $M = 207{,}000$ miles. The Federal Highway Administration estimated that 2002 vehicle lifetimes were 152,000 miles, and lifetimes have been increasing over time (Davis et al., 2013), so the estimate for M is reasonable.

The point of presenting new vehicle production in this way is to highlight that there are only two variables that can change the number of vehicles produced: total VMT, which has a direct relationship with vehicle production, and vehicle lifetime, which has an inverse relationship with vehicle production. It is also worth emphasizing here that vehicle production is equivalent to *new* car sales; used car sales simply shuffle existing cars around among owners until they reach their M-mile lifetime. Used car sales, therefore, do not have any impact on vehicle production except to the extent that they change either total VMT or vehicle lifetime. This important fact has been misunderstood in prior car sharing literature, a point to which we shall return shortly.

Because the only variables that affect car production are VMT and vehicle lifetime, car sharing can only affect net vehicle production to the extent that it causes changes in either of these variables. The previous sections detailed how car sharing is likely to result in VMT reductions; all that is left is to ask how car sharing might affect vehicle lifetime.

Average vehicle lifetime is collectively determined by car owners who must make decisions about whether to maintain or retire aging vehicles. Setting aside sentimentality and other noneconomic concerns, the car owner's fix-or-scrap decision is based on minimizing transportation costs in order to meet desired levels of travel. As a vehicle ages, more repairs are required and therefore vehicle maintenance becomes more expensive on the margin. At the same time, the option exists to scrap the vehicle and use the scrap value toward the purchase of a newer car. Presumably, scrap values are constant, based on the metal content of the vehicle. Therefore, the individual will choose to scrap the vehicle at the point when the annual cost of maintaining the vehicle (P_{maint}) becomes greater than the annualized fixed cost of purchasing a newer one (P_f, as above), less the scrap value (P_{Scrap}):

$$P_{maint} > P_f - P_{Scrap} \tag{7.8}$$

Thus, under these conditions, there are three determinants of vehicle lifetime: maintenance cost, scrap value, and replacement vehicle cost. It is difficult to imagine close causal links between the existence of car sharing and maintenance costs or scrap values. However, car sharing could very well change the cost of buying a replacement vehicle by affecting the supply of vehicles in the market. Car sharing companies maintain very young fleets in order to provide users with modern, trouble-free rental vehicles. Zipcar Inc., for instance, only purchases new vehicles and maintains an average vehicle age of eleven months (Zipcar Inc., 2013), after which the cars are sold on the used car market. In 2012, there were twenty-six U.S. car sharing organizations operating 12,634 vehicles (Shaheen, 2012); if each is replaced every eleven months, this equates to over 13,700 cars, or 0.18% of U.S. annual new car sales (Davis et al., 2013), entering the used car market annually due to car sharing. It is conceivable that this increase in supply will reduce the price of used cars, which lowers P_f in eq. 7.8 and therefore decreases vehicle lifetime. The size of this effect is unknown, and is likely impossible to test until shared car fleets makes up a larger share of total vehicle sales.

Nonetheless, the key insight of this section is to realize that new car production is affected only by total VMT and vehicle lifetime. This is an interesting insight, since much is said in the car sharing literature about shed cars being “taken off the road.” Because cars shed by car sharing members are sold, not scrapped, this can be a misleading statement. Only foregone future vehicles—not shed vehicles—reduce net vehicle production and thus “take cars off the road.”

With this in mind, let us assess the Zipcar marketing statement that “each and every Zipcar takes fifteen personally owned vehicles off the road” (Zipcar Inc., 2014b). Zipcar draws this statistic from Table 4 of Martin et al. (2010, p. 14), which estimates that the number of car sharing members across the entire car sharing industry who shed vehicles ranged between 36,565 and 73,129, and the number of members who “maybe, probably, or definitely would [have bought] a car in the absence of carsharing” (i.e., avoided vehicles) ranged between 39,299 and 78,598. This study also reports that 9,818 car sharing vehicles were in operation in 2010. The authors add the total number of vehicles shed and avoided and divide by the number of operational car sharing vehicles to arrive at a value of “vehicles removed per carsharing vehicle” between 7.7 and 15.5. Zipcar adopts the higher of these numbers and claims that each Zipcar removes fifteen cars from the road.

The preceding discussion reveals that this methodology is flawed for two reasons. First, as mentioned, shed cars are not avoided cars. The method of summing shed cars and avoided cars as “removed cars” ignores the fact that shed cars continue to operate as used cars to the end of their useful lives. Second, in their survey, Martin and his colleagues did not ask car sharing members whether they would have bought a *new* car in the absence of car sharing, only whether they would have bought *any* car. As discussed, only new car sales increase vehicle production—used car sales simply shuffle existing cars around until they reach the end of their lives. Therefore, only foregone new car sales can truly be said to be avoided and therefore to reduce net vehicle production and disposal. However, this information was not recorded in the survey.

We can calculate a different estimate for the change in vehicle production caused by car sharing using real-world data in eq. 7.7. Assuming the "full" VMT change of –1,728 miles per car sharing user per year, as discussed in focus question 2, and 806,332 U.S. car sharing users in 2012 (Shaheen, 2012), and assuming that the effect of car sharing on vehicle lifetimes is negligible and average vehicle lifetimes are 207,000 miles, the change in vehicle production is:

$$\begin{aligned}\Delta V_t = \frac{\Delta VMT_t}{M} &= \frac{-1{,}728 \text{ miles } (\text{year} \times \text{user})^{-1} \times 806{,}332 \text{ users}}{207{,}000 \text{ miles car}^{-1}} \\ &= -6{,}731 \text{ cars year}^{-1}\end{aligned} \tag{7.9}$$

Using the 2012 car sharing fleet size of 12,634 vehicles (Shaheen, 2012), this equates to –6,731/12,634 = –0.53, or half of a new vehicle avoided for every shared vehicle. These estimates are 11–23 times smaller than those reported by Martin et al. (2010). Even using an extremely conservative estimate for M of 100,000 miles results in 13,933 avoided cars, or 1.1 avoided cars per shared car. The discrepancy between these numbers and those of Martin and his colleagues is due to the fact that those authors 1) count shed cars as avoided cars and 2) assume that avoided used cars reduce vehicle production. This discussion has shown that the true parameters of interest are total VMT and vehicle lifetime, and that a more reasonable estimate of the net effect of car sharing on vehicle production is less than one avoided new car per shared car. Thus, car sharing does appear to create net benefit through reduced vehicle production and disposal, though the quantity of avoided cars is smaller than previously estimated.

7.1.3 Is car sharing net green?

In this, the most complex of the four case studies, we used the lens of the net green definition to examine the practice of dematerializing vehicle transportation by sharing cars. We recognized that there are four different sets of effects that car sharing can have on the environment: shifting travel between more and less efficient vehicles, changing vehicle miles traveled, shifting travel between personal vehicles and public transportation, and changing the production and disposal of new personal vehicles. In each of these, there was potential for car sharing to either increase or decrease net environmental impacts. By applying the net green definition and following chains of causality we determined that the answer to whether car sharing is net green rests with four key questions:

1) Are shared cars likely to be more or less efficient than the personal cars with which they compete?
2) What effect does car sharing have on personal vehicle-miles traveled?
3) What is the effect of car sharing on mileage shifts to and from public transportation use?
4) What is the effect of car sharing on the production and disposal of new cars?

Answering the first question was simply a matter of using data from Martin and his colleagues (2010) to determine the average fuel efficiency of vehicles previously used by car sharing members vs. those of car sharing fleet vehicles used instead. The data indicate that car sharing vehicles are 41% more efficient than shed personal vehicles, on average.

I attempted to answer the second question two ways. First, I developed a behavioral model that described people’s decision to buy a car or use a shared car. The model showed that people will choose both options depending on prices and preferences, and that within the range of real-life prices, either choice is possible. Within this range, the decision to drive a personal car will always result in higher VMT. The decision to car share can lead to either higher or lower VMT, depending on preferences for car travel in general and on preferences for personal car travel over shared car travel. Second, I drew on findings from Martin and Shaheen (2011b), who found that even though the majority of car sharing members increased their VMT, the fact that the minority decreased VMT by a larger amount meant that, on average, car sharing members reduced their VMT by 43%.

For the third question, first pointed out that because I already accounted for changes in car VMT in the second question, increases in public transportation offset reductions in vehicle VMT caused by car sharing; conversely, reductions in public transport from carless households partially offset the car VMT increases of using shared cars. To quantify these effects, I turned again to Martin and Shaheen (2011a), who found that car sharing causes transportation mode shifts both toward and away from public and alternative transportation. As a result of car sharing, fewer people travel by bus and train, but more people walk and bike. However, data on the VMT changes in each of these modes was unavailable, so I was unable to calculate net GHG emissions from these modal shifts.

The fourth question focused on vehicle production changes as a result of car sharing, a topic largely ignored in scholarly literature on car sharing, but often used in marketing information from car sharing companies. I started from a vehicle production framework that views cars as consumptive goods that have a fixed lifetime based on mileage. Using this framework, I showed that the only two parameters that affect net vehicle production are total VMT and vehicle lifetime. Using VMT change data from Martin and Shaheen (2011b) and reasonable vehicle lifetimes, car sharing decreases vehicle production by half a car per shared car, as compared to the 7- to 15-car decrease per shared car reported by Martin et al. (2010)

and used in Zipcar marketing. In this case, applying the net green definition allowed us to cut through marketing statements to determine the real extent to which car sharing decreases vehicle production.

8 CONCLUSION

With the passage of the Pollution Prevention Act, environmental management focus moved from pollution control to pollution prevention, with the idea that "pollution prevention … offers the exciting possibility of reconciling economic growth with environmental protection to enhance the quality of life for ourselves and our children" (Browner, 1993). Pollution prevention was seen as the solution to sustainable development.

However, this article has shown that true *sustainable* development requires going further. I introduced a new definition of greenness, "net green," which states that an activity is net green if and only if it produces net environmental benefit. This definition shifts the focus from policies and procedures to actual environmental consequences, and in four case studies I demonstrated that no pollution control or prevention activities are guaranteed to produce net environmental benefit—indeed some, such as corn ethanol, are all but guaranteed to do the opposite.

We stated that all industrial activity causes environmental damage, and raised the question of how, then, can we hold industrial activities to a standard of creating environmental benefit? The answer rests in consequential thinking: the idea that the environmental impact of a product or activity is not just its direct impacts, but the impacts of changes it causes to the economic system in which it exists. Consequential thinking involves following cause-effect chains as they ripple out from an activity and cause changes to other systems, which themselves have environmental implications. Some of those changes may increase environmental impacts from the baseline; others may decrease them. Under the new net green definition, what determines whether an activity is green is the sum of these positive and negative changes: If the net effect of the activity is to decrease total environmental impacts from the baseline, the activity is net green; if it increases total impacts, it is not.

8.1 Common themes

To demonstrate the method and usefulness of the net green definition, I applied it to four case studies representing the four categories of pollution control and prevention (PCP) activities. Though the specific methods of analysis and findings varied among all four, several common themes emerged:

First, the potential to create net environmental benefit rests with the displacement of more harmful alternative activities. Without displacement, any industrial activity—no matter how "green" it may seem—necessarily increases net environmental impact. Only by displacing other activities can an industrial activity create negative impacts and thus create environmental benefit. Maximizing this displacement, both in terms of the environmental impact of the displaced activity and the amount displaced, is the key to maximizing net environmental improvement.

This leads to the second common theme, which is the importance of determining *what* the displaced alternative activity is. This question has two pieces. First is a methodological question: Against what alternative should the activity be compared to determine its net effect? The second is a forecasting question: What is the counterfactual future that would occur in the absence of the activity? The methodological comparison question was most salient in the carbon capture and storage (CCS) and corn ethanol cases. In both cases, there were two types of comparisons discussed. First, there was a "before vs. after" comparison. In the CCS case, we compared the direct emissions of a coal power plant before and after CCS was installed. It was relatively straightforward to determine that CCS reduces CO_2 emissions relative to a non-CCS plant. In the corn ethanol case, it was clear that corn ethanol creates lower source-to-wheels CO_2 emissions than gasoline (although the issue of indirect land use change made matters more complicated). Second, there was a “with vs. without” comparison. In both the CCS and corn ethanol cases, this centered on the more complicated issue of whether CCS or corn ethanol changes the future trajectory of the energy industry by lowering the incentive to transition to renewable energy sources.

The distinction between the before/after and the with/without comparisons is illustrated in Figure 1.16. The before/after comparison is depicted by the change in the level of the solid “activity” line: Before, emissions are at the status quo level, and after, they are lower. This sort of comparison is commonly made in environmental assessments, and in life cycle assessment it is known as “attributional” analysis; however, the before/after comparison is not equivalent to net environmental impact. The net green definition requires that we look beyond the before/after comparison to determine the *net consequences* of the activity. This requires a forecast about the future both *with* the activity and *without* the activity; the future without the activity is the counterfactual. Whether the activity creates net environmental benefit or harm is determined by whether the future with the activity is environmentally better or worse than the counterfactual.

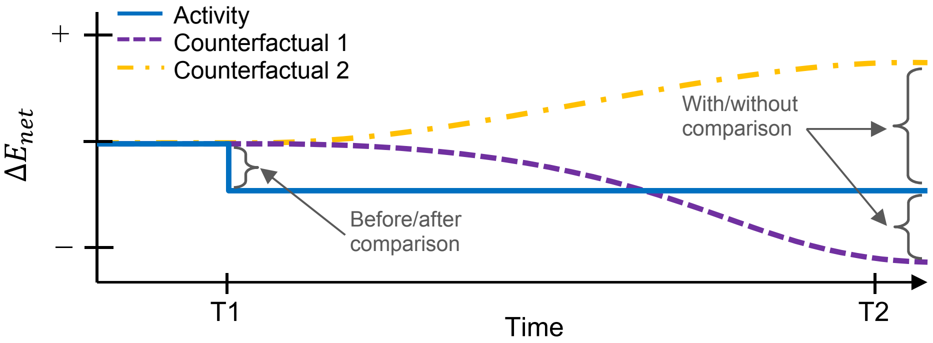

Figure 1.16: How before/after comparison differs from with/without comparison: The activity that occurs in period T1 appears to have environmental benefits as compared to the prior state. In the future, whether the activity results in net benefit or damage depends on the assumed counterfactual scenario. Under counterfactual 1, the activity causes additional environmental damage; under counterfactual 2 the activity results in net benefit.

This brings us to the forecasting question. As shown in the figure, the determination of net impact rests not only on the environmental impact of the activity itself, but also on the assumed counterfactual. For example, applying the CCS case to Figure 1.16, the line for Counterfactual 1 could represent a future where CO_2 emissions force the world to transition to renewable energy. Based on this comparison, CCS results in a net increase in CO_2 emissions by the amount of the difference between the Activity line and the Counterfactual 1 line. The line for Counterfactual 2 could represent a future where no renewable energy transition occurs; in this case, CCS would be seen to reduce net CO_2 emissions.

Determining the most appropriate comparison is difficult because it relies on counterfactual reasoning, asking “what would have happened in the absence of this activity?” Yet, this type of analysis is required in order to know whether an activity increases or decreases environmental damage, and therefore whether it is net green. Careful consideration, accurate modeling, and, when possible, exploiting natural experiments can help select the most appropriate alternative scenario for comparison. Often, however, the best one can do might be to use scenario modeling to derive conditional answers, such as “in scenario A, this activity is net green, but in scenario B, it is not." This was the case in the paper recycling case, and in the behavioral utility model of the car sharing case. If the probability of different scenarios occurring can be determined, as was the case with the displaced fine paper production technology, then probabilities can be likewise be attached to the activity's net green status.

Determining *what* is displaced is difficult, but it is not all we need to know. The third theme that emerged is the importance of determining *how much* of an activity is displaced. As we saw in the corn ethanol and car sharing cases, this can often be the most difficult determination since it involves sociobehavioral considerations. Chapter 2 will delve further into the factors that affect how much displacement occurs and will propose a methodology for estimating displacement rate.

The fourth common emergent theme is that companies engaged in PCP activities have some control over the impact their activities have in the economic system, and therefore have some control over their net green status. For instance, there were differences in the mode-change and driving distance behavior of car sharing users among the eleven car sharing companies surveyed by Martin et al. (2011a), indicating that there may be differences in the companies' marketing or target consumers that encourage either increased or decreased public transportation usage. If a car sharing company wanted to ensure that it created net environmental benefit, and if it could somehow craft its service to be most visible or beneficial to people who would otherwise buy new cars and least visible or useful to those who presently ride public transport, it could maximize the environmental benefit of its car sharing service.

8.2 General findings about PCP activities

Each case study examined a specific example of each type of PCP activity. Yet, through this examination we were able to distill some general results about each PCP category. Overall, it emerged that the different PCP categories had particular strengths and weaknesses. End-of-pipe pollution controls, while often effective at reducing the focal emission, require energy inputs and disposal of the captured emission that increase impacts in other life cycle stages and impact categories. The gains achieved by pollution controls may be outweighed by losses in other areas. However, if the pollutants of concern are harmful enough and the losses in other areas are small, as in the case of SO_x and NO_x filtration, end-of-pipe controls can be effective.

Similarly, recycling is an end-of-life solution that is limited by the quality of scrap input and the presence of a market for recycled material output, and the recycling process itself requires energy and material inputs. Recycling can potentially create large benefits by displacing the production of more harmful primary materials, but how much displacement actually occurs is not clear.

Theoretically, material substitution has more promise in general, since it moves the locus of change upstream in product life cycle, seeking to reduce waste at the point of creation rather than at end-of-life or end-of-pipe. Substantial gains can be achieved in this category, but only if the future implications of the new substitute material or technology are examined across all impact categories and throughout the entire life cycle. Unforeseen macro-level consequences (for instance, indirect land use change in the case of corn ethanol) that ripple through the economic system can offset any gains from the substitution, and may involve impact category tradeoffs or difficult social justice issues.

Dematerialization, in principle, offers the most potential to create environmental benefit because it seeks to reduce material consumption entirely rather than swap it for other materials or treat downstream waste. Yet, dematerialization has its drawbacks. Most importantly, servicizing functions changes their cost structure and therefore the behavior of their users. These changes may create rebound effects, where people use more of the function because it is cheaper or more convenient, reducing or negating any material reduction gains. Additionally, to the extent that servicizing functions makes them cheaper, this essentially increases consumers' available income to spend on other goods. The environmental impact of this marginal consumption may be higher or lower than that of the original function; quantifying this effect was beyond the scope of this paper but deserves research attention.

Overall we saw that PCP activities in all four categories have potential benefits as well as important drawbacks. Yet, it should be pointed out that the above case studies were selected because they highlight interesting tradeoffs and complications; sometimes, however, applying the net green definition is much simpler and clearer, particularly for activities that fail to meet the standard. For instance, consider the recent meteoric rise of single-serving, pod-based coffee. Sales of pod coffee machines in the U.S. increased from 1.6 million to 11.6 million units from 2008 to 2013 (Ferdman, 2014). As of 2012, pod-coffee giant Nestlé had sold over 27 billion Nespresso pods worldwide, a staggering figure which does not even take into account the roughly 5 billion Keurig pods sold every year by Nestlé's largest competitor, Green Mountain (Cornelius, 2012). At the same time, the added convenience for the user of being able to brew coffee with no preparation or cleanup means that pod coffee systems may encourage more coffee consumption overall (although the convenience factor may be tempered by the fact that pod coffee is considerably more expensive per pound than traditional coffee). What this represents is the exact opposite of dematerialization: Whereas the function of at-home coffee brewing was traditionally fulfilled by replaceable or reusable filter drip coffee machines, which have very little or no material waste per cup, pod-based coffee systems fulfill the same function with many times the material production and disposal. This is a drastic *over*-materialization to achieve the same function. In this case, the net green determination is straightforward: Single-serve pod coffee is unambiguously not net green.

Nonetheless, from this discussion it should be apparent that even activities that on the surface seem to be clearly net green can often be very complex once their various possible consequences are unpacked. By applying the net green definition to activities that seem to be green, we are forced to closely and rigorously examine the likely impacts of the activity rather than use ad hoc or heuristic judgments about what seems to be green. The value of the new definition of greenness, therefore, is not simply to assist us in labeling some things green and others not, but to create a fundamental shift in our thinking, moving from things that *seem environmental* to things that *actually improve the environment*.

8.3 Implications for corporate environmental management

Realizing this shift in thinking is difficult. Following through cause-effect chains can require significant amounts of data, complex modeling, determinations of consumer behavior, and time-consuming analysis. Yet, the payoff of making this shift can be large, particularly for corporate environmental management scholars, as well as for corporate environmental managers and environmentally minded entrepreneurs. Applying the net green definition is useful in this realm for four principal reasons.

First, the net green definition provides much-needed rigor, structure, and direction to the "pays-to-be-green" debate. As discussed, this debate has focused on how, why, and when environmental business activities can increase profitability, but this discussion has been disconnected and remains unresolved, not least because there is no agreed-upon definition of what constitutes a green business activity. This paper fills that gap with the net green definition.

This paper also highlights that business strategy and the environment, as a scholarly field, has much further to go in terms of answering the PTBG question. If, for the first time, we have a concrete definition of green, prior work examining the link between greenness and profitability must be reexamined with this new lens, or at least reframed. For instance, King and Lenox (2002) empirically showed that pollution prevention activities tend to be more profitable than pollution control activities. The authors assume pollution prevention is greener than pollution control, and therefore present this as evidence of a link between environmental benefit and financial benefit. However, the foregoing case studies showed that pollution prevention *may* be more environmentally beneficial than pollution controls, but we also saw that not all pollution prevention activities lead to net environmental benefit. Thus, King and Lenox's findings do not necessarily support the "do well by doing good" argument. In fact, much of the literature in the PTBG arena may not actually contribute at all to answering the question of whether it pays to be green, since a clear definition of greenness has only now been described. Previous studies provided links between individual environmental measures and profitability. This paper has shown, however, that simple measures are not equivalent to—and may not even be related to—net environmental benefit, and thus cannot answer whether improving the environment is profitable.

This paper, by proposing and demonstrating the net green definition, establishes a clear research agenda aimed at unraveling the connection between profitability and environmental performance. To begin, we must evaluate activities that we use as independent variables in PTBG studies—our "environmental performance measures"—according to whether they result in net environmental benefit or damage. We must move beyond convenient measures such as TRI, KLD, and Trucost, and instead engage with industrial ecology scholars to determine the net environmental impact of the activities we are studying.[18] Only then can we use those activities as measures in examinations of profitability.

The second reason the net green definition is useful is that it provides guidance for corporate managers and entrepreneurs on how to actualize environmental performance. Increasingly, managers receive stakeholder pressure to green their companies, and more entrepreneurs start environmentally based ventures each year. Just as the lack of a definition of greenness in BS&E literature has waylaid the PTBG debate, a similar lack of definitional clarity exists in the practical business world that has left managers and entrepreneurs without guidance on how to create environmental companies. Many attempts to define green business exist outside of scholarly work. Many are extremely vague, such as Koester's (2010) definition in his Green Entrepreneur Handbook: "A green business requires a balanced commitment to profitability, sustainability, and humanity." Others are more specific, such as the Green Business Network (2012) green business standards, which include items such as "conserving resources and minimizing waste," "using renewable energy," "using chlorine-free cleaning products," "maximizing use of local organic food for events," and "avoiding

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[18] In fact, we need much closer ties in general between BS&E and industrial ecology. Both fields study the interaction of industrial activity—business—and the environment. BS&E does so from the perspective of economics, while industrial ecology does so from the perspective of engineering, but both sides have much they can learn from the other to enhance the depth, credibility, and usefulness of their studies.

huge lawns." These are statements without a benchmark, so it is unclear at what point they are achieved. (What is the "maximum" of local organic food? How big is a "huge" lawn? What constitutes a "balanced commitment" to the triple bottom line?)

By contrast, the net green definition provides a clear mandate: Reduce net environmental impact. Unlike past conceptualizations of greenness, the net green definition does not attempt to prescribe specific actions, because the path toward impact reduction will be different in every case and will continually evolve. Instead, it provides a proactive goal (rather than a list of prohibitions) and a clear benchmark for success: If an activity improves the natural environment, it is net green; if not, it is not. If an entrepreneur wants to create an environmental firm, she should create one that, through its activities, reduces net environmental impact. She will know she has succeeded when she measures the environmental impact her company creates and that number is negative. In this way the net green definition is objective and specific without being prescriptive. This flexibility allows managers to capitalize on their companies' strengths and resources with the clear goal of creating environmental benefit by shifting industrial activity from more damaging alternatives to cleaner ones—in other words, by taking business away from their dirtier competitors.

The third reason the net green definition is useful is that it creates a foundation of legitimacy for a firm to make robust, transparent environmental marketing claims. As environmentalism becomes more important to consumers and policy makers, firms seek to use environmental marketing either to allay concerns about perceived negative environmental performance or to use their superior environmental performance as a source of competitive advantage. In order for their marketing messages to be effective, firms need to convey to their stakeholders a sense of legitimacy—that they have their stakeholders' best interests at heart, they are honest, and their messages are trustworthy (Suchman, 1995). Communication lies at the heart of this legitimacy (Suchman, 1995), yet firms currently struggle to effectively communicate the veracity of their environmental performance claims. This difficulty is due in large part to the lack of definition of greenness. Without such a metric, firms are forced to use incomplete measures or vague, hollow statements such as those discussed above.

Vague or incomplete concepts of greenness are particularly problematic for firms that seek to communicate real environmental performance, because the value of their superior environmental position can only be realized if they can credibly distinguish themselves from their dirtier competitors. If they are unable to do so, distrust in the market leads to a classic "lemons market" problem that self-reinforces low selling prices and distrust from buyers, and ultimately drives legitimate firms out of business (Akerlof, 1970). Incomplete quantitative measures can easily be manipulated, and appeals to sustainability are just as frequently made by highly damaging companies as they are by virtuous ones. These messages thus become meaningless and are ineffective at differentiating truly green companies.

Furthermore, in order to avoid their messages being attacked by environmental watchdog groups as "greenwashing," firms must be able to defend the legitimacy of their claims. For instance, in 2007 Bente Oeverli, a senior official at the office of the Norwegian Consumer Ombudsman, announced that new advertising rules required that "phrases such as 'environmentally friendly,' 'green,' 'clean,' 'environmental car,' 'natural' or similar descriptions not be used in marketing cars" (Doyle, 2007). A variety of auto manufacturers, including Toyota, Opel, Mitsubishi, and Saab, had all used advertising that the ombudsman found misleading, and all have since been banned from using environmental language in

Norwegian advertising. With this decision, the ability of auto companies to leverage the environmental performance of their products vis-à-vis their competitors was swiftly eliminated.

The net green definition is thus particularly well suited to alleviate this lemons market problem by providing a method of communicating environmental performance in a way that is transparent and rigorous. Thus, the net green definition can enable firms to capitalize on their greenness and create a real impression of environmental performance safe from attacks of greenwashing.

The fourth reason the net green definition is useful is that applying the net green definition and following through causal chains can expose loci of impact and potential benefit that were before hidden, allowing companies to examine their activities in these areas and work to create net environmental benefit. As the adage goes, "what gets measured gets managed," and the net green definition provides a framework for quantifying net environmental impact. Because the net green definition rests on the notion of displacement, applying the sort of consequential analysis demonstrated in the case studies above may highlight interesting possibilities to expand into new markets, compete more effectively with other firms, and improve on weaknesses, all while creating net environmental benefit.

In summary, the net green definition provides rigor and clarity to what counts as a green activity that will greatly assist researchers in industrial ecology and environmental business strategy, and will also provide guidance and a proactive goal for corporate environmental managers and environmental entrepreneurs. The methodology is demanding, but applying it allows us to ensure that our efforts in environmental management are not mere lip service, but result in physical, measurable improvements in the quality of the natural environment. If we are serious about protecting the natural environment, the net green definition—net reduction in physical environmental impact—is the only acceptable measure of greenness on a corporate, governmental, and personal level.

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APPENDIX: SENSITIVITY OF CAR SHARING UTILITY MODEL

This section provides additional information on the sensitivity of the car sharing utility model described in Section 7 (p. 69).

One source of variation in the utility and mileage intersection curves is the size of the annualized fixed price of car ownership relative to income. Lower fixed costs relative to income cause both utility and mileage intersection curves in to shift downward, as shown in Figure 1.A.1. As stated in the text, when fixed costs are 12% of income, the utility intersection curve never crosses the line $x/z = 1$, meaning trip-type-indifferent people will not choose to own a car even if the shared mileage price is five times higher than the owned mileage price. However, when fixed costs are 3% of income, the utility intersection curve crosses the line $x/z = 1$ at a price ratio of about 1.5. The utility intersection curve lowers because with higher levels of income, the fixed cost lowers consumption by a smaller relative amount and thus makes owned car travel attractive below a certain price ratio. This suggests that people with higher income or lower fixed ownership costs are more likely to own cars, even if they are indifferent in their owned vs. shared car preferences—a result that aligns well with what we observe in reality.

Another source of variation in the model is the individual's preference for car travel in general, relative to other consumption (i.e., x or z as compared to 1, the coefficient on Y in the utility function, eq. 7.1). Since trip type preference in the utility and mileage graphs is normalized to the value of z, we can test how different levels of general mileage preference affect the utility and mileage decisions by testing different values of z. In these calculations, the coefficient on consumption of Y remains constant at 1. As the individual's preference for mileage increases from 0.05 to 1.5, the overall quantity of mileage consumed increases under both scenarios, as expected, and the mileage intersection curve becomes more acute, as shown in Figure 1.A.2. Additionally, the utility intersection curve moves downward to converge at a place where it crosses the line $x/z = 1$ at a price ratio of about 1.33. The mileage intersection curve also rotates around this point, meaning that with any value of z, trip-type-indifferent people ($x/z = 1$) will drive more when they own a car than if they shared a car if the price ratio is at least 1.33.

The variation observed with both of these factors is small, and does not change the shape of the curves or the behavior of the model. Therefore, neither of these factors changes the overall outcome or findings of the model.

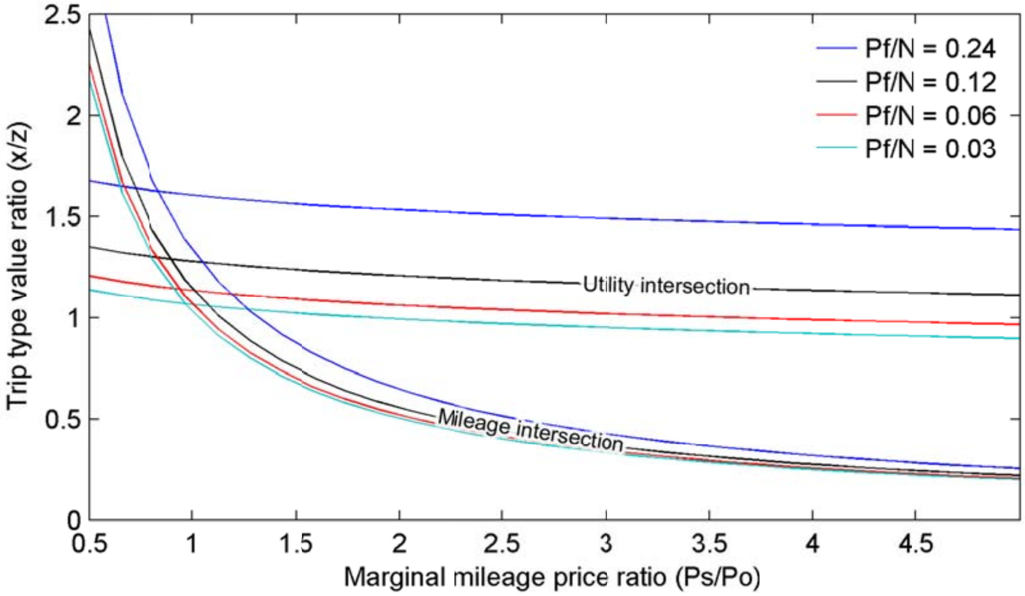

Figure 1.A.1: Utility and mileage intersection curves at different levels of fixed costs relative to income

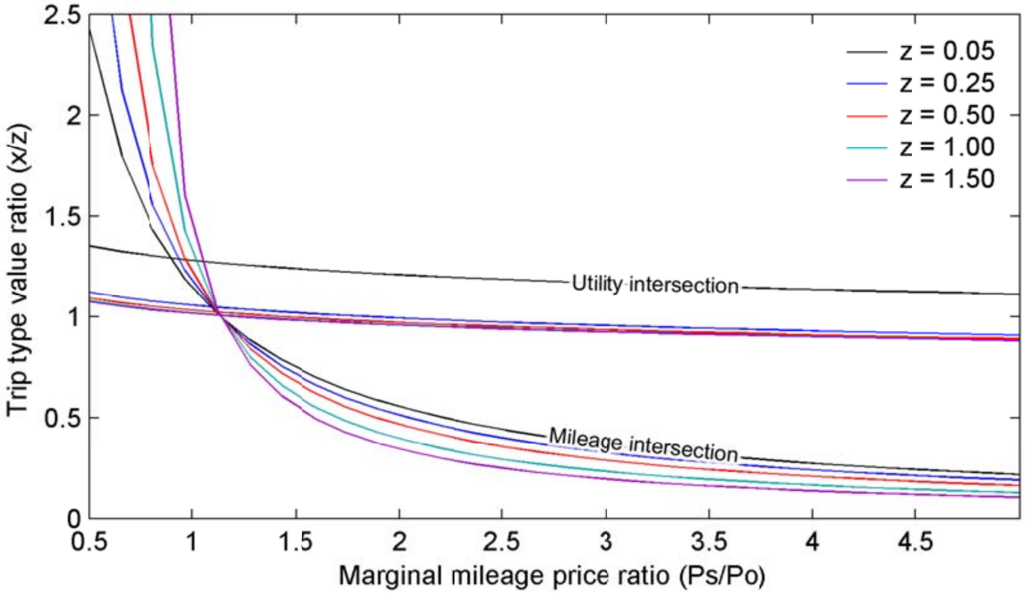

Figure 1.A.2: Utility and mileage intersection curves at different levels of general mileage preference

CHAPTER 2
QUANTIFYING PRIMARY PRODUCTION DISPLACEMENT: METHODOLOGY DEVELOPMENT AND ALUMINUM RECYCLING CASE STUDY

ABSTRACT

The most significant environmental benefit of recycling or reusing a wide range of products and materials is typically the potential to displace material production from primary resources; lack of displacement would significantly reduce these environmental benefits. Therefore, a method for quantifying the true "displacement rate" of primary production is essential to accurately assess the environmental benefits of reuse or recycling. As no consensus method has emerged, environmental assessments have tended to assume that secondary materials displace primary equivalents on a one-to-one basis. However, displaced production is a complex phenomenon governed primarily by market mechanisms rather than physical relationships. This two-part paper advances the understanding of displacement by presenting a displacement estimation methodology based on partial equilibrium market modeling. In the first part, a basic market model is developed that reveals the underlying mechanisms of displaced production and identifies key parameters affecting displacement rate. Results from the basic model suggest that one-to-one displacement occurs only under specific parameter restrictions that are unlikely in a competitive commodity market. In the second part, the modeling methodology is demonstrated by developing an econometric model of the U.S. aluminum industry, which is the first metal industry model to include primary and secondary metals as substitutes and to estimate cross-price elasticities between them. The aluminum market model suggests that displacement rates vary from 10% to 45% but tend to be below 20% in recent decades, although this finding is sensitive to model uncertainty and could be as high as 40% in recent decades. The demonstrated methodology can be generally

applied to any system in which recycled or reused materials compete as substitutes with primary equivalents or other types of materials altogether. Implications for improving recycling and reuse efficacy, environmental assessment methodology, and corporate environmental strategy are discussed.

1 INTRODUCTION

At the heart of the industrial ecology metaphor is the idea of closing material loops, with the reuse and recycling of end-of-life materials being a central aspect of this idea. Despite the prominence of reuse and recycling in environmental research over the past decades, properly accounting for the benefits of these activities in quantitative environmental assessments remains a significant obstacle. One popular methodology in life cycle assessment (LCA), called the "avoided burden method," is to credit recycling or reuse with the avoided or "displaced" production of comparable primary materials (Guinée et al., 2002). The assumption underlying this approach is that increased secondary material from recycling or reuse displaces equivalent primary production, which often has larger impacts. The avoided burden method is illustrated in Figure 2.1, which shows a general product system involving recycling or reuse.

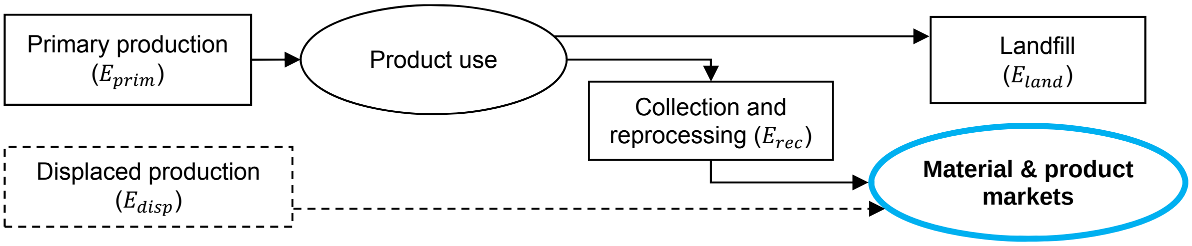

Figure 2.1: Life cycle impacts of a recycled product under the avoided burden method

In this system, a product is produced from virgin materials, which creates environmental impacts E_{prim}. After the product is used, the material is either landfilled or reprocessed. Reprocessing requires energy and material inputs, creating environmental damage E_{rec}. Although the possibility of avoiding landfill creates some benefits, the most significant environmental benefit of reuse or recycling is typically the potential to prevent the production—and therefore the associated environmental impacts—of equivalent primary materials. Under the avoided burden method, primary production is said to be displaced by secondary production and the avoided impacts, E_{disp}, are credited to the system. If the impacts of primary production are larger than the impacts of recycling (as is the case with nearly all highly recycled materials), recycling can result in significant environmental benefit. Net life cycle impacts from the product are calculated by summing the incurred impacts and subtracting the avoided impacts (without loss of generality, in the present discussion I ignore landfill impacts; see appendix A.1):

$$E_{net} = E_{prim} + E_{rec} - E_{disp} \tag{1.10}$$

The most common assumption in environmental assessments is that primary materials are displaced by recycled or reused materials on a one-to-one basis. However, whether primary production displacement actually occurs—and furthermore that it occurs on a one-to-one basis—is not a given. One-to-one, or “full,” displacement makes the implicit assumption that “the demand for [the good] is not changed and that increased recycling does not affect recycling in other parts of the system” (Merrild, Damgaard, & Christensen, 2008, p. 2). In reality, secondary products and materials may replace primary production of a different kind, or may simply expand overall demand and displace less material than is recycled (Ekvall, 2000), leading to incomplete displacement. In fact, it has been suggested that sales of used goods may actually stimulate increased sales of new goods (Thomas, 2003), leading to negative displacement.

The effect of incomplete displacement can be demonstrated by including a term d, for displacement rate, to the calculation of net environmental impact in eq. 1.10:

$$E_{net} = E_{prim} + E_{rec} - d \cdot E_{disp} \tag{1.11}$$

where d is defined as the change in primary production quantity (ΔQ_p) caused by a change in secondary production (ΔQ_s), multiplied by -1 so that d is positive under the expected outcome that Q_p decreases in response to an increase in Q_s:[19]

$$d = -\Delta Q_p / \Delta Q_s \tag{1.12}$$

If $d = 1$ (the full displacement assumption) the result is the same as shown in eq. 1.10: Primary production cancels with displaced production and the only relevant impacts are those of recycling. However, if $d < 1$, net impacts can increase dramatically.

The possibility of incomplete displacement arises because displaced production is not only governed by engineering or physical relationships, but primarily by market mechanisms such as prices, market structure, supply and demand, and strategic firm interaction. Specifically, by influencing prices, recycling or reuse can increase overall material demand, reducing displacement. Although the reality of incomplete displacement has been recognized in the literature (Ekvall, 2000; Frees, 2007; Thomas, 2003; Weidema, 2003), a complete understanding of the drivers of displacement and a methodology for accurately estimating displacement rate was heretofore lacking. Because no consensus method for estimating displacement emerged, environmental assessments have typically rested on the "inaccurate assumption" (Ekvall, 2000) of one-to-one, or full, displacement (Thomas, 2003). In some cases heuristics have been used, such as assuming 0% or 50% displacement (Ekvall & Weidema, 2004; Klöpffer, 1996).

It has been shown that the displacement rate parameter is extremely important: Different assumptions about displacement rate can frequently reverse the results or

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[19] Q_{sec} refers to the quantity of material leaving the reprocessing stage and entering the material market after accounting for recycling rate and yield loss. In this discussion we are primarily concerned with economic drivers of displacement; physical factors such as collection rates and recycling yields have received thorough treatment elsewhere (Newell & Field, 1998). See Appendix A.2 for more details.

preference order of an environmental assessment (Geyer & Doctori Blass, 2009; Heijungs & Guinée, 2007; Zink, Maker, Geyer, Amirtharajah, & Akella, 2014). Therefore, it is the goal of this paper to improve the understanding of displaced production by exploring the underlying mechanisms and developing a general methodology for estimating displacement rate.

The remainder of the paper is organized as follows: In Section 2, I develop the basic market modeling methodology, show how it can be used to reveal the underlying market dynamics and estimate displacement rate, identify the most important parameters, and derive the conditions for zero and full displacement. In Section 3, I illustrate the basic model by expanding it to capture the dynamics of the U.S. aluminum market. In Section 4 I discuss general lessons from both models, including implications for improving recycling and reuse efficacy, lessons for improving environmental assessment methodology including areas for future research, and takeaways for managers seeking to leverage their products' environmental performance.

2 BASIC MODELING METHODOLOGY

I model market interactions using supply and demand partial equilibrium analysis (PEA). Following standard approaches used by authors in microeconomics and industrial organization (Blomberg & Hellmer, 2000; Fisher, Cootner, & Baily, 1972; Foley & Clark, 1981; Gilbert, 2006; Gomez, Guzman, & Tilton, 2007; Hojman, 1981; Slade, 1980; US EPA, 1998) I employ PEA to describe market interactions of producers and consumers of primary and secondary material. I make typical assumptions of a competitive market, including that suppliers sell a homogenous good and are profit-maximizing price-takers who choose production levels based on selling prices.[20] Buyers are downstream producers or final goods consumers who maximize production or utility by choosing consumption quantities of all goods based on their prices. Buyers set their demand and can choose between substitute materials based on relative prices, technical substitution constraints, and preferences.[21]

Typically, markets are modeled using structural equations that describe the behavior of actors in the market. A very basic general market model for primary and secondary materials that are substitutes can be described by the following system of equations:

$$\begin{aligned} S_{sec} &= \alpha_1 P_{sec} + \alpha_0 \\ S_{prim} &= \beta_1 P_{prim} \\ D_{sec} &= \gamma_1 P_{sec} + \gamma_2 (P_{prim} - P_{sec}) \\ D_{prim} &= \lambda_1 P_{prim} + \lambda_2 (P_{sec} - P_{prim}) \\ S_{sec} &\equiv D_{sec} \\ S_{prim} &\equiv D_{prim} \end{aligned} \tag{2.1}$$

where S_i, D_i, and P_i represent the supply, demand, and price of material i, respectively, and α_0 is the intercept on secondary supply, which captures the effect of all omitted variables. This intercept will manipulated in the next section to simulate an increase in recycling (equivalently, one could include intercept coefficients on the other three supply and demand equations as well, but they are extraneous in this demonstration). In market-clearing equilibrium, supply of each material is equal to demand. The coefficients on the price variables are price responses and represent the sensitivity of supply or demand to changes in prices. I refer to α_1 and β_1 as own-price responses and to γ_2 and λ_2 as cross-price

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[20] Even if individual suppliers cannot or do not adjust production in response to price changes in the short term (i.e., fixed levels of capital), the aggregate effect over all suppliers will be to adjust capital investments and levels of production based on selling price.

[21] For a more detailed treatment of the theory of the firm and consumer utility theory, see any economics textbook; Pepall, Richards, and Norman (2008) provide an excellent treatment of firm behavior.

responses.[22] The cross-price responses reflect buyers' ability and willingness to switch from their usual material to the competing material as a function of the price differential between the two materials.[23] Economic theory predicts that α_1, β_1, λ_2, and γ_2 should be positive and that λ_1 and γ_1 should be negative. For a step-by-step development of a simple market model such as this, see Blomberg and Hellmer (2000) and Blomberg (2007).

2.1 Supply shock experiment

The model presented in eq. 2.1 exists in equilibrium until an exogenous shock is introduced. Since the system of equations is simultaneous—that is, interdependent and linked via shared endogenous price variables—a shock to one exogenous variable will affect the entire system. To see this explicitly, eq. 2.2 shows the system solved to the reduced form, in which each endogenous variable is expressed as a function of the exogenous variables:

$$\begin{aligned}
P_{prim} &= \frac{\alpha_0\lambda_2}{-\alpha_1\beta_1+\beta_1\gamma_1-\beta_1\gamma_2+\alpha_1\lambda_1-\alpha_1\lambda_2-\gamma_1\lambda_1+\gamma_1\lambda_2+\gamma_2\lambda_1} \\
P_{sec} &= \frac{\alpha_0(\beta_1-\lambda_1+\lambda_2)}{-\alpha_1\beta_1+\beta_1\gamma_1-\beta_1\gamma_2+\alpha_1\lambda_1-\alpha_1\lambda_2-\gamma_1\lambda_1+\gamma_1\lambda_2+\gamma_2\lambda_1} \\
S_{prim} = D_{prim} &= \frac{\alpha_0\beta_1\lambda_2}{-\alpha_1\beta_1+\beta_1\gamma_1-\beta_1\gamma_2+\alpha_1\lambda_1-\alpha_1\lambda_2-\gamma_1\lambda_1+\gamma_1\lambda_2+\gamma_2\lambda_1} \\
S_{sec} = D_{sec} &= \frac{\alpha_0(\beta_1\gamma_1-\beta_1\gamma_2-\gamma_1\lambda_1+\gamma_1\lambda_2+\gamma_2\lambda_1)}{-\alpha_1\beta_1+\beta_1\gamma_1-\beta_1\gamma_2+\alpha_1\lambda_1-\alpha_1\lambda_2-\gamma_1\lambda_1+\gamma_1\lambda_2+\gamma_2\lambda_1}
\end{aligned} \tag{2.2}$$

From eq. 2.2 it can be seen that the equilibrium price and quantity of both materials are a function of all the price response coefficients and the secondary supply intercept, α_0. The extent to which each endogenous variable is affected by a change in this intercept is

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[22] Supply or demand responses to price changes are sometimes generically referred to as elasticities (e.g., Weidema, 2003); however, price elasticity has a precise definition as the *percentage* change in supply or demand relative to the *percentage* changes in price. Since eq. 2.1 is linear, the term "elasticity" is inappropriate in this context. Regardless of the terminology, what is of interest is the response of suppliers and consumers to changes in prices. See Appendix A.4 for sensitivity analysis of the basic model in log-log specification.

[23] Another way to model cross-price responses would be to use the absolute price of the competing material instead of the price differential between the two materials. I believe the specification shown in eq. 2.1 more accurately describes the purchase decision of buyers of primary and secondary material. Nonetheless, results for the competing specification are shown in Appendix A.3; the results of the basic model are qualitatively unchanged under either specification.

determined by the functional form and the values of the coefficients.[24] Thus, displacement can be measured by introducing a shock to the supply intercept and observing how both primary and secondary supply are affected.[25] Specifically, following a shock, displacement can be calculated by first computing the difference between supply (or demand, since they are equivalent) of each material before and after the shock, and then by taking the ratio of the change in primary supply to the change in secondary supply, in accordance with eq. 1.12. For instance, if in 2.2 we introduce a 10% shock to α_0, we can label the "before" intercept α_{0B} and the "after" intercept $\alpha_{0A} = 1.1\alpha_{0B}$. We can then compute d by dividing the difference between primary supply before and after the shock by the difference in secondary supply before and after the shock, as shown in eq. 2.3:

$$\begin{aligned}
\Delta S_p = \Delta D_p &= \frac{(\alpha_{0A} - \alpha_{0B})\beta_1\lambda_2}{-\alpha_1\beta_1 + \beta_1\gamma_1 - \beta_1\gamma_2 + \alpha_1\lambda_1 - \alpha_1\lambda_2 - \gamma_1\lambda_1 + \gamma_1\lambda_2 + \gamma_2\lambda_1} \\
\Delta S_s = \Delta D_s &= \frac{(\alpha_{0\mathrm{A}} - \alpha_{0B})(\beta_1\gamma_1 - \beta_1\gamma_2 - \gamma_1\lambda_1 + \gamma_1\lambda_2 + \gamma_2\lambda_1)}{-\alpha_1\beta_1 + \beta_1\gamma_1 - \beta_1\gamma_2 + \alpha_1\lambda_1 - \alpha_1\lambda_2 - \gamma_1\lambda_1 + \gamma_1\lambda_2 + \gamma_2\lambda_1} \\
d = \frac{-\Delta S_p}{\Delta S_s} &= \frac{-(\alpha_{0\mathrm{A}} - \alpha_{0B})\beta_1\lambda_2}{(\alpha_{0\mathrm{A}} - \alpha_{0B})(\beta_1\gamma_1 - \beta_1\gamma_2 - \gamma_1\lambda_1 + \gamma_1\lambda_2 + \gamma_2\lambda_1)} \\
d &= -\frac{\beta_1\lambda_2}{\beta_1\gamma_1 - \beta_1\gamma_2 - \gamma_1\lambda_1 + \gamma_1\lambda_2 + \gamma_2\lambda_1} \qquad (2.3)
\end{aligned}$$

2.2 Results from the basic model

The primary results of the basic model are both the symbolic equation for displacement in eq. 2.3 as well as an understanding of how price responses govern displacement. Although the basic model is simplified, it is useful for several reasons. First, the basic model is simple enough to be solved symbolically, which allows us to see the

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[24] The ability of the model to produce reliable results rests on the accuracy of both of these aspects. For this reason we leave the basic model as simple and general as possible; the system presented in eq. 2.1 assumes only linearity and the most fundamental economic theories of supply and demand.

[25] It has been shown that supply-side and demand-side price shocks have different effects in some markets (Kilian, 2009). In this paper I focus only on supply-side shocks because they represent the kind of situation in which displacement is relevant in environmental assessments of recycling and reuse. As discussed in Section 1, displacement becomes a factor in environmental assessments when increased scrap is collected and reprocessed, so this is the change I intend to capture with the supply-side price shock.

general structure and behavior of the model and the supply shock experiment without introducing complexities and uncertainties associated with parameter estimation. Second, it demonstrates the general methodology for estimating displacement rate, which can be summarized as follows:

(1) Describe the market in a system of simultaneous equations.
(2) Solve the system to the reduced form.
(3) Introduce a shock to an exogenous variable that appears in the secondary supply equation, such as an intercept, or input prices.
(4) Write the reduced form "after" equations using this new shocked variable.
(5) Subtract the "before" reduced form supply equations from the "after" equations.
(6) Compute displacement rate by dividing the difference in primary supply by the difference in secondary supply.

The outcome of the simple model presented in eq. 2.3 reveals several general facts about the displacement relationship: First, eq. 2.3 reveals the conditions under which $d = 0$ (zero displacement) and $d = 1$ (full displacement), which will be discussed in Sections 2.4.1 and 2.4.2. Second, the model highlights what parameters are important for determining displacement. Displacement is determined by the relationships among β_1, λ_1, λ_2, γ_1, and γ_2. Based on eq. 2.3, the direction of the effect that each price response variable has on displacement is summarized in Table 2. It emerges that γ_1, γ_2, and λ_1 have an inverse relationship with displacement (in terms of absolute value), while the own-price and cross-price responses of primary demand, β_1 and λ_2, have a direct relationship with displacement. The net determination of displacement depends on the relative magnitudes of these competing forces. These general facts point to important lessons for environmental assessment and environmental management at large, which will be discussed in Sections 2.4 and 4.

Third, the model highlights what parameters are *not* important for the determination of displacement: The size of the secondary supply shock and the own-price response of secondary suppliers (α_1) are inconsequential—although they affect the changes in supply and demand, they affect both proportionally and the terms end up canceled out of the displacement equation (note, however, that this relies on an assumption of linearity in the parameters that may not be valid for large-magnitude shocks). As we will see in Section 3, estimating price responses is a nontrivial task, so knowing which variables are important is useful.

Variable	Description	Effect on displacement[a]
β_1	Own-price response of supply (primary)	Positive
λ_1	Own-price response of demand (primary)	Negative
λ_2	Cross-price response of demand (primary)	Positive
γ_1	Own-price response of demand (secondary)	Negative
γ_2	Cross-price response of demand (secondary)	Negative

[a] Indicates what happens to d as the absolute value of the price response increases (i.e., is more elastic).

Table 2.1: Summary of how displacement following a supply-side shock is affected by relevant price response variables

2.3 Understanding the displacement mechanism

We can use the structure of the basic model to better understand the mechanisms that govern displacement by examining the relationships between the components of the system. Solving the system to the reduced form shows how the components are mathematically interconnected, but it does not necessarily provide an intuitive sense of how causality flows through the system or why the supply of the two materials might be affected differently. To explain these mechanisms, I turn to the methodology of system dynamics, which is an approach for understanding the behavior of complex systems such as markets (Morecroft, 2007). At the heart of system dynamics are diagrams that show the direction and sign of relationships between modeled processes.

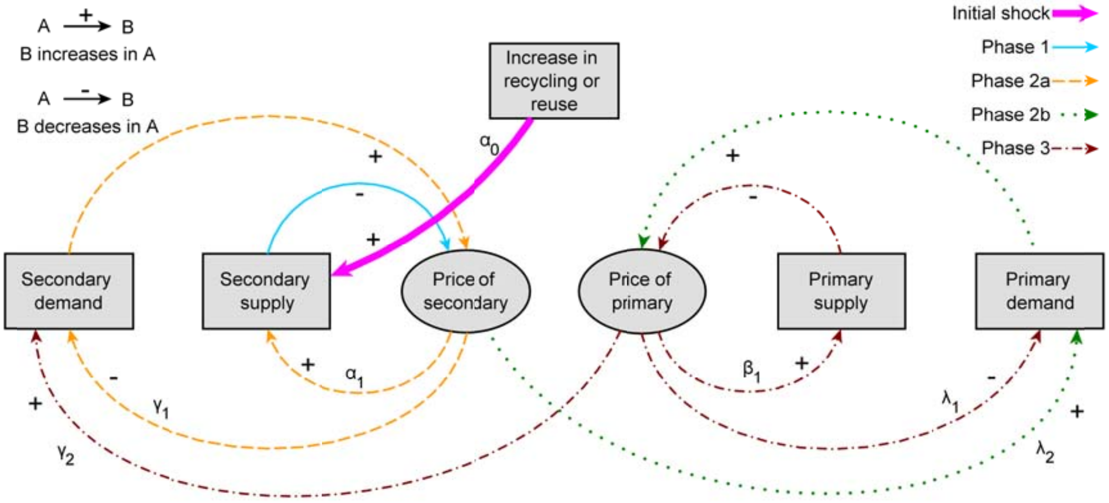

Figure 2.2: System dynamics diagram showing the flow of causality through the basic market model. Signs above each arrow indicate whether the relationship is direct (+) or inverse (-).

Figure 2.2 shows the dynamics of the primary and secondary material market. Boxes represent physical processes; ovals represent information; arrows represent causal relationships, with the positive or negative sign on the arrow indicating whether the relationship is direct or inverse. The entire system adjusts simultaneously and, before any intervention, is assumed to be at equilibrium; that is, all arrows initially have a magnitude of zero.

We can use the diagram to observe how the system responds to a shock. The experiment discussed above introduces a shock to supply, shown with a solid bold arrow. We can follow the effects of this shock through the system, broken down into phases shown in the figure (however, even though dividing the effects into phases facilitates understanding, it bears repeating that all changes subsequent to the initial shock occur simultaneously). In the first phase, shown in a solid line, the increase in secondary supply releases excess material to the market above what was traded in equilibrium, meaning that the price of secondary material will fall.

Phase 2 has two components. In phase 2a, shown with a dashed line, the decrease in secondary price simultaneously triggers reduced incentive on the part of suppliers and an increase in secondary demand. This increase in secondary demand also increases the price of secondary material, causing effects to ripple around the circle again, with the opposite sign (supply is increased, demand is decreased). These counteracting forces eventually reach a new equilibrium price and quantity. Phase 2b, shown with a dotted line, arises from the fact that primary and secondary material are substitutes; the demand for one is a function of the price of the other. The initial decrease in secondary price will decrease primary demand (since the higher secondary material price makes it less attractive as a substitute), which will in turn decrease the price of primary material.

In phase 3, shown with a dash-dot line, the decrease in primary price will have two simultaneous effects. First, it will lower primary supply. This will in turn raise the price of primary, which will lower demand, lowering the price of primary, and so on. At the same time, the lower price of primary will draw consumers from secondary material, lowering secondary demand. This will lower secondary price and supply, and so on. These forces will continue until they balance at a new equilibrium price and quantity for each material.

The simultaneous nature of the model means that the new equilibrium cannot be determined without solving the system as shown earlier. Figure 2.2 highlights that the model is entirely driven by price changes and responses to these changes, which means it may ignore nonmarket factors, such as government recycling targets. This is useful to consider when moving on to more complex market models; though the number of parameters increases, price responses remain the fundamental factors that drive the model results. In the model, displacement less than 100% occurs when increased secondary supply decreases prices of both materials such that overall production and consumption increases.

2.4 Discussion of the basic model results

The basic model described the underlying structure of a market where primary and secondary materials compete. By symbolically solving for displacement following an exogenous supply-side shock, I showed that there are five parameters that affect displacement: the own-price response of primary supply (β_1), the own-price responses of demand for both materials (γ_1, λ_1), and cross-price responses of demand for both materials (γ_2, λ_2). Thus, accurately estimating these parameters is critical, and these response parameters should be the focus of future market models that seek to estimate displacement.

To explore the sensitivity of displacement rate to these parameters, I performed a number of Monte Carlo simulations, drawing values for each price response parameter from uniform distributions spanning a range of hypothetical upper and lower bounds designed to test both "high" and "low" price responses (from [$\pm$0.01,$\pm$2] to [$\pm$0.01,$\pm$15000], using negative values for own-price demand responses).[26] In every 1 million-iteration simulation, calculated displacement rates were recorded using the above procedure. A histogram of calculated displacement rates from the simulation using representative upper and lower bounds of [$\pm$0.01,$\pm$100] is shown inFigure 2.3. Though calculated displacement ranged from nearly zero to just under 200, in all cases the vast majority of displacement values were concentrated at the lower end of the range: 97% of the calculated displacement rates were

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[26] Uniform distributions and a variety of parameter ranges were used in order to illustrate a general case where no specific information about price responses is known; using normal distributions around the midpoints of the ranges shown above results in a distribution of displacement values even more heavily skewed toward zero. What is considered a "high" or "low" price response of course depends on the product in question; the simulation presented is designed to show a wide range of hypothetical ranges, although as stated, the response turns out not to affect the model outcome. When studying an actual product system, one could construct different probability distributions centered around likely price response values based on knowledge of the products in question.

below 100%, 90% were below 50%, and 47% were below 15%. Less than 0.5% of the simulated parameters resulted in displacement between 95% and 105%. This general pattern held for any of the parameter ranges tested, no matter how large.

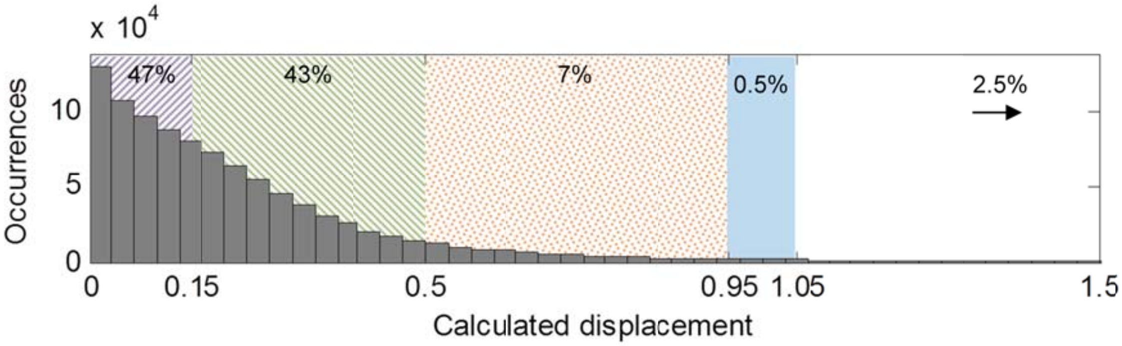

Figure 2.3: Histogram of Monte Carlo output. Labels represent the portion of observed displacement values that fall within the shaded region.

The Monte Carlo simulation suggests that if one knows truly nothing about the market for the product or material of interest, choosing lower displacement values will be more accurate more often. However, it would be useful for LCA practitioners and others to have some additional guidelines regarding how to choose displacement rates without having to estimate market models for every product or material of interest. As mentioned, two common approaches to selecting displacement rates in life cycle assessments are to assume full displacement or zero displacement. The basic model allows us to examine these cases and derive general guidelines for when displacement is likely to be near one or near zero. These findings can help practitioners select a value for d with only a limited understanding about the product or material market.

2.4.1 Conditions for zero displacement

Zero displacement occurs only when the numerator is equal to zero and the denominator does not equal zero. The necessary and sufficient conditions for $d = 0$ are:

$$\begin{aligned} &\beta_1 = 0 \text{ and } \gamma_2\lambda_1 \neq \gamma_1(\lambda_1 + \lambda_2), \text{ or} \\ &\lambda_2 = 0 \text{ and } (\beta_1 - \lambda_1)(\gamma_1 - \gamma_2) \neq 0 \end{aligned} \qquad (2.4)$$

It was shown in eq. 2.3 that displacement is equal to zero when either the own-price response of primary supply (β_1) or the cross-price response of primary demand for secondary material (λ_2) is zero (and the denominator is not zero). Conversely, if both of these coefficients are not zero, displacement is necessarily greater than zero. To visualize why values of zero for these coefficients lead to zero displacement, refer again to Figure 2.2 and imagine a break in either the line from "price of primary" to "primary supply" (β_1) or the line from "price of secondary" to "primary demand" (λ_2). If either of these pathways is broken (i.e., the corresponding coefficient is zero), the changes in the secondary market will not loop back to affect primary supply: If primary demand is unresponsive to secondary price changes ($\lambda_2 = 0$), additional secondary production will have no effect on the primary material market; if primary supply is unresponsive to primary price changes ($\beta_1 = 0$), even if primary price falls in response to a decrease in primary demand, this will have no effect on primary supply. If either β_1 or λ_2 is zero, primary supply is isolated from changes in the secondary market; primary supply will thus fail to decrease when secondary supply increases, and displacement will be equal to zero.

In terms of real-life products where these conditions might be the case, it is hard to imagine realistic cases in a competitive market where primary producers are utterly unresponsive to selling prices. This condition may be possible in cases where production is intentionally decoupled from prices, such as in the provision of public services. However, these are not cases where displacement is likely to be relevant. For commodity goods and materials in well-behaved markets, we can safely assume that $\beta_1 > 0$.

However, the possibility that primary demand is insensitive to changes in the price of secondary material is more realistic and even likely in certain situations. The parameter λ_2 measures the willingness and ability of buyers of primary material to substitute secondary material for primary material. In many commodity markets, these buyers are in fact intermediary producers who transform material inputs into semifabricated goods or final products. Therefore their willingness and ability to substitute secondary material for primary material may be limited by technical constraints or quality requirements. If the quality of recycled or reused material is unsuitable for their needs, it may be difficult or impossible to substitute secondary for primary material, meaning that λ_2 will be close or equal to zero.

A clear example of this situation is the paper pulp market, where the shorter fibers of recycled pulp make it unsuitable or very costly to use in many paper applications. A similar case is recycled polyethylene terephthalate (RPET), which is often not of sufficient quality to be reused in bottle-grade applications and must be "downcycled" into other products. In these cases, primary producers are unresponsive to price changes in the secondary market in the same way they are unresponsive to price changes for any material that they do not use as a production input. Thus, real-life situations where displacement rate is equal to or near zero most likely arise from technical limitations on material substitutability.

2.4.2 Conditions for full displacement

On the other end of the spectrum from zero displacement, the model showed that full displacement occurs under the following conditions:

$$\begin{gathered}-\beta_1\lambda_2 = \beta_1\gamma_1 - \beta_1\gamma_2 - \gamma_1\lambda_1 + \gamma_1\lambda_2 + \gamma_2\lambda_1, \text{ and} \\ (\beta_1 - \lambda_1)(\gamma_1 - \gamma_2) \neq 0, \text{ or } \gamma_1\lambda_2 \neq 0\end{gathered} \tag{2.5}$$

Unlike the condition for $d = 0$, there is an infinite set of solutions that satisfy the condition for $d = 1$, which makes it more difficult to draw general conclusions about when full displacement is likely to occur. However, we can make some progress by remembering that this infinite set is bounded by economic theory regarding price responses: β_1, λ_2, and γ_2 must be positive, while λ_1 and γ_1 must be negative. For instance, $d = 1$ if $\beta_1 = -\gamma_1 = -\gamma_2$ and $\beta_1 \lambda_2 \neq 0$. However, this condition fails immediately because β_1 and γ_2 must have the same (positive) sign. A similar full-displacement case is where $\beta_1 = -\gamma_1 = \lambda_1$ and $\beta_1^2 \lambda_2 \neq \beta_1 \gamma_2 \lambda_1$, which fails because β_1 and λ_1 must have opposite signs.

Additionally, the conditions for $d = 0$ combined with the denominator restrictions for $d = 1$ provide useful bounds: If $\beta_1 = 0$ or $\lambda_2 = 0$ then displacement is either zero or undefined; if all of the own-price elasticities are zero, displacement is undefined.

Beyond these restrictions we cannot place economically meaningful analytic bounds on when full displacement should *not* occur. We can, however, discuss an interesting case where we can expect that full displacement *will* occur. Specifically, if the cross-price responses of both materials are equal but not zero ($\gamma_2 = \lambda_2 \neq 0$), both the own-price responses of demand are equal to zero ($\gamma_1 = \lambda_1 = 0$), and the own-price response of primary supply is not zero ($\beta_1 \neq 0$), then $d = 1$. In real-life terms, this means that buyers of both types of material have exactly the same technical ability or preference to use the alternative material, that their willingness to switch is nonzero (i.e., at some price differential they will begin using the other material), that they are completely unresponsive to changes in the price of their usual material, and that suppliers of primary material do respond to price changes.

These conditions are unrealistic for any standard good in any reasonably behaved competitive market. The second condition implies completely fixed demand no matter how drastically the price changes, and the first condition implies that downstream producers have the exact same ability and willingness to use the alternative material (i.e., their marginal costs of substitution are identical). For the major recycled materials this is certainly not the case since primary material is more easily substituted for secondary material than the other way around. For these materials, the response of primary demand to changes in the price of secondary material will be lower than the response of secondary demand to changes in the price of primary material.

However, special cases that meet these criteria are possible. Another way of looking at the above restrictions is to say that demand is fully satiable (after which the own-price demand response will be zero) and that consumers are indifferent between the two goods (meaning the cross-price responses will be equal). Again, these conditions are unlikely for many products, but one can think of special cases where they may hold. For instance, Zink et al. (2014) consider a case study of repurposing a smartphone as an in-car parking meter. The displacement question in this case is whether the repurposed phone prevents the production of a purpose-built parking meter. A case could be made that demand for in-car parking meters is fully satiable, especially since a person typically only purchases an in-car parking meter because it is required to park at her work/school/etc. Once she has one in-car parking meter, she is unlikely to desire more. One could also argue that consumers are more or less indifferent between a smartphone-turned-parking meter and a purpose-built model: Both provide the same function, neither have any special features or ancillary benefits, both are equally reliable, durable, long-lasting, etc. For the last condition, producers of purpose-built parking meters presumably respond to changes in parking meter selling prices. Thus, this represents a fairly strong candidate for a product system where full displacement occurs.

However, many product systems fail one of the above criteria. For instance, when primary-production options have better features, as is often the case, consumers are not indifferent and displacement will thus be lower than one (see Thomas, 2003). Additionally, demand for most goods is insatiable (albeit with diminishing returns).

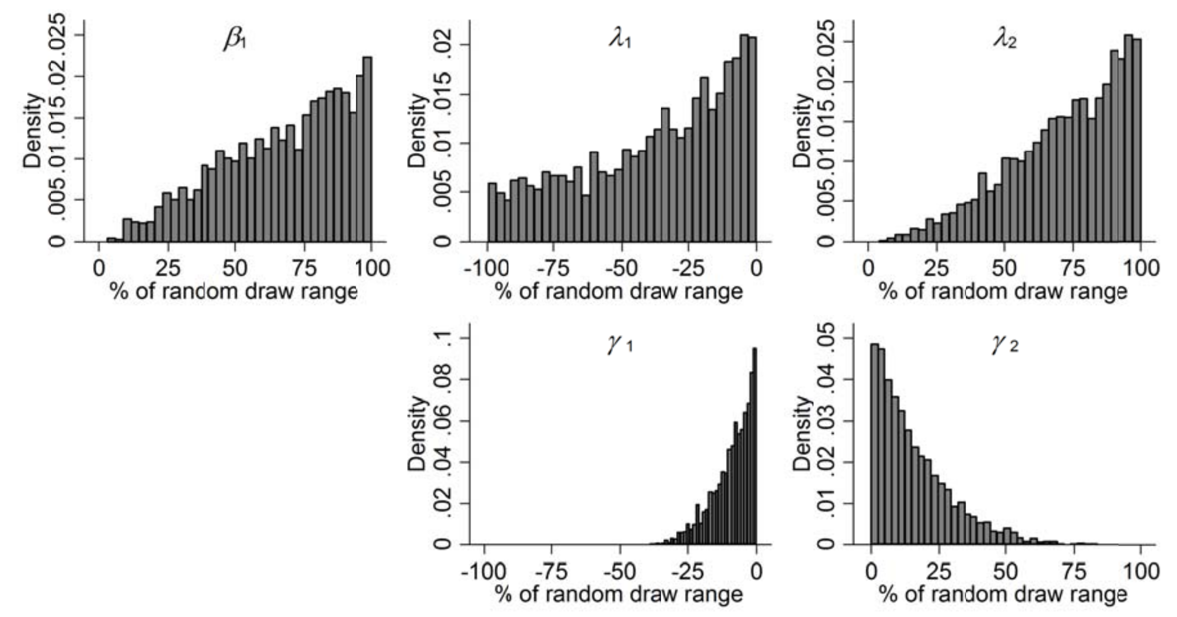

Figure 2.4: Distributions showing which parameter values were most common in runs that resulted in $d \geq 1$. The horizontal axis is expressed in terms of the parameter value relative to the range from which random values were drawn. Values with taller bars appeared more often in cases with full displacement. For example, full displacement occurred more often when β_1 was within the top 25% of the random draw range and when γ_1 was in the lowest 25% of the range (in terms of absolute value).

Unfortunately, these are the only simple analytical cases that result in full displacement. To learn more about the types of conditions that lead to full displacement, I turned to numeric methods, again utilizing Monte Carlo simulation. My approach was to conduct the Monte Carlo analysis as described above, after which I selected only those simulation runs that resulted in displacement greater than or equal to one. As stated above, this constitutes roughly 2.5% of the total iterations, or with 1 million initial runs, about 25,000 "successful" runs. Then, for each success, I collected the five price response parameter values used in that iteration. The distribution of these "success values" is plotted in a histogram for each variable in Figure 2.4.

From Figure 2.4 we see that full displacement is much more likely when the primary supply and cross-price demand price responses (β_1, λ_2) are high and those of own-price primary demand and secondary supply and demand (λ_1, γ_1, γ_2) are low. Nearly half of the values of own-price response of primary supply (β_1) and cross-price response of primary demand (λ_2) that resulted in $d = 1$ were in the upper 25% of the random draw range. More than two-thirds of values of own-price response of primary demand (λ_1) that resulted in $d = 1$ were in the lower half of the random draw range (in absolute value). Full displacement never occurred when the value for own-price response of secondary demand (γ_1) was greater than 35% of the random draw range (in absolute value), or when the cross-price response of secondary demand (γ_2) was greater than 80% of the random draw range.

Whereas Figure 2.4 shows distributions of values that produced $d \geq 1$, Figure 2.5 shows a sample of actual sets of parameter values that resulted in $d \geq 1$. There are a few patterns that emerge. First, for all cases where $d \geq 1$, γ_2 is smaller than λ_2, so we can treat this requirement as a necessary condition for full displacement and amend eq. 2.5 to include it:

$$\begin{gathered}-\beta_1\lambda_2 = \beta_1\gamma_1 - \beta_1\gamma_2 - \gamma_1\lambda_1 + \gamma_1\lambda_2 + \gamma_2\lambda_1, \\ (\beta_1 - \lambda_1)(\gamma_1 - \gamma_2) \neq 0, \text{ or } \gamma_1\lambda_2 \neq 0, \text{ and} \\ \lambda_2 \geq \gamma_2\end{gathered} \tag{2.6}$$

Additionally, in nearly every case, γ_1 is smaller than λ_1, but there are some sets of parameter values where this does not hold, so we cannot treat this as a necessary condition.

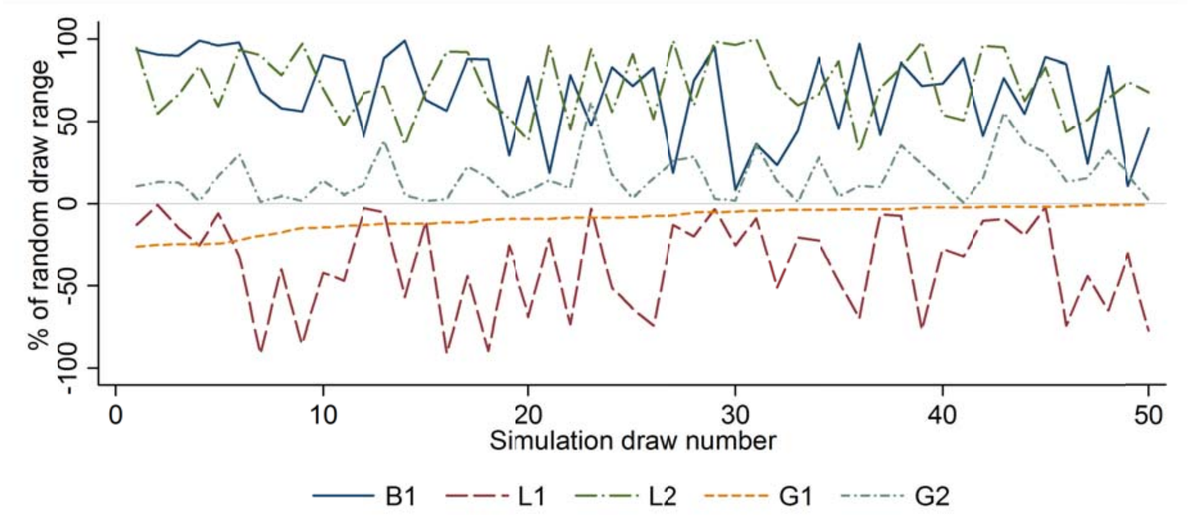

Figure 2.5: Sample of price response parameter values that result in $d \geq 1$. Each point on the horizontal axis represents a Monte Carlo iteration that resulted in $d \geq 1$, and the values of each line represent the parameter values for that run. Values are sorted on γ_1.

This numeric exploration can provide qualitative guidance as to when it is appropriate to choose $d = 1$. For example, another pattern that emerged from Figure 2.5 is that when $\gamma_1$is at its largest (~15-35% of the random draw range), β_1 is constrained to the top 50% of the random draw range, but as γ_1 approaches zero, β_1 exhibits more variability. This means that if secondary buyers are very sensitive to the price of secondary material, primary buyers must also be very sensitive to the price of primary material in order for full displacement to occur. If secondary buyers are price sensitive and primary buyers are not, displacement will be less than 100%.

Additionally, from Figure 2.4 we see that full displacement is more likely in cases where secondary supply and demand price responses are low, primary own-price demand responses are low, and primary own-price supply and cross-price demand responses are high. In real-world terms, these are cases where secondary material suppliers are unresponsive to changes in price, perhaps because they are limited by input scrap availability. At the same time, buyers of both materials are unresponsive to price changes of their own material, perhaps due to limited demand for final goods. Buyers of secondary material, however, must be unresponsive to the price of primary material while buyers of primary material must be highly responsive to the price of secondary material.

This last piece, which is also the last necessary condition for full displacement ($\lambda_2 > \gamma_2$), is the most problematic for real-world products or materials in well-behaved competitive markets. As mentioned, for nearly all highly recycled materials, the primary version of the material is more versatile than the secondary version: Primary aluminum can be used for wrought or cast products, whereas secondary aluminum is typically only suitable for cast applications; primary PET is useful for any range of products, whereas RPET is unsuitable for bottle production. In these cases, buyers of primary material will be less responsive to price changes of secondary material than buyers of secondary material are to price changes in primary material, which violates the above condition. Doubtless, there are special products that satisfy this condition, as in the case of the parking meter example above. It seems, however, that unless one has particularly convincing reasons to believe that primary buyers are more sensitive to secondary prices than secondary buyers are to primary prices, assuming full displacement is likely the incorrect choice and will thus overstate the benefits of reuse or recycling.

3 CASE STUDY: U.S. ALUMINUM MARKET

In this section, I demonstrate the applicability of the modeling and supply shock experiment methodology by building an industry model describing supply and demand of primary and secondary aluminum in the U.S. Aluminum provides an ideal case study because it is highly recycled, data quality and availability are excellent, and the recycled material is very similar but not identical to the primary material, such that the two are substitutes but still have distinct prices. Additionally, aluminum is of current practical interest due to trends in the automotive industry toward lightweight vehicles for increased fuel efficiency. Aluminum industry groups propose that aluminum provides a lower-energy solution to light-weighting than high-strength steel, a result that pivots on assumptions about primary aluminum displacement by recycled aluminum (European Aluminium Association, 2013; Industry Today, 2013; International Aluminum Instutute, 2006). Aluminum is therefore ideal for a case study to demonstrate the market model–based displacement estimation methodology, although the method is generally applicable to any system where materials compete with recycled alternatives. I begin with the basic structure of the aluminum industry before detailing the estimation methodology and data. I then present and discuss the estimated parameters and the resulting aluminum displacement rates, including a sensitivity analysis.

3.1 Market structure and factors of production

Aluminum begins as the naturally occurring mineral bauxite. Bauxite is mined worldwide in large, open-pit mines and minimally processed before being shipped to refineries where it is turned into alumina via the Bayer process. Refined alumina is then shipped to aluminum smelters where it is dissolved in an electrolyte with a carbon anode, using large amounts of electricity, to produce molten aluminum metal in the Hall-Héroult process. This pure aluminum may be alloyed with other metals to achieve specific properties and is then transported either in molten or cast form to semifabricator facilities that cast, roll, extrude, or forge semifabricated products that are used to produce final goods (Plunkert, 2000). Primary aluminum production is fairly centralized, both internationally and within major producing countries. In 2012 the top ten producing countries accounted for 80% of global production (USGS, 2012); the top ten refiners worldwide accounted for over half of global output in 2011 (Bell, 2011; USGS, 2012).

Secondary aluminum processing is a much more disaggregated industry. Collection is distributed across countless individual and corporate collectors who deposit end-of-life aluminum at material recovery facilities (MRFs) or at independent scrap yards. From there, scrap is sold by dealers, often through scrap brokers, on the international market. Scrap is more valuable if it is of known and consistent grade and quality, so scrap dealers sort and preprocess scrap to the extent that it is cost-effective. Scrap is purchased by recyclers who melt it in one of several types of furnaces before alloying the metal and selling it to semifabricators (Plunkert, 2000). Secondary aluminum is substitutable for primary aluminum in most but not all applications. Most secondary aluminum is used in cast rather than wrought products.

Both primary and secondary aluminum are globally traded commodities, and the primary industries for aluminum are transportation, packaging (mainly beverage cans), construction, and electrical (Plunkert, 2000). Since the 1970s the price of various aluminum alloys has been determined through futures trading on the London Metal Exchange (LME); prior to that, published prices were set by the major producers and discounts were independently negotiated with buyers. In contrast to other markets such as agriculture, aluminum producers are able to change production quantity relatively quickly in response to changes in price, whereas consumers are often unable to easily switch to substitutes due to choices in manufacturing technology and product design (Gilbert, 2006).

3.2 Aluminum market model

For the current model I focus on the U.S. aluminum market due to the availability of high-quality data, and I account for international trade by including imports and exports. Beginning with the general model presented in Section 2, the goal is to estimate the own- and cross-price responses that drive the displacement relationship. Estimation of these parameters is complicated by the fact that supply and demand are determined simultaneously, making ordinary least squares estimates biased. Estimation requires two-stage least squares (TSLS) using instrumental variables to isolate the slopes of the supply and demand curves. To this end, I augment the model with additional control variables that allow us to statistically identify each price response parameter. In addition to prices of both types of material on the right-hand side of each equation, I now include exogenous explanatory variables such as the price of other substitutes (in this case, copper, but the results are nearly identical if using steel as a substitute), factors of production (such as wages, energy costs, and input prices), production capacity, and indicators of demand (such as levels of industrial manufacturing and aluminum castings activity). Additionally included on the right-hand side are lagged dependent variables. These lagged variables mean, for instance, the supply of secondary aluminum each year is a function of the amount supplied in the previous year—that is, for each time period t, $S_{sec_t} = f\left(S_{sec_{t-1}}\right)$.

The addition of lagged dependent variables makes the model dynamic. In contrast to the basic, static model, shocks to the system will not take full effect immediately, but only after some time as a new equilibrium is reached. The final modification to the simple model is that the supply-demand equality is changed to reflect real-life conditions. Now supply and demand are equated according to a stock-and-flow identity using changes in physical stockpiles ($\Delta Stock$) and levels of imports (IM) and exports (EX) of each material. As a simplification, I treat imports, exports, and stock as exogenous. The modified model is shown in eq. 3.1.

$$
\begin{aligned}
\log(S_{sec}) &= \alpha_0 + \alpha_1 \log(P_{sec}) + \alpha_2 \log(P_{scrap}) + W + \alpha_3 \log(S_{sec_{t-1}}) + \varepsilon \\
\log(S_{prim}) &= \beta_0 + \beta_1 \log(P_{prim}) + X + \beta_2 \log(S_{prim_{t-1}}) + \varepsilon \\
\log(D_{sec}) &= \gamma_0 + \gamma_1 \log(P_{sec}) + \gamma_2 (\log(P_{prim}) - \log(P_{sec})) + Y + \gamma_3 \log(D_{sec_{t-1}}) + \varepsilon \\
\log(D_{prim}) &= \lambda_0 + \lambda_1 \log(P_{prim}) + \lambda_2 (\log(P_{sec}) - \log(P_{prim})) + Z + \lambda_3 \log(D_{prim_{t-1}}) + \varepsilon \\
S_{sec} &\equiv D_{sec} + \Delta Stock_{sec} - IM_{sec} + EX_{sec} \\
S_{prim} &\equiv D_{prim} + \Delta Stock_{prim} - IM_{prim} + EX_{prim}
\end{aligned}
\tag{3.1}
$$

where

$$
\begin{aligned}
W &= \alpha_4 \log(P_{wages}) + \alpha_5 \log(P_{scrap}) + \alpha_5 (P_{silicon}) + \alpha_6 (P_{capital}) \\
X &= \beta_3 \log(P_{wages}) + \beta_4 \log(P_{energy}) + \beta_5 \log(Cap) \\
Y &= \gamma_4 (\log(P_{Cu}) - \log(P_{sec})) + \gamma_5 \log(A_{castings}) \\
Z &= \lambda_4 (\log(P_{Cu}) - \log(P_{prim})) + \lambda_5 \log(A_{indmfg})
\end{aligned}
$$

The variables that make up W, X, Y, and Z are regressors detailed in Table 2.2. These variables are exogenous except in the case of the price difference between copper and each type of aluminum, where only the price of copper is exogenous. The subscript $t-1$ denotes a one-year lag. Log-log form is used so that estimated coefficients can be interpreted as elasticities.

3.3 Model limitations

The aluminum model is simplified in several ways. First, like the basic model, it does not consider various nonmarket factors such as government recycling targets, subsidies, and quotas. It also treats all primary aluminum as a single product and all secondary aluminum as a single product, when in reality there are many grades and alloys of both. Additionally, scrap is treated as homogenous and a single scrap price is used, which is a production quantity-weighted average of mixed low-copper-content clippings, clean dry turnings, old sheet and castings, and used beverage cans. This mix represents both old and new scrap, which may in reality be handled separately by different industrial actors. This simplification also ignores the fact that not all scrap is suitable for all recycling uses. However, scrap enters the model only as in input price to secondary supply, and these four grades of scrap vary in price by only 10–15% during the estimation period. Thus, treating scrap as homogenous is justified; sensitivity analysis using only used beverage cans does not change the overall findings.

The aluminum model is geographically limited to the U.S. market. This limitation was necessitated by the considerable data requirements of the study and the availability of public data in the U.S. The U.S. relies heavily on imports of bauxite for aluminum production and relies on exports for refined aluminum and for scrap, primarily to China. An attempt was made to account for these flows by including actual annual data on imports and exports for each type of material, but those flows were kept exogenous in the model. The effect of this limitation is that domestic supply and demand in the model react to price changes without intervention from international markets.

However, endogenizing imports and exports would require a significantly more complex global model with similar data demands for six or more major producing countries. Previous authors have attempted such models for aluminum-bauxite (Hojman, 1981) and copper (Fisher et al., 1972), though they were forced to significantly simplify the control variables used and ultimately arrived at own-price elasticities roughly in line with those estimated in this study, suggesting that the added complexity may not deliver more accurate or useful model results. Additionally, the quality of data on secondary metals production and prices is significantly worse on a global scale; neither of the multicountry models explicitly considers the effect of recycled material on the market. Limiting the study to the U.S. was therefore necessary without access to further high-quality global data, and appropriate for this case study, whose primary purpose is to demonstrate the displacement estimation methodology.

Additionally, aluminum stock is simplified in that I modeled stock as an exogenous variable, whereas in reality the level of stock is a function of both random fluctuations and suppliers' expectations about future demand and preferred stock size. Expanding the model to include intentional fluctuations in stock size would increase the realism of the model, but was outside the scope of this study.

Finally, as I will discuss more in the following section, it should be acknowledged that like-kind displacement (i.e., secondary aluminum displacing primary aluminum as opposed to steel, plastic, etc.) is not the only kind of displacement and in some cases may not be the most appropriate comparison. In this illustrative case study, I restricted the notion of displacement to like-kind material in order to demonstrate the displacement estimation methodology. This focus was necessary due to the massively increased data requirements and modeling complexity if considering alternative displaced materials. As I will discuss, further research along this vein is needed to fully understand the environmental consequences of aluminum recycling.

3.4 Datasets and estimation

To estimate each equation, time series data were required for aluminum price and production data, each of the explanatory variables, and the stock and trade variables. Collecting reliable data with sufficient time coverage is a significant challenge to this type of analysis, particularly for scrap and secondary material prices. I drew annual price and production data from the U.S. Geological Survey (USGS), the U.S. Census Bureau, the U.S.

Federal Reserve, the U.S. Energy Information Administration (EIA), and the U.S. Bureau of Labor Statistics (BLS). A complete list of variables and associated datasets is provided in Table 2.2. The estimation period was 1969–2010 (N=41) in order to most accurately reflect current conditions rather than past anomalies.

Specifications for the equations in eq. 3.1 were developed by reviewing previous econometric models of aluminum markets (e.g., Blomberg & Hellmer, 2000; Blomberg & Söderholm, 2009) and by investigating the structure and history of the U.S. aluminum market. Various specifications, including competing autoregressive lag structures, were tested. The final specifications were selected based on standard diagnostics, their ability to produce accurate forecasts, and a preference for parsimony.

Equations were estimated using two-stage least squares (TSLS) with instrumental variables. Instruments consisted of all exogenous variables in the equations, one-period lagged dependent variables, and exogenous variables from the opposite supply or demand equation (i.e., for each supply equation, the regressors from the corresponding demand equation were used as instruments, and vice versa). Regressions were checked for serial correlation using the Breusch-Godfrey statistic, shown at the bottom of Table 2.3; no significant serial correlation was observed.

Variable	Description	Units	Source
Sprim	Production quantity of primary aluminum from bauxite	tonne	USGS
Ssec	Production quantity of secondary aluminum from old and new scrap	tonne	USGS
Pprim	Price of primary aluminum	$/tonne	USGS
Psec	Price of secondary aluminum, average of various aluminum-based alloys	$/tonne	USGS
Pscrap	Price of aluminum scrap, weighted average	$/tonne	USGS
Pwages	Average hourly earnings of production and nonsupervisory durable goods employees	$/hr	BLS
Cap	Capacity of primary refineries	thousand tonnes	USGS
Pcapital	Price of capital, approximated by U.S. 10-year constant maturity treasury bill	% yield per annum	US Federal reserve
Penergy	Price of West Texas Intermediate crude	$/barrel	US EIA
Psilicon	Price of silicon	$/tonne	USGS
Dprim	Demand/consumption of primary aluminum	tonne	Identity: Di = Si + IMi - Exi - stockchangei
Dsec	Demand/consumption of secondary aluminum	tonne	Identity: Di = Si + IMi - Exi - stockchangei
Acasting	Net shipments of total cast products	thousand tonnes	USGS
Aindmfg	Value of shipments from industrial manufacturing sectors	million $	US Census
Pcu	Price of copper	$/tonne	USGS
defl_PPI	Deflator for each year using U.S. Producer Price Index		BLS
defl_CPI	Deflator for each year using Consumer Price Index		BLS
IMp	Imports of primary aluminum	tonne	USGS
EXp	Exports of primary aluminum	tonne	USGS
IMs	Imports of secondary aluminum	tonne	USGS
EXs	Exports of secondary aluminum	tonne	USGS
StockPrim	Quantity of primary aluminum in industry and government stockpiles	tonne	USGS
StockSec	Quantity of secondary aluminum in industry and government stockpiles	tonne	USGS

Table 2.2: Variables and data sources

3.5 Estimation results and calculation of displacement

Results for the estimation of eq. 3.1 are shown in Table 2.3. As in the basic model, to calculate displacement, the procedure is to solve the system of equations using the estimated parameters, introduce a secondary supply shock, and calculate the difference in primary and secondary supply before and after the shock. In the basic model, the price response parameters were linear and expressed in terms of absolute supply changes, meaning displacement was a constant that depended on the price response parameters.

The aluminum model, however, differs in two important ways: First, eq. 3.1 is nonlinear due to the fact that the stock-change identity is in levels and the supply and demand equations are in logs. Thus, eq. 3.1 cannot be solved analytically. Rather, I solved the system using the Broyden method (Broyden, 1965), using actual data for the exogenous variables for each year of the estimation period. Second, the price response parameters are elasticities, and thus expressed in percentage changes to supply; to calculate displacement, these percentage changes must be converted to absolute quantity changes by multiplying by the actual production quantity of each material. Since these actual production quantities as well as the exogenous imports, exports, and stockpiles change each year, the model solution (and therefore the calculated displacement rate) also varies by year. Instead of a single value for primary and secondary supply, therefore, we instead arrive at a set of solutions—one for each year. The solved values for supply of both materials are shown in Appendix B.2.

To calculate displacement rates for each solution-year, I introduced a 10% increase to the secondary supply intercept (α_0) from 1980 to 2010, and once again solved the system for each year. The set of solved levels of primary and secondary supply under the baseline scenario were subtracted from those under the supply shock scenario. Figure 2.6 shows the difference between the supply shock scenario and the baseline for supply of both materials. Prior to the shock in 1980, the difference is zero, but after the secondary supply intervention, secondary supply increases and primary supply decreases, as expected. Because supply of each material in eq. 3.1 is dependent on exogenous factors, the supply changes following the shock are not constant, but vary each year; because the model is dynamic, the changes each year are also a function of the previous years' change. Figure 2.6 shows that the increase in secondary supply is larger and grows more over time than the decrease in primary supply.

Next, the change in supply of primary material was divided by the change in supply of secondary material to obtain the displacement rate, in accordance with eq. 1.12. Because the supply changes vary each year, so too does the displacement rate; thus we arrive not at a singular displacement rate, but a time series of displacement rates over the estimation period, shown in Figure 2.7. Prior to the shock in 1980 there is, of course, no displacement rate; thereafter, displacement starts out around 45% but gradually drops as secondary supply outpaces the decline in primary supply, ending at 10%. The intervention year is inconsequential; a similar pattern emerges no matter when the secondary supply shock is introduced (see Appendix B.2).

3.6 Sensitivity analysis

Table 2.3 shows that there is considerable uncertainty in many of the parameter estimates. Of particular concern are the elasticities that drive the displacement relationship, as summarized in Table 2.1. To assess the effect of the estimation uncertainty on the results, I conducted sensitivity analysis by solving the model incorporating stochastic equation error (residuals from each equation). From these upper- and lower-bound supply change values I computed upper- and lower-bound displacement rates using the same method as above. These bounds are shown as dash-dot 95% confidence intervals in Figures 2.6 and 2.7. See Appendix B.2 for more information on the model solving procedure and calculation of confidence intervals.

The sensitivity analysis shows that the uncertainty in the equation estimates does indeed create uncertainty in the estimated displacement rate. Estimated displacement can vary by 50% in the first period after the shock, and can be as high as 80%. For the majority of the time series, and especially in more recent years, the range of estimated displacement rates tends to be below 50%, and only reaches 100% once, in 1981.

	Dependent variable			
Independent variable	$\log(S_{prim})$	$\log(D_{prim})$	$\log(S_{sec})$	$\log(D_{sec})$
$\log(P_{prim})$	0.366	-0.241		
	(0.178)**	(0.404)		
$\log(P_{wages})$	-0.844		-0.658	
	(0.567)		(0.620)	
$\log(P_{energy})$	-0.077			
	(0.035)**			
$\log(Cap)$	0.594			
	(0.360)*			
$\log(P_{sec}) - \log(P_{prim})$		0.269		
		(0.597)		
$\log(P_{cu}) - \log(P_{prim})$		-0.138		
		(0.110)		
$\log(A_{indmfg})$		0.063		
		(0.083)		
$\log(P_{sec})$			0.493	-0.352
			(0.431)	(0.658)
$\log(P_{scrap})$			-0.055	
			(0.116)	
$\log(P_{silicon})$			-0.178	
			(0.174)	
$\log(P_{capital})$			-0.040	
			(0.046)	
$\log(P_{prim}) - \log(P_{sec})$				0.646
				(0.844)
$\log(P_{cu}) - \log(P_{sec})$				-0.071
				(0.165)
$\log(A_{casting})$				0.227
				(0.128)*
$\log(D.V._{t-1})$	0.604	0.694	0.947	0.674
	(0.149)***	(0.199)***	(0.129)***	(0.222)***
Intercept	0.861	5.802	0.653	5.950
	(1.466)	(4.531)	(4.176)	(7.708)
Estimation period	1969–2010	1969–2010	1969–2010	1969–2010
Adj. R-squared	0.84	0.41	0.95	0.91
BG statistic, 1 lag (p-value)	0.056 (0.814)	0.000 (0.988)	0.000 (0.988)	1.444 (0.230)

Standard errors in parentheses

*, **, *** coefficient significant at the 10%, 5%, 1% level

Table 2.3: Estimation results using TSLS with instrumental variables (see text for description of instruments)

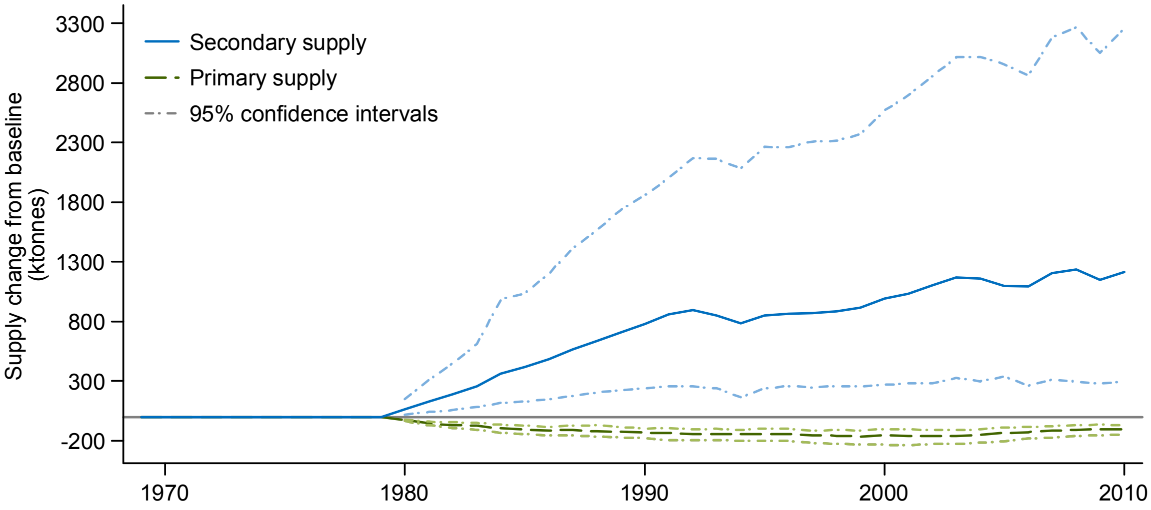

Figure 2.6: Dynamic response of primary and secondary production to 10% scrap price decrease

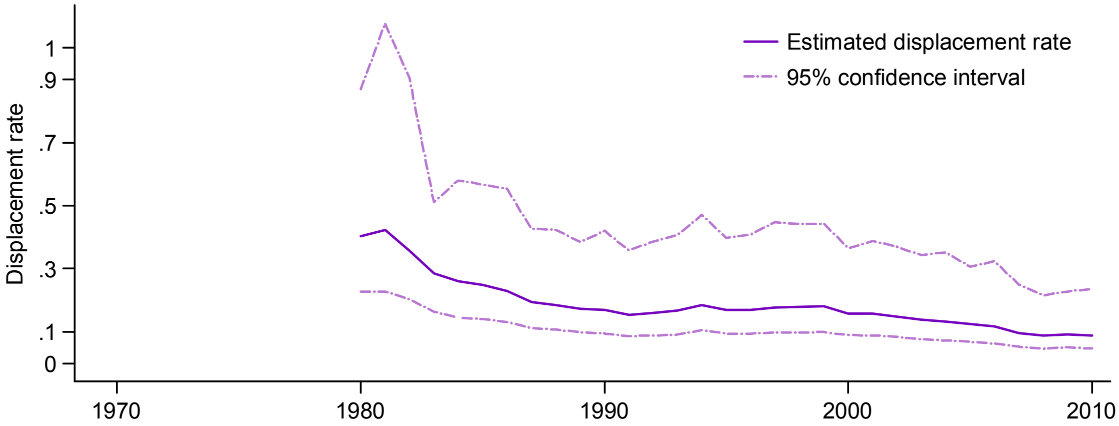

Figure 2.7: Estimated U.S. aluminum displacement rate over time (see text)

3.7 Discussion of the aluminum model results

The coefficient estimates in Table 2.3 correspond well with economic theory and previous literature. The own- and cross-price elasticities all have the theoretically predicted sign, although most are not statistically significant. It is worth pointing out that achieving price elasticities with the theoretically predicted sign is not a trivial task due to data limitations (Fisher et al., 1972), and the fact that all six estimates of interest point the expected direction is encouraging.

The coefficient estimates on the exogenous variables are less interesting for the current discussion, but it is worth noting that all but two (the differential copper price in the demand equations) have the expected sign, although again, most fail to achieve statistical significance. The variables with the most influence and tightest errors are the dependent variable autoregressive terms, suggesting that supply and demand have inertia from year to year. Looking at the model response to a 10% secondary supply shock in Figure 2.6, the initial response of the system is similar to that of the basic, static model: When the shock is introduced in 1980, secondary supply immediately increases and primary supply decreases. However, the decrease in primary supply is less than the increase in secondary supply, an effect that increases throughout the remainder of the simulation period.

The amount of variability that results from the sensitivity analysis suggests that more work is needed to develop advanced econometric models that can provide more tightly estimated elasticity parameters. Nevertheless, the fact that the 95% confidence range of displacement rates is below 45% from 1987 on and only reaches 100% on one occasion suggests that even with loose elasticity estimates, we can have some confidence that displacement in the U.S. aluminum industry may be lower than 100%.

4 CONCLUSION

The basic model uncovered the underlying mechanisms of displacement and revealed the market conditions that are likely to result in zero displacement or full displacement. The aluminum market model predicted actual displacement rates of primary aluminum by recycled aluminum to be below 45% in the U.S. in the last several decades. These results together indicate that displacement of primary material by recycled material is unlikely to be

100% for many commonly recycled commodity materials, and, according to model estimates, is likely lower than 100% in the U.S. aluminum market.

4.1 Increasing displacement

These results should be troubling to environmentalists in general and to industrial ecologists in particular. Over the past four decades significant effort has been focused on increasing collection and recycling of a variety of materials, notably steel, aluminum, glass, and plastic. The results of this study suggest that recycling and reuse in general do not result in the environmental benefits previously assumed, and in some cases, if displacement is below the break-even rate, may in fact *increase* overall environmental impacts.[27]

Nevertheless, by no means is the solution to start landfilling recyclable materials. After all, in the case of aluminum, based on the relative CO_2 intensity of primary and secondary aluminum production, the break-even displacement rate is 5% (PE International, 2012). This means that even at the lowest displacement rates predicted by the aluminum market model, recycling aluminum does result in net benefit; if displacement approaches 100% that benefit becomes substantial. Instead, therefore, the solution is to influence the way secondary and primary aluminum interact in the market in such a way as to maximize displacement. For instance, all else being equal, an increase in the cross-price response of primary demand for secondary material (λ_2 in the basic model) increases displacement rate. Cross-price demand response is a measure of buyers' ability to substitute between alternatives, so one way to increase this response is to improve the ability of secondary material to substitute for primary material. In the case of aluminum, in many applications the

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[27] Break-even displacement rate is the rate at which the net benefit of recycling is zero. The break-even rate can be calculated as the ratio of recycling impacts to displaced production impacts (E_{rec}/E_{disp}) in any impact category of interest. Displacement above this rate will ensure environmental benefit; displacement below this rate means recycling causes increased impacts. See eq. 5.1 in Chapter 1 for more detail.

two materials are perfect substitutes; however, some applications require high-grade primary aluminum. Secondary aluminum is of lower quality primarily due to other contaminant metals that are introduced during the collection and processing steps, particularly with the mixing of different alloys. Therefore, increased efforts to separate different grades and alloys of scrap could improve overall secondary aluminum quality. An increase in secondary aluminum quality would increase primary producers' willingness to substitute secondary material, thereby increasing displacement rate.

Another way to increase displacement is to reduce secondary buyers' price sensitivity, both to changes in the price of secondary material and to changes in the price of primary material. We learned from examining the market system dynamics in Figure 2.2 that one of the keys to high displacement rates is ensuring that decreases in the price of primary material, which occur when primary buyers substitute for secondary material, do not translate induce secondary buyers to substitute more primary material. From the discussion in Section 2.4.2, we saw that full displacement is only possible when secondary buyers are quite unresponsive to the price of secondary material.

In practice, ensuring low own- and cross-price price sensitivity for secondary buyers may be achievable through subsidies or other incentives to produce goods with higher recycled content. For instance, if there were a tax subsidy tied to the percentage of goods produced from secondary materials, this would make producers more willing to use secondary material and make them less price sensitive, since the subsidy would help hedge against increases in input prices. Such a subsidy would also make secondary buyers less willing to switch to primary material since they would receive a lower subsidy, and it would also help to increase primary buyers' willingness to switch to secondary material in order to receive more of the subsidy. All of these factors would contribute to a higher displacement rate.

4.2 Displacement of other types of material

This study has been focused on displacement of primary material by secondary material *of like kind*. That is, in eq. 1.12 we constrain Q_p and Q_s to be essentially the same type of material: virgin aluminum vs. recycled aluminum, PET vs. RPET, etc. However, like-kind displacement is not the only type of displacement that can occur as a result of reuse or recycling, and may not always be the most appropriate or interesting in an LCA context. For instance, even if secondary aluminum has low primary aluminum displacement rates, in some applications it may still displace primary production of other materials such as copper, steel, or plastics. As another example, even though RPET is unsuitable for bottle production and will therefore have very low displacement rates for primary bottle-grade PET, RPET may still displace primary production of a *different* material. RPET can be turned into clamshell containers, molded pieces, and everyday objects like park benches and speed bumps. To the extent that these objects would have been created even in the absence of the recycled plastic, downcycled RPET displaces the alternative primary material such as polypropylene, steel, wood, or asphalt. This type of displacement relationship is less common in life cycle assessments, but some examples do exist (e.g., Schmidt & Weidema, 2007), which typically assume full displacement of a different type of material.

Even though this study has focuses on like-kind displacement, the demonstrated approach is equally applicable to displacement of other materials. Eq. 1.11 can easily be generalized to handle any combination of potentially displaced materials as follows:

$$E_{net} = E_{prim} + E_{use} + E_{rec} - \sum d_i E_{disp_i} \tag{4.1}$$

where E_{disp_i} is the per-unit impact of production for material i and d_i is the displacement rate for material i, where displacement rate is defined as the change in production quantity of material i caused by a change in secondary production of the material of interest:

$$d = -\Delta Q_{p_i}/\Delta Q_s \tag{4.2}$$

Eqs. 4.1–4.2 are completely general in that not only can material i refer to primary production of any other potentially displaced material, it can also refer to secondary production of any potentially displaced material. Thus, if one has reason to believe, for instance, that recycled aluminum might not only displace primary aluminum but also primary and recycled steel, each of these materials could be included in eq. 4.1 and individual displacement rates could be estimated for each material in eq. 4.2.[28] The main methodological difference in evaluating these other-material displacement relationships would be that the relevant cross-price responses would not be between primary and secondary material, but between the secondary material of interest and the competing material.

However, other-material displacement significantly complicates the environmental assessment: As discussed, recycling has the potential to create environmental benefit because most recycled materials have lower impacts than their primary production counterparts. In the case of other-material displacement, there is no guarantee that the displaced primary material has higher impacts than the recycled material, since they are of different kind. For instance, if recycled aluminum displaces primary steel at 100% displacement, the greenhouse gas (GHG) benefits will be about one-fifth as large as if it displaced primary aluminum at

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[28] Additionally, eq. 4.1 need not be limited to production of a physical good; it could, for instance, refer to displacement of one production technology by a newer one—such as displacement of fossil-based energy by renewables. However, development of this extension is beyond the scope of the current study and must left to future research.

100%; if it displaces recycled steel, it will roughly double GHG impacts as compared to not recycling the aluminum at all (recycled steel creates about half the GHG impacts of recycled aluminum) (PE International, 2012). A comprehensive investigation into multimaterial displacement is needed to gain a better understanding of recycling impacts, but was outside the scope of the current study.

4.3 Lessons for environmental assessment practitioners and corporate managers

The demonstrated methodology and findings suggest a number of general lessons for both environmental assessment practitioners and would-be green firms. First is that environmental analyses involving recycled or reused products must consider and take steps to quantify displacement. Assumptions about displacement can reverse the environmental preference order of alternatives, and this study has shown that the full displacement assumption leads to overstated benefits of reuse and recycling, and possibly to suboptimal environmental choices. Reducing uncertainty of displacement by conducting market studies using the demonstrated methodology should be of prime importance. Considering the importance of price elasticities to a wide range of scholarly and practical pursuits, the dearth of rigorous elasticity estimates, including cross-price estimates between primary and secondary versions of a commodity, represents an important research gap. Additionally, the idea of multimaterial displacement is critical. To fully understand the environmental consequences of a reuse or recycling activity, we need to know not only *how much*, but also *what kind of* competing material is displaced. This paper has advanced the methodology on answering the first question; similarly robust, market-based methodologies are needed to answer the second.

Secondly, companies that wish to differentiate their products through superior environmental performance must recognize the importance of displacement in their environmental claims. The assumption of displacement of environmentally harmful alternatives lies at the heart of environmental claims made by many firms to differentiate their products. Car sharing firms, for instance, rely on the assumption that car sharing displaces production and use of personal vehicles; however, as we saw in Chapter 1, it may be the case that car sharing in fact attracts consumers who would otherwise use public transport. The environmental benefit of a Patagonia recycled plastic fleece rests partly on the assumption that it displaces a fleece made from primary fabrics; it may, however, simply displace a similar recycled fiber fleece from North Face, or something else entirely.

This means two things for managers: First, managers must take steps to model the market in which the product competes and attempt to measure the effect it has on competing products. As watchdog NGOs and consumers become more interested and savvy, firms must be prepared to back their environmental claims with robust research on how a green product actually takes market share from dirtier products and therefore benefits the environment (under the net green definition from Chapter 1). Second, firms that wish to maximize the environmental benefit of their products (whether out of goodwill or for financial purposes) should seek to design their products and position them in markets where displacement of the dirtiest alternatives is most likely to occur.

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APPENDIX A: BASIC MODEL

A.1 Landfill is only avoided if production is displaced

One popular belief is that the benefit of recycling arises from the avoidance of landfill. However, recycling does not necessarily avoid landfill. For instance, consider a case where PET bottles are recycled into a fleece jacket. If the fleece jacket is discarded to landfill at the end of its life, then recycling the PET into the fleece has not changed its fate but merely delayed it; in the end, the material is still landfilled. The same is true even of so-called "closed-loop" recycling, such as steel sections being recycled back into steel sections. Even if this material is recycled many times, the laws of thermodynamics dictate that during each iteration some material is lost to landfill or other environmental releases. For instance, if a 1 kg steel section is recycled indefinitely at 10% yield loss, after forty-five cycles 90% of the material will have been lost. Thus, even in closed-loops, recycling does not avoid landfill—it merely delays it.

However, recycling can reduce the amount of material reaching landfill by reducing the amount of material produced in the first place. If recycling displaces primary production, it effectively reduces the amount of extant industrial material in circulation, and thus eliminates the need to dispose of this material. Thus, recycling and reuse can pay "double dividends" by preventing the impacts of both material production and material landfilling—but only if (and to the extent that) displacement occurs.

A.2 Displacement rate, recycling rate, and recycling yield

Figure 2.1 is simplified to highlight the role of displaced primary production as the main source of environmental benefits from recycling and reuse. Two concepts that are missing from the diagram are recycling rate and recycling yield. Figure 2.A.1 replicates

Figure 2.1, including these two concepts shown as parameters that determine the sizes of the flows out of “product use” and out of “collection and reprocessing.” After M material is used, the parameter $X \in [0,1]$ determines the collection rate: After products are used, X are collected and the remainder are landfilled. The parameter Y determines the recycling yield: During the recycling process some material may be lost, so only $Y \in [0,1]$ secondary material is produced and the remainder is landfilled. Therefore, the total amount of secondary material entering the material and product market after accounting for recycling rate and recycling yield is $Q_{rec} = M \cdot X \cdot Y$.

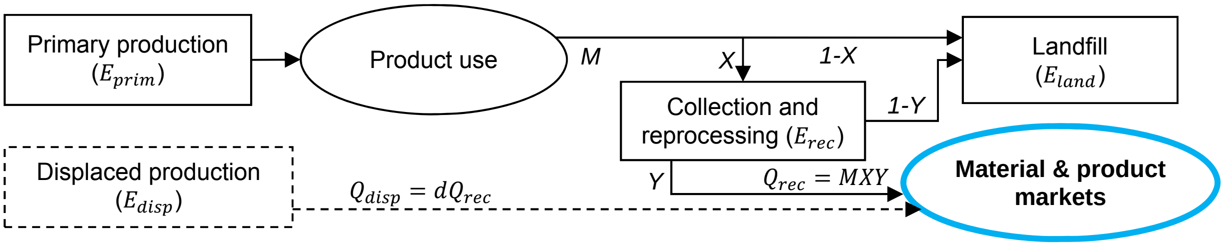

Figure 2.A.1: Product system involving recycling or reuse, showing recycling rate and yield loss

These parameters are ignored in the present study for two reasons. First, recycling rate and recycling yield loss are physical quantities that can easily be determined simply by measuring the difference between the quantity of material used and the quantity collected (for recycling rate) and between the quantity collected and the quantity of secondary material produced (for recycling yield). These parameters have been well studied for a number of product systems (e.g., Geyer et al., 2007; Geyer, Kuczenski, Henderson, & Zink, 2013; Kuczenski & Geyer, 2011).

Second, and more importantly, it can be seen that while recycling rate and recycling yield help to determine the *amount* of primary production displaced, they are not involved in the determination of displacement *rate*. The amount of primary production displaced is equal to the quantity of secondary material entering the materials market multiplied by the displacement rate: $Q_{disp} = dQ_{rec}$, or equivalently, $Q_{disp} = dMXY$, using the formula for Q_{rec} from above. Thus, d is a separate parameter from X and Y and can be considered independently from them. The current study is focused on a methodology to determine displacement rate, and therefore recycling rate and recycling yield can be ignored without loss of generality.

A.3 Alternate cross-price response specification

In eq. 2.1 the cross-price response is a coefficient on the price differential between primary and secondary materials. An alternative approach would specify the cross-price response as the coefficient on the price of the competing material:

$$\begin{aligned} S_{sec} &= \alpha_1 P_{sec} + \alpha_2 P_{inS} \\ S_{prim} &= \beta_1 P_{prim} + \beta_2\, P_{inP} \\ D_{sec} &= \gamma_1 P_{sec} + \gamma_2 P_{prim} \\ D_{prim} &= \lambda_1 P_{prim} + \lambda_2 P_{sec} \\ S_{sec} &= D_{sec} \\ S_{prim} &= D_{prim} \end{aligned} \tag{A.1}$$

The reduced form equations for this specification are as follows:

$$\begin{aligned} P_{prim} &= \frac{\alpha_0 \lambda_2}{\beta_1\gamma_1 - \alpha_1\beta_1 + \alpha_1\lambda_1 - \gamma_1\lambda_1 + \gamma_2\lambda_2} \\ P_{sec} &= \frac{\alpha_0(\beta_1 - \lambda_1)}{\beta_1\gamma_1 - \alpha_1\beta_1 + \alpha_1\lambda_1 - \gamma_1\lambda_1 + \gamma_2\lambda_2} \\ S_{prim} = D_{prim} &= \frac{\alpha_0\beta_1\lambda_2}{\beta_1\gamma_1 - \alpha_1\beta_1 + \alpha_1\lambda_1 - \gamma_1\lambda_1 + \gamma_2\lambda_2} \\ S_{sec} = D_{sec} &= \frac{\alpha_0(\beta_1\gamma_1 - \gamma_1\lambda_1 + \gamma_2\lambda_2)}{\beta_1\gamma_1 - \alpha_1\beta_1 + \alpha_1\lambda_1 - \gamma_1\lambda_1 + \gamma_2\lambda_2} \end{aligned} \tag{A.2}$$

Introducing a 10% shock to the intercept on secondary supply, we can compute d using the methodology described in Section 2:

$$\Delta S_p = \Delta D_p = \frac{(\alpha_{0I} - \alpha_{0B})\beta_1\lambda_2}{\beta_1\gamma_1 - \alpha_1\beta_1 + \alpha_1\lambda_1 - \gamma_1\lambda_1 + \gamma_2\lambda_2}$$

$$\Delta S_s = \Delta D_s = \frac{(\alpha_{0I} - \alpha_{0B})(\beta_1\gamma_1 - \gamma_1\lambda_1 + \gamma_2\lambda_2)}{\beta_1\gamma_1 - \alpha_1\beta_1 + \alpha_1\lambda_1 - \gamma_1\lambda_1 + \gamma_2\lambda_2}$$

$$d = \frac{\Delta S_p}{\Delta S_s} = \frac{(\alpha_{0I} - \alpha_{0B})\beta_1\lambda_2}{(\alpha_{0I} - \alpha_{0B})(\beta_1\gamma_1 - \gamma_1\lambda_1 + \gamma_2\lambda_2)}$$

$$d = -\frac{\beta_1\lambda_2}{\beta_1\gamma_1 - \gamma_1\lambda_1 + \gamma_2\lambda_2} \tag{A.3}$$

Comparing eqs. 1.12 and A.3, we see that under the alternative cross-price response specification, the equation for d is slightly changed. The numerator remains the same, whereas the denominator has fewer terms under the alternate specification. The same variables drop out of the before-after subtraction, leaving the same five parameters of interest, each of which has the same direction of influence on d as shown in Table 2.1. Repeating the Monte Carlo simulation as described in Section 2, the alternate specification results in minimum displacement near zero and maximum displacement of 4.3. The distribution of simulated displacement values is also nearly identical to the original specification: 97% below $d = 1$, 90% below $d = 0.5$, 56% below $d = 0.15$, and 0.5% where $0.95 < d < 1.05$.

Thus, the difference in specification of the cross-price response is largely inconsequential for the calculation of displacement following a secondary supply shock. Ultimately, I chose to use the original price-differential specification because this specification more accurately portrays the purchase decision facing consumers of primary and secondary material. Whereas they are likely to choose the *level* of production based on the absolute price of material, they are more likely to make decisions about *which* material to purchase based on the price of each relative to one another. Nevertheless, as this section demonstrates, the decision has little bearing on the model results.

A.4 Log-log specification

The basic model in eq. 2.1 is expressed in terms of linear price responses. This was done for exposition to maximize understanding of the basic concepts. Typically, however, market models are constructed in logarithms on both sides of the equation ("log-log form"), as follows:

$$\begin{aligned}
\log(S_{sec}) &= \alpha_1 \log(P_{sec}) + \alpha_0 \\
\log(S_{prim}) &= \beta_1 \log(P_{prim}) \\
\log(D_{sec}) &= \gamma_1 \log(P_{sec}) + \gamma_2 \big(\log(P_{prim}) - \log(P_{sec})\big) \\
\log(D_{prim}) &= \lambda_1 \log(P_{prim}) + \lambda_2 \big(\log(P_{sec}) - \log(P_{prim})\big) \\
S_{sec} &= D_{sec} \\
S_{prim} &= D_{prim}
\end{aligned} \tag{A.4}$$

The advantage to the specification in eq. A.4 is that the coefficients can be interpreted as price elasticities. A price elasticity is the ratio of percentage changes in quantity to percentage changes in price. Formally:

$$\eta = \frac{dQ/Q}{dP/P},$$

which can be equivalently expressed in logs:

$$\eta = \frac{d\log(Q)}{d\log(P)}$$

Expressing the basic model in log-log form makes the exposition slightly more complex, but it has the benefit that the price responses are now in percentage change format, and therefore "reasonable" values fall within a smaller range. Additionally, it more closely approximates real-world econometric industry models. To see how this specification affects the overall basic model results, I repeated the Monte Carlo simulation, as described in Section 2.4, using eq. A.4. Ten thousand values for the five elasticity parameters were chosen from uniform distributions with a range of [0,±5] (again using negative values for own-price elasticities).

Figure 2.A.2 shows the results of the Monte Carlo simulation. Compared to the linear specification in Figure 2.3, the log-log specification results in a more skewed distribution with more observed values of displacement close to zero. In fact, over the 10,000 simulation repetitions, only twenty-six instances of $d \geq 1$ were recorded. Focusing on these twenty-six occurrences, the distribution of elasticity values that produced them is shown in Figure 2.A.3. While the low number of occurrences makes the histograms less smooth than with the linear model, the basic pattern remains the same: Full displacement is more likely when primary own- and cross-price demand are more elastic, primary own-price demand is less elastic, and secondary supply and demand are less elastic. Figure 2.A.4 shows the actual values for each elasticity parameter for each simulation repetition that resulted in $d \geq 1$. Here, again, the full displacement condition that $\lambda_2 \gg \gamma_2$ holds, as in the linear model.

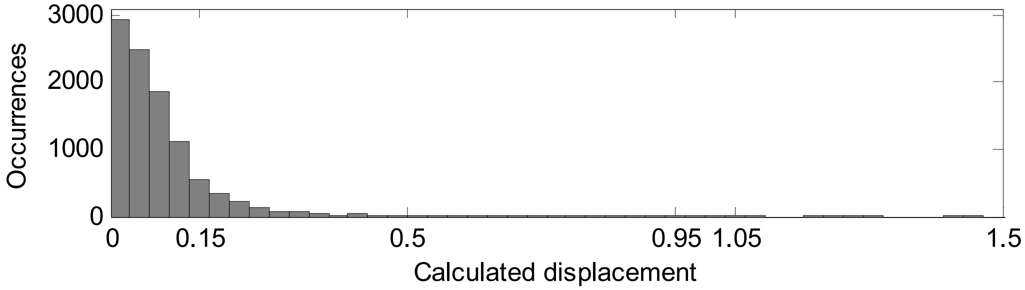

Figure 2.A.2: Monte Carlo results from the basic model with log-log specification (10,000 repetitions). See Figure 2.3 for comparison.

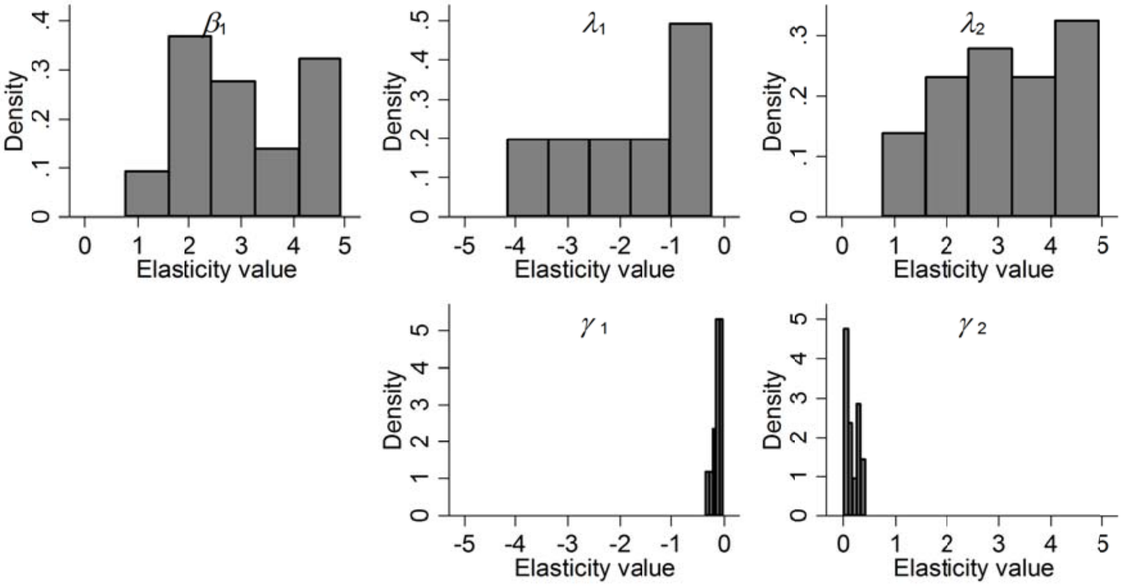

Figure 2.A.3: Distribution of price elasticities that result in $d \geq 1$. See Figure 2.4 for comparison and more information.

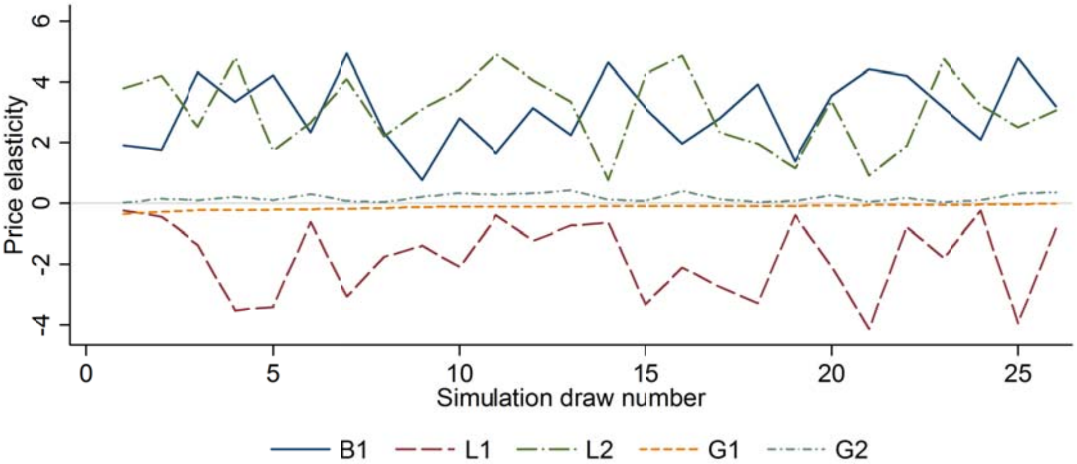

Figure 2.A.4: Elasticity values resulting in $d \geq 1$ under the log-log specification. See Figure 2.5 for comparison.

APPENDIX B: ALUMINUM MODEL

B.1 Aluminum model diagnostics

I tested the predictive power of the model by computing a dynamic forecast,[29] comparing the model's predicted values to actual values over the estimation period 1969–2010 and computing Theil's UII index for the predictions. Theil's UII is a diagnostic of forecast accuracy that can be interpreted as the ratio of the residual mean square error (RMSE) of the proposed forecasting model to the RMSE of the naïve model, $\hat{y}_t = y_{t-1}$:

$$UII = \frac{\sqrt{\sum_{t=1}^{n}(\hat{y}_t - y_t)^2}}{\sqrt{\sum_{t=1}^{n} y_t^2}}$$

which takes a value of $UII = 1$ for the naïve model and $UII = 0$ for a perfect fit. $UII < 1$ indicates an improvement in forecast accuracy as compared to the naïve model; $UII > 1$ indicates worse forecast accuracy than the naïve model (Theil, 1966; Bliemel, 1973). For a discussion of two competing indices generally known as "Theil's U" and why UII rather than UI is used here, see Bliemel (1973).

Figure 2.B.1 shows the actual values against the modeled dynamic forecast. Theil's UII statistics for each endogenous variable are presented in Table 2.B.4.

Forecast variable	Theil's *UII* statistic
Primary aluminum supply	0.105
Primary aluminum demand	0.532
Secondary aluminum supply	0.496
Secondary aluminum demand	0.577

Table 2.B.4: Theil *UII* statistics for endogenous variable forecasts

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[29] As is standard practice, the dynamic forecast was computed using previous-period predicted dependent variable values for current-period lagged dependent variable values.

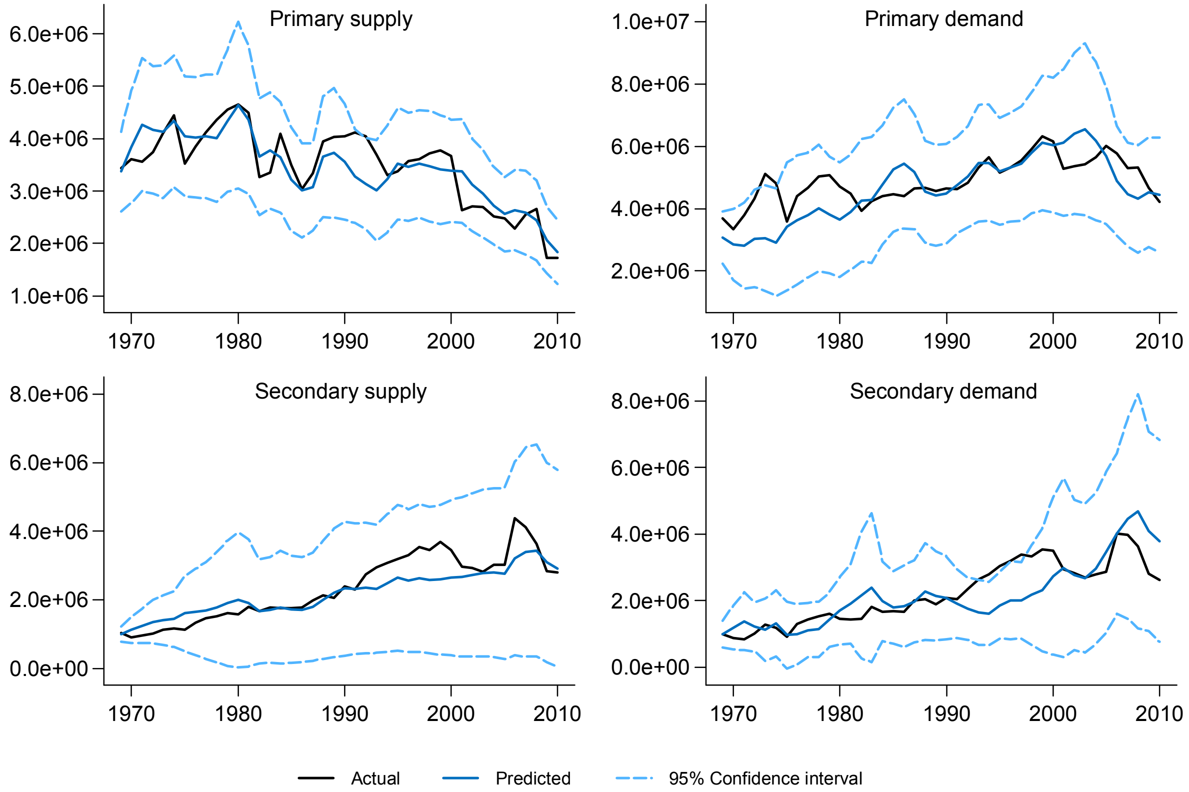

Figure 2.B.1: Dynamic model predictions vs. actual values from 1969 to 2010

A visual check of the dynamic forecast in Figure 2.B.1 shows the fit to be quite good, particularly in the latter thirty years. All six endogenous variable forecasts result in Theil index statistics lower than 0.6, indicating that they provide reasonably accurate forecasts for our purposes. The ability to fit historic data builds confidence that the model is able to reveal the displacement dynamics between secondary and primary production. Overall, the estimated parameters from the model are in line with previously estimated models, shown in Table 2.B.5.

	Price elasticity: Primary		Price elasticity: Secondary	
Study	Supply β_1	Demand λ_1	Supply α_1	Demand γ_1
Slade (1980)	-0.25[c]		0.24	
Hojman (1981)[a]			0.05	-0.17
Deadman & Grace (1979)	0.23			
Gilbert (1994)	0.14	-0.127		
EPA (1998)			2.33	-0.34
Grant (1999)			0.6[b]	
Carlsen (1980)			0.32	
Blomberg & Hellmer (2000)			0.17	0.07[c]
Blomberg (2007)			0.21 – 0.78	
Blomberg & Soderholm (2009)			0.21	

[a] Only short-run elasticities reported
[b] Elasticity of scrap supply; not the same as secondary supply
[c] Economic theory predicts coefficient should have the opposite sign

Table 2.B.5: Price elasticity estimates from previous econometric models of aluminum

B.2 Aluminum model solution, supply shock, and confidence intervals

The model in eq. 3.1 was solved for each year in the estimation period by finding a set of primary and secondary supply, demand, and prices that satisfied the estimated equations given values of the exogenous variables each year. Because eq. 3.1 is nonlinear, an analytic solution is not possible. Rather, the model was solved using the Broyden method (Broyden, 1965) built into EViews 7 to arrive at simultaneous solutions for every equation in the model. The model was solved dynamically, meaning that the previous-period solved values of the endogenous variables were plugged into the lagged dependent variables in each equation (as opposed to a static solution, in which actual, historical previous-period endogenous variable values are plugged in for lagged variables).

To calculate 95% confidence intervals, the model was solved stochastically, incorporating estimation error in each equation (residuals). The stochastic solution was performed over 50,000 iterations, drawing values for the random components of the equations from random normal distributions.

To incorporate the effect of the secondary supply shock, α_0 in eq. 3.1 was increased by 10% from 1980 to 2010 and the model solve procedure was repeated, including calculation of confidence intervals. Figures 2.6 and 2.7 show the deviation of the supply shock scenario solutions from the baseline model solutions. To see how these were calculated, Figures 2.B.2 and 2.B.3 show both the baseline and supply shock solutions in absolute rather than relative terms. Figures 2.6 and 2.7 simply show the difference between the dashed line (supply shock) and the solid line (baseline) in Figures 2.B.2 and 2.B.3, respectively.

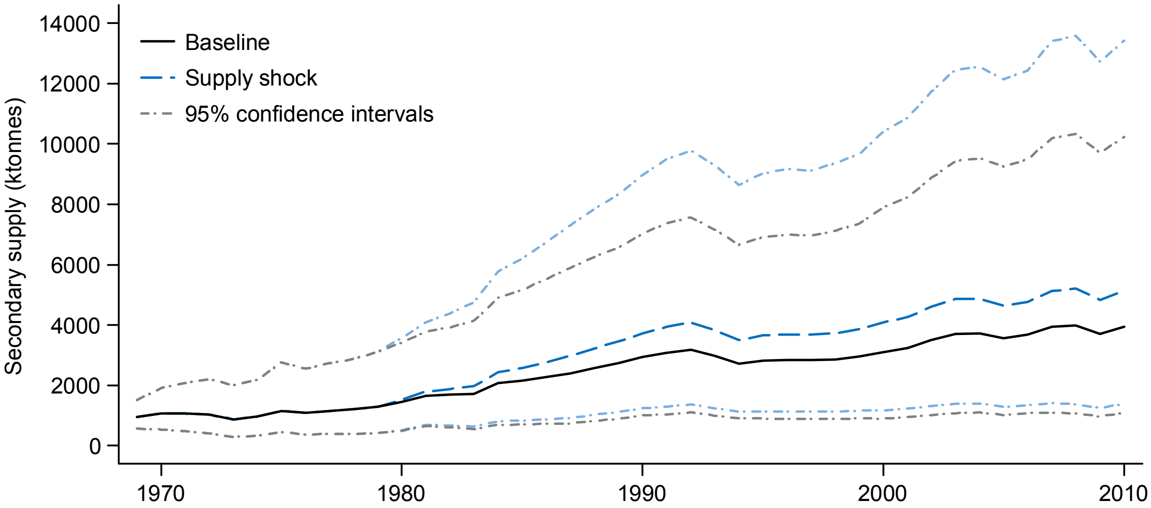

Figure 2.B.2: Baseline and supply shock scenario solutions for secondary supply

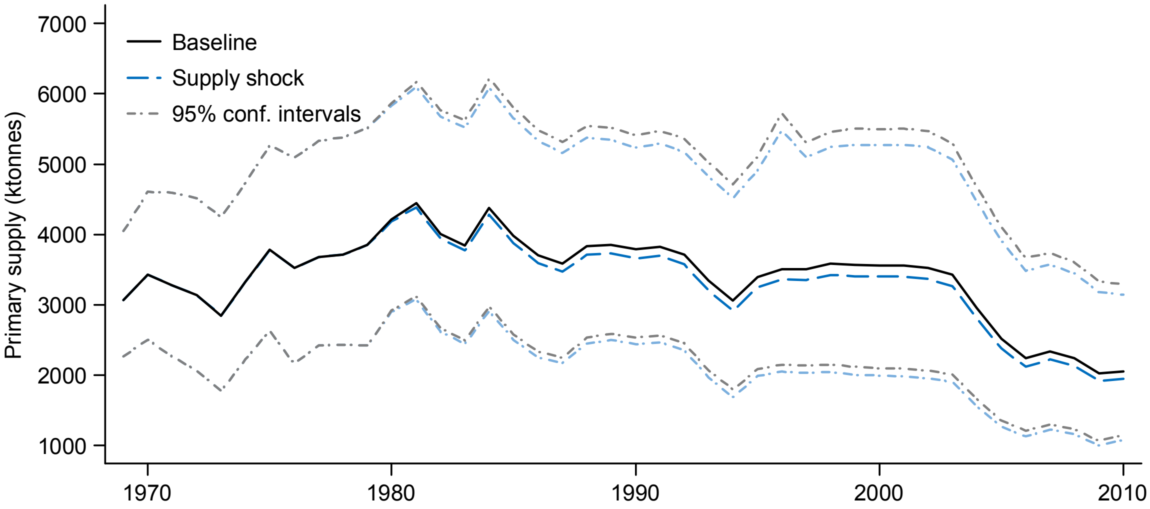

Figure 2.B.3: Baseline and supply shock scenario solutions for primary supply

The results are not sensitive to the period in which the supply shock occurs. Figures 2.B.4 and 2.B.5 show the results if the intervention occurs in 1995 rather than 1980. The main result that secondary supply increases more than primary supply decreases is still visible, and the calculated displacement is consistent with the predictions from the 1980 intervention (Figure 2.B.6).

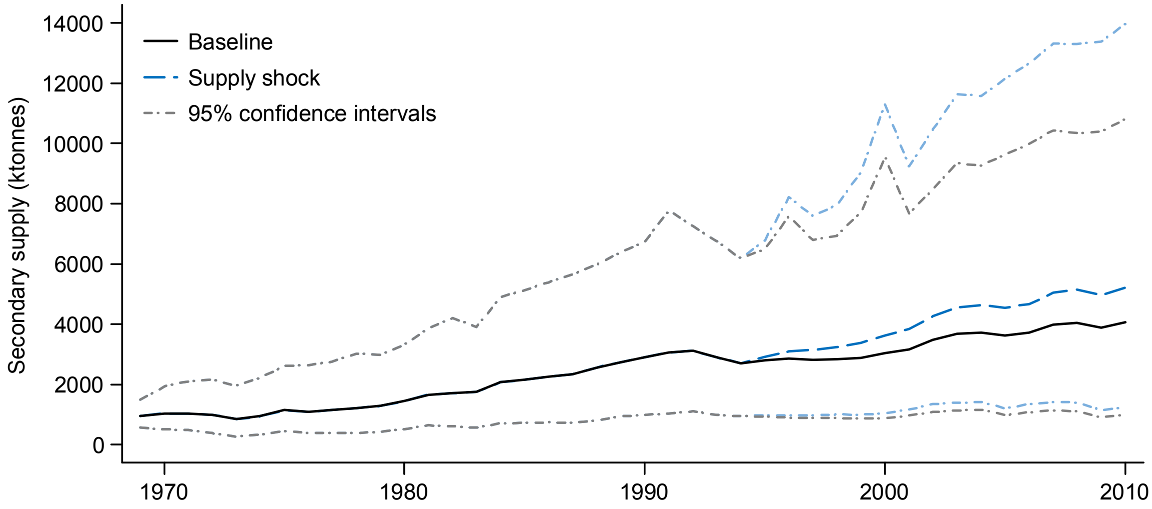

Figure 2.B.4: Secondary supply solutions with supply shock introduced in 1995

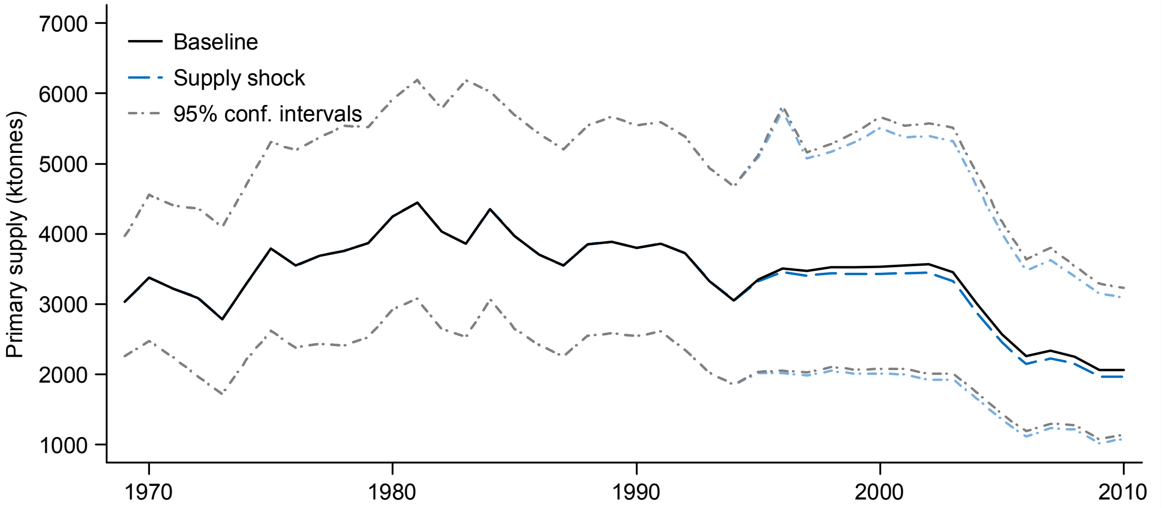

Figure 2.B.5: Primary supply solutions with supply shock introduced in 1995

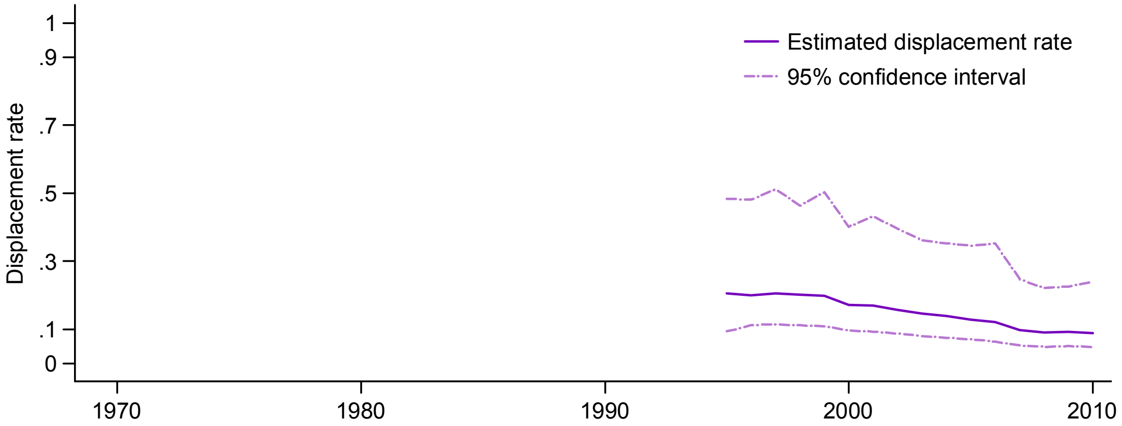

Figure 2.B.6: Estimated displacement with supply shock introduced in 1995

CHAPTER 3
CORPORATE SOCIAL RESPONSIBILITY AND EMPLOYEE SATISFACTION

ABSTRACT

Increasingly, managers see corporate social responsibility (CSR) as a way to increase employee satisfaction and thereby improve firm performance. Social identity theory suggests that CSR should affect employee satisfaction, yet empirical evidence for this relationship is scarce. Using a novel dataset, I measure CSR performance and employee satisfaction for 3,121 U.S. firms from 1998 to 2012 and find that companies' performance in six out of seven CSR dimensions can explain whether they are rated by their employees as one of the best places to work in the country. I disaggregate each dimension into forty-four individual CSR measures, and from those identify ten measures that are most likely to lead to higher employee satisfaction—six areas in which to improve (employee ownership plans, family benefits, gay and lesbian policies, charitable giving, conscientious labor rights, and product innovation) and four areas in which to reduce negative impacts (toxic emissions, workforce reductions, poor labor rights, and deceptive marketing). I discuss managerial lessons for most effectively utilizing CSR to improve employee satisfaction.

1 INTRODUCTION

The importance of human assets for firm performance has been increasingly recognized in strategic management (e.g., Koch & McGrath, 1996; Huselid, Jackson, & Schuler, 1997; Campbell & Ganco, 2012). Employee satisfaction has been shown to be a critical determinant of firm performance (Hansen & Wernerfelt, 1989; Huselid, Jackson, & Schuler, 1997). It has been shown to increase customer service ratings (Yee, Yeung, & Cheng, 2010), product quality (Zhou et al., 2008), team performance (Nerkar, McGrath, & MacMillan, 1996), worker productivity (Oswald, Proto, & Sgroi, 2013) and stock price (Edmans, 2012). Conversely, dissatisfaction causes increased turnover (Jaros & Jermier, 1993; Carsten & Spector, 1987), which has been shown to reduce worker productivity (Campbell & Ganco, 2012), profit margin, customer service, and product quality (Ton & Huckman, 2008; Hancock et al., 2011; Chi & Gursoy, 2009), as well as to increase the cost of capital (McElroy, Morrow, & Rude, 2001). Therefore it is imperative for managers to understand how firm policies can affect employee satisfaction.

Given the critical role of employee satisfaction in firm performance, a large body of research has emerged from theories of human resources that attempts to identify and explain factors affecting satisfaction (Hausknecht & Trevor, 2010). One set of firm policies that has been purported to affect employee satisfaction and in turn affect firm performance is corporate social responsibility (CSR) activities—for example, engaging in environmental cleanups, adopting progressive social policies, building schools, and voluntarily limiting emissions (Aguilera et al., 2007; Ambec & Lanoie, 2008).

Although companies invest in CSR for a variety of reasons (Reinhardt, 1999; Barnett, 2007), employee satisfaction is the third-most-cited reason by executives for engaging in

CSR (KPMG, 2011). Grolleau, Mzoughi, and Pekovic (2012), citing a 1991 McKinsey study, report that 68% of 403 senior executives around the world think that “organizations with a poor environmental record will find it increasingly difficult to recruit and retain high caliber employees.” However, beyond the anecdotal evidence provided in consulting studies, robust empirical evidence to support the view that CSR affects employee satisfaction is scarce.

The connection between CSR and employee satisfaction is complicated by the fact that CSR is multidimensional (Clarkson, 1995). CSR includes social, environmental as well as governance components (Chen & Delmas, 2011). Although CSR has been defined in a multitude of ways (Bansal, 2005; Carroll, 1999), recent empirical work has tended to focus on a set of dimensions delineated on stakeholder needs: environmental performance, employee relations, corporate governance, community relations, diversity, human rights, and product-related issues (e.g., Kotchen & Moon, 2011; Dawkins & Fraas, 2008). Furthermore, the CSR literature has been criticized for its overaggregation of the various CSR dimensions (Chen & Delmas, 2011). It is therefore unclear which components of CSR are most likely to relate to employee satisfaction.

This study represents a substantial step toward filling these gaps by quantifying the effect of multiple dimensions of CSR on employee satisfaction. I test the relationship between the adoption of CSR initiatives and employee satisfaction and address two primary research questions: whether CSR can affect employee satisfaction, and, if so, what specific aspects of CSR have the largest impact on employee satisfaction.

This study answers these questions by examining 3,121 U.S. firms in eight broad industries spanning fifteen years. Using a novel dataset, I measure the firms’ performance in seven dimensions of corporate social responsibility in order to determine if their CSR performance explains whether they are rated by their employees as one of the most desirable places to work. I test the general CSR-satisfaction relationship, and disaggregate each dimension into individual CSR activities to identify the aspects of CSR that are most important to employees. To my knowledge, this paper represents the first empirical study using firm-level panel data to test the effect of a wide range of corporate social responsibility activities on employee satisfaction. The results hold important general lessons for managers on how to maximize returns to competitive advantage on investments in CSR.

2 LITERATURE REVIEW

2.1 Corporate social responsibility

The idea of corporate social responsibility has received considerable attention in strategy literature (Carroll & Shabana, 2010). Although CSR has been defined in many ways (Bansal, 2005) the most often used definition (Dahlsrud, 2008) is that of the Commission of the European Communities (2001): “A concept whereby companies integrate social and environmental concerns in their business operations and in their interaction with their stakeholders on a voluntary basis.” CSR studies commonly focus on three main principles of sustainability: social, environmental, and economic (Bansal, 2005).

Of particular interest in strategy research has been whether CSR can increase a firm’s competitive advantage. Whether firms can “do well by doing good” remains a topic of considerable debate in the strategy literature, as an extensive amount of empirical testing of the relationship between CSR and firm performance has resulted in mixed findings (Barnett & Salomon, 2012; Margolis, Elfenbein, & Walsh, 2009; Margolis & Walsh, 2003). While the empirical literature on the link between CSR and competitive advantage, mostly rooted in economics, emphasizes external drivers such as regulation, we still have little understanding of the organizational mechanisms that link CSR to competitive advantage (Marcus, 2005). This omission could lead to misspecified models that ignore the effect of such organizational mechanisms on both social and environmental strategy and competitive advantage (McWilliams & Siegel, 2000).

Furthermore, it has been recognized that CSR is not one concept, but is multidimensional (Clarkson, 1995), incorporating stakeholders, society, economics, the environment, and governance (Dahlsrud, 2008). The multidimensional nature of CSR makes it particularly difficult to measure and implement in research (Chen & Delmas, 2011). In some cases authors have simplified the complex nature of CSR by aggregating the concept into a single measure (Hillman & Keim, 2001). However, the CSR literature has been criticized for overaggregating CSR (Chen & Delmas, 2011). It has been argued that aggregation not only makes comparing and unifying studies difficult, but also renders the measurement invalid, as a single measure cannot capture the breadth of the CSR construct (Rowley & Berman, 2000). By definition, aggregation sacrifices valuable information, limiting my ability to discover the differing effects of the underlying CSR dimensions on competitive advantage. Therefore, some authors have sought to retain the complexity of CSR by measuring the effects of multiple CSR dimensions on firm performance outcomes (e.g., Greening & Turban, 2000).

2.2 CSR and employee satisfaction

One of the ways CSR has been theorized to contribute to competitive advantage is by improving employee satisfaction (Ambec & Lanoie, 2008; Bhattacharya, Sen, & Korschun, 2008). However, very little empirical work is focused directly on this question. Some authors have studied factors that may be related to satisfaction, such as organizational commitment and ratings of employer attractiveness. Carmeli and his colleagues (2007) surveyed employees in the electronics and media industry in Israel and found that perceived CSR leads to higher organizational identification, and ultimately to higher job performance. Aggregated measures of CSR performance have been shown to predict organizational commitment (Peterson, 2004; Turker, 2008; Ali, Rehman, & Ali, 2010; Brammer, Millington, & Rayton, 2007), perceived external prestige (H. R. Kim et al., 2010), and workers' attitudes and behaviors (Zheng, 2010). However, as discussed above, the aggregated measures of CSR used in these studies make generalization difficult and obscure which aspects of CSR are most important to employees.

Other authors have examined multiple dimensions of CSR. Stites and Michaels (2011) surveyed 136 kitchen cabinet manufacturing workers and found that community-related and environmentally related CSR were related to workers' organizational commitment. Turban and Greening (1997; 2000) found that firms' environmental performance, employee relations, diversity, community-relations, human rights, and product-related CSR affected undergraduates' job pursuit intentions, willingness to accept job offers, and ratings of firms' attractiveness as employers. Albinger and Freeman (2000) found that companies' employee relations, community relations, and diversity CSR made them more attractive to job seekers. Backhaus, Stone, and Heiner (2002) also surveyed undergraduates and found that employee relations, environmental performance, diversity, community relations, and product-related CSR were important to job seekers deciding whether or not to accept an offer. Grolleau, Mzoughi, and Pekovic (2012) used cross-sectional data from the French Organizational Changes and Computerization's (COI) 2006 survey to assess the effect of adoption of voluntary product standards on employers' difficulties in recruiting, and found that the adoption of these voluntary standards reduced difficulties in recruitment of both professional and nonprofessional employees. Sen, Bhattacharya, and Korschun (2006) found that undergraduates were more likely to seek employment with a firm after it had given a large charitable gift. While these studies are an improvement in that they examine multiple dimensions of CSR, they are not directly focused on employee satisfaction.

Some studies have looked specifically at employee satisfaction, but only in connection with one dimension of CSR. In terms of employee relations, Sutton (1985) surveyed employees and found that higher employee benefits were linked to higher satisfaction and lower turnover. This finding was later extended by Heneman (2007), who showed that longer-term benefits such as stock options and retirement plans were most effective at improving satisfaction and reducing turnover. Bernardi, Bosco, and Vassill (2006) looked at diversity CSR and found a correlation between the number of women on a firm's board of directors and membership on the *Fortune* "100 Best Companies to Work for in America" list. Walsh and Sulkowski (2010) found a positive correlation between environmental CSR and employee satisfaction using cross-sectional employee survey data. In terms of corporate governance, Kim and Brymer (2011) found that hotel middle managers' satisfaction was predicted by their perceptions of executives' ethical leadership, and Schwepker (2001) found that perceptions of a positive ethical climate led to higher job satisfaction among salespeople. Valentine and Fleischman (2007) found that CSR mediates the positive relationship between ethics programs and job satisfaction.

Although these studies looked specifically at employee satisfaction, they are limited by their narrow focus on only one CSR dimension. There may be some overlap between the dimensions or shared variance with measures of employee satisfaction, which could lead single-dimension models to produce biased results that inflate the importance of the studied dimension, a possibility I further explore later.

This prior work has made initial strides in uncovering the relationship between CSR and employee satisfaction. However, these studies are insufficient to form generalized conclusions about this relationship. All of these studies used cross-sectional data, and many sampled few firms or few employees. I therefore cannot establish that the findings of these studies are valid for the majority of firms, for firms in many industries, or over time. Additionally, a cohesive picture of the relative importance of the various dimensions of CSR is lacking. For these reasons, Turban and Greening (2000) called for a large-sample panel data analysis looking at a wide range of CSR dimensions. The goal of this study is to take a substantial step toward filling that research need.

3 THEORY AND HYPOTHESES

3.1 Theoretical framework

Previous studies looking at the effects of CSR on internal stakeholders, such as employees, have tended either to focus on prospective or current employees (Turker, 2008). Studies that focus on prospective employees have asked how CSR might be used to attract the best talent (Albinger & Freeman, 2000; Backhaus, Stone, & Heiner, 2002; Turban & Greening, 1997; Greening & Turban, 2000). Authors in this area build on signaling theory (Spence, 1973; for an excellent review, see Connelly et al., 2010) and argue that companies send signals with CSR that indicate the firm’s commitments and goals (Greening & Turban, 2000).

Studies that focus on existing employees have asked how CSR can be used to retain employees and increase their satisfaction, organizational commitment, and productivity

(Peterson, 2004; Maignan, Ferrell, & Hult, 1999; Riordan, Gatewood, & Bill, 1997; Rupp & Ganapathi, 2006; Ali, Rehman, & Ali, 2010; H. R. Kim et al., 2010; Carmeli, Gilat, & Waldman, 2007; Bhattacharya, Sen, & Korschun, 2008). Authors arguing for a link between CSR and current employees have most commonly built their arguments around social identity theory; however, I also draw on loss aversion theory in order to extend this theoretical framework.

3.1.1 Social identity theory and discrepancy theory

Social identity theory (SIT) asserts that people classify themselves and others into social categories and construct their self-image within a social context (Ashforth & Mael, 1989; Tajfel & Turner, 1985; Dutton, Dukerich, & Harquail, 1994). According to SIT, the concept of "social identity" comprises the totality of one's memberships in various social groups (communities, political affiliations, etc.) and prescribes how one should behave as a member of those groups (Turker, 2008). The extent to which one feels a "oneness" or "belongingness" with a group determines one's identification with that group (Ashforth & Mael, 1989). The higher an individual's identification with a group, the more he or she vicariously takes part in and internalizes the successes or failures of the group (Ashforth & Mael, 1989); therefore more successful or prestigious groups will provide their members with higher self-esteem and improved self-image (Dutton, Dukerich, & Harquail, 1994).

Although SIT began as a psychological theory of interpersonal behavior, authors have noted that one's membership in a business organization is an important component of one's social identity (Ashforth & Mael, 1989; Brammer, Millington, & Rayton, 2007). Therefore the relationship of one's organization to other organizations, its distinctiveness, and its prestige contribute importantly to one's self-esteem and self-description (Ashforth & Mael, 1989).

Some have extended this to the realm of CSR and argued that if employees perceive their organizations to be socially and environmentally responsible, they will feel more pride, well-being, and connection with the company, which ultimately lead to higher job satisfaction and productivity (Turker, 2008; Smith et al., 2001; Frank, 2003; Akerlof & Kranton, 2005; Maignan & Ferrell, 2001). One often-cited example is the "near cultlike" sense of identity at the Timberland Company, which has been attributed in part to the company's CSR (Bhattacharya, Sen, & Korschun, 2008).

According to Locke (1969, p. 316), job satisfaction is "the pleasurable emotional state resulting from the appraisal of one's job as achieving or facilitating the achievement of one's job values." Locke's (1969; 1976) discrepancy theory of satisfaction states that job satisfaction is based on the distance between one's job expectations as compared to reality. Thus, employee satisfaction with respect to CSR depends not only on the firm's actual CSR performance but also on employee expectations. Accordingly, working for a socially responsible company has been theorized to increase happiness by reducing cognitive dissonance caused by conflicts between an individual's personal beliefs and those of her organization (Grolleau, Mzoughi, & Pekovic, 2012; Ashforth & Mael, 1989).

While employees may feel more identity and therefore have higher job satisfaction working for a company with higher CSR performance, conversely, they may also experience reduced job satisfaction working for a company with low CSR performance. Prior research has determined that poor CSR performance is not the mirror image of good CSR performance (Delmas, Etzion, & Nairn-Birch, 2012; Mattingly & Berman, 2006; Strike, Gao,

& Bansal, 2006; Minor & Morgan, 2011). For many dimensions of CSR, a distinction between positive and negative performance is intuitively meaningful: For example, if negative environmental performance means emitting toxic chemicals, positive environmental performance means something more than simply *not* emitting toxic chemicals. It means, for instance, developing environmental products, innovating new pollution control technologies, or spearheading environmental regulation.

Because positive and negative performance in CSR are not mirror images, it may be that they have asymmetric impacts on employee satisfaction. Theory and experimental research in economics has shown that gains and losses of equal size can have asymmetric effects on happiness (Kahneman & Tversky, 1984; Thaler, 1980), which may also be true of CSR and satisfaction. Therefore, throughout the study I distinguish between positive and negative CSR performance, leaving open the possibility that they will have asymmetric effects on employees' satisfaction. Based on social identity theory and the limited empirical evidence on general concepts of CSR, I therefore propose two initial hypotheses:

> *Hypothesis H1a: Higher levels of positive CSR performance are positively associated with employee satisfaction.*
>
> *Hypothesis H1b: Higher levels of negative CSR performance are negatively associated with employee satisfaction.*

3.2 Multiple dimensions of CSR

As discussed, CSR is not a single concept but is made up of multiple dimensions (Chen & Delmas, 2011; Clarkson, 1995). In the context of employee satisfaction, it is important to consider multiple dimensions of CSR because employees in different firms, industries, or job types may find some aspects of CSR more important than others (Albinger & Freeman, 2000; Bhattacharya & Sen, 2013). Again turning to Locke's (1969; 1976) theory of job satisfaction, employees may have preferences over the optimal level of different types of CSR, which will mean that not all types of CSR are equally effective at improving satisfaction. In the next sections I review the evidence specific to seven different dimensions of CSR—environmental performance, employee relations, diversity, corporate governance, community relations, human rights, and products—as they relate to employee satisfaction. However, the preceding theoretical arguments are valid for all dimensions of CSR and contribute to my specific hypotheses in each area, particularly when the empirical evidence in a particular dimension is lacking.

3.2.1 Environmental CSR and employee satisfaction

Environmental CSR includes measures of emissions, pollution prevention initiatives, green energy programs, or environmental products. Ambec and Lanoie (2008) reviewed the pays-to-be-green research and identified seven avenues by which environmental performance could improve the firm's competitive position. One of these was that environmental performance lowers labor costs by making it easier to attract and retain talented employees. Drawing on prior work from Lankoski (2006) and Henriques and Sadorsky (2007), Ambec and Lanoie theorized that three types of companies are likely to realize labor cost reductions from improved environmental performance: (1) companies whose emissions affect worker health; (2) companies that seek to attract young, well-educated professionals; and (3) companies located in areas sensitive to environmental concerns. The authors point to anecdotal evidence that supports these ideas, but were unable to find any empirical studies linking environmental performance to labor cost reduction.

There were, however, two studies related to the recruitment side of this issue. Turban and Greening (1997) measured the effect of firm environmental performance (as well as employee relations, diversity, community relations, human rights, and product issues, which will be discussed in the following sections) on undergraduates' ratings of the companies' attractiveness as employers. They found no significant association between environmental performance and attractiveness as an employer. However, in a subsequent study, Greening and Turban (2000) found that firms' environmental performance was positively associated with undergraduates' job pursuit intentions and willingness to accept a job offer, a finding later confirmed by Backhaus, Stone, and Heiner (2002).

Grolleau, Mzoughi, and Pekovic (2012) used cross-section data from the French Organizational Changes and Computerization's (COI) 2006 survey to regress employers' difficulties in recruiting on the adoption of the voluntary standards ISO14000, Fair Trade, and Certified Organic. They found that the adoption of these voluntary standards reduced difficulties in recruitment of both professional and nonprofessional employees.

While those studies focus on the effect of CSR on prospective employees, Stites and Michael (2011) surveyed manufacturing workers and found that environmentally related CSR was related to workers' organizational commitment. Walsh and Sulkowski (2010) performed a simple analysis using data on satisfaction and environmental performance ratings culled from online news stories and social media and found that perceptions of a firm's environmental performance were positively associated with employee satisfaction. Thus, based on this evidence, I propose Hypotheses 2a and 2b:

> *Hypothesis 2a: Higher levels of positive environmental performance are positively associated with employee satisfaction.*
>
> *Hypothesis 2b: Higher levels of negative environmental performance are negatively associated with employee satisfaction.*

3.2.2 Employee relations CSR and employee satisfaction

The relationship between employee relations and employee satisfaction is the most intuitively direct. Employee relations CSR includes union relations, retirement benefits, health and safety, employee ownership plans, and workforce stability. Behavioral theory holds that in order for employees to be productive, satisfied, and remain with a firm, their basic security needs such as good working conditions and compensation must be met (Sutton, 1985). However, not all aspects of employee relations may be equally effective at improving satisfaction. Barber and her colleagues (1992) found that flexible benefits plans that allow employees to choose personally optimal levels of health insurance, retirement, stock options, etc. are more effective at improving employee satisfaction than one-size-fits-all benefits plans.

There has been empirical evidence in the management literature to support the relationship between employee relations CSR and employee satisfaction. Turban and Greening (1997) and Albinger and Freeman (2000) found that higher employee relations performance was positively associated with undergraduates' ratings of firms' attractiveness as an employer. Greening and Turban (2000) and Backhaus, Stone, and Heiner (2002) found that employee relations were related to undergraduates' willingness to accept a job offer.

Sutton (1985) used surveys to study drivers of employee turnover in different types of firms and across different types of employees, and found that high benefits are significantly linked to low turnover, particularly in larger firms and among nonsalaried employees. Heneman (2007) extended this work and found that certain types of benefits are more effective than others at increasing satisfaction. Particularly, benefits with longer-term vesting schedules (retirement plans, employee ownership plans, stock options) are more effective at reducing employee turnover and increasing employee satisfaction than other types of benefits. Based on this evidence, I propose Hypotheses 3a and 3b:

> *Hypothesis 3a: Higher levels of positive employee relations performance are positively associated with employee satisfaction.*

> *Hypothesis 3b: Higher levels of negative employee relations performance are negatively associated with employee satisfaction.*

3.2.3 Diversity CSR and employee satisfaction

Diversity issues concern a company's policies and practices toward women, minorities, gay/lesbian/bisexual/transgender, and disabled employees. The business case for diversity, particularly in terms of board and top management makeup, has received considerable attention with mixed results (e.g., Adams & Ferreira, 2009; Carter et al., 2010; Triana, Miller, & Trzebiatowski, 2013). Here I focus only on the impact of diversity on employee satisfaction.

The link between diversity and satisfaction has been argued for and in some cases demonstrated in the social psychology literature as well as the management literature. Social psychologists primarily draw on the theory of minority influence, which holds that more diverse groups lead to increased divergent thinking and wider perspectives (Nemeth, 1992). Bowman and his colleagues (2011) suggested that diversity can provide opportunities for personal, social, and intellectual development, positively contributing to psychological well-being and satisfaction. In a longitudinal study of college graduates, they found that diversity experiences in college positively influence well-being after graduation. Additionally, racial minorities are perceived to contribute to the novelty of ideas produced by a group (Antonio et al., 2004).

Within management literature, Turban and Greening (1997) and Albinger and Freeman (2000) found that higher diversity scores were positively associated with undergraduates' ratings of a firm's attractiveness as an employer. Greening and Turban (2000) and Backhaus, Stone, and Heiner (2002) found that diversity performance was related to undergraduates' willingness to accept a job offer. Baer, Rahman, and Post (2010) found that board gender diversity was positively associated with firms' rankings on the *Fortune* Most Admired Companies list, while Bernardi, Bosco, and Vassill (2006) found that higher female representation on a company's board of directors is positively correlated to being listed on *Fortune*'s "100 Best Companies to Work For" list. Pitts (2009) argued that as the workforce becomes more diverse, if companies adopt leadership or policies that value diversity, they will be more responsive to employees' needs and will therefore be better able to retain employees. He tested this theory empirically using a sample of U.S. federal employees and found that diversity management increases workers' team productivity and job satisfaction, particularly for women and ethnic minorities. Based on the foregoing theories and evidence, I propose Hypotheses 4a and 4b:

Hypothesis 4a: Higher levels of positive diversity performance are positively associated with employee satisfaction.

Hypothesis 4b: Higher levels of negative diversity performance are negatively associated with employee satisfaction.

3.2.4 Corporate governance CSR and employee satisfaction

Corporate governance issues concern a company's ethical leadership, reporting transparency, and executive pay. Prior authors have theorized that aspects of corporate governance, particularly ethical leadership, are associated with higher employee satisfaction

(W. G. Kim & Brymer, 2011). Brown et al. (2005) proposed that employees will be more satisfied when leadership is fair, considerate, and just.

Initial evidence for these theories exists. Schwepker (2001) surveyed salespeople and found that perceptions of positive ethical climates in their organizations led to higher job satisfaction and organizational commitment. Kim and Brymer (2011) surveyed hotel middle managers and found that perceptions of ethical leadership by executives is a significant predictor of job satisfaction and organizational commitment. Other studies have confirmed that ethical CSR considerations are significant predictors of job satisfaction (Peterson, 2004; Valentine & Fleischman, 2007).

Along with ethical leadership, another component of governance is transparent reporting. In terms of reporting, Bhattacharya, Sen, and Korschun (2008) argue that many companies' CSR efforts are less effective than they could be due to ineffective communication on the part of the company. They argue that if CSR initiatives are communicated transparently to employees, they are more likely to feel connected and committed to the organization. Based on this evidence, I propose Hypotheses 5a and 5b:

> *Hypothesis 5a: Higher levels of positive corporate governance performance are positively associated with employee satisfaction.*

> *Hypothesis 5b: Higher levels of negative corporate governance performance are negatively associated with employee satisfaction.*

3.2.5 Community relations CSR and employee satisfaction

Community relations issues have to do with a company's charitable giving to local communities, support for local housing and education, and tax evasion issues. Research in neuropsychology and management has shown that contributing to the welfare of one's community increases one's satisfaction and happiness in a number of ways. Examining neural responses to taxation and voluntary giving, Harbaugh et al. (2007) found that people respond positively to both voluntary and involuntary giving in areas of the brain linked to reward processing. Harbaugh and his colleagues theorized that involuntary giving produces happiness through “pure altruism,” while voluntary giving provides a sense of “warm glow.” While warm glow is associated with more powerful feelings of happiness, pure altruism from involuntary giving does increase happiness.

In the management literature, Parsons and Broadbridge (2006, p. 121) found that managers of nonprofit charity shops, though dissatisfied with job factors such as pay and benefits, feel a sense of satisfaction from “the knowledge that their efforts are benefiting a charitable cause.” This “altruism payoff” can make up for and overcome the dissatisfaction caused by other aspects of their jobs.

Turban and Greening (1997) and Albinger and Freeman (2000) found that higher community relations performance was positively associated with undergraduates’ ratings of firms’ attractiveness as an employer. Greening and Turban (2000) and Backhaus, Stone, and Heiner (2002) found that community relations performance was related to undergraduates’ willingness to accept a job offer.

Fombrun and Shanley (1990) tested a number of CSR variables, including firms’ charitable giving, for their effect on the *Fortune* Most Admired Companies list and found that people assign higher reputations to firms that give proportionally more to charities than other firms. Sen, Bhattacharya, and Korschun (2006) surveyed undergraduates on their interest in seeking employment with a large company before and after the company gave a large gift to the university. They found that awareness of the gift was positively related to interest in seeking employment.

In terms of current employees, the evidence is thinner. In their study of kitchen cabinet manufacturers, Stites and Michael (2011) found that community relations CSR was related to workers' organizational commitment. Based on this evidence, I propose Hypotheses 6a and 6b:

Hypothesis 6a: Higher levels of positive community relations performance are positively associated with employee satisfaction.

Hypothesis 6b: Higher levels of negative community relations performance are negatively associated with employee satisfaction.

3.2.6 Human rights CSR and employee satisfaction

Human rights CSR centers on a company's relationship with its overseas supply chain, including supply chain transparency, controversies, overseas labor relations, and involvement in conflict areas. As with charitable giving to local communities, the same feelings of altruism and warm glow as discussed by Harbaugh et al. (2007) that arise when giving to charity may contribute to employee satisfaction if employees know that their company is contributing to positive work environments for people overseas. Consistent with social identity theory and loss aversion theory, employees should feel more connected to a company that treats overseas workers fairly, and should identify less with a company with a poor reputation for labor rights abuses.

However, limited empirical evidence exists in this domain. In their two studies, Turban and Greening (1997; 2000) found that higher human rights performance was positively associated with undergraduates' ratings of both employer attractiveness and willingness to accept a job offer. Grolleau and his colleagues (2012) also found that companies with the voluntary Fair Trade certification, which ensures that upstream suppliers pay workers a living wage, face less difficulty in recruiting. I found no studies directly related to human rights CSR and satisfaction of current employees. Nevertheless, based on the foregoing theoretical arguments, I propose Hypotheses 7a and 7b:

> *Hypothesis 7a: Higher levels of positive human rights performance are positively associated with employee satisfaction.*

> *Hypothesis 7b: Higher levels of negative human rights performance are negatively associated with employee satisfaction.*

3.2.7 Product-related CSR and employee satisfaction

Product-related CSR is concerned with a company's product quality and safety, product innovation, antitrust issues, and deceptive marketing. In accordance with social identity theory, employees should feel more connected and proud of a company that has a positive reputation for product quality, safety, and bringing innovative products to market. At the same time, loss aversion theory suggests employees should feel more embarrassed to work for a company that engages in false or deceptive marketing or has a reputation for market manipulation. Additionally, employees are happier working with the most cutting-edge technologies. A recent survey shows that companies with progressive policies that allow employees to use their own new technologies in the workplace are 37% more likely to report improved employee satisfaction (Avanade Inc., 2013).

To my knowledge, the only studies to include product-related CSR in a management context are the two studies of Turban and Greening (1997; 2000), who found that higher product CSR performance was positively associated with undergraduates' ratings of both employer attractiveness and willingness to accept a job offer. I found no studies related directly to product CSR and current employee satisfaction. Based on the theoretical arguments above, I propose Hypotheses 8a and 8b:

> *Hypothesis 8a: Higher levels of positive product-related performance are positively associated with employee satisfaction.*

Hypothesis 8b: Higher levels of negative product-related performance are negatively associated with employee satisfaction.

3.3 Interactions between dimensions and measures

It may be the case that the various dimensions and aspects of CSR have differing effects on satisfaction depending on their levels relative to each other. For instance, a firm that already performs well in one area may see smaller satisfaction gains from increasing performance in another area. Or it may be that synergies exist and higher performance in two areas may be more effective at increasing satisfaction than in either area alone. It may also be that poor performance in one area may offset good performance in another area, or vice versa. Additionally, poor performance in two areas could compound into a "negative synergy." I found no theory or evidence to provide support or guidance in this area, so I do not propose any formal hypotheses here. Nevertheless, initial analysis showed that this seems to be an important consideration and is worthy of exploration. I therefore conduct an exploratory analysis to brush the surface of the types of interactions that can occur between different measures of CSR.

4 DATA AND MEASURES

To test my hypotheses, I compiled a novel dataset from a variety of existing sources described in this section. A summary of the number of observations each year from each individual data source and the matched dataset are shown in Table 3.1. Descriptive statistics and correlations for key explanatory and control variables are provided in Table 3.5, and the descriptive statistics and correlations for all variables are found in the appendix (Table 3.A.2).

4.1 Dependent variables

Employee satisfaction is measured using the list of the “100 Best Places to Work for in America” compiled by the Great Place to Work Institute. I refer to this list as the “Great Place list” and abbreviate it in some charts and tables as “GP.” The Great Place list is considered one of the most reputable employee satisfaction studies in existence (Joo, 2006).

The scores are based on two company surveys: one completed by 250 randomly selected employees, called the “Trust Index,” and one completed by a company representative about the firm’s programs and policies, including pay and benefits programs, workforce diversity, and culture, called the “Culture Audit” (Edmans, 2012). The employee survey “measures engagement by surveying employee opinions, attitudes and perceptions on the level of trust between colleagues and between management and employees” (Great Place to Work Institute, 2013). Over 400 companies participate in the survey process each year, meaning that data is gathered from more than 100,000 employees per year. More information on the content of the survey, including sample questions, can be found in two recent papers by Edmans (2011; 2012).

