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Some Inconvenient Truths About Climate Change Policy: The Distributional Impacts of Transportation Policies

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Some Inconvenient Truths About Climate Change Policy: The Distributional Impacts of Transportation Policies

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Abstract

Instead of efficiently pricing greenhouse gases, policy makers have favored measures that implicitly or explicitly subsidize low carbon fuels. We simulate a transportation-sector cap & trade program (CAT) and three policies currently in use: ethanol subsidies, a renewable fuel standard (RFS), and a low carbon fuel standard (LCFS). Our simulations confirm that the alternatives to CAT are quite costly—2.5 to 4 times more expensive. We provide evidence that the persistence of these alternatives in spite of their higher costs lies in the political economy of carbon policy. The alternatives to CAT exhibit a feature that make them amenable to adoption—a right skewed distribution of gains and losses where many counties have small losses, but a smaller share of counties gain considerably—as much as $6,800 per capita, per year. We correlate our estimates of gains from CAT and the RFS with Congressional voting on the Waxman-Markey cap & trade bill, H.R. 2454. Because Waxman-Markey (WM) would weaken the RFS, House members likely viewed the two policies as competitors. Conditional on a district's CAT gains, increases in a district's RFS gains are associated with decreases in the likelihood of voting for WM. Furthermore, we show that campaign contributions are correlated with a district's gains under each policy and that these contributions are correlated with a Member's vote on WM.

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1 Introduction

Economists often point to Pigouvian taxes and cap & trade programs as the preferred policy tools for reducing externalities. In contrast, to reduce greenhouse gas emissions, policy makers have relied on a number of alternatives that center around either explicit or implicit subsidies. Given the inherent inefficiency of these alternatives, what explains the persistence of these policies in spite of their higher costs? We provide evidence that the answer lies in the political economy of climate change policy.

In the transportation sector, the policies currently in place essentially translate into subsidies for biofuels, most notably ethanol.[1,2]Two major policies exist at the national level: direct subsidies to ethanol and the Renewable Fuel Standard requiring minimum levels of ethanol consumption each year, which we show acts as an implicit subsidy for ethanol. In addition, California recently adopted a Low Carbon Fuel Standard which requires the average greenhouse gas content of fuels to fall over time; Holland, Hughes, and Knittel (2009) show that a LCFS acts as an implicit subsidy for any fuel with a greenhouse gas content below the standard and that a LCFS can be highly inefficient.

We construct a model of advanced biofuels in the transportation sector and compare the equilibrium outcomes across carbon trading (CAT) and the three policy alternatives that currently exist: direct subsidies for renewable fuels (SUBs); renewable fuel standards (RFSs); and low carbon fuel standards (LCFSs). In particular, for each policy, we simulate prices, quantities, changes in farming activity, and changes in private surplus at the county level. Our results represent long run equilibria in the liquid fuels market by exploiting feedstock-specific ethanol supply curves that solve a GIS-based optimal ethanol plant location problem for the US in 2022. Our simulations confirm that the alternatives to CAT are quite costly. Under CAT, average abatement costs are \$20 per metric ton of carbon dioxide equivalent (\$/MTCO_2e). Costs under the alternative policies are substantially higher at \$50 to \$80 per MTCO_2e.[3]

While the alternatives to CAT are more expensive, they differ considerably in both their incidence and the variance in the annual per capita gains and losses across counties. We find that the alternatives to CAT exhibit a feature that make them more amenable to adoption—a right skewed distribution of annual per capita gains and losses where many counties have small losses,

[1]Prominent policies in the electricity sector, also implicitly or explicitly subsidize low carbon fuels.

[2]Ethanol is a biofuel produced by converting corn or other plant material into alcohol. .

[3]We constrain the emission reductions under CAT and the LCFS to be equal to those under the RFS. The emission reductions under SUBs are actually roughly 30 percent lower than these.

but a smaller share of counties gain considerably. For example, under SUBs we find that 5 percent of the counties gain more than $1,250 per capita, while one county gains $6,600 per capita; but, no county loses more than $100 per capita. In contrast, the 95th percentile county under CAT gains only $70 per capita, with no county gaining more than $1,015 per capita. Furthermore, the gains are more concentrated in the sense that the winning-counties are less populated, while small losses are spread over heavily populated counties. Nationally, the average *person* loses $30 per capita under the SUBs, but the average *county* gains $180 per capita,. Under the RFS, the average person loses $34, while the average county gains $160. Similar characteristics exist with the LCFS. This contrasts considerably with CAT, where the average person loses only $11 per year, but the average county gains less than $3 per capita.

To test whether our simulation results translate into political incentives, we correlate our estimates of county-level gains and losses with Congressional voting on H.R. 2454, better known as the Waxman-Markey cap & trade bill. One provision in Waxman-Markey was a new accounting of ethanol carbon emissions that would substantially weaken the RFS. Therefore, House members likely viewed the two policies as substitutes. We find that, holding a district's per capita gains CAT and House member's party affiliation constant, the greater the district's RFS gains, the *less* likely the House member voted for Waxman-Markey. In addition there is some evidence of the opposite effect, *i.e.* that holding a district's per capita gains under the RFS and the House member's party affiliation constant, the greater the district's CAT gains, the *more* likely the House member voted for Waxman-Markey. The effects are substantial. The probability that a House member votes for Waxman-Markey falls by 40 percentage points when a district's gains from the RFS increase from the first to the fourth quartile. Similar effects exist when correlating voting behavior with subsidies. The results remain significant even after controlling for measures of House member's political ideology, state and district-level carbon emissions from sources other than transportation, and current corn production.

We also investigate one of the major mechanisms through which the district-level gains and losses influence voting behavior. In particular, we correlate campaign contributions from organizations that either supported or opposed WM with our district estimates of the gains and losses from the RFS and CAT. We find that the greater a district's gain from the RFS, the more money the district's House Member received from organizations opposing Waxman-Markey. Over a two year period around the Waxman-Markey vote, a Member whose district falls in the upper quartile of RFS gains and the bottom quartile in terms of CAT gains receives roughly $33,000 more from organizations opposing Waxman-Markey compared to a member whose district is in the bottom quartile of RFS gains and the upper quartile of CAT gains. This represents over a fourfold increase from the average member. When we correlate voting behavior with contributