Life Cycle Paralysis:
Managing Uncertainty in California and US Biofuel Policies

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ABSTRACT

California's Low Carbon Fuel Standard (LCFS) and the United States' Renewable Fuel Standard (RFS2) are policies that originally incentivized biofuel production under the premise that biofuels produce fewer greenhouse gas emissions than fossil fuels. However, recent studies have shown that when the indirect emissions of biofuels are taken into account, some biofuels are more carbon intensive than fossil fuels. This information led researchers to account for indirect environmental harms in new ways. One such method is through a consequential life cycle assessment (CLCA), which predicts environmental impacts outside of a production chain by linking life cycle assessment (LCA) methodology with economic processes. While some scientists praise CLCA as a superior way of accounting for the total environmental impacts of a policy, its results remain uncertain and scientists have yet to agree on a common analytical framework. Models that predict greenhouse gas emissions from biofuels and use this CLCA approach have been adopted in national and state biofuel policies in different ways. However, this has sparked controversy because model predictions have not converged as expected, and experts continue to debate how to apply LCA methodology to bioenergy. Moreover, biofuel producers resent being penalized for uncertain indirect emissions. I conduct a multi-case analysis of the role of LCA in quantifying indirect environmental impacts and how it has become contentious in California's Low Carbon Fuel Standard (LCFS) and the United States' Renewable Fuel Standard (RFS2).

KEWORDS

Low Carbon Fuel Standard (LCFS), Renewable Fuel Standard (RS2), indirect land use change (ILUC), life cycle assessment (LCA), regulatory science

INTRODUCTION

The United States implemented the Renewable Fuel Standard (RFS2) as part of the Energy Independence and Security Act (EISA) of 2007. The purpose of the EISA was to spur energy independence, diversify the energy sector, and reduce subsidies to the petroleum industry. The EISA was a comprehensive energy bill encompassing a wide range of alternative energy initiatives while the Renewable Fuel Standard (RFS2) focused specifically on incentivizing biofuel production. The EISA and RFS2 were passed as part of the United States' ongoing efforts to reduce greenhouse gas emissions and its dependence on foreign sources of oil. Meanwhile, California implemented the Low Carbon Fuel Standard (LCFS) in 2009 as a way to reduce the carbon intensity of California's fuels by ten percent by 2020. The LCFS was also part of a longstanding initiative to combat climate change, following in the footsteps of Assembly Bill 32 (AB 32), California's state-sponsored cap and trade program (also known as the Global Warming Solutions Act of 2006). Both the RFS2 and LCFS were passed as a way to achieve energy independence and became part of the climate change discourse that has developed over the past several decades.

Biofuels were long believed to be sustainable alternatives to fossil fuels and in order to reduce greenhouse gas emissions and combat climate change, the RFS2 and LCFS penalized high-emitting fuels and subsidized biofuels. Specifically, the California Air Resources Board (CARB) assigned greenhouse gas ratings to particular fuels in the LCFS and required experts to construct life-cycle inventories for dozens of fuels. To reduce greenhouse gas emissions, CARB set an emission cap for the entire transportation fuel sector that required fuel producers to reduce the carbon intensity of their fuel mix, usually by replacing high-carbon fuels with lower emitting fuels such as biofuels. Meanwhile, the Environmental Protection Agency (EPA) set volumetric targets in the RFS2 for four categories of biofuels to be blended into transportation fuels each year: conventional biofuels, biomass-based biodiesel, advanced biofuels, and cellulosic biofuels, and the requirements for cellulosic biofuels have been the most contentious with biofuel producers (Edwards 2009; NAS 2011; Brown 2013).

Over the past decade research has emerged highlighting some of the negative indirect effects of biofuels, which has brought the sustainability of biofuels into question. While biofuels produce fewer direct greenhouse gas emissions than fossil fuels during combustion, new research has illustrated that biofuels may produce unintended environmental impacts. Timothy Searchinger and his collaborators published the most prominent of these studies in 2008 by illustrating that some biofuels produce more total greenhouse gas emissions than fossil fuels when indirect emissions are included. Searchinger et al. (2008) focused on the phenomenon of indirect land use change (ILUC), which he claimed was responsible for high greenhouse gas emissions from biofuels (Searchinger et al. 2008). Indirect land use change (ILUC) occurs when biofuel production displaces food crops and necessitates the conversion of land to agriculture elsewhere to meet existing food demand, thereby emitting additional greenhouse gases (Dunkelberg et al. 2011).

When scientists at CARB and EPA realized the importance of including emissions from indirect land use change (ILUC) when quantifying sustainability, they developed and implemented fuel-specific ILUC factors to estimate how much indirect land use change and greenhouse gas emissions would be caused by a particular biofuel. This played out differently in the two policy contexts. In the case of the United States' RFS2, environmental groups had early access to Searchinger's findings on ILUC and, at their behest, policymakers incorporated his findings in the initial draft of the RFS2 in 2007 (Breetz interview; Plevin interview). In the case of California's LCFS, policymakers incorporated language on indirect effects and ILUC verbatim from the RFS2 (Plevin interview). While policymakers in each jurisdiction decided to incorporate ILUC factors to evaluate and compare fuels, scientists at CARB and EPA applied life cycle assessment (LCA) methodology in different ways and controversy emerged over the appropriate use of these methods. Moreover, each jurisdiction used different accounting mechanisms to generate their respective ILUC factors.

Life cycle assessment (LCA) is the main analytical framework used to specify the types of environmental impacts to quantify (such as greenhouse gas emissions, water pollution, soil contamination, etc.) and it played a critical role in how both the LCFS and RFS2 quantified the emissions from indirect land use change caused by expanded biofuel production. LCA studies of bioenergy typically use one of two main types of accounting mechanisms to quantify the total emissions caused by a biofuel policy: general equilibrium and partial equilibrium models (Kretschmer and Peterson 2010). It is important to remember that life cycle assessment (LCA) is the analytical framework used to specify the types of emissions to quantify, while tools such as economic equilibrium models are the devices used to quantify and estimate these emissions. Economic equilibrium models can be used to quantify direct emissions, indirect emissions, or both, depending on the LCA approach used. While these accounting tools are highly sophisticated, their results often depend on scientists' assumptions of key input parameters such as soil carbon content, agricultural yield, price elasticity, the location of land use change, and treatment of co-products (Chalmers et al. 2011). Consequently, different models may produce vastly different greenhouse gas estimates and ILUC factors for particular fuels, which caused conflict with biofuel producers who resented being penalized for uncertain quantities of indirect emissions.

Due to the controversy surrounding each policy, California's LCFS and the US's RFS2 have both undergone revisions and faced legal challenges since being implemented. California's LCFS has survived two lawsuits, one of which claimed it violated the Commerce Clause by treating fuels from other states differently, while the other claimed policymakers at CARB didn't sufficiently rely on consultant input in its environmental impact analysis. While the lawsuit regarding the Commerce Clause was defeated, CARB was required to conduct its environmental impact analysis again, though the rest of the language of the LCFS remained the same. Additionally, CARB has regularly updated its modeling of ILUC factors, and the most recent updates were discussed at a CARB board meeting in February 2015 (Plevin interview). Meanwhile, EPA has annually adjusted the volumetric targets of biofuels to be blended into transportation fuels, though it delayed rulemaking for 2014 and has faced multiple legal challenges from biofuel producers (BPC 2014). The American Petroleum Institute petitioned the U.S. Court of Appeals for the District of Columbia to throw out the requirements on cellulosic biofuels for the RFS2 targets for 2011, 2012, and 2013. Most of these attempts have failed to alter the structure of the RFS2 itself, though EPA has had to re-evaluate its annual volumetric targets several times (Brown 2013). Moreover, there are still calls to repeal the RFS2 and the decision to reform or repeal the mandate will likely be decided later in 2015 (BPC 2014). These lawsuits and controversies surrounding both the LCFS and RFS2 started because of how each policy negatively impacted stakeholders, usually biofuel producers. While LCA was not mentioned in the lawsuits, LCA played a critical role in quantifying ILUC factors and the volumetric targets and fuel-specific greenhouse gas ratings used in the RFS2 and LCFS respectively, which puts it at the center of the controversy and is why I focus on LCA in my analysis.

In many ways LCA sits at the interface of science and value because policymakers must choose an appropriate analytical framework by which to mitigate climate change, even in the face of uncertainty. Moreover, policymakers are increasingly asked to address highly technical problems and must decide how to select scientific advisors, how to request and weigh scientific advice, and how to frame issues (Jasanoff 1990). Both the United States and California have used LCA as an analytical framework to account for the indirect effects of biofuel production based on the recommendations of their scientific advisors. Policymakers at both EPA and CARB have also made value judgments and drawn criticism from some stakeholders in the biofuel industry by choosing to account for indirect impacts and by using economic equilibrium models with high degrees of uncertainty. This is evident in the fact that EPA has been criticized for its uncertainty analysis in the RFS2 and CARB has been sued for incorporating ILUC factors in the LCFS (Farber 2011; Plevin 2010). Moreover, the appropriate use of ALCA versus CLCA is still debated by experts (Plevin et al. 2013; Guinee et al. 2010). All of these problems indicate a fundamental knowledge gap between scientists and policymakers and raise the question of how regulatory agencies should manage scientific advice during scenarios of high uncertainty. Unfortunately, questions about the nature and practice of scientific advice and its role in influencing policy remain relatively unexplored considering its importance. There is a shortage of research regarding the way advice is characterized, the processes through which policies are created and modified, and the ways in which power is exercised in modern democratic societies (Owens 2011). I speak to this gap in the literature by addressing these questions as they apply to LCA and biofuel mandates in California and the United States.

I use the analytical framework developed by Sheila Jasanoff in *The Fifth Branch: Science Advisers as Policymakers* as a lens through which to view my study system, as a guide about which aspects of the science-policy interface to investigate, and as a way to analyze the way regulatory science has played out in US and California biofuel mandates. Numerous researchers have used Jasanoff's ideas as a guide by which to investigate regulatory science and her work has been heavily cited in the regulatory science and Science and Technology Studies literature. In *The Fifth Branch*, Jasanoff analyzes how scientific methods and knowledge claims are used in policymaking, and discusses the strengths and limitations of scientific advice within and outside of the policy context. Specifically, she analyzes a phenomenon well known in Science and Technology Studies literature called "boundary work," which is the phenomenon by which boundaries are created between science and policy to establish the legitimacy of both institutions, and is crucial for the political acceptability of receiving scientific advice (Jasanoff 1990). As part of her analysis of boundary work, she evaluates several aspects of the science-policy interface, including the flaws of peer review, the role of advisory bodies, uncertainty, quantifying risk, justifications and values, among other things. Drawing on her approach, I base my research sub-questions on three aspects of regulatory science that underscore my central research question. In each case I investigate scientific uncertainty, the choice and treatment of accounting tools, and how policymakers and scientists interacted and justified their methodological choices.

RESEARCH QUESTIONS AND HYPOTHESES

My main objective is to understand how LCA was used to quantify indirect environmental impacts and how it became contentious in California's Low Carbon Fuel Standard (LCFS) and the United States' Renewable Fuel Standard (RFS2). In both cases, policymakers were under pressure to account for indirect effects even though there weren't ready accounting tools (Plevin interview). Consequently, estimates for the quantity of land use change and greenhouse gas emissions caused by biofuels diverged across models and raised doubts about regulating the indirect environmental effects of biofuels. To analyze this controversy and answer my central research question I investigate three aspects of regulatory science: uncertainty, accounting tools, and the interaction of scientists and policymakers concerning the justifications of their methodological choices. Specifically, I first investigate how the scientific uncertainty associated with LCA was treated in the RFS2 and LCFS. Second, I investigate how LCA influenced each jurisdiction's choice and treatment of accounting tools – specifically, economic equilibrium models and ILUC factors. Third, I investigate how policymakers and scientists interacted and justified their methodological choices and management of scientific uncertainty. I discuss my key findings and arguments related to the three aspects of regulatory science I highlighted above in my Results and Discussion sections.

Regarding the uncertainty of LCA, I argue that the political context in which the RFS2 was implemented created an environment that didn't allow scientists to question the basic premise of the RFS2 and that scientists at EPA couldn't focus enough energy on questioning the methodological uncertainties of LCA, why they were using LCA in the first place, and whether it was an appropriate analytical framework. Meanwhile, policymakers at CARB were under pressure to pass biofuel legislation quickly and put pressure on scientists to generate single ILUC factors, which I argue discouraged scientists from making informative policy recommendations to decision makers about LCA and its associated uncertainty. With regard to the choice and treatment of accounting tools, I argue in the case of the RFS2 that these seemingly technical decisions actually embody value choices influenced by EPA's LCA analysis and political factors. Furthermore, in the case of the LCFS, I argue two major factors influenced the way CARB treated the output of its chosen accounting mechanism: the way Searchinger et al. theorized direct and indirect emissions and political pressure to generate single fuel-specific ILUC values. Regarding the interaction of scientists and policy makers and how they justified their methodological choices, I argue that there was an epistemological weakness in the way EPA relied on experts to regulate and quantify biofuels, which, in addition to the political context in which the RFS2 was drafted, prevented scientists from thoughtfully addressing scientific uncertainty. Finally, I argue policymakers at CARB were willing to tolerate a high degree of uncertainty in the LCFS because they wanted to protect the environment and be seen as leaders in environmental governance.

RESEARCH METHODS

To better understand the evolution of LCA methodology, the technical details of biofuel models and parameters, and the politics of scientific uncertainty, I conducted three literature reviews, each of which focused on one of the three aspects of regulatory science I highlighted in the section above: the uncertainty of LCA, the choice and treatment of accounting tools (economic equilibrium models and ILUC factors), and science-policy interactions and justifications. Specifically, I used GoogleScholar, JSTOR, and Hein Online to find articles using the following key words: "LCFS, CLCA," "LCFS, ALCA," "RFS2, CLCA," "RFS2, ALCA," "economic equilibrium models," "LCFS, scientific uncertainty," "RFS2, scientific uncertainty," "LCFS, ILUC," and "RFS2, ILUC." I then sorted each document into peer-reviewed primary literature, government documents, and newspaper articles. I also made note of which documents applied to the LCFS, the RFS2, or both. The information from the literature review helped me become more familiar with each topic and devise interview questions. I gave more weight to the peer-reviewed primary documents and government documents because they include more specific details about different biofuel models and how each policy managed scientific uncertainty. I used newspaper articles to understand the context behind the controversy surrounding these biofuel policies and the biofuel industry's response.

I conducted semi-structured interviews with experts involved in the creation of the LCFS and RFS2 to understand how the LCFS and RFS2 evolved, how each policy managed LCA and attempted to quantify indirect land use change (ILUC), and how scientists and policymakers interacted in each case to manage scientific uncertainty and choose certain accounting tools. The interviews allowed me to gather a variety of perspectives because the experts had different expertise and opinions about the rationality and effectiveness of the analytical approach used in each policy. I conducted the interviews in person (which I recorded with a handheld recorder) and by phone (which I recorded with the iPhone application "TapeACall"), which I then transcribed for future reference. I asked each interview subject different questions depending on their area of expertise - for instance, I asked LCA scholars questions related to ALCA and CLCA while I asked biofuel model experts questions related to biofuel model parameters and assumptions and rationales for choosing particular models in each policy.

RESULTS AND DISCUSSION

Sub Question 1: Uncertainty

Uncertainty in LCA Standards

For my first sub question I investigate how the scientific uncertainty associated with life cycle assessment (LCA) was treated in the LCFS and RFS2. LCA is commonly used to account for the total environmental burden associated with the production, use, and end-of-life of a product or service (Rajagopal and Zilberman 2013). There are two types of LCA: attributional LCA (ALCA) and consequential LCA (CLCA). ALCA provides information about the impacts of a production process while CLCA provides information about the consequences of changes in a production process caused by a policy (Brander et al. 2009). Consequential LCA has emerged over the past two decades and differs from attributional LCA in that it accounts for indirect market-mediated processes outside of the supply-use-disposal chain. Traditionally, LCA's for transportation fuels used the ALCA approach, but CLCA has recently gained prominence as scientists have begun to understand the indirect effects of energy production on climate and the economy (Plevin et al. 2013).

CLCA became more widely discussed after Timothy Searchinger published his landmark study in 2008. It's important to understand that Searchinger's paper was published at a time when few people were talking about or understood indirect land use change (ILUC) or how to apply LCA to bioenergy. Searchinger was not the first to apply LCA to bioenergy or talk about indirect effects. However, he was the first to use economic equilibrium models and CLCA to demonstrate the environmental drawbacks of biofuels and make regulators question biofuels as a sustainable fuel, which is why his analysis received a lot of attention. His paper was published in 2008, right after the RFS2 was implemented and just before the LCFS was implemented, which contributed to the controversy surrounding each policy. Moreover, the widespread publicity of Searchinger's paper effectively made his LCA approach the *de facto* framework for addressing indirect environmental effects, a phenomenon that can be referred to as "anchoring" (Plevin interview). Searchinger's significance cannot be understated, especially since scientists at EPA incorporated his findings at the behest of environmental groups who had early access to his analysis and because his study directly impacted how CARB conducted its LCA analysis.

Searchinger's paper was groundbreaking in two key ways: he and his collaborators shattered the perception of biofuels as a sustainable fuel, and they highlighted the limitations of applying the traditional attributional life cycle assessment (ALCA) to biofuels. Searchinger and his collaborators used a CLCA approach and proved previous ALCA studies had failed to account for the indirect greenhouse gas emissions caused by expanded biofuel production (Wang et al. 2011; Wiloso and Heijungs 2013). Searchinger et al. (2008) illustrated that biofuel production drives land use change and that many biofuels are more carbon-intensive than fossil fuels when the greenhouse gas emissions from indirect land use change are included (Searchinger et al. 2008). These findings shocked the governments of California and the United States, which had originally implemented the LCFS and RFS2 respectively as a way to incentivize biofuel production and, by extension, reduce greenhouse gas emissions. Searchinger's analysis brought the basic premise of both policies into question by showcasing the environmental drawbacks of biofuels. As a result, policymakers in both jurisdictions attempted to account for the negative indirect environmental impacts of biofuels by incorporating fuel-specific ILUC factors, which they generated using economic equilibrium models as part of their revised LCA analyses.

LCA is usually performed according to guidelines specified by the International Standards Organization, which is a network of national standards institutes that creates standards for a range of products and services (Mukherjee and Sovacool 2014; Green 2014). It's important to examine ISO standards because they impacted the treatment and understanding of LCA in both the LCFS and RFS2. Many biofuel mandates don't distinguish between ALCA and CLCA due to the unresolved debate over when it is appropriate to use each method and because the ISO hasn't defined ALCA and CLCA (Plevin et al. 2013; Delucchi interview). While the LCFS and RFS2 discuss the difference between these two approaches, some researchers have criticized the way each policy applied LCA. All LCA studies involve subjective choices over how to define the goal and scope of a study, define the system boundary, select impact categories, weigh impacts, conduct inventory analysis, etc. LCA's of bioenergy are more complicated because they involve additional methodological choices that aren't included in traditional LCA studies, including decisions about how to treat co-products, how to incorporate land use data, and what time horizon to use. While the ISO creates and maintains LCA standards, the ISO never aimed to standardize LCA methods in detail and there is no single method for conducting LCA (Guinee et al. 2010). This may explain why LCA studies of bioenergy often involve arbitrary choices over the system boundary and lack agreement on how to quantify certain impact categories (Wiloso and Heijungs 2013). Biofuel mandates in California and the US have received a lot of criticism since being implemented, which is largely a result of the way these policies applied LCA. As such, researchers have started to question whether LCA is an appropriate analytical framework for bioenergy and to acknowledge the subjective and uncertain nature of LCA.

While LCA studies (both CLCA and ALCA) involve making subjective choices, CLCA is generally considered uncertain when compared to ALCA. However, proponents of CLCA argue that the real world is uncertain and CLCA is capable of properly seeing this uncertainty and is therefore more useful in predicting the full range of a policy's potential environmental outcomes (Plevin interview; Plevin et al. 2013). Meanwhile, supporters of ALCA claim that because ALCA is based on stoichiometric relationships between inputs and outputs and doesn't try to predict indirect effects, it can produce results with known levels of accuracy and precision (Brander 2009). However, the idea that accuracy and precision can be known creates a false sense of objectivity, especially given the subjective choices and lack of standard methodology inherent in LCA studies. The realization that science is influenced by values is not new, but there still appears to be a bias against subjective decision-making within the ISO and many scholars are starting to realize that LCA shouldn't be viewed as flawed because of the presence of values (Hertwich et al. 2000).

However, many researchers still highlight and criticize the subjective choices in CLCA studies as the reason for its methodological uncertainty while the subjective choices and uncertainty in ALCA studies go largely ignored.

Regarding my central research objective, it is important to note that the controversy surrounding biofuel mandates centers on quantifying indirect emissions using CLCA but not on applying ALCA. The debate over CLCA versus ALCA indicates an evident bias against subjective decision-making, which is reflected in the controversy surrounding biofuel mandates in California and the US. Furthermore, scientists have criticized California's application of LCA in the LCFS, which reflects the ISO's lack of guidance on how to apply LCA to policy. LCA played a critical role in how both the LCFS and RFS2 quantified the greenhouse gas emissions from indirect land use change (ILUC) of biofuels, but policymakers at CARB seemed blind to its significance and associated methodological uncertainties, which may explain why CARB's LCA analysis in the LCFS has been accused of containing serious methodological problems. Meanwhile, scientists at EPA didn't have time to question whether LCA was an appropriate analytical framework in the first place. Consequently, they failed to adequately evaluate the uncertainty of LCA as an analytical framework, impacting EPA's entire analysis.

LCA Uncertainty in the United States' RFS2

I argue that the political context in which the RFS2 was implemented created an environment that didn't allow scientists to question the basic premise of the legislation. Consequently, scientists at EPA were able to sufficiently investigate how to apply LCA, but couldn't focus enough energy on questioning the methodological uncertainties of LCA, why they were using LCA in the first place, and whether it was an appropriate analytical framework. Indirect environmental impacts were incorporated into the language of the RFS2 largely behind closed doors and at the behest of environmental groups that had early access to Searchinger's findings on indirect land use change (ILUC) and pressured regulators to incorporate ILUC factors in order to account for some of the negative environmental effects of biofuels (Breetz interview). It is interesting that although scientists at EPA had access to Searchinger's ILUC values, they did not adopt his LCA approach even though his study is what prompted them to account for ILUC in the first place. Searchinger's LCA analysis essentially added together direct emissions from ALCA and indirect emissions from CLCA to estimate the total environmental burden of biofuels, which some have criticized as an inappropriate way to apply LCA because it can double count emissions (Plevin Dissertation 2010; Wang et al. 2011).

Unlike Searchinger and the researchers at CARB, scientists at EPA used CLCA from the beginning, which some researchers consider more methodologically appropriate than CARB's approach because they defined CLCA to include both direct and indirect emissions and apparently better understood the system boundary. Furthermore, they compared the benefits and drawbacks of ALCA versus CLCA, though they did not include a thorough discussion about the uncertainty of either LCA approach in their impact analysis (EPA 2010). House and Senate staff incorporated the language on indirect effects in the RFS2 very quickly as part of a Ping-Pong Reconciliation process behind closed doors. Because of this back-door reconciliation process between House and Senate staff, there isn't direct evidence on how indirect effects or CLCA were incorporated in the legislation (Breetz interview). Therefore, although EPA scientists applied LCA in a way many experts consider reasonable, they didn't have much opportunity to discuss the uncertainties of LCA until they made later revisions to the RFS2. This was translated into the EPA's methodologically questionable uncertainty analysis as I discuss in the following section. Scientists at EPA focused on how to effectively apply the chosen analytical framework (LCA) to quantify indirect land use change (ILUC) without questioning the framework itself in enough detail, which resulted in the incomplete and problematic uncertainty analysis that I discuss in the next section.

LCA Uncertainty in California's LCFS

Policymakers at CARB were under pressure to pass biofuel legislation quickly and put pressure on scientists to generate single fuel-specific ILUC factors, which I argue discouraged scientists from making informative policy recommendations to decision makers about LCA and its associated uncertainty. Language about accounting for indirect emissions from land use change was incorporated into the LCFS verbatim from the RFS2 (EPA 2010; CARB 2009; Plevin interview). Although language on emissions from ILUC is the same in both policies, scientists at CARB modeled their LCA analysis on Searchinger's approach rather than on EPA's approach. Consequently, the methodological choices experts criticized in in Searchinger's LCA analysis were incorporated into CARB's LCA analysis and were likewise criticized. Searchinger is a lawyer, not a scientist, which may explain why his LCA analysis and studies that followed his approach received criticism. Searchinger's credibility was questioned because his background was not considered sufficiently technical, which is an interesting manifestation of boundary work considering that later studies supported his conclusions about the negative impacts of biofuels caused by indirect land use change. However, although later studies supported Searchinger's conclusions, his choice to use LCA over other analytical frameworks warrants investigation, especially because his approach became the *de facto* way of quantifying the indirect environmental impacts of biofuels and influenced CARB's treatment of LCA.

Only a few scientists on CARB's expert workgroup discussed in depth the limitations and drawbacks of applying LCA to bioenergy, including Richard Plevin and Mark Delucchi (Sperling interview). The fact that only a few scientists discussed this phenomenon reflects the large degree of uncertainty within the field of LCA itself and the divide among scientists on CARB's expert workgroup. Unlike scientists at EPA, CARB's expert workgroup questioned LCA as an analytical framework by noting in the technical report that LCA was an evolving field of study with methodological uncertainties and that it might not be the best tool to measure certain phenomena (Breetz interview; CARB 2007; Delucchi interview). Clearly there were scientists at CARB who understood the strengths and limitations of applying LCA to bioenergy. So why wasn't their expertise translated into meaningful policy recommendations? One researcher I spoke with recalled that Mary Nichols (one of the senior policymakers at CARB) asked for an ILUC value but wasn't interested in hearing some of the uncertainties and details surrounding ILUC (O'Hare interview). This account echoes the sentiment expressed by several experts, who spoke of how policymakers were under immense political pressure to pass biofuel legislation quickly and weren't interested in hearing detailed accounts of uncertainty (O'Hare interview; Plevin interview). This reflects the knowledge gap between scientists and policymakers at CARB and may explain why experts only briefly discussed the limitations of LCA in the policy report (Breetz interview; CARB 2007, Part 1; CARB 2007, Part 2). In later revisions to the LCFS, scientists and policymakers recognized the methodological problems in their LCA analysis. However, by that point, there was additional political pressure to keep using the same approach despite its inadequacy because it would have been difficult, time-consuming, and politically damaging to reevaluate the entire intellectual framework of the LCFS (Delucchi interview; Plevin interview).

Sub Question 2: Accounting Tools

Accounting Tools in the United States' RFS2

For my second sub question, I investigate how each jurisdiction's treatment of LCA influenced its choice and treatment of accounting tools – specifically, economic equilibrium models and ILUC factors. While EPA's choice and treatment of accounting tools seem like purely technical decisions, I argue these decisions actually embody value choices influenced by EPA's LCA analysis and other political factors. EPA's LCA analysis impacted its choice and treatment of accounting mechanism because conducting an LCA (whether ALCA or CLCA) requires making subjective decisions about which factors are the most important to quantify. Choosing the most important factors to quantify impacts the choice of accounting mechanism because some models are better predictors of certain factors than others. For instance, general equilibrium models provide coarse detail of the entire economy while partial equilibrium models provide detailed coverage of a few relevant economic sectors. Scientists at EPA chose to apply CLCA to account for both the direct and indirect environmental impacts of biofuels, which usually involves applying either general equilibrium or partial equilibrium models as accounting mechanisms.

EPA selected FAPRI and FASOM (both partial equilibrium models) because, in their view, existing general equilibrium models didn't capture agricultural sector interactions in enough detail and EPA claimed these interactions were critical to their analysis (Delucchi interview; EPA 2010; Plevin interview). Moreover, EPA specifically chose FAPRI and FASOM because the federal government already funded these models to do trade analysis (Kaffka interview). While EPA acknowledged that one of the reasons it chose FAPRI was because it had been used by the USDA Office of Chief Economist, Congress, and the World Bank to examine agricultural impacts from government policy changes, EPA didn't mention funding as a reason for its choice in its impact assessment (EPA 2010). This is interesting from a regulatory science perspective because some of the political factors that influenced some of EPA's technical decisions weren't explicitly acknowledged, which this is further evidence of the need to explore how science-policy interactions shape decision-making. In addition to political factors, scientists at EPA made subjective choices within their CLCA analysis about which economic sectors were the most important to quantify, which clearly influenced their choice of accounting tool. Moreover, these same values influenced the assumptions EPA scientists used to assign values to key model input parameters, which are specified and justified in EPA's impact assessment (EPA 2010). While policy decisions within EPA's CLCA analysis certainly impacted the choice of accounting tool and assumptions of key model input parameters, these decisions impacted EPA's analysis in other key ways.

The way EPA treated CLCA was most significant in how it affected EPA's parametric uncertainty analysis of FAPRI and FASOM. LCA is the analytical foundation of the RFS2, and by failing to adequately discuss the uncertainty of its analytical approach (CLCA), EPA failed to understand and address the uncertainty of its chosen accounting mechanisms; specifically, the parameters used in the FAPRI/FASOM models. Some scholars (including Richard Plevin, whom I interviewed and who was a member of CARB's expert workgroup on the LCFS) have criticized the EPA's uncertainty analysis for being incomplete, claiming it evaluated only the uncertainty of carbon accounting and remote sensing data but treated the input parameters of FAPRI and FASOM as known (Plevin interview; Plevin 2010). EPA's impact assessment substantiates this argument, stating that making accurate predictions of many model parameters wasn't relevant to the analysis and that EPA only incorporated an approach to quantify the uncertainty of satellite data and greenhouse gas emission estimates (EPA 2010). Scientists at EPA generated probability distributions for the factors it included in its uncertainty analysis by using Monte Carlo simulations to quantify the range of possible values for model inputs. However, other researchers have criticized EPA scientists for using the median, rather than the mean, of these probability distributions as the central estimate for each parameter (Farber 2011).

Many experts have criticized EPA's uncertainty analysis for being inadequate because scientist didn't evaluate the uncertainty of the values they assigned to key model input parameters. Choosing what values to assign model parameters involves subjective decision-making, which requires scientists to offer transparent justification for these assumptions, as scientists at EPA did. Moreover, using any type of accounting tool, including economic equilibrium models, requires careful evaluation of which parameters are the least certain and have the greatest impact on model output. Considering the tools and knowledge available to them at the time, it would be unfair to blame EPA scientists for conducting their LCA analysis or applying their accounting tools in methodologically imperfect ways. However, evaluating uncertainty is common practice for any modeling study and scientists at EPA should have known better about evaluating the uncertainty of FAPRI and FASOM's model input parameters. By failing to adequately acknowledge the uncertainty of FAPRI and FASOM's input parameters, scientists at EPA made the fuel-specific ILUC factors generated from these models seem more concrete than they actually were. This understandably upset biofuel producers, who were forced to comply with ILUC factors that were not only uncertain, but for which even the degree of uncertainty was uncertain. The way EPA managed its LCA approach impacted how EPA treated the inputs and outputs of its chosen accounting mechanisms because EPA didn't adequately evaluate the uncertainty of either tool. This highlights the importance of thoroughly understanding both the analytical approach (LCA) and its associated uncertainties before applying it in a regulatory framework.

Accounting Tools in California's LCFS

I argue two major factors influenced how CARB treated the output of its chosen accounting mechanism: the way Searchinger theorized direct and indirect emissions and political pressure to generate single ILUC values. Additionally, a variety of scientific and political factors influenced CARB's choice of particular accounting tools and model parameter assumptions, including scientists' understanding of LCA and uncertainty at the time and pressure from regulators to pass legislation quickly and to prioritize transparency. It's important to remember that the LCFS was passed shortly after Searchinger and his collaborators published their groundbreaking paper in 2008. By that point, the LCFS had been in the works for years and regulators were unwilling to re-do their entire analysis. However, to account for indirect effects, regulators used fuel-specific carbon intensity values and ILUC factors to penalize high-carbon fuels.

CARB used the GTAP general equilibrium model to quantify indirect emissions (CLCA approach) and the GREET model to quantify direct emissions (ALCA approach). CARB selected GTAP over other economic equilibrium models because it was transparent and had a public, open-source code (CARB 2009; Kaffka interview; O'Hare interview; Plevin interview). GTAP's public source code means anyone can open the model to see how it runs and generates its results. People can also take a course to get trained on how to use GTAP, which isn't available for most economic equilibrium models (Kaffka interview; O'Hare interview; Plevin interview). Furthermore, GTAP has a global scope and has long been used to analyze international economic effects (CARB 2009).

CARB did not justify why it chose GREET to quantify direct emissions other than claiming it was the best publicly available LCA accounting tool for fuels (CARB 2007 Part 1). Transparency was one of the most important factors for regulators at CARB, not only in choosing accounting tools, but also in the treatment and communication of model uncertainties. As discussed above, most of the controversy surrounding the LCFS was about the uncertainty of the ILUC factors generated by GTAP (CLCA approach). What's interesting is that the output of GREET (ALCA approach) was arguably just as uncertain because GREET had not undergone rigorous peer review and was not considered adequate by all experts (CARB 2007 Part 1). However, the output of GTAP is what became controversial, which reflects some of the larger uncertainties of applying LCA in policy contexts and the existing bias against CLCA for being more subjective, and therefore considered less accurate, than ALCA.

Some scientists at CARB had a sophisticated understanding of the strengths and weaknesses of applying LCA to bioenergy but had difficulty translating this expertise into meaningful policy recommendations because of political pressure. Despite this pressure, scientists at CARB were transparent in their assumptions of key model input parameters in GTAP and, unlike EPA, performed a thorough parametric uncertainty analysis for the LCFS by generating probability distributions for each model input parameter. However, many regulators at CARB weren't interested in hearing about uncertainty distributions because they wanted to pass the regulation quickly and pressured scientists to generate single fuel-specific ILUC values (O'Hare interview). To appease policymakers, scientists at CARB essentially took different combinations of input parameters and averaged the results, which some have criticized for being an arbitrary choice (Plevin interview; Kaffka interview). Consequently, the ILUC values CARB assigned to particular fuels were essentially arbitrary because policymakers weren't interested in hearing about the parametric uncertainty of GTAP. This indicates how scientists and policymakers at CARB interacted, and is further evidence of not only the knowledge gap between science and policy, but suggests that more research on regulatory science is needed. While the aforementioned political factors clearly impacted how scientists at CARB treated the inputs and outputs of their chosen accounting tools, these weren't the only determinants of how CARB treated the output of its chosen models.

I argue that the way Searchinger theorized direct and indirect emission heavily influential how scientists at CARB treated model output. Searchinger's landmark paper was published shortly before the LCFS was implemented and at a time when even less was known about applying LCA to bioenergy than now, which is why his approach became the *de facto* way of applying LCA to bioenergy. Like Searchinger, scientists at CARB initially viewed greenhouse gas emissions in terms of a binary system (direct versus indirect emissions), the quantities of which required two separate analytical frameworks (ALCA versus CLCA) and two separate accounting mechanisms (GREET versus GTAP) to quantify the total system. In the LCFS, GTAP was used to generate fuel-specific ILUC factors, which describe the quantity of greenhouse gas emissions produced by indirect land use change (ILUC) caused by expanded biofuel production. These ILUC factors were then added to direct fuel emissions to estimate the total greenhouse gas burden of a fuel. The binary view of environmental impacts as either direct or indirect was problematic because it directly affected how CARB inappropriately combined the results of GREET and GTAP.

Scientists at CARB used different accounting tools than Searchinger, but they combined model outputs in the same way. Regardless of the accounting tool, adding direct and indirect emissions from two different LCA's has been criticized of being methodologically inappropriate because it can double count emissions (Plevin Dissertation 2010; Wang et al. 2011). Distinguishing between direct and indirect environmental effects is not necessarily a bad thing, but in the case of the LCFS scientists failed to understand what emissions were included in their separate ALCA and CLCA approaches and, consequently, they inappropriately combined the outputs of each model. The way Searchinger framed indirect and direct effects impacted how CARB framed CLCA and ALCA and may explain why CARB has been criticized for the way it applied its chosen accounting tools to quantify the environmental impacts of biofuels.

Sub Question 3: Interactions and Justifications

Scientists, Policymakers, and Justification of Choices in the United States' RFS2

I argue that there was an epistemological weakness in the way EPA relied on experts to regulate and quantify biofuels, which, in addition to the political context in which the RFS2 was drafted, prevented scientists from thoughtfully addressing scientific uncertainty. As previously mentioned, language on indirect effects was incorporated into the RFS2 at the last minute behind closed doors as part of a Ping-Pong reconciliation process between staff at the House and Senate

(Breetz interview). Given that the language was incorporated at the last minute and non-transparently, it's understandable that scientists at EPA didn't initially address the scientific uncertainty associated with LCA, its chosen accounting mechanisms (FAPRI and FASOM), or ILUC factors because they didn't have time to do so. However, the RFS2 has undergone numerous revisions since then and many experts feel EPA's parametric uncertainty analysis of FAPRI and FASOM remains inadequate. There were clearly other factors that impacted the way EPA managed scientific uncertainty, one of which was an inherent epistemological weakness in EPA's problem-solving approach and the way it relied on experts.

EPA sought input on its lifecycle analysis from a broad range of experts and stakeholders, including specialists from the US Department of Agriculture and Department of Energy as well as policymakers from California and Europe in their parallel efforts to regulate biofuels. However, before making decisions on the final ruling for the RFS2, EPA conducted a formal and independent peer review of its analysis (including its CLCA approach, accounting mechanisms, and uncertainty analysis) based on four key components of its methodology: (1) land use modeling of satellite data; (2) methods to account for the timing of greenhouse gas emissions; (3) greenhouse gas emissions from foreign crop production; and (4) how the models EPA relied on were used to provide overall lifecycle estimates (EPA 2010). However, the peer reviewers addressed only the aspects of the analysis that EPA specified and, consequently, ignored some important questions about the scientific uncertainty of LCA and whether LCA was an appropriate analytical framework for bioenergy. One of the stakeholders I interviewed felt that EPA didn't ask the right questions about LCA, and his opinion is substantiated by the fact that EPA didn't discuss or justify the uncertainty of LCA in its regulatory impact analysis (EPA 2010; Plevin, interview).

EPA also did not perform a thorough parametric uncertainty analysis, which may have occurred because policymakers at EPA relied only on advice from experts it specifically consulted. When I interviewed Richard Plevin, he substantiated this argument by claiming EPA didn't investigate his comments (he was then a graduate student working on analysis for a coalition of environmental groups but was later a member of CARB's expert workgroup) about some of the problems in EPA's analysis. Plevin claimed EPA justified ignoring his concerns on the basis that none of its consulted experts had pointed out the problems he highlighted (Plevin interview). EPA may have also ignored Plevin's concerns because at the time he was a graduate student and was not considered a credible expert, which could be an interesting manifestation of boundary work regarding the types of advice that is considered legitimate. While EPA did appear to accept advice only from its chosen experts, EPA gathered input from a wide variety of stakeholders from academia, government, NGO's, and the public. If EPA gathered sufficient diversity of stakeholder opinions and expert judgment, this could justify EPA's reliance on only its chosen experts and stakeholders because arguably if there were problems, some of these experts or stakeholders would have mentioned it.

While choosing to rely solely on chosen experts is justifiable, the way policymakers at EPA solicited advice from these experts and peer reviewers prevented them from seeing serious methodological problems and knowledge gaps in their analysis. It also prevented scientists from questioning the premise of the RFS2 itself. As I previously outlined, EPA asked peer reviewers to address a certain set of concerns – specifically, to evaluate how EPA managed its chosen accounting mechanisms (component 4), the uncertainty of satellite data (component 1), and the uncertainty of greenhouse gas emissions data (components 2 and 3) (EPA 2010). This is a clear epistemological weakness because policymakers and scientists at EPA ignored important questions without realizing they were ignoring these concerns because of the way they solicited expert advice. EPA received feedback only on the concerns it specifically addressed but not on other problematic parts of its analysis. This epistemological weakness manifested in the form of structural blindness because EPA limited the scope of its peer review without allowing further exploration of other aspects of the analysis that needed improvement. For instance, EPA's inadequate parametric uncertainty analysis wasn't included in the questions it asked peer reviewers to address even though this aspect of EPA's analysis needed improvement. The way policymakers at EPA interacted with experts had a serious impact on EPA's entire analysis for the RFS2, not just the way it handled scientific uncertainty.

Scientists and policymakers at EPA relied on experts to justify how they managed scientific uncertainty and for their choice to use CLCA and particular accounting tools. I have already discussed *how* EPA managed the scientific uncertainty of LCA in the first part of my Discussion section for sub question 1, but questions remain concerning how EPA *justified* the way it managed the uncertainty of LCA and its choice of analytical framework (CLCA) and accounting tools (FAPRI and FASOM). EPA discussed the benefits and drawbacks of CLCA versus ALCA in its impact assessment and justified applying CLCA by claiming ALCA didn't capture indirect effects (EPA 2010). However, while the EPA justified its choice of CLCA over ALCA, it didn't discuss the uncertainty surrounding either approach and likewise didn't provide justification for this lack of discussion. Furthermore, EPA only conducted an uncertainty analysis for the satellite data and greenhouse gas emission factors used in its analysis, but not for the input parameters used in FAPRI and FASOM. EPA justified its inadequate parametric uncertainty analysis by claiming peer reviewers had reviewed the initial uncertainty analysis and that EPA had incorporated their feedback in its updated uncertainty analysis (EPA 2010). However, as I have already demonstrated, the way EPA relied on expert advice was problematic because by asking peer reviewers to address only a narrow set of questions, EPA was essentially blind to other relevant concerns. Consequently, EPA's uncertainty analysis was still inadequate even after incorporating the advice from peer reviewers. The way EPA solicited advice from experts prevented it from considering the full range of potential outcomes of implementing the RFS2, alternative management options, and other methodological weaknesses that needed correction.

Scientists, Policymakers, and Justification of Choices in California's LCFS

In regulatory frameworks, communication between scientists and policymakers is often difficult because scientists may be frustrated that policymakers can't understand scientific results while policymakers may be frustrated because scientists don't give clear, concise answers in an understandable language (Kurth and Glasmacher 2011). The way policymakers and scientists interacted in the case of the LCFS is especially complicated because of the disagreement among members of CARB's expert workgroup. If scientists CARB disagreed with each other and had difficulty communicating and reaching a consensus, then it shouldn't have been surprising that these scientists had difficulty communicating their insight to policymakers in the policy report. The fact that many policymakers weren't interested in hearing about uncertainty distributions and wanted a concrete ILUC values is also indicative of this difficulty in communication between scientists and policymakers (O'Hare interview). The way scientists interacted with each other and with top decision makers at CARB may explain how they managed and justified scientific uncertainty in the LCFS.

I argue that policymakers at CARB were willing to tolerate a high degree of uncertainty in the LCFS because they wanted to protect the environment and be seen as leaders in environmental governance. This is evident in the language policymakers and scientists used to justify incorporating uncertain ILUC factors generated by the GTAP model in the LCFS. As previously mentioned, several scientists on CARB's expert workgroup discussed the benefits and drawbacks of applying LCA to bioenergy and its associated uncertainty and CARB's expert workgroup also performed a thorough uncertainty analysis for the input parameters for GTAP. While scientists at CARB included thorough discussions of scientific uncertainty related to LCA, GTAP, and ILUC factors in the technical report, they were under pressure from regulators to generate single, fuel-specific ILUC values for use in the LCFS. Consequently, they used different combinations of input parameters in GTAP and averaged the results to generate their ILUC estimates, resulting in arbitrarily assigning ILUC values to biofuels (Plevin interview; Kaffka interview).

Both scientists and policymakers at CARB justified assigning arbitrary ILUC values by claiming they knew the value of ILUC was a non-zero number and that it was better to assign an arbitrary value than assume zero emissions (Breetz interview; Kaffka interview; Sperling interview). Moreover, they argued it was important to send the right signal by assigning values to ILUC in the LCFS (Breetz interview; Sperling interview). They believed that models like GTAP would improve over time and that eventually they would be able to generate more accurate ILUC values that they could later correct (Breetz interview; Kaffka interview). The language about sending the right signal supports my argument that CARB wanted to protect the environment and be seen as a leader in environmental governance because a signal can only be right or wrong depending on the values and goals of the organization. By sending the right signal, CARB was arguably saying that it wanted to regulate and penalize unsustainable fuels and, by extension, demonstrate that it was taking steps to address climate change through the regulatory mechanisms of the LCFS. After all, California has a history of passing innovative environmental regulations (such as AB 32) and the whole point of assigning ILUC factors in the LCFS was to account for the indirect greenhouse gas emissions caused by the expanded production of biofuels. The fact that much of the discourse surrounding greenhouse gas emissions revolves around mitigating and adapting to climate change supports my argument about CARB wanting to protect the environment and be a first-mover in environmental regulation.

While both scientists and policymakers used the aforementioned arguments to justify the high degree of uncertainty surrounding CARB's ILUC values in the LCFS, not all scientists at CARB agreed. I have briefly touched on the fact that there were methodological disagreements among members of CARB's expert workgroup, many of whom were researchers from UC

Berkeley and UC Davis. The experts on the workgroup who were critical of applying LCA to bioenergy (including Mark Delucchi, Richard Plevin, and Michael O'Hare) were wary of how CARB decided to use fuel-specific ILUC factors and assign them essentially arbitrary values. While these experts were critical of CARB's approach, several of them acknowledged that CARB was trying to solve a problem to which there were no ready or available tools and that it used the tools that were available in the best way it knew how (Plevin interview; O'Hare interview). However, these experts didn't hesitate to point of the flaws of assigning arbitrary values for ILUC and criticized the way CARB summed direct and indirect emissions from two different LCA approaches and models (Delucchi interview). Meanwhile, other members of the expert workgroup (including Stephen Kaffka and Daniel Sperling) supported the way CARB assigned ILUC values and echoed the language of sending the right signal and justified describing ILUC as a non-zero number (Kaffka interview; Sperling interview).

BROADER IMPLICATIONS

Although my research focuses on biofuel policies in California and the United States, my findings offer insight about the role of science in informing policy decisions and the ambiguity of applying LCA within and outside of policy contexts. I previously mentioned that all LCA studies involve making subjective decisions about defining the system boundary, choosing impact categories, and assigning values to particular impact categories. Moreover, there isn't a standard way to conduct attributional or consequential LCA, yet ALCA is commonly used to quantify the total environmental impacts of individual products and its results are treated as concrete and objective despite the lack of standard methodology for conducting ALCA. My findings showcase the subjective nature of LCA, the lack of agreement on standard ways to conduct LCA, and illustrate the need for scientists to recognize and accept that values are inherent to LCA and not view these tools as flawed because of the presence of values (Hertwich et al. 2000).

Moreover, my findings illustrate the need for more research on how knowledge is generated and applied in different policy contexts. Society relies on scientists and experts for authoritative knowledge claims, but producing knowledge to aid decision makers introduces political and other factors that influence how that advice is applied. By exploring the role of

LCA in quantifying indirect environmental impacts in each policy I illustrated how expert advice was solicited, weighed, and used to inform policy decisions in the RFS2 and LCFS and how it contributed to the controversy surrounding each policy. While I was able to answer some questions about the role of uncertainty, accounting tools, and justifications in both cases, my investigation raised more questions about these complex science-policy interactions in other regulatory contexts, which warrants further research. Understanding these interactions in other policy contexts is crucial to producing policies that rely on expert advice in ways that are considered legitimate by stakeholders and solve the problem policymakers set out to address.

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APPENDIX A: Abbreviations

LCA: Life Cycle Assessment

CLCA: Consequential Life Cycle Assessment (indirect effects)

ALCA: Attributional Life Cycle Assessment (direct effects)

ILUC: Indirect Land Use Change

LCFS: Low Carbon Fuel Standard (California's biofuel mandate)

RFS2: Renewable Fuel Standard (United States' biofuel mandate)

EISA: Energy Independence and Security Act

EPA: Environmental Protection Agency

AB 32: Assembly Bill 32 (aka: the Global Warming Solutions Act of 2006)

CARB: California Air Resources Board

ISO: International Standards Organization

GTAP: General Trade Analysis Project (California's accounting tool for indirect effects)

GREET: Greenhouse gases, Regulated Emissions, and Energy use in Transportation (California's accounting tool for direct effects)

FAPRI: Food and Agricultural Policy Research Institute (US accounting tool)

FASOM: Forestry and Agricultural Sector Optimization Model (US accounting tool)