Roughly two-thirds of the company’s assessment score is based on the employee survey and one-third on the Culture Audit. Once the results are received by Great Place to Work, they are judged according to the Great Place to Work model. This model measures, among other things, whether the employees trust their employers, have pride in what they do, and enjoy their coworkers (Great Place to Work Institute, 2013). Once the scores for all participating companies are determined, a list of the top 100 companies is published in the January issue of *Fortune* magazine.

4.1.1 Selection bias

There is some concern about selection bias with this list. The Great Place Institute does not solicit survey responses from companies, and the survey does not include all companies. Rather, companies volunteer to participate. Companies are incentivized to participate because of the potential prestige of being included on the top 100 list and because they receive their own employee satisfaction survey data, which they can use for internal review. Additionally, not all firms are eligible for consideration; firms must be five or more years old and have at least 1,000 regular full- and part-time employees in the U.S. to be considered for the Great Place list. Thus the survey cannot be considered a random sample.

However, Edmans (2011; 2012), who also uses the Great Place list in two studies, argues convincingly that this selection bias should not bias the results of the analysis. He argues that the selection bias can manifest in only two ways: The first way is if companies that know they have low employee satisfaction self-select out of the study; this simply increases the list's accuracy. The second way is if companies with high employee satisfaction self-select out of the study because think their high satisfaction is well-known and they do not need the additional publicity. This lowers the overall satisfaction of companies on the list and attenuates the overall results; that is, if these companies were included in the survey process, the overall results of my study would be even stronger. Therefore I do not believe the nonrandom selection process biases or inflates my findings.

4.2 Independent variables

Independent ratings of company corporate social responsibility performance are measured using the Kinder, Lydenberg, and Domini (KLD) dataset, now owned and maintained by MSCI Inc. Over time, the KLD dataset has expanded the number of firms covered and now includes over 3,100 of the largest U.S. companies. This dataset is one of the most widely used and reputed sources in CSR research (Wagner, 2010), and its quality, reliability, and validity have been vetted by prior scholars (Benson & Davidson, 2010; Szwajkowski & Figlewicz, 1999). Previous studies have established the KLD database as the "standard for quantitative measurement of corporate social actions" (Mattingly & Berman, 2006; Y. Kim, Park, & Wier, 2012). The KLD database has also been identified as a particularly promising source of data to reveal the differing effects of various aspects of CSR (Barnett, 2007).

4.2.1 KLD ratings

KLD collects information on companies and rates them on seven qualitative issue areas and six controversial business issues ranging from corporate governance to firearms. I use only the qualitative issue areas, which are divided into areas of strength and areas of concern and correspond to the seven dimensions of CSR discussed above. Within each qualitative issue area, KLD rates a firm on multiple individual measures—for instance, within the dimension "employee relations," firms are rated on work/life benefits, union relations, retirement benefits, etc. A firm is assigned a binary score in each of these individual measures according to whether or not it exhibits the criteria described in the measure. Not all firms are rated on all variables in all years, and a firm is only rated on a measure if enough information is available. Additionally, some variables were introduced or dropped over the twenty-plus-year history of the dataset. Data points that are missing or not rated are omitted from the sample.

I use the dataset in two ways: First, I create fourteen measures of social responsibility across the seven issues covered by KLD by separately summing the strengths and concerns in each qualitative issue area. Several prior studies using KLD have subtracted a firm's concern scores from its strength scores to create a single variable (Goss, 2009; Goss & Roberts, 2007; Turban & Greening, 1997). However, as discussed above, other researchers have emphasized a distinction between "good" versus "bad" social responsibility performance (Delmas, Etzion, & Nairn-Birch, 2012; Mattingly & Berman, 2006; Strike, Gao, & Bansal, 2006; Minor & Morgan, 2011). I do not sum positive strengths and negative weaknesses, but retain each as a separate variable.

The second way I use the KLD dataset is by retaining each individual measure in each CSR dimension as separate variables. This approach allows us insight into what aspects of the environmental dimension determine employee satisfaction. The individual measures that make up the KLD dataset have changed over the lifetime of the database. I include only variables that are available at least between 2002 and 2009. Additionally, I omit the item "ENVconF," which essentially measures a firm's involvement in the utilities sector and is already controlled for with industry fixed effects. I also omit the catchall "other" categories due to a lack of clarity about what constitutes a strength or concern in these areas. For transparency, I adopt the variable names used in the KLD dataset. A complete list of variable names and brief descriptions is included in the appendix (Table 3.A.1).

4.2.2 Actual vs. perceived CSR performance

In my view, KLD should not be viewed as a complete or accurate assessment of a firm's *true* CSR performance; developing an accurate assessment of a firm's CSR performance would require significantly more and different data than those used by KLD, and complex modeling methodologies such as life cycle assessment and social cost-benefit analysis. However, my goal in this study is not to measure the effect of *true* CSR performance, but rather how a company's CSR performance is *perceived* by its employees. Since most employees presumably do not have the knowledge or resources needed to develop scientifically rigorous assessments of their companies' CSR, I can assume that these are not the types of information on which employees base their perceptions. Rather, employees must construct their perceptions about a firm's CSR based on more basic information, such as public disclosures on toxic emissions and greenhouse gas releases, company reports and policies, legal cases, labor disputes, and news stories. These are also precisely the kinds of data from which the KLD ratings are drawn, making KLD an excellent proxy for employee perceptions of CSR performance.

4.3 Control variables

I obtain financial and size data for each firm from the Compustat database. Employee satisfaction is likely to be related to firm size and profitability, though existing theory is mixed about the expected direction: Larger firms are expected to have better human resources support and promotion opportunities (Atkinson & Storey, 1994; Grolleau, Mzoughi, & Pekovic, 2012); on the other hand, with more employees comes increased competition for resources and more rigid work structure, which have been shown to decrease employee satisfaction (Idson, 1990). More profitable firms are likely to have better reputations (Turban & Greening, 1997; B. Brown & Perry, 1994), though it is not clear that this will directly affect satisfaction. Other authors have shown that while employee satisfaction affects firm performance, firm performance does not affect employee satisfaction (Koys, 2001), so the expected directions for profitability and size are unclear. Nonetheless, prior research has shown size and profitability to be important control variables. Therefore, I follow other authors in this area and control for size using the number of employees, and profitability using return on assets (ROA; defined as net income before interest and taxes divided by total assets) (Turban & Greening, 1997; Grolleau, Mzoughi, & Pekovic, 2012), but remain agnostic on their effects.[30]

Additionally, it is important to control for average firm salary, as higher salaries are expected to improve employee satisfaction (Grolleau, Mzoughi, & Pekovic, 2012; Phelps, 1968) and because employees may be willing to accept lower pay to work for more altruistic companies or accept a pay premium to work for companies with poor CSR performance (Grolleau, Mzoughi, & Pekovic, 2012; Frank, 2003). Because I do not have access to average salary data for the majority of companies in the sample, I approximate the amount of money paid to employees using available data in the Compustat database. The Compustat item "XLR: staff expense – total" is likely to be a close approximation of wages; unfortunately, this item is unavailable for 84% of firms in the sample. However, the income statement item Selling, General, and Administrative Expense (SG&A) in the Compustat database is available for over 70% of the firms included in KLD. This item is a useful approximation because it reflects salaries and wages of officers and employees, including pension and employee benefits. It is not an exact measure, as it also includes furniture and equipment rental cost and servicing. Nonetheless, it is highly correlated to the more desirable measure of "staff expense" $(r = 0.86, p < 0.0000)$ and is preferable to including no control for salary.[31]

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[30] Based on its growing popularity as a measure of firm financial performance, I also considered using Tobin's Q as a measure of profitability (Ambec & Lanoie, 2007; Chung & Pruitt, 1994). However, I prefer the straightforward interpretation of ROA and the fact that it is more likely to reflect profitability that is visible to employees, rather than investors. Ultimately, the choice between ROA and Tobin's Q turns out to be inconsequential, as it does not appreciably change any other coefficient estimates.

[31] Using a per-employee measure of SG&A spending was also considered. However, since I also include a measure for size using the number of employees, untransformed SG&A spending represents spending holding the number of employees constant. Nonetheless, I tested model specifications using SG&A divided by the number of employees, which yielded qualitatively unchanged results.

All of the estimated models include industry fixed effects at the one-digit SIC-code level, following the industry breakdown of Cheng, Ioannou, and Serafeim (2013), to control for unobserved variation between sectors. Additionally, year fixed effects are included to control for annual variations in actual CSR performance as well as methodological inconsistencies over time in the KLD dataset. Finally, because firms that have applied for and been listed on the Great Place list in the past should be more likely to know about the list and apply for membership in subsequent years, and to eliminate endogeneity concerns discussed in the appendix, I include a dummy for one-year lagged list membership.

4.4 Sample and matching

4.4.1 Dataset matching methodology

Because the Great Place list did not include company identifiers, matching was performed manually based on company name. A semiautomated process was used to match the KLD and Compustat databases based on company name, using CUSIP as an additional check for accuracy, where available. This process also included manually researching company name change histories and matching individual observations that, for a variety of reasons, were not automatically matched. Company name was used because ticker symbols can change over time and nine-digit CUSIP information is only available for 58% of the KLD dataset. Matching by name resulted in an initial match between Compustat and KLD of 31,876 matched observations, out of a total of 33,511 KLD observations (95% matched). The percentage of matched observations is considerably higher than previous studies using automated methods (e.g., Benson & Davidson, 2010) and comparable to other studies using manual matching (Benson et al., 2011; Y. Kim, Park, & Wier, 2012; Goss & Roberts, 2011). Some of these matched firms were dropped from the final sample due to missing data.

4.4.2 Sample

The sample consisted of all firms in the KLD dataset that have the minimum number of employees required to be eligible for the Great Place list (at least 1,000). The KLD dataset has expanded in scope since its inception in 1991, now covering over 3,100 public and private companies. I constructed an unbalanced matched panel dataset over the period 1998–2012, collected from the datasets described above.

Observations were omitted if any required financial information was missing. Additionally, companies in SIC industry 9 had no variation across in the dependent variable and were dropped (thirty-eight observations). The final sample consisted of 3,121 firms with an average of 1,643 observations per year and a total of 20,966 firm-year observations. A subset of this sample consists of firms on the Great Place list. Although the list includes 100 firms each year, many are privately held with no financial or KLD information available, and were dropped. The final sample included 124 firms listed on the Great Place list with an average of 36 firms per year and each firm appearing in the dataset an average of 4.3 times (538 firm-year observations).

Table 3.2 shows the percentage of firms in each one-digit SIC code industry, and Figure 3.1 shows how this breakdown differs by list membership. The difference in makeup between nonlisted companies and companies on the Great Place list is apparent: Firms in mining and construction, transportation, communication and electricity, and finance, insurance, and real estate are underrepresented on the Great Place list; firms in services and sales are overrepresented on the Great Place list. These differences highlight the need for industry fixed effects, as certain industries are more likely to be included on the Great Place list.

Figure 3.2 shows distributions of the financial variables by list membership. The log-transformed variables exhibit normal distributions, and clear differences can be seen between listed and nonlisted firms in terms of size and employee compensation: Overall, firms on the Great Place list tend to be larger (more employees) and have higher employee compensation expenditures (as measured by SG&A). Bonferroni pairwise mean comparisons confirm that the observed differences are significant (adj. $p < 0.000$). Additionally, listed firms also have significantly higher ROA than nonlisted firms ($\Delta\mu = 0.0364, \text{adj.}\, p = 0.008$).

Firms not only differ by list membership on financial metrics but also by KLD CSR scores. Table 3.3 shows mean KLD scores by list membership. Overall, it can be seen that listed firms tend to score higher on strength variables, though there is no clear pattern in the concern variables.

As an example of the distribution of the number of KLD strengths and concerns, Table 3.4 tabulates the summed environmental strength and concern scores, ENVstr and ENVcon. Over 1,200 observations in the sample include at least one environmental strength, and over 900 include at least one environmental concern. The number of observations with more strengths and concerns drops off precipitously above the first, and only a handful obtain a score of 3 or higher in either variable.

5 MODELS AND ESTIMATION

Because membership on each list is distributed binomially (a firm is either on the list or not), I use the logit link function to explain likelihood of inclusion on a list. Specifically, the probability of a firm appearing on the Great Place list is given by the logistic function

$$P(y = 1|\boldsymbol{x}) = G(\boldsymbol{x\beta}), \text{ where } G(z) = \frac{e^z}{1 + e^z}, \tag{5.1}$$

and the logit function is the inverse of the probability, or the log of the odds of a firm appearing on the Great Place list:

$$\text{logit}(P) = \log\left(\frac{P}{1-P}\right). \tag{5.2}$$

I estimate each model with maximum likelihood estimation in Stata version 12.0 with heteroskedasticity-robust standard errors. All continuous variables are standardized to facilitate interpretation.

I test the hypotheses using a number of variations on a base model. The model explains the log odds of a firm being listed on the Great Place list as a function of its CSR performance as measured by its KLD scores, controlling for financial variables and industry and year fixed effects as well as a dummy variable indicating one-year lagged list membership:

$$\log\left(\frac{P_{it}}{1-P_{it}}\right) = \lambda LIST_{\mathrm{t-1}} + \alpha_j + \gamma_t + \boldsymbol{\varphi}'\boldsymbol{Z_{it}} + \boldsymbol{\beta}'\boldsymbol{X_{it}} + u_{it} \tag{5.3}$$

where P_{it} is the probability of firm i being included on a best places list in year t, $LIST_{t-1}$ takes a value of 1 if the firm was on the Great Place list the previous year and 0 otherwise, α_j is the time-invariant unobserved industry effect, γ_t is the firm-average unobserved year effect, $\boldsymbol{Z}$ is the vector of control variables, $\boldsymbol{X}$ is the vector of explanatory variables, and u_{it} is mean-zero error.

I test sixteen versions of eq. 5.3, all of which differ on the explanatory variables included in $\boldsymbol{X}$. Model 1 tests only the control variables (i.e., explanatory variables are omitted) to ensure they are behaving as expected. Model 2 tests all of the KLD strength and concern variables together, allowing us to test Hypothesis 1 and each of the dimension-specific hypotheses (2–8). Models I1–I7 test strengths and concerns in each CSR dimension individually, allowing us to determine if individually estimated models are likely to be biased. Models 3–9 test the disaggregated components of each CSR dimension, respectively, while including the strength and concern totals from all other dimensions. These last models are not specific to particular hypotheses, but provide insight into what specific aspects of each dimension are most important to employees.

Additionally, I test whether the various dimensions and individual measures of CSR can interact by introducing an interaction term to eq. 5.3:

$$\log\left(\frac{P_{it}}{1-P_{it}}\right) = \lambda LIST_{\mathrm{t}-1} + \alpha_j + \gamma_t + \boldsymbol{\varphi}'\boldsymbol{Z_{it}} + \boldsymbol{\beta}'\boldsymbol{X_{it}} + \lambda(X_{1it} \times X_{2it}) + u_{it} \tag{5.4}$$

I test a number of variations of eq. 5.4, which differ on the items X_1 and X_2. Since there are over seventy-one pairwise comparisons among the seven dimensions alone without including the individual measures, I do not present results for every possible interaction pair. Rather I will present graphical results that exemplify the kinds of interactions that can occur generally.

In the appendix, I discuss at length potential study design issues of possible reverse causality and rare-events bias and conclude that neither is a concern for my study. Also in the appendix, I discuss interpretation of coefficients under a logit model, explain my use of marginal effects reported at the sample average observation, and discuss my model diagnostic criteria and their interpretation.

6 RESULTS

The results of estimating each of the sixteen models are presented in Table 3.6 through 3.14. Estimates for Model 1, showing only the control variables, are presented in column 1 of Table 3.6. Estimates for Model 2, the KLD strength and concern totals estimated collectively, are presented in column 2 of Table 3.6. Estimates for Models I1–I7, each CSR dimension estimated individually, are presented in the remaining columns of Table 3.6. Table

3.7 shows chi-square statistics for Wald tests of coefficient equality for Model 2 vs. the individually estimated models. Tables 3.8–3.14 show the estimates for Models 3–9, the disaggregated components of each CSR dimension. In this section I discuss each model in turn.

6.1 Control variables (Model 1)

In Model 1, I include only the control variables, and I find that the controls affect employee satisfaction in unsurprising ways. Conflicting theories left us agnostic about the effect of firm size and profitability, and I find that while profitability is not a significant predictor of employee satisfaction, larger firm size negatively impacts membership on the Great Place list. My proxy for employee compensation, SG&A, significantly and positively affects list membership, which is evidence that this measure is an effective approximation. The marginal effect of a one standard deviation increase in SG&A on the log-odds of Great Place list membership is 0.0105 ($p < 0.000$). As expected, lagged list membership is also a significant positive predictor of current list membership across all models, showing that there is "stickiness" or momentum gained by listed firms that helps them appear on the list in subsequent years. The direction and significance of the controls variables are consistent across all of the other models. I tested the joint significance of year fixed effects and industry fixed effects using F-tests and found that both were highly significant in all models.

6.2 CSR strength and concern totals (Model 2)

Model 2 includes all fourteen strength and concern variables. These results first allow us to test Hypotheses 1a and 1b, that *any* aspects of CSR influence employee satisfaction. I find that at least some CSR strengths and concerns significantly predict whether a firm is included on the Great Place list, and therefore significantly influence employee satisfaction. Thus, Hypotheses 1a and 1b are supported.

Environmental strengths are not significant, meaning that Hypothesis 2a is not supported, but environmental concerns are significant and negative, as predicted by Hypothesis 2b. The effect of environmental concerns is larger than any other concern variables; the marginal effect on the probability of appearing on the GP list of a one standard deviation increase in environmental concerns is -0.003 ($p = 0.011$). Employee relations strengths and concerns are each significant in the expected direction, supporting Hypotheses 3a and 3b. The positive effect of employee relations strengths is more than twice as large as any other variable, with a marginal effect of 0.004 ($p < 0.000$).

Also significant in the positive direction are diversity strengths (marginal effect $=$ 0.001, $p = 0.110$), community relations (marginal effect $=$ 0.002, $p = 0.007$), product-related strengths (marginal effect $=$ 0.001, $p = 0.013$), and, to a lesser degree, human rights strengths (marginal effect $=$ 0.001, $p = 0.025$). These findings support Hypotheses 4a, 6a, 8a, and 7a, respectively. Diversity concerns, community relations concerns, and human rights concerns are negative and nearly significant at the 90% level ($p = 0.132$, $p = 0.197$, $p = 0.123$, respectively), providing very weak support for Hypotheses 4b, 6b, and 7b.

Corporate governance strengths are estimated at nearly zero and are not significant. However, the coefficient estimate for corporate governance concerns is *positive* and significant, which is the opposite direction than predicted by Hypothesis 5b. The marginal effect of a one standard deviation increase in corporate governance concerns is to *increase* the probability of being included on the Great Place list by 0.2% ($p = 0.028$). This finding suggests that more information is needed about the underlying components that make up each CSR dimension than can be learned from the strength and concern totals alone. Models 3–9 provide deeper insight into each dimension.

In sum, the results of Model 2 strongly support seven of the sixteen hypotheses tested by this model and provide weak support for three additional hypotheses.

6.3 Individual vs. collectively estimated CSR dimensions (Models I1–I7)

Models I1–I7 estimate the effects of each CSR dimension separately in order to attempt to replicate results of prior studies that study a single dimension (Heneman, 2007; Sutton, 1985; Walsh & Sulkowski, 2010; Bernardi, Bosco, & Vassill, 2006; W. G. Kim & Brymer, 2011; Schwepker, 2001) and determine if such an approach may artificially inflate the importance of the studied dimension. The results of Models I1–I7 confirm the results of previous studies and show that in every dimension except human rights, the coefficients in the individually estimated models are significant in the expected direction.

However, looking at the results of the individually estimated models compared to Model 2, which estimates all seven dimensions at once, it is immediately clear that the individual models appear to be biased and that studies investigating only one aspect of CSR will likely overstate the impact of studied dimension. In nearly every case, the coefficient estimates of the individual models are larger in absolute value than in the collectively estimated model. In many cases, such as environmental strengths, diversity strengths, diversity concerns, and community concerns, estimates of the individual models appear significant when they are nonsignificant when estimated in the larger model. Most striking is the difference in the estimates of environmental strengths between Model I1 and Model 2. When estimated collectively, the results are nonsignificant and slightly negative. When estimated individually, however, the estimate is significant and positive.

To formally test the differences between the individually and collectively estimated models, I performed Wald tests of coefficient equivalence for the estimates in Model 2 vs. those in each of the individual models I1–I7. The results of these tests are presented in Table 3.7. In eight of the fourteen tests, the null hypothesis of equivalence between the coefficients is rejected with 90% confidence.

6.4 Disaggregated CSR measures (Models 3–9)

In this section I present results for each of the disaggregated models 3–9, shown in Tables 3.8–3.14. The tables provide brief descriptions of each component variable, and more detailed descriptions are provided in the appendix (Table 3.A.1).

6.4.1 Environmental CSR

Included in the environmental dimension are measures of beneficial products, pollution prevention, recycling and packaging, clean energy, regulatory compliance, Toxics Release Inventory emissions, and agricultural chemicals. Of these components, only ENVconD, emissions reported to the U.S. EPA Toxics Release Inventory, was significant. The marginal effect was -0.010 ($p = 0.023$), meaning that firms with high toxic emissions are 1% less likely to be listed on the Great Place list. None of the environmental strength variables were significant.

6.4.2 Employee relations CSR

In employee relations, I measured union relations (positive and negative), employee cash profit sharing, employee ownership plans, retirement benefits (positive and negative), health and safety conditions (positive and negative), and recent workforce reductions. The only employee relations strength that was significant was employee ownership plans; the marginal effect of employee ownership plans was 0.018 ($p < 0.000$), meaning that adopting an employee ownership plan increases a firm's probability of appearing on the Great Place list by 1.8%. In terms of employee relations concerns, only recent workforce reductions were significant (marginal effect = -0.010, $p = 0.065$).

6.4.3 *Diversity CSR*

In terms of diversity, I included measures of women and minority representation in executive and line positions and on the board of directors, quality of family benefits, contracting with women and minorities, employment of disabled people, and progressive policies toward gay and lesbian employees, such as providing health benefits to employees' same-sex partners. Both family benefits (marginal effect = 0.010, $p = 0.001$) and progressive gay and lesbian policies (marginal effect = 0.006, $p = 0.012$) were significant. Neither of the diversity concerns was significant.

6.4.4 *Corporate governance CSR*

Corporate governance measures included both limited and high executive pay, ownership of subsidies with high or low CSR scores, and reporting transparency. Of these, only high executive pay was significant (marginal effect = 0.006, $p = 0.002$). The effect is positive, meaning that higher executive pay is associated with higher employee satisfaction. As no other variables were significant, I can see that this variable was what drove the previously puzzling result in Model 2, where it appeared that higher corporate governance concerns led to higher employee satisfaction. However, looking at the disaggregated results, the result is less alarming: The debate over high executive pay is far from settled (e.g., Faulkender et al., 2010; Florin, Hallock, & Webber, 2010; Bebchuk & Fried, 2006), so a finding that suggests employees value well-paid leadership or, conversely, that the most talented, best-paid executives are more effective at creating a culture with high employee satisfaction, is understandable.

6.4.5 Community relations CSR

Included in community relations are measures of charitable giving, support for housing and education, controversial investments, a firm's negative economic impact on the local community, and tax disputes. Of these, only charitable giving was significant (marginal effect $= 0.008$, $p = 0.003$). The distinction between KLD's definition of "charitable giving" and "innovative giving" is somewhat vague, so I tested a specification with these variables combined, which produced qualitatively unchanged results.

6.4.6 Human rights CSR

Human rights issues consisted of only three measures: positive labor rights, negative labor rights, and operations in Burma.[32] The labor rights variables measure a firm's relationship with its overseas supply chain, including transparency, relations with overseas labor unions, and recent labor disputes or controversies. Measures for both positive labor rights (marginal effect $= 0.025$, $p = 0.013$) and negative labor rights (marginal effect $=$ -0.006, $p = 0.042$) were significant in the expected directions.

6.4.7 Product-related CSR

Product-related CSR was measured in terms of product quality and safety, research and development (R&D) spending, marketing and contracting practices, and recent antitrust issues. Of these, only R&D spending was significant (marginal effect $= 0.010$ $p = 0.034$), although the measure of questionable marketing and contracting practices approaches significance ($p = 0.179$). The measure for R&D spending includes companies that bring

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[32] KLD periodically introduces measures of a firm's involvement in areas of the world that are in conflict or that are controlled by oppressive regimes. Many of these measures are active for only two or three years; operations in Burma is the only such measure that has been active over the entire sample period.

notably innovative products to market; the results show that employees derive satisfaction from the opportunity to work with cutting-edge products.

6.5 CSR interactions

Myriad variations of eq. 2, using different combinations of pairwise interactions, were estimated. They are too numerous to present here, but taken as a whole several common patterns emerge. I will illustrate these patterns as using specific interactions that exemplify the kinds of dynamic relationships that can occur.

The first general type of interaction concerns CSR strengths, and is what I term the "saturation effect," exemplified with an interaction between community strengths and employee relations strengths in Figure 3.4. From the figure it is apparent that for companies with the lowest levels of community strengths (community strength = 0; the blue line), higher performance in employee relations results in higher probability of appearing on the Great Place list. For companies with moderate community strength (community strength = 4; the red line), this effect is attenuated. For companies with the highest levels of community strengths, higher performance in employee relations can actually lead to slightly *lower* employee satisfaction. This effect is not only seen in aggregate CSR strengths, but also in individual strength measures: Figure 3.5 shows an interaction between work/life benefits and progressive gay and lesbian policies. Companies without gay and lesbian policies experience a benefit from adopting work/life benefits, and companies without work/life benefits are more likely to appear on the Great Place list if they adopt gay and lesbian policies. However, for companies that already have work/life benefits, adopting gay and lesbian policies decreases the probability of appearing on the Great Place list very slightly (albeit insignificantly).

In contrast, in some limited cases, synergies between strengths can exist. Figure 3.6 shows an interaction between human rights strengths and community relations strengths. For companies with low community relations strengths (blue and red lines in Figure 3.6), higher performance in human rights strengths have no effect on employee satisfaction. However, companies with high community relations strengths (the green line) do benefit from higher community relations strengths. Thus, there is a synergy between community relations strengths and human rights strengths in that the impact of each alone is negligible, but higher performance in both can increase employee satisfaction.

A similar effect can also be seen in reverse in the case of two CSR concerns creating a "negative synergy." Figure 3.7 shows an interaction between environmental concerns and employee relations concerns. For firms with no employee relations concerns, higher environmental concerns decrease the probability of appearing on the Great Place list, as expected. However, for firms with higher levels of employee relations concerns (the blue line), this effect is magnified. Not only is the baseline probability for these firms lower, but the negative effect of additional environmental concerns is even greater (i.e., the slope is steeper on the red and green lines). The effect is so severe that for companies with a score of 8 in employee relations concerns and 4 in environmental concerns, there is essentially no possibility of appearing on the great places list.

7 DISCUSSION

This study explored the relationship between employees' perceptions of their employers' CSR performance and employee satisfaction. I drew on social psychology and economics and based my theoretical framework on social identity theory and loss aversion. Based on these theories, prior authors have suggested that better CSR performance should increase employee satisfaction and therefore lower labor costs by making talented employees easier to attract and retain (e.g., Ambec & Lanoie, 2008).

I discussed a number of previous studies that have empirically tested the connection between CSR and factors related to employee satisfaction. Some of these found evidence for a connection between a general concept of CSR and employee identification, commitment, and perceptions of employer attractiveness. Other authors divided CSR into components and studied one or more of these, finding evidence for a link between CSR and job satisfaction, job offer acceptance, and lowered recruitment difficulty. All of these studies used cross-sectional data, and many sampled few firms or used surveys. Thus, the results were insufficient to inform generalized strategy theory. Additionally, studies that examined more than one dimension of CSR conflicted with studies that examined only one dimension, suggesting that there may be overlap or shared variance between the dimensions. For these reasons, Turban and Greening (1997; 2000) called for a panel data analysis of this question looking at a wide range of CSR dimensions.

To my knowledge, this study is the first to employ a matched panel data approach looking at multiple dimensions of CSR to test the link between CSR and employee satisfaction at the firm level. Generally, I was interested in answering the question, “Do employees value the social and environmental performance of their companies?” I also went deeper, asking, “If so, which aspects of CSR are the most important to employees?” Based on theoretical arguments and prior studies I predicted that positive CSR performance in each of seven CSR dimensions is positively related to employee satisfaction, whereas negative performance in each dimension is related to lower employee satisfaction.

To test these predictions I created a novel dataset and studied 3,121 U.S. firms spanning a fifteen-year period, measuring both their CSR performance and their employee satisfaction. I measured employee satisfaction using the list of the “100 Best Places to Work in America,” which is based on more than 100,000 employee satisfaction surveys each year. I measured companies’ CSR performance using data from KLD, which represents a robust picture of employees’ perceptions of companies’ CSR performance. I controlled for industry classification and various financial measures, and employed logistic regression to determine the effect of seven different dimensions of CSR on the probability of a firm’s employees rating it as one of the most desirable places to work in the U.S.

I then estimated a series of models that express the probability of a firm appearing on the Great Place list as a function of its CSR performance and financial control variables. I first found that these financial variables are important predictors of employee satisfaction and should be included in subsequent studies. My results show that studies that omit financial controls (e.g., Walsh & Sulkowski, 2010) are likely to report biased estimates.

I then turned to a model that includes firms’ strength and concern scores for seven different dimensions of CSR. Results from this model largely confirmed my predictions and found that employee relations, community relations, and product-related strengths are the strongest predictors of higher employee satisfaction, whereas high environmental and employee concerns are the strongest predictors of lower employee satisfaction. My results support social identity theory in that companies’ higher CSR strengths seem to contribute to employees’ pride and identity, manifested in their workplace satisfaction ratings.

Of my sixteen hypotheses, nine were supported and seven were not. However, of the seven hypotheses that were not supported, three (4b, 6b, and 7b) were nearly supported at the

90% confidence level. Additionally, although 5b was not supported, the fact that corporate governance concerns had the opposite sign than expected led to interesting results about the relationship between employee satisfaction and high executive pay.

Not only did I unpack the corporate governance dimension, I also examined the individual measures that make up the other six dimensions. Two results from these disaggregated models stand out.

First, in terms of environmental CSR, I found that none of the environmental strength variables seem to be important to employees. However, employees' perceptions of environmental concerns are primarily driven by toxic releases reported to the U.S. EPA's Toxics Release Inventory—information that is freely available to the public. Thus, my findings also support loss aversion theory (Kahneman & Tversky, 1984; Standifird, 2001; Doh et al., 2009): Whereas environmental damages are the most important CSR concerns to employees, environmental strengths do not significantly contribute to employee satisfaction. Thus, employees seem to view a company's environmental initiatives and damages asymmetrically, and, as predicted by loss aversion theory, find the negative, embarrassing effects of environmental damages more important than positive environmental initiatives. In other words, even if employees do not value their employers' positive environmental initiatives, they are very concerned about being associated with a visibly harmful company.

Second, disaggregating the diversity dimension, I found that a company's progressive policies toward gay and lesbian employees were a significant predictor of employee satisfaction, with an effect nearly as large as a company's family benefits. Considering that in July 2013, roughly half of Americans supported gay marriage, and especially considering that only 35% of Americans supported gay marriage in 1999 (Saad, 2013), this is a surprising finding. Why should gay and lesbian policies be such an important driver of employee satisfaction when less than half of employees supported gay marriage for the majority of the study period? To test whether it was the result of outlier observations—perhaps of a small group of pro-gay/lesbian companies that consistently appear on the Great Place list for other reasons—I looked in depth at companies who received positive ratings in this measure. There are 547 firms that receive a score of 1 in DIVstrG (gay/lesbian policies) with a total of 4,349 observations, or 17.5% of the entire dataset. Of these 547 firms, 69 are listed on the Great Place list at least once. Although these 547 firms tend to have higher mean KLD scores (in both strengths and concerns), their industry makeup is nearly identical to that of the entire sample. Inspection of the companies on this list does not suggest any pattern or common characteristics. Thus, with the current data I see no direct evidence to suggest that this finding is the result of outliers or nonrepresentative companies. Nonetheless, it remains an intriguing result and would be an interesting focus for a subsequent study.

In terms of potential interactions between dimensions and individual measures of CSR, I demonstrated three general effects that can occur. First is what I call the "saturation effect," where higher performance in one area of CSR strength is less effective if the firm is already performing well in another area. This effect may be due to decreasing returns on CSR to satisfaction: Employees may have a threshold for the total amount of satisfaction that they can derive from their employer's CSR, and as the company reaches that point, each additional investment in CSR provides less satisfaction. Above that point, the employee receives no further benefit from additional CSR performance. If the company invests in CSR well beyond that point, employees may actually see these investments as wasteful of firm resources, and satisfaction may be lower. For example, Timberland Company has long held a tradition of charitable giving and community service. However, in the mid-1990s when the company was suffering financial hardship, some within the company called for less charitable involvement in order to put resources to more productive use (Austin, Leonard, & Quinn, 2004).

The second general interaction effect was that of synergy, where investment in one area of CSR strength is more effective with higher performance in another area. This was exemplified in the case of community relations and human rights. Firms that have low community relations strengths will not see a benefit from higher human rights strengths, but those with high community relations strengths will. This perhaps reflects employees' preferences for the well-being of their own community over those abroad. Only once the home community is secured and thriving will employees value their impacts on people in other countries whom they will likely never meet or interact with.

The last general interaction effect is a "negative synergy," in which higher levels of poor performance in two areas of CSR concerns can compound and be even more damaging to employee satisfaction than poor performance in either area alone. This finding supports the combination of social identity theory and loss aversion. While people may experience gains in satisfaction through their association with a well-performing company, being associated with a company that is not only performing badly, but performing badly in multiple areas of CSR, drastically decreases employee satisfaction.

7.1 Implications for researchers

7.1.1 Methodological contributions

There are several methodological contributions of this research that can improve future empirical work. The first is to suggest the value of the 100 Best Places to Work in

America list as a reputable source of employee satisfaction data at the firm level. Thus far, this dataset has been underutilized: I am aware of only three other authors who use this data (Edmans, 2012; Bernardi, Bosco, & Vassill, 2006; Filbeck & Preece, 2003). Considering the methodological rigor with which the survey process is conducted and the high sample size of employees, it is a valuable source. Additionally, data from 2006 to 2012 are freely available online, and prior data can be obtained from the authors of this study.

Another methodological contribution is to demonstrate the importance of including multiple dimensions of CSR as opposed to single measures. Some prior studies have examined single measures (e.g., Walsh & Sulkowski, 2010; Bernardi, Bosco, & Vassill, 2006), whereas others have examined multiple dimensions (e.g., Turban & Greening, 1997). To test the importance of including multiple measures of CSR, I estimated my model with each dimension of CSR individually and compared these to the collectively estimated results. I found substantial evidence to suggest that focusing on individual dimensions of CSR and excluding others will artificially inflate the importance of the studied dimension. Because the other dimensions are important to the CSR-satisfaction relationship, excluding them in single-dimension models will introduce omitted variable bias and the results will likely be incorrect. Although my study found this result in the context of employee satisfaction, it may exist with other outcome variables as well. I therefore argue that future research should, as much as possible, incorporate a wide range of CSR measures to avoid introducing omitted variable bias.

The final methodological contribution for future studies is to suggest the importance of matching the KLD and Compustat databases by company name, using a combination of automated and manual matching. These two databases are commonly matched in CSR research (e.g., Mattingly & Berman, 2006; Benson & Davidson, 2010), and maximizing the number and accuracy of matches is important for the accuracy and generalizability of the results. Using automated matching based on CUSIP or stock ticker is unreliable as ticker symbols can change over time, and nine-digit CUSIP information is unavailable for much of the KLD database. Such approaches are also ultimately less successful: Using automated methods I was only able to match 88% of KLD observations, similar to prior studies (Benson & Davidson, 2010); using name matching, I was able to match 95% of KLD observations.

7.1.2 Limitations

While I believe the presented results are robust, there are ways this study could be improved. First, because I am unable to see the entire list of companies that applied for membership in the Great Place list, my measure of employee satisfaction is truncated. Furthermore, since there are roughly only forty observations per list per year, I was unable to use a linear model to predict satisfaction. While this limitation does not affect the accuracy of the study, a source of continuous satisfaction data over a larger pool of companies would allow for more nuanced analysis.

Second, there is some concern about endogeneity in the model specification. As discussed in the appendix, if it is the case that firms adjust their CSR performance in response to employee satisfaction, the estimates may be biased. To fully account for this, one would need to utilize an instrumental variables approach. In this study, I argued that to the extent that firms do adjust their level of CSR in response to employee satisfaction, this effect takes time and can be captured by including a lagged dependent variable. Thus, I believe I have satisfactorily accounted for potential endogeneity. However, I would caution future researchers in this area to be wary of potential endogeneity and to consider identifying a valid set of instruments to reduce this possibility.

7.1.3 Suggestions for future research

Several fruitful lines of inquiry stem from this work. First, although I scratched the surface of disaggregating what precise aspects of CSR employees do or do not value, there is much more to be done in this area. The specific factors measured in the KLD database are not the totality of CSR activities that may be important to employees. For instance, there is no measure in the database for company-sponsored volunteerism, which may improve satisfaction. Looking into this activity specifically, but also looking at more CSR activities generally, would be a worthwhile inquiry.

Along these lines, research is direly needed to improve the measurement of CSR performance in a meaningful way at the firm level. KLD has long been the standard in scholarly work, but as my understanding of the complexities of CSR develop, the limitations of KLD are beginning to show. MSCI, the current owner of the database, has started making changes that may eventually improve KLD's utility, but during this transition the changes in methodology make longitudinal studies more challenging—at present it is not completely clear how to incorporate variable changes that MSCI has implemented since acquiring the dataset in 2010. In general, a transparent, consistent, and more accessible (ideally university-led) database of CSR impacts would be of great value to the scholarly community.

7.2 Implications for managers

Managers realize that increasing employee satisfaction is an important goal to increase firm value. One of the ways companies have tried to improve employee satisfaction is by engaging in corporate social responsibility. However, until now, whether these investments were effective has been an open question. This research establishes that some, but not all, dimensions of CSR are likely to be effective at improving employee satisfaction. In general, managers should strive to improve employee relations, community relations, company diversity, and product strengths while reducing their environmental damages and avoiding poor employee relations.

However, by unpacking each CSR dimension and examining the disaggregated results, I am able to provide much more specific and useful direction to managers. Looking at the disaggregated results, I found that in every dimension, employee satisfaction was driven by usually one, and at most two, significant variables. Although I tested forty-four individual measures of CSR, I determined that only ten are significant predictors of employee satisfaction: six in which companies should increase their performance and four in which to minimize impacts. The significant positive components of CSR are:

- Employee ownership plans
- Family benefits
- Progressive gay/lesbian policies
- Charitable giving
- Conscientious labor rights
- Innovative products

The significant negative components of CSR are:

- Visible toxic emissions
- Recent workforce reductions
- Poor labor rights
- Deceptive marketing and controversial contracting

Not only does this list point to ways that are likely to be effective at improving employee satisfaction, but by omission it also highlights many other ways that are *not* likely to be effective. Environmental initiatives, investments in product safety, and local housing or education investments, for instance, are not likely to be effective at improving employee satisfaction. Of course, there may be other sound financial reasons to pursue such investments, but strictly in terms of improving employee satisfaction, CSR investments are better spent elsewhere.

Managers also must be aware that the positive components can interact to produce decreasing returns to satisfaction on higher CSR performance. In the most extreme cases, excess investment may be seen as wasteful of firm resources by employees and can *reduce* satisfaction. Therefore managers must select from among them the aspects of CSR that are most closely tied to the firm's core business and core competencies in order to maximize the return on investment.

This study stops short of being able to prescribe in which positive aspects of CSR a firm should invest. Whether increasing CSR performance in each area is cost-effective is highly firm-dependent: What is cheap for one firm may be expensive for another. However, it was outside the scope of this research to attempt to establish the monetary costs and benefits of these CSR investments. Executives should use the above list as a menu of the most effective CSR measures, and from them choose those that are the least costly and most aligned with the firm's existing core competencies and core business. A major contribution of this study is that we now know which aspects of CSR are most effective at improving employee satisfaction in general, and thus where to focus a cost-benefit analysis in the future.

Furthermore, even though selecting among the positive aspects of CSR is firm-dependent, higher levels of poor performance in the four significant negative components of CSR can compound and be even more damaging to employee satisfaction than poor performance in one area alone. Therefore, managers should strive to reduce their impacts in all four of these areas as much as possible.

8 CONCLUSION

In conclusion, I performed a novel study of the effects of CSR on employee satisfaction. I found that some aspects of CSR are clearly important to employees, such as employee relations, community relations, and diversity, while others, such as positive environmental initiatives and product-related concerns, are not. Consistent with theories of loss aversion and social identity theory, I found evidence that employees are more concerned about the negative environmental impacts of their firms, particularly with respect to toxic emissions, than they are about their firms' positive environmental initiatives.

I also determined that employee satisfaction was affected by only ten specific CSR measures out of forty-four that I studied. This suggests that random or blanket investments in CSR are unlikely to be effective at improving employee satisfaction. However, targeted investments in the ten key areas I have identified, and that are closely aligned with a company's core competencies, are likely to improve employee satisfaction and therefore increase firm value.

ACKNOWLEDGMENTS

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TABLES AND FIGURES

Year	Count: CPS	Count: KLD	Count: GP	Matches: KLD-CPS	Matches: KLD-CPS-GP
1998	6803	655	100	454	38
1999	6729	659	100	455	36
2000	7516	658	100	470	29
2001	7382	1105	100	744	32
2002	7057	1107	100	778	36
2003	6810	2960	100	1726	43
2004	6695	3032	100	1787	41
2005	6675	3013	100	1845	45
2006	6678	2960	100	1848	40
2007	6573	2934	100	1816	34
2008	6413	2920	100	1832	34
2009	6122	2910	100	1857	33
2010	5926	2962	100	1832	30
2011	5855	2845	100	1763	34
2012	5706	2791	100	1759	33
Total	98940	33511	1500	20966	538

KLD: Kinder, Lydenberg & Domini; CPS: Compustat; GP: Great Place list

Table 3.1: Observations in each dataset and matched datasets by year

SIC code	Industry description[a]	Obs.	Percent
0xxx	Agriculture, fishing, and forestry	61	0.29
1xxx	Mining and construction	1,183	5.64
2xxx	Manufacturing of food, textile, lumber, publishing, chemicals, and petroleum products	3,461	16.51
3xxx	Manufacturing of plastics, leather, concrete, metal products, machinery, and equipment	6,146	29.31
4xxx	Transportation, communications, electric, gas, and sanitary services	1,346	6.42
5xxx	Trade	2,815	13.43
6xxx	Finance, insurance, and real estate	2,371	11.31
7xxx	Personal, business, and entertainment services	2,750	13.12
8xxx	Professional services	833	3.97
9xxx	Public administration (omitted due to lack of variance)	0	0.00
	Total	20,966	100

[a] Industry descriptions adapted from Cheng, Ioannou, and Serafeim (2013).

Table 3.2: Sample industry breakdown

	Not listed		On Great Place list	
	Mean	s.d.	Mean	s.d.
ENVstr	0.119	0.388	0.303	0.619
ENVcon	0.142	0.465	0.125	0.440
EMPstr	0.213	0.504	0.978	0.842
EMPcon	0.324	0.560	0.308	0.561
DIVstr	0.450	0.868	1.798	1.466
DIVcon	0.366	0.491	0.165	0.389
CGOVstr	0.140	0.349	0.233	0.444
CGOVcon	0.224	0.421	0.560	0.510
COMstr	0.133	0.420	0.622	0.767
COMcon	0.066	0.260	0.084	0.292
HUMstr	0.001	0.034	0.022	0.147
HUMcon	0.030	0.172	0.059	0.237
PROstr	0.071	0.266	0.244	0.455
PROcon	0.163	0.462	0.354	0.709

Table 3.3: Descriptive statistics of KLD strength and concern scores by list membership

	ENVcon					
ENVstr	0	1	2	3	4	Total
0	17,321	954	408	33	10	18,726
1	1,267	292	169	12	1	1,741
2	267	87	59	7	2	422
3	44	15	12	6	0	77
Total	18,899	1,348	648	58	13	20,966

Table 3.4: Tabulation of environmental strengths and concerns

	Variable	Mean	sd	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1)	ENVstr	0.004	1.03																	
2)	ENVcon	0.018	1.03	.27																
3)	EMPstr	-0.001	1.00	.26	.31															
4)	EMPcon	0.025	1.03	.16	.06	.14														
5)	DIVstr	-0.007	0.97	.26	.25	.42	.10													
6)	DIVcon	0.011	1.16	.06	.03	.08	.07	.06												
7)	CGOVstr	0.027	1.05	.22	.22	.18	.03	.16	-.01											
8)	CGOVcon	-0.005	1.00	.25	.22	.12	.02	.13	-.01	.07										
9)	COMstr	0.029	1.03	.10	.10	.13	.07	.03	.02	.04	.21									
10)	COMcon	0.013	1.01	-.05	-.09	-.18	.04	-.11	-.01	-.07	-.06	.06								
11)	HUMstr	0.024	1.02	.04	.20	.29	-.08	.13	.05	.05	.14	.16	-.05							
12)	HUMcon	-0.009	0.98	.13	.15	.15	.06	.12	-.01	.02	.29	.12	-.01	.10						
13)	PROstr	0.039	1.12	.03	.04	.16	.02	.08	.19	.01	.06	.08	-.02	.12	.05					
14)	PROcon	-0.017	0.99	.19	.17	.31	.04	.24	.01	.09	.30	.13	-.05	.20	.20	.08				
15)	No. employees, logged	8.193	1.85	.25	.24	.37	-.08	.32	.04	.18	.29	.18	-.17	.27	.15	.16	.35			
16)	ROA, logged	0.631	0.36	.02	.01	.02	-.09	-.03	.03	.02	.03	.09	-.02	.05	-.10	.09	.03	.37		
17)	SG&A, logged	5.314	1.58	.29	.30	.48	-.07	.41	.05	.22	.27	.14	-.20	.34	.17	.16	.41	.82	.24	
18)	Year	2005.29	5.21	-.02	-.13	-.06	.03	-.19	.01	-.09	-.19	.00	.16	-.09	-.01	-.03	-.06	-.28	-.12	-.19

N = 20,966. Correlations above .01 are significant at the <.05 level.

Table 3.5: Descriptive statistics and correlations

DV: GP list	Model 1	Model 2	Model I1	Model I2	Model I3	Model I4	Model I5	Model I6	Model I7
ENVstr		-0.0569	0.0946*						
		(0.0599)	(0.0556)						
ENVcon		-0.258**	-0.254***						
		(0.101)	(0.0891)						
EMPstr		0.371***		0.374***					
		(0.0527)		(0.0477)					
EMPcon		-0.157*		-0.136*					
		(0.0817)		(0.0727)					
DIVstr		0.110			0.241***				
		(0.0685)			(0.0609)				
DIVcon		-0.115			-0.127*				
		(0.0766)			(0.0746)				
GCOVstr		0.00210				0.221***			
		(0.0745)				(0.0615)			
CGOVcon		0.156**				-0.117*			
		(0.0708)				(0.0686)			
COMstr		0.174***					0.125**		
		(0.0648)					(0.0618)		
COMcon		-0.105					0.190***		
		(0.0811)					(0.0668)		
HUMstr		0.0522**						0.0535	
		(0.0232)						(0.0358)	
HUMson		-0.0967						-0.0747	
		(0.0627)						(0.0584)	
PROstr		0.138**							0.173***
		(0.0556)							(0.0524)
PROcon		-0.0450							-0.0904
		(0.0731)							(0.0732)
Lagged GP list	5.815***	5.429***	5.770***	5.598***	5.708***	5.746***	5.801***	5.798***	5.769***
	(0.157)	(0.163)	(0.158)	(0.161)	(0.159)	(0.156)	(0.157)	(0.157)	(0.158)
Log of employees	-0.463***	-0.397***	-0.433***	-0.469***	-0.533***	-0.509***	-0.495***	-0.445***	-0.490***
	(0.144)	(0.147)	(0.145)	(0.150)	(0.146)	(0.144)	(0.142)	(0.144)	(0.145)
Log of ROA	0.0667	0.119	0.0782	0.107	0.0860	0.0787	0.0850	0.0533	0.0560
	(0.0804)	(0.0820)	(0.0812)	(0.0828)	(0.0808)	(0.0800)	(0.0788)	(0.0807)	(0.0819)
Log of SG&A	0.937***	0.548***	0.941***	0.790***	0.764***	0.840***	0.851***	0.936***	0.950***
	(0.129)	(0.139)	(0.127)	(0.129)	(0.130)	(0.128)	(0.131)	(0.129)	(0.134)
Year FE	Included	Included	Included	Included	Included	Included	Included	Included	Included
Industry FE	Included	Included	Included	Included	Included	Included	Included	Included	Included
Observations	20,966	20,966	20,966	20,966	20,966	20,966	20,966	20,966	20,966
Number of firms	3121	3121	3121	3121	3121	3121	3121	3121	3121
χ^2 (df)	1815 (26)***	1709 (40)***	1814 (28)	1717 (28)	1770 (28)	1779 (28)	1787 (28)	1807 (28)	1791 (28)
McFadden pseudo R^2	0.578	0.602	0.580	0.591	0.582	0.582	0.580	0.579	0.581
Area under ROC curve	0.953	0.966	0.953	0.960	0.956	0.954	0.955	0.954	0.954

Robust standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$ (two-tailed test).

Table 3.6: Estimates of Great Place to Work list membership: KLD strength and concern totals

Null hypothesis:	Variable	χ^2
Model 2 = Model I1	ENVstr	31.63***
Model 2 = Model I1	ENVcon	0.01
Model 2 = Model I2	EMPstr	0.02
Model 2 = Model I2	EMpcon	0.83
Model 2 = Model I3	DIVstr	18.53***
Model 2 = Model I3	DIVcon	0.33
Model 2 = Model I4	CGOVstr	4.16**
Model 2 = Model I4	CGOVcon	0.12
Model 2 = Model I5	COMstr	10.34***
Model 2 = Model I5	COMcon	3.57**
Model 2 = Model I6	HUMstr	0.00
Model 2 = Model I6	HUMcon	1.58*
Model 2 = Model I7	PROstr	4.62**
Model 2 = Model I7	PROcon	5.3**

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$ (one-tailed test).

Table 3.7: Wald tests of coefficient equality, Hypothesis 2

DV: GP list	Model 3
ENVstrA: Beneficial products	-0.0963
	(0.288)
ENVstrB: Pollution prevention	0.0114
	(0.431)
ENVstrC: Recycling / Packaging	-0.213
	(0.572)
ENVstrD: Clean energy	-0.290
	(0.405)
ENVconB: Regulatory compliance	-0.240
	(0.386)
ENVconD: TRI emissions	-0.935**
	(0.409)
ENVconE: Ag. chemicals	-0.0853
	(0.731)
EMPstr	0.400***
	(0.0543)
EMPcon	-0.175**
	(0.0814)
DIVstr	0.150**
	(0.0713)
DIVcon	-0.138*
	(0.0820)
CGOVstr	0.0276
	(0.0756)
CGOVcon	0.171**
	(0.0681)
COMstr	0.140**
	(0.0684)
COMcon	-0.0898
	(0.0804)
HUMstr	0.0546**
	(0.0212)
HUMcon	-0.104*
	(0.0593)
PROstr	0.142**
	(0.0609)
PROcon	-0.0191
	(0.0746)
Lagged GP list	5.115***
	(0.179)
Log of employees	-0.366**
	(0.162)
Log of ROA	0.215**
	(0.0857)
Log of SG&A	0.496***
	(0.156)
Year FE	Included
Industry FE	Included
Observations	15,576
Number of firms	2826
χ^2 (df)	1359 (41)***
McFadden pseudo R^2	0.581
Area under ROC curve	0.962

Robust standard errors in parentheses.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$ (two-tailed test).

Table 3.8: Effect of disaggregated environmental factors on GP list membership

DV: GP list	Model 4
EMPstrA: Union relations	-0.620
	(0.558)
EMPstrC: Cash profit sharing	0.235
	(0.408)
EMPstrD: Employee ownership plans	1.600***
	(0.267)
EMPstrF: Retirement benefits	0.371
	(0.427)
EMPstrG: Health & safety	0.00723
	(0.494)
EMPconA: Union relations	0.0143
	(0.608)
EMPconB: Health & safety	0.00912
	(0.343)
EMPconC: Workforce reductions	-1.545*
	(0.849)
EMPconD: Retirement benefits	-0.264
	(0.268)
ENVstr	-0.0498
	(0.115)
ENVcon	-0.173
	(0.164)
DIVstr	0.147
	(0.0993)
DIVcon	-0.234**
	(0.115)
CGOVstr	-0.0401
	(0.106)
CGOVcon	0.183*
	(0.102)
COMstr	0.199*
	(0.113)
COMcon	-0.0163
	(0.113)
HUMstr	0.0619**
	(0.0241)
HUMcon	-0.0780
	(0.0618)
PROstr	0.117
	(0.0963)
PROcon	-0.205*
	(0.123)
Lagged GP list	5.522***
	(0.239)
Log of employees	-0.190
	(0.215)
Log of ROA	0.291**
	(0.122)
Log of SG&A	0.399*
	(0.207)
Year FE	Included
Industry FE	Included
Observations	12,711
Number of firms	2685
χ^2 (df)	946.6 (39)***
McFadden pseudo R^2	0.654
Area under ROC curve	0.965

Robust standard errors in parentheses.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$ (two-tailed test).

Table 3.9: Effect of disaggregated employee relations factors on GP list membership

DV: GP list	Model 5
DIVstrB: W/M CEO/line representation	0.0777
	(0.170)
DIVstrC: W/M Board representation	-0.231
	(0.239)
DIVstrD: Family benefits	0.724***
	(0.226)
DIVstrE: W/M Contracting	-0.261
	(0.315)
DIVstrF: Employment of disabled	-0.335
	(0.386)
DIVstrG: Gay/lesbian policies	0.505**
	(0.200)
DIVconA: Diversity controversies	-0.339
	(0.273)
DIVconB: W/M Nonrepresentation	-0.254
	(0.233)
ENVstr	-0.0762
	(0.0689)
ENVcon	-0.258***
	(0.0946)
EMPstr	0.389***
	(0.0551)
EMPcon	-0.170**
	(0.0819)
CGOVstr	0.0386
	(0.0758)
CGOVcon	0.155**
	(0.0682)
COMstr	0.114*
	(0.0685)
COMcon	-0.0895
	(0.0792)
HUMstr	0.0482**
	(0.0210)
HUMcon	-0.0900
	(0.0575)
PROstr	0.150**
	(0.0583)
PROcon	-0.0331
	(0.0711)
Lagged GP list	5.005***
	(0.180)
Log of employees	-0.246
	(0.159)
Log of ROA	0.241***
	(0.0873)
Log of SG&A	0.444***
	(0.160)
Year FE	Included
Industry FE	Included
Observations	15,612
Number of firms	2826
χ^2 (df)	1329 (43)***
McFadden pseudo R^2	0.584
Area under ROC curve	0.962

Robust standard errors in parentheses.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$ (two-tailed test).

Table 3.10: Effect of disaggregated diversity factors on GP list membership

DV: GP list	Model 6
CGOVstrA: Limited exec. compensation	0.400
	(0.279)
CGOVstrC: Ownership of high CSR subs.	-0.460
	(3.428)
CGOVstrD: Reporting transparency	-0.351
	(0.377)
CGOVconB: High executive compensation	0.469***
	(0.178)
CGOVconF: Ownership of low CSR subs.	-0.435
	(0.858)
ENVstr	-0.0324
	(0.0716)
ENVcon	-0.289***
	(0.106)
EMPstr	0.385***
	(0.0573)
EMPcon	-0.187**
	(0.0883)
DIVstr	0.158**
	(0.0752)
DIVcon	-0.167*
	(0.0852)
COMstr	0.160**
	(0.0704)
COMcon	-0.0797
	(0.0805)
HUMstr	0.0568***
	(0.0220)
HUMcon	-0.105*
	(0.0597)
PROstr	0.155**
	(0.0609)
PROcon	-0.0535
	(0.0801)
Lagged GP list	5.264***
	(0.188)
Log of employees	-0.255
	(0.164)
Log of ROA	0.196**
	(0.0930)
Log of SG&A	0.474***
	(0.165)
Year FE	Included
Industry FE	Included
Observations	15,157
Number of firms	2825
χ^2 (df)	1261 (39)***
McFadden pseudo R^2	0.654
Area under ROC curve	0.963

Robust standard errors in parentheses.

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$ (two-tailed test).

Table 3.11: Effect of disaggregated corporate governance relations factors on GP list membership

DV: GP list	Model 7
COMstrA: Generous giving	0.596**
	(0.262)
COMstrB: Innovative giving	0.174
	(0.294)
COMstrC: Housing support	-0.214
	(0.410)
COMstrD: Education support	0.219
	(0.291)
COMconA: Investment controversies	-0.185
	(0.473)
COMconB: Negative economic impact	-0.402
	(0.535)
COMconD: Tax disputes	-0.460
	(0.573)
ENVstr	-0.0653
	(0.0696)
ENVcon	-0.280***
	(0.107)
EMPstr	0.383***
	(0.0551)
EMPcon	-0.188**
	(0.0830)
DIVstr	0.149**
	(0.0721)
DIVcon	-0.132
	(0.0816)
CGOVstr	0.0168
	(0.0759)
CGOVcon	0.168**
	(0.0684)
HUMstr	0.0514**
	(0.0211)
HUMcon	-0.0973
	(0.0594)
PROstr	0.136**
	(0.0599)
PROcon	-0.0268
	(0.0727)
Lagged GP list	5.106***
	(0.180)
Log of employees	-0.395**
	(0.163)
Log of ROA	0.206**
	(0.0870)
Log of SG&A	0.545***
	(0.162)
Year FE	Included
Industry FE	Included
Observations	15,612
Number of firms	2826
χ^2 (df)	1366 (41)***
McFadden pseudo R^2	0.581
Area under ROC curve	0.962

Robust standard errors in parentheses.

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$ (two-tailed test).

Table 3.12: Effect of disaggregated community factors on GP list membership

DV: GP list	Model 8
HUMstrG: Labor rights	1.734**
	(0.683)
HUMconC: Ops. in Burma	-0.360
	(0.695)
HUMconF: Labor rights	-0.783**
	(0.382)
ENVstr	0.0242
	(0.0931)
ENVcon	-0.342**
	(0.145)
EMPstr	0.398***
	(0.0749)
EMPcon	-0.210**
	(0.102)
DIVstr	0.150*
	(0.0901)
DIVcon	-0.176*
	(0.0987)
CGOVstr	-0.0730
	(0.0994)
CGOVcon	0.175*
	(0.0916)
COMstr	0.226**
	(0.0953)
COMcon	-0.0746
	(0.0993)
PROstr	0.0806
	(0.0889)
PROcon	-0.0986
	(0.105)
Lagged GP list	5.623***
	(0.215)
Log of employees	-0.160
	(0.201)
Log of ROA	0.159
	(0.119)
Log of SG&A	0.398**
	(0.197)
Year FE	Included
Industry FE	Included
Observations	13,489
Number of firms	2705
χ^2 (df)	1034 (33)***
McFadden pseudo R^2	0.645
Area under ROC curve	0.966

Robust standard errors in parentheses.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$ (two-tailed test).

Table 3.13: Effect of disaggregated human rights factors on GP list membership

DV: GP list	Model 9
PROstrA: Product quality	0.360
	(0.327)
PROstrB: R&D	0.698**
	(0.330)
PROconA: Product safety	-0.000959
	(0.376)
PROconD: Marketing / Contracting practices	-0.327
	(0.244)
PROconE: Antitrust	0.321
	(0.325)
ENVstr	-0.0589
	(0.0693)
ENVcon	-0.290***
	(0.0998)
EMPstr	0.394***
	(0.0548)
EMPcon	-0.167**
	(0.0810)
DIVstr	0.148**
	(0.0714)
DIVcon	-0.130
	(0.0816)
CGOVstr	0.0256
	(0.0754)
CGOVcon	0.169**
	(0.0679)
COMstr	0.129*
	(0.0711)
COMcon	-0.0936
	(0.0782)
HUMstr	0.0522**
	(0.0210)
HUMcon	-0.0950*
	(0.0565)
Lagged GP list	5.108***
	(0.177)
Log of employees	-0.354**
	(0.163)
Log of ROA	0.227***
	(0.0870)
Log of SG&A	0.506***
	(0.156)
Year FE	Included
Industry FE	Included
Observations	15,612
Number of firms	2826
χ^2 (df)	1339 (39)***
McFadden pseudo R^2	0.581
Area under ROC curve	0.962

Robust standard errors in parentheses.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$ (two-tailed test).

Table 3.14: Effect of disaggregated product-related factors on GP list membership

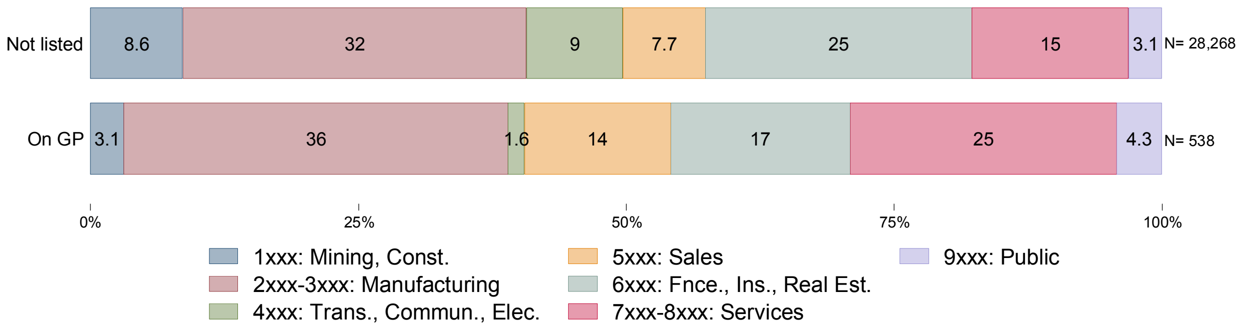

Figure 3.1: Industry breakdown by list membership (1 digit SIC code industries)

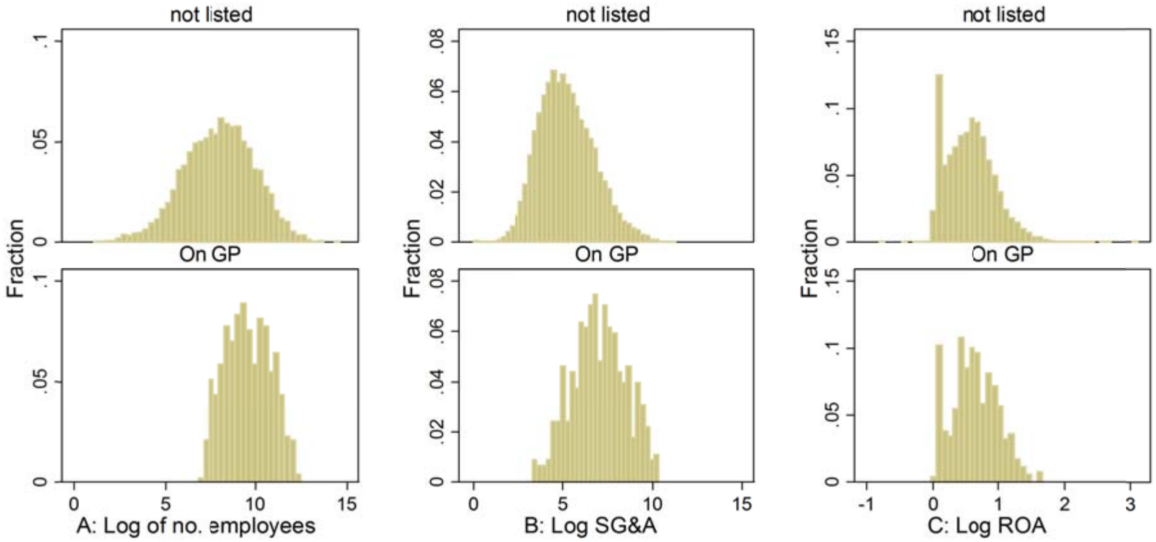

Figure 3.2: Distribution of financial metrics by list membership

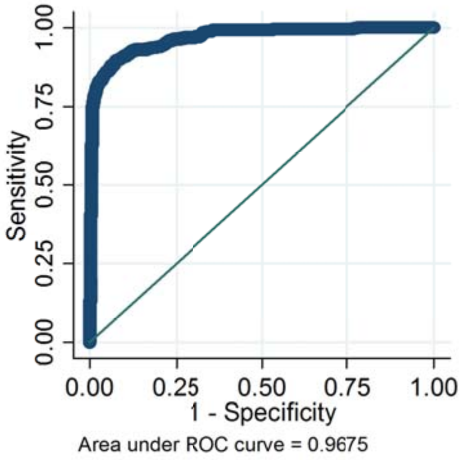

Figure 3.3: ROC curve for model 2

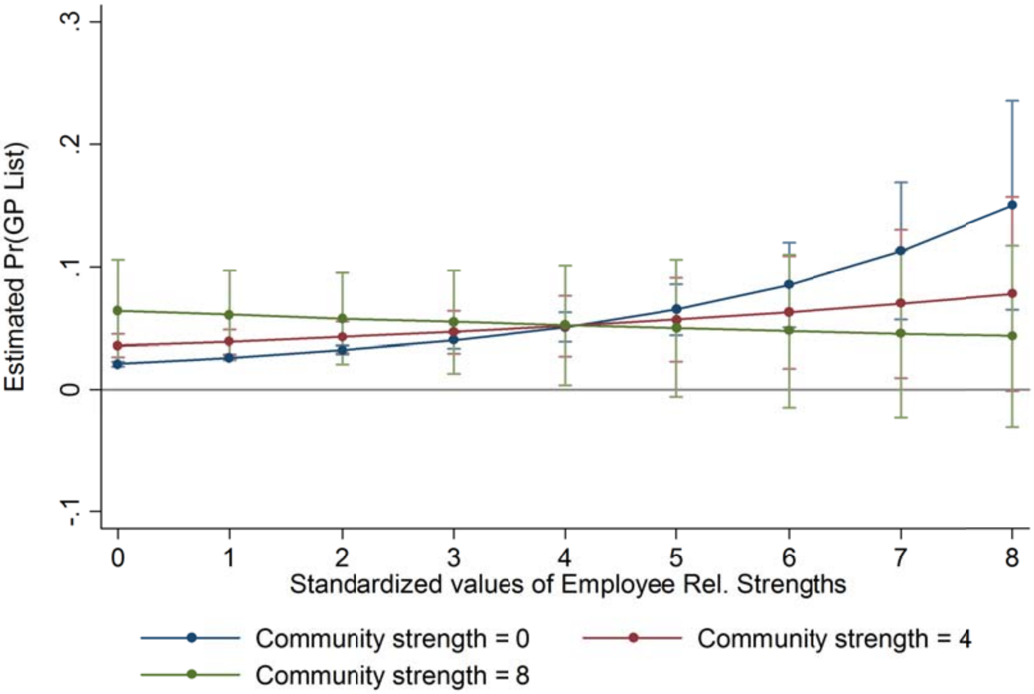

Figure 3.4: Interaction between community strengths and employee strengths showing the "saturation effect"

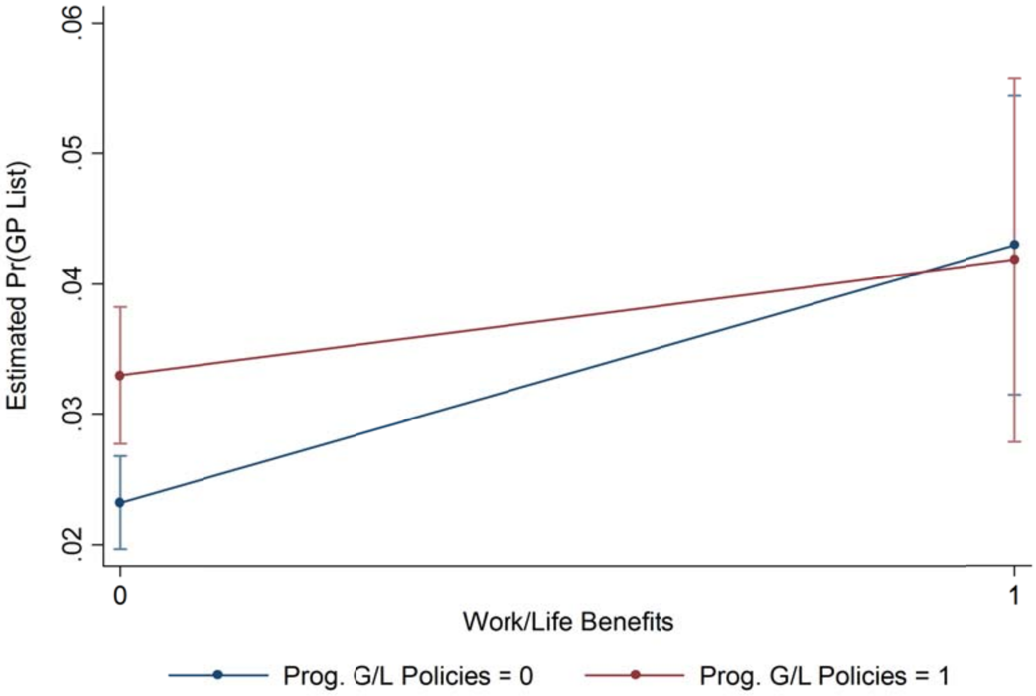

Figure 3.5: Interaction between work/life benefits and progressive gay and lesbian policies, showing "saturation effect"

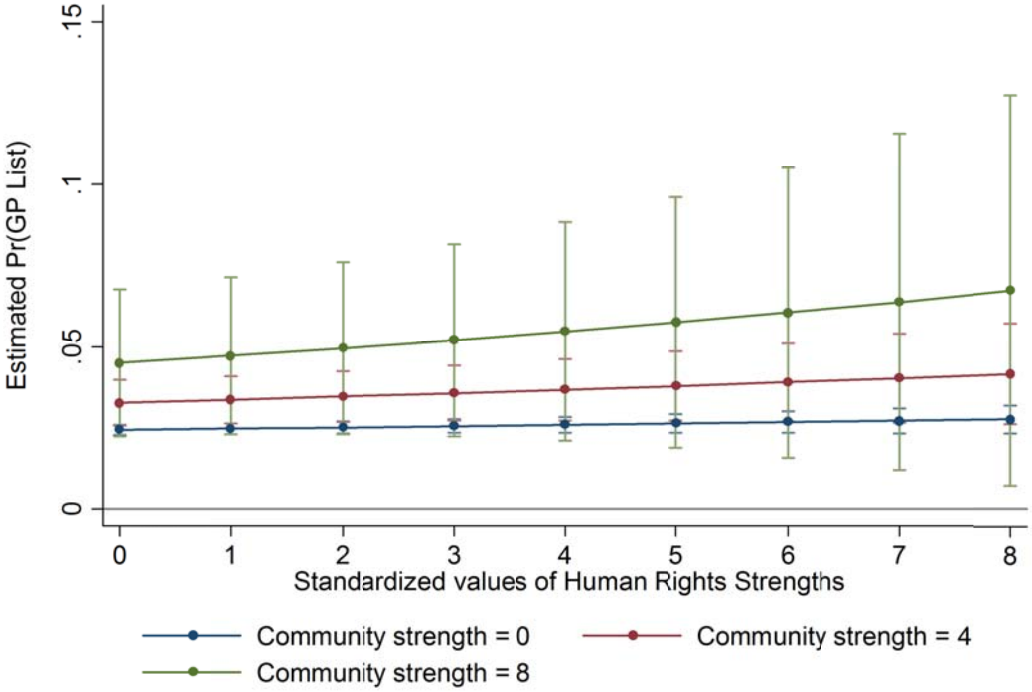

Figure 3.6: Interaction between human rights strengths and community strengths showing a slight synergy

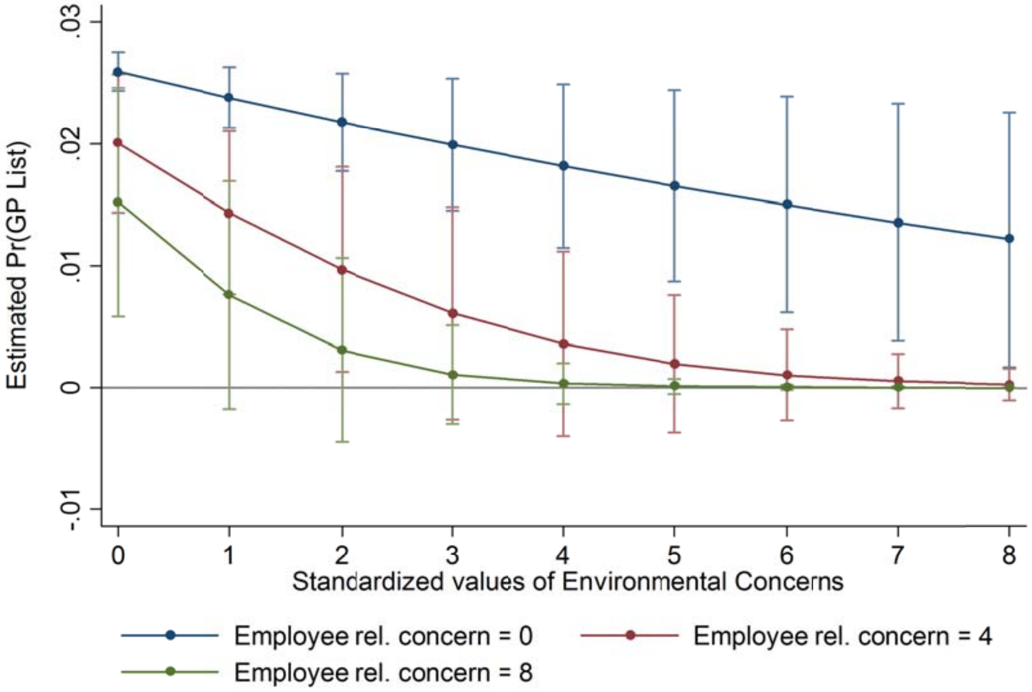

Figure 3.7: Interaction between environmental concerns and employee relations concerns, showing a "negative synergy"

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APPENDIX

This appendix contains supporting information not included in the main text. It includes a discussion of potential study design issues and resolutions, interpretation of logit models and model diagnostics, as well as descriptions, descriptive statistics, and correlations for all variables in the study.

A.1 Potential study design concerns, model interpretation, and diagnostics

A.1.1 Endogeneity and lagged list membership

The models presented are designed to examine the effect of employees' perceptions of their companies' CSR performance on their level of satisfaction. I approximate employees' perceptions of CSR using KLD ratings, and I approximate employee satisfaction using the Great Place list. However, there may be some concern with potential endogeneity in this specification: If firms adjust their CSR performance by increasing or decreasing investment in CSR-related areas *in response to their employees' satisfaction*, then the causality of the models is reversed, the models are misspecified, and estimates will be biased. The bias could be particularly misleading in this case, because firms with the least satisfied employees would invest the most in CSR, and would thus be seen to have the highest levels of CSR performance.

However, in contrast to previous studies that were cross-sectional, the panel design of this study allows us to eliminate this problem. Suppose a firm participates in the survey process for a "best places" list in period t, but does not, in fact, make the top 100 list. The firm then determines that its employees are dissatisfied and responds by increasing its levels of CSR investment in period $t + 1$. In a one-year cross-section of period $t + 1$, it would appear as if this company had both low employee satisfaction and high CSR performance.

With panel data, however, I can observe whether the investment in period $t + 1$ causes higher levels of employee satisfaction in period $t + 2$. Specifically, by including a dummy variable for lagged list membership, as shown in the model specifications above, I can control for the level of past employee satisfaction and partial out the effect of past satisfaction, leaving the pure effect of the improved CSR performance in period $t + 2$.

This solution does rely on an assumption of lag time between a firm learning about levels of employee satisfaction, adjusting levels of CSR performance, and employees updating their satisfaction ratings. However, I believe this assumption is justified. Employee satisfaction assessment and CSR investment are processes that necessarily take time. Moreover, if a firm's source of employee satisfaction data is the Great Place survey, this information arrives at most once per year, limiting the speed with which the company can react.

A.1.2 Rare events bias

Firms appearing on the Great Place list comprise only 2.1% of the sample. It might seem that this fact is of some concern for the analysis. The problems associated with modeling so-called "rare events" such as these have been recognized in econometrics literature for some time (Manski & Lerman, 1977).

King and Zeng (2001) provide a very thorough explanation of how samples with large numbers of zeros ("failures," or "nonevents") and few ones ("successes," or "events") can give rise to biased estimates when using logit models. In essence, because the distribution of the zeros is very precisely estimated, but that of the ones is imprecise, the "cutting point"—the value of an explanatory variable that maximally distinguishes zeros from ones in the dependent variable—will be estimated too high since little information is available about the "tails" of the success data (see King & Zeng, 2001, figure 1). The authors go on to present simulation results that show the estimation bias as a function of the total sample size and the percentage of ones. The evidence is quite convincing that with a small N and a small percentage of events, the bias can be large—up to 500% in the extreme case.

However, the simulation data show that with a sample of 20,000 observations, 2% of which are ones, the absolute estimate bias is less than 5% (see King & Zeng, 2001, figure 3). In my case, with nearly 21,000 observations and event probabilities above 2%, the risk of rare events bias is minimal.

Nonetheless, King and Zeng offer two methods for bias correction: prior correction and weighting. Both of these methods involve correcting the estimated probabilities based on the difference between the sample event probability and a known population event probability. In my case, the population probability is known: Although some firms on each list had to be excluded from the sample because of nonmatches or missing information, the full set of firms on each list divided by the matched sample of firms in KLD represents the proportion of events in the population. To test the potential bias introduced in my sample, I estimated several of the smaller and larger models discussed above using the corrected methods presented by King and Zeng. In all cases, the difference in estimated coefficients and standard errors between corrected and uncorrected models was negligible. Therefore, I conclude that rare events bias is not a problem in the present study and proceed using standard logit specifications.

A.2 Interpretation of coefficients and model fit

A.2.1 Interpretation and marginal effects

Interpretation of effect sizes in logit models is not straightforward, certainly as compared to linear models such as ordinary least squares (OLS). Hoetker (2007) provides a well-cited guide for the use of logit models in management research, the recommendations of which I incorporate in my analysis. As recommended by Hoetker, I report untransformed estimates from the logit model in results tables. While the sign, significance, and relative size of these coefficients can be determined by inspection, the magnitude of the coefficients is presented in units of "changes in log-odds," a measure without intuitive meaning. In various cases I therefore facilitate interpretation by presenting marginal effects.

Unlike in OLS, however, where the marginal effect of y on x in the equation $y = \beta x + \gamma z + u$ is given by β and is constant for all values of x and is independent of values of z, in logit estimation this is not the case. In the logit model, the marginal effect of x on the probability of a positive outcome $P(y = 1)$ depends not only on the level of x, but also on the level of all other explanatory variables (for a thorough explanation, see Wooldridge, 2010). In order to report the *ceteris paribus* effect of any given variable, therefore, it is necessary to hold both x and all other explanatory variables constant at some prescribed value. Following Hoetker's recommendations, I report marginal effects by computing predicted values for each observation and then averaging across predictions. This method provides a picture of the marginal values as they are actually observed in the data. Because all continuous variables are standardized, the marginal effects of continuous variables represent the effect on the predicted probability of inclusion on a list of a one standard deviation increase in the explanatory variable; in the case of binary variables, the marginal effect is the change in predicted probability from changing the explanatory variable from zero to one.

A.2.2 Model performance diagnostics

In each results table, I also present McFadden's "pseudo" R^2 statistic (McFadden, 1974), which compares the likelihood statistic of the model as specified to the likelihood of the model with only a constant (i.e., if the only proportion of successes in the dataset were used to predict the probability of success for each observation). Unlike the usual R^2 in OLS, McFadden's pseudo R^2 does not describe the proportion of variance explained by the model. Specifically, it is computed as

$$\text{McFadden pseudo } R^2 = 1 - \frac{\ln(\hat{L}_U)}{\ln(\hat{L}_R)}$$

where $\hat{L}_U$ and $\hat{L}_R$ are the likelihood of the model as specified and with only a constant, respectively (Hoetker, 2007). Thus, if a model has a McFadden pseudo R^2 of 0.58, the likelihood of the model is 58% higher than the constant-only alternative. The real meaning of this information is, as Hoetker argues, unobvious; as with many model criteria, it is most useful as a means to compare models rather than as stand-alone information.

Along with pseudo R^2, each results table also displays the area under the Receiving Operator Characteristic (ROC) curve, which is widely used in medical diagnostic test design and is a very useful metric for binary-outcome models (Zweig & Campbell, 1993). The ROC curve measures the ability of a model to accurately distinguish true positive outcomes ($\hat{y} = 1 \mid y = 1$, where $\hat{y}$ is the predicted value of the dependent variable) from false positive outcomes ($\hat{y} = 1 \mid y \neq 1$). The curve is drawn by plotting the true positive rate (called the "sensitivity") against the false positive rate (1 – the "specificity," or the true negative rate) for various “success cutoff points” between 0 and 100.[33] A sample is shown in Figure 3.3, which displays the ROC curve for model 3.

The curve shows a number of useful pieces of diagnostic information. First, it shows how much better the model is at distinguishing between true and false positives as compared to a naïve 50/50 guess, represented by the diagonal line. The closer the plot is to the upper-left corner, the more accurate the model predictions; a model that perfectly predicts positive and negative outcomes would touch the corner.

Second, it gives the area under the curve, which quantifies the ability of the model to distinguish between positive and negative outcomes. The naïve 50/50 guess has an area of 0.5, whereas a perfect model has an area of 1. The interpretation of the value of the area is surprisingly straightforward: It represents the probability that a randomly selected true-positive observation will have a higher predicted $\hat{y}$ than a randomly selected true-negative observation. So, in the case of model 3, with ROC area of 0.976, a randomly selected firm-year observation that, in reality, appears on the Great Place list (i.e., has GP_dummy=1) will have a higher predicted value ($\hat{y}$) than 97.6% of the firm-year observations that, in reality, do not appear on the Great Place list.

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[33] The cutoff point is the predicted value of the model above which is deemed a success. Thus, if the cutoff point is 50%, any $\hat{y} > 0.5$ will be labeled as a success. As the cutoff point increases, the probability of false positives falls, but the ability to predict true negatives also diminishes.

Variable	Source	Description
GP list	Great Place to Work Institute	Dummy variable denoting membership on the Great Place to Work Institute's 100 Best Places to Work in America list. See above for complete description.
ENVstr	KLD	Sum of environmental strengths, including measures of proactive investment, strong waste management, climate change initiatives, and green energy.
ENVcon	KLD	Sum of environmental concerns, including measures of poor regulatory compliance, toxic releases, greenhouse gas (GHG) emissions, and involvement with harmful products and services.
EMPstr	KLD	Sum of employee relations strengths, including measures of good union relations, cash profit sharing, employee involvement, health and safety, and protection of employee rights throughout the supply chain.
EMPcon	KLD	Sum of employee relations concerns, including measures of poor union relations, health and safety issues, and supply chain controversies.
DIVstr	KLD	Sum of diversity strengths, including measures of representation by women and minorities in line positions and on the board of directors, work/life benefits, gay and lesbian policies, and employment of underrepresented groups.
DIVcon	KLD	Sum of diversity concerns, including measures of controversies, history of fines due to diversity issues, and lack of representation of women and minorities.
CGOVstr	KLD	Sum of corporate governance strengths, including measures of CSR reporting quality and GRI adherence, and limited executive compensation.
CGOVcon	KLD	Sum of corporate governance concerns, including measures of CSR reporting quality and GRI adherence, and high executive compensation.
COMstr	KLD	Sum of community strengths, including measures of charitable giving, community engagement, and programs to benefit disadvantaged communities.
COMcon	KLD	Sum of community concerns, including measures of the severity of controversies involving land use, negative community impacts, or criticism by third parties.
HUMstr	KLD	Sum of human rights strengths, including measures of relations with indigenous peoples, policies, and initiatives.
HUMcon	KLD	Sum of human rights concerns, including measures of complicity in killings, abuse, and freedom of speech violations, and operations in Burma or Sudan.
PROstr	KLD	Sum of product strengths, including measures of quality, benefits to the economically disadvantaged, and commitment to microfinance and community development.
PROcon	KLD	Sum of product concerns, including measures of product safety concerns, false or misleading marketing, antitrust problems, or customer relations legal cases.
ENVstrA	KLD	Environmental Opportunities – Proactive investment in products and services that address issues of resource conservation and climate change, and pursue green building certifications.
ENVstrB	KLD	Waste Management – Strong programs and track records of reducing

Variable	Source	Description
		emissions and waste, including well-managed product recovery and recycling programs for electronic products.
ENVstrC	KLD	Packaging Materials and Waste – Proactive reduction of environmental impact of packaging, including use of recycled content material and establishment of take-back and recycling programs.
ENVstrD	KLD	Climate Change – Strong initiatives in renewable energy generation, comprehensive carbon policies including process improvements, carbon capture equipment, and cleaner energy sources, efficiency improvements, and supply chain carbon measurement and reduction.
ENVconB	KLD	Regulatory Compliance – Fines or sanctions for causing environmental damage or violations of operating permits.
ENVconD	KLD	Toxic Spills & Releases – History of involvement in land or air emissions-related legal cases, widespread or egregious impacts due to hazardous emissions, resistance to improved practices, and criticism by NGOs or other third parties. Information for this variable is derived from the Toxics Release Inventory (TRI) prepared by the US Environmental Protection Agency (EPA), including comparisons with a firm's industry peers.
ENVconE	KLD	Agricultural chemicals – Substantial producer of agricultural chemicals
EMPstrA	KLD	Union relations – Exceptional steps to treat unionized workforce fairly
EMPstrC	KLD	Cash profit sharing – Has a cash profit sharing program and has recently made distributions to its workforce
EMPstrD	KLD	Employee ownership plans – Strongly encourages worker involvement and ownership through stock options, gain sharing, or participation in decision making
EMPstrF	KLD	Retirement benefits – Notably strong retirement benefits program
EMPstrG	KLD	Health and safety – Strong health and safety programs
EMPconA	KLD	Union relations – History of notably poor union relations
EMPconB	KLD	Health and safety – Recently paid fines for willful health and safety violations or otherwise involved in health and safety controversies
EMPconC	KLD	Workforce reductions – Significant reductions in workforce in recent years
EMPconD	KLD	Retirement benefits – Substantially underfunded benefit pension plan or inadequate retirement benefits program
DIVstrB	KLD	CEO/line representation – CEO is a woman or minority, or notable progress in promoting women and minorities to line positions
DIVstrC	KLD	Board representation – Women, minorities, or the disabled hold four seats or more on the board of directors
DIVstrD	KLD	Work/life benefits – Outstanding employee benefits or other programs addressing work/life or family concerns, including child care, elder care, or flextime
DIVstrE	KLD	Women and minority contracting – At least 5% of subcontracting is done with women- or minority-owned businesses
DIVstrF	KLD	Employment of the disabled – Innovative hiring programs or other innovative resource programs for the disabled
DIVstrG	KLD	Gay and lesbian policies – Notably progressive policies toward gay and lesbian employees, including providing benefits to domestic

Variable	Source	Description
		partners
DIVconA	KLD	Diversity controversies – Paid substantial fines as a result of affirmative action controversies or has otherwise been involved in diversity controversies
DIVconB	KLD	Nonrepresentation – No women or minorities on the board of directors or line positions
CGOVstrA	KLD	Limited executive compensation – The CEO earns total compensation less than $500,000/year, and outside directors earn less than $30,000/year
CGOVstrC	KLD	Ownership strength – Owns between 20% and 50% of another company that KLD has rated as having high CSR scores
CGOVstrD	KLD	Transparency – Effective at reporting on a wide range of social and environmental performance measures, including the use of the Global Reporting Initiative (GRI) guidelines
CGOVconB	KLD	High executive compensation – The CEO earns total compensation more than $10 million/year, or outside directors earn more than $100,000/year
CGOVconF	KLD	Ownership concern – Owns between 20% and 50% of another company that KLD has rated as having low CSR scores
COMstrA	KLD	Charitable giving – Consistently has given over 1.5% of trailing three-year net earnings before taxes to charity
COMstrB	KLD	Innovative giving – Notably innovative giving programs that support nonprofit organizations, or nontraditional federated workplaces drives
COmstrC	KLD	Support for housing – Prominent participant in public-private partnerships that support housing initiatives for the economically disadvantaged
COMstrD	KLD	Support for education – Notably innovative in its support for primary and secondary school education, particularly those programs that benefit the economically disadvantaged, or job-training programs for youth
COMconA	KLD	Investment controversies – The company is a financial institution whose lending or investment practices have led to controversies
COMconB	KLD	Negative economic impact – The company’s actions have resulted in major controversies concerning its impact on the community, including environmental contamination, water rights disputes, or activities that affect property values or quality of life
COMconD	KLD	Tax disputes – Recently involved in tax disputes or is involved in controversies over tax obligations to the community
HUMstrG	KLD	Labor rights strength – Outstanding transparency on overseas sourcing disclosure and monitoring, or particularly good union relations overseas
HUMconC	KLD	Operations in Burma – Operations or direct investment in, or sourcing from Burma
HUMconF	KLD	Labor rights concerns – Recent major controversies primarily related to labor standards in its supply chain
PROstrA	KLD	Quality – Has a long-term, well-developed, companywide quality program
PROstrB	KLD	R&D/innovation – Leader in its industry for research and development and brings notably innovative products to market

Variable	Source	Description
PROconA	KLD	Safety – Recently paid substantial fines or is involved in controversies or regulatory actions relating to the safety of its products
PROconD	KLD	Marketing/contracting concern – Recently involved in major marketing or contracting controversies relating to advertising practices, consumer fraud, or government contracting
PROconE	KLD	Antitrust – Recently paid substantial fines for antitrust violations such as price fixing, collusion, or predatory pricing
lnemp	Compustat	Number of employees; log transformed
lnROA	Compustat	Return on Assets, defined as net income before interest and taxes divided by total assets; log transformed
lnxsga	Compustat	Selling, general, and administrative expense; log transformed. Includes salaries and wages of officers and employees (including pension and benefits), furniture and equipment rental cost and servicing.
SIC code	Securities and Exchange Commission (SEC); Compustat	Standard Industrial Classification at the one-digit SIC level. See Table 3.2 for more detail.

Source for KLD descriptions: (MSCI Inc. 2013)

Table 3.A.1: Variable descriptions

	Mean	s.d.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1 ENVstrA	0.039	0.19																	
2 ENVstrB	0.027	0.16	.09																
3 ENVstrC	0.023	0.15	.02	.08															
4 ENVstrD	0.047	0.21	.18	.24	.10														
5 EMPstrA	0.017	0.13	.04	.05	.02	.07													
6 EMPstrC	0.078	0.27	.10	.10	.09	.10	.02												
7 EMPstrD	0.102	0.30	.08	.08	.06	.10	.02	.17											
8 EMPstrF	0.055	0.23	-.01	.05	.05	.10	.05	.07	.03										
9 EMPstrG	0.038	0.19	.10	.24	.17	.26	.12	.11	.08	.14									
10 DIVstrB	0.241	0.43	-.03	.05	-.01	.04	.00	.05	.11	.00	.05								
11 DIVstrC	0.077	0.27	.03	.09	.03	.11	.04	.05	.07	.01	.11	.23							
12 DIVstrD	0.075	0.26	.05	.25	.10	.21	.03	.13	.20	.11	.24	.16	.25						
13 DIVstrE	0.049	0.22	.09	.20	.17	.32	.07	.11	.13	.10	.25	.13	.21	.34					
14 DIVstrF	0.018	0.13	.03	.14	.09	.08	.06	.10	.12	.06	.17	.08	.13	.26	.31				
15 DIVstrG	0.155	0.36	.06	.17	.05	.25	.06	.14	.21	.05	.20	.20	.27	.38	.30	.20			
16 COMstrA	0.054	0.23	.07	.15	.09	.17	.02	.11	.12	.09	.21	.09	.13	.24	.20	.12	.20		
17 COMstrB	0.055	0.23	.09	.18	.08	.27	.06	.06	.10	.05	.14	.11	.14	.29	.28	.13	.24	.23	
18 COMstrC	0.039	0.19	-.02	.01	.00	-.01	.00	.00	.02	.09	-.02	.06	.08	.12	.08	.02	.05	.08	.10
19 COMstrD	0.042	0.20	.05	.20	.06	.10	.01	.14	.15	.06	.19	.11	.14	.35	.28	.21	.25	.21	.21
20 CGOVstrA	0.137	0.34	-.02	-.06	-.05	-.04	-.03	-.06	-.05	-.07	-.09	-.01	-.05	-.08	-.07	-.03	-.10	-.05	-.06
21 CGOVstrC	0.002	0.05	.01	.02	-.01	-.01	-.01	.01	.03	.01	.00	-.01	.01	.07	.03	-.01	.00	.01	.02
22 CGOVstrD	0.040	0.20	.18	.35	.15	.44	.09	.12	.13	.07	.33	.08	.18	.33	.38	.24	.29	.28	.32
23 HUMstrG	0.002	0.05	.03	.07	.01	.13	-.01	.01	.00	.04	.05	.02	.05	.12	.03	.07	.08	.07	.18
24 PROstrA	0.057	0.23	.10	.17	.06	.18	.11	.12	.10	.04	.15	.02	.10	.13	.16	.12	.13	.09	.18
25 PROstrB	0.030	0.17	.06	.15	.05	.10	-.01	.16	.16	.03	.09	.05	.00	.18	.09	.12	.08	.09	.07
26 ENVconB	0.063	0.24	.07	.15	.14	.12	.07	.07	.03	.10	.27	-.02	.04	.11	.11	.09	.04	.08	.04
27 ENVconC	0.003	0.06	.00	.05	.00	.03	.05	.03	.02	.05	.12	.01	.02	.07	.03	.07	.02	.01	.01
28 ENVconD	0.083	0.28	.06	.22	.16	.17	.06	.08	.04	.12	.37	-.02	.04	.15	.15	.10	.08	.12	.06
29 ENVconE	0.011	0.10	.01	.10	-.01	.08	.00	.01	.01	.05	.12	-.01	.02	.07	.02	.03	.00	.01	-.01
30 EMPconA	0.026	0.16	.03	.03	.03	.09	.02	.00	-.01	.01	.06	.01	.08	.03	.09	.04	.07	.07	.08
31 EMPconB	0.085	0.28	.09	.09	.08	.19	.14	.00	.00	.07	.22	-.03	.07	.06	.15	.05	.12	.07	.08
32 EMPconC	0.058	0.23	-.01	.02	-.02	.02	.00	.06	.07	.00	.00	.02	.00	.03	.02	.02	.07	-.01	-.01
33 EMPconD	0.230	0.42	.01	-.01	-.01	.00	.01	-.03	-.04	-.03	.05	.02	.02	-.03	-.01	-.01	.01	-.02	-.03
34 DIVconA	0.042	0.20	.02	.05	.02	.07	.06	.02	.02	.01	.11	.04	.14	.11	.17	.16	.14	.06	.07
35 DIVconB	0.355	0.48	-.03	-.08	-.03	-.05	-.01	-.06	-.08	-.04	-.12	-.33	-.17	-.15	-.11	-.08	-.16	-.11	-.07
36 COMconA	0.023	0.15	-.02	-.02	-.02	-.02	-.02	.00	-.01	.05	-.03	.00	.05	.02	.02	.00	-.01	.00	-.02
37 COMconB	0.031	0.17	.08	.11	.04	.14	.07	.07	.01	.08	.23	.00	.05	.09	.14	.10	.07	.08	.06
38 COMconD	0.025	0.16	.02	.05	.05	.14	.00	.04	-.01	.11	.15	.02	.04	.10	.11	.06	.11	.07	.05
39 CGOVconB	0.304	0.46	.03	.07	.03	.07	.02	.10	.13	.05	.17	.13	.14	.19	.19	.12	.28	.07	.06
40 CGOVconF	0.009	0.09	.06	.01	.01	.03	.06	.02	.02	.04	.06	.00	-.02	.03	.03	-.01	.00	.04	.06
41 HUMconC	0.005	0.07	.01	.01	-.01	.06	-.01	.02	-.01	.03	.06	.00	-.01	.03	.02	.00	.01	.03	.01
42 HUMconF	0.041	0.20	-.01	.03	.04	.06	.02	.02	.00	.00	.07	.08	.10	.14	.11	.10	.12	.10	.16
43 PROconA	0.058	0.24	.06	.15	.02	.16	.07	.05	.04	.07	.18	.03	.08	.17	.14	.08	.12	.10	.12
44 PROconD	0.077	0.27	.00	.11	.02	.09	.03	.01	.04	.04	.15	.07	.14	.21	.21	.16	.21	.13	.09
45 PROconE	0.039	0.19	.02	.11	.03	.13	.03	.04	.05	.05	.19	.06	.08	.18	.15	.10	.16	.13	.11
46 lnemp	8.193	1.85	.10	.19	.13	.18	.09	.13	.13	.07	.24	.11	.22	.28	.31	.20	.30	.20	.25
47 lnROA	0.631	0.36	.04	.01	.03	-.03	.03	.03	.00	-.07	.04	.01	.04	-.03	.01	.01	.01	.03	.05
48 lnxsga	5.314	1.58	.10	.23	.10	.24	.07	.15	.19	.12	.26	.17	.25	.38	.37	.24	.43	.23	.32
49 year	2005.29	5.21	.00	-.07	-.07	.11	.07	-.11	-.06	-.02	.02	.02	.03	-.04	.07	-.04	.15	-.11	-.02

Table 3.A.2: Summary statistics and correlations for individual KLD indicators

	Mean	s.d.	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
19 COMstrD	0.042	0.20	.10																
20 CGOVstrA	0.137	0.34	.01	-.08															
21 CGOVstrC	0.002	0.05	.02	.01	.00														
22 CGOVstrD	0.040	0.20	.03	.21	-.06	-.01													
23 HUMstrG	0.002	0.05	-.01	.04	-.02	.00	.23												
24 PROstrA	0.057	0.23	.01	.08	-.05	.00	.21	-.01											
25 PROstrB	0.030	0.17	.00	.13	-.04	.00	.08	-.01	.07										
26 ENVconB	0.063	0.24	.01	.10	-.10	.02	.17	-.01	.04	.04									
27 ENVconC	0.003	0.06	.01	-.01	-.02	.00	.01	.00	.03	.06	.09								
28 ENVconD	0.083	0.28	.02	.15	-.11	.03	.23	-.01	.05	.06	.48	.12							
29 ENVconE	0.011	0.10	-.01	.00	-.04	-.01	.08	.00	-.01	.04	.20	.39	.21						
30 EMPconA	0.026	0.16	-.01	.01	-.03	.01	.09	.03	.08	-.02	.12	.02	.11	.01					
31 EMPconB	0.085	0.28	-.03	.05	-.08	.00	.20	.01	.10	-.02	.26	.04	.25	.06	.17				
32 EMPconC	0.058	0.23	-.02	.04	-.01	.00	.01	-.01	.00	.04	.00	-.01	.01	-.02	.00	-.02			
33 EMPconD	0.230	0.42	-.07	-.02	.03	-.01	.01	.01	-.02	-.01	.02	-.01	.03	.01	.03	.08	-.01		
34 DIVconA	0.042	0.20	.04	.10	-.07	-.01	.11	.03	.05	-.01	.11	.02	.12	.00	.14	.13	.00	.03	
35 DIVconB	0.355	0.48	-.08	-.12	.13	-.03	-.09	-.03	-.05	-.05	-.10	-.01	-.11	-.03	-.03	-.04	.00	.08	-.11
36 COMconA	0.023	0.15	.08	.01	.08	-.01	.00	-.01	-.03	-.02	-.04	-.01	-.04	-.02	-.02	-.04	-.03	-.03	.00
37 COMconB	0.031	0.17	.00	.08	-.07	-.01	.18	-.01	.06	.01	.28	.07	.33	.15	.09	.20	.02	.02	.13
38 COMconD	0.025	0.16	.02	.10	-.06	.00	.09	-.01	.02	.00	.13	-.01	.14	.03	.05	.11	.01	.01	.06
39 CGOVconB	0.304	0.46	.00	.16	-.20	-.01	.13	.05	.07	.06	.09	.02	.11	.02	.06	.13	.03	.03	.14
40 CGOVconF	0.009	0.09	.03	.06	-.03	.03	.01	.00	.01	.01	.10	.00	.08	.03	.00	.04	.00	.00	-.02
41 HUMconC	0.005	0.07	.00	.02	-.03	.00	.02	.00	.00	.04	.09	.00	.10	.05	.02	.02	-.01	.00	.01
42 HUMconF	0.041	0.20	-.03	.06	-.05	.02	.13	.21	.01	.02	.03	-.01	.03	.01	.05	.05	.02	.03	.09
43 PROconA	0.058	0.24	.01	.08	-.08	.03	.18	.01	.10	.03	.16	.07	.25	.13	.07	.16	-.01	.00	.14
44 PROconD	0.077	0.27	.06	.19	-.09	.01	.17	.01	.04	.03	.11	.02	.14	.07	.10	.11	.00	-.02	.19
45 PROconE	0.039	0.19	.05	.14	-.07	-.01	.16	-.01	.03	.04	.19	.06	.23	.13	.07	.12	.01	.01	.10
46 lnemp	8.193	1.85	.08	.26	-.28	.03	.25	.07	.18	.07	.22	.06	.29	.07	.18	.24	-.04	.01	.27
47 lnROA	0.631	0.36	-.19	.00	-.13	-.01	.01	.04	.02	.01	.03	.00	.02	.01	.06	.08	-.03	.07	.07
48 lnxsga	5.314	1.58	.12	.34	-.30	.03	.30	.07	.20	.12	.20	.06	.27	.09	.15	.20	.03	-.03	.24
49 year	2005.29	5.21	-.11	-.12	.13	-.06	.08	.02	-.01	-.11	-.15	-.06	-.13	-.06	-.01	.10	-.02	.15	.00

Table 3.A.2: Summary statistics and correlations for individual KLD indicators (continued)

	Mean	s.d.	35	36	37	38	39	40	41	42	43	44	45	46	47	48
36 COMconA	0.023	0.15	-.03													
37 COMconB	0.031	0.17	-.05	-.03												
38 COMconD	0.025	0.16	-.03	-.02	.11											
39 CGOVconB	0.304	0.46	-.11	-.03	.09	.06										
40 CGOVconF	0.009	0.09	-.03	-.01	.05	.08	.00									
41 HUMconC	0.005	0.07	-.03	-.01	.06	.12	.02	.04								
42 HUMconF	0.041	0.20	-.07	-.03	.03	.02	.09	.00	.03							
43 PROconA	0.058	0.24	-.09	-.04	.17	.07	.09	.06	.01	.03						
44 PROconD	0.077	0.27	-.14	.03	.11	.10	.19	.00	.00	.07	.23					
45 PROconE	0.039	0.19	-.10	-.02	.13	.14	.14	.05	.08	.08	.18	.18				
46 lnemp	8.193	1.85	-.32	-.02	.15	.10	.30	.03	.08	.19	.22	.28	.21			
47 lnROA	0.631	0.36	-.06	-.21	.00	-.02	.05	-.02	.01	.13	.02	.03	.00	.37		
48 lnxsga	5.314	1.58	-.33	.00	.15	.14	.40	.04	.07	.19	.24	.34	.26	.82	.24	
49 year	2005.29	5.21	.23	.02	.01	.04	.12	-.06	-.05	-.03	.00	-.05	-.07	-.28	-.12	-.19

Table 3.A.2: Summary statistics and correlations for individual KLD indicators (continued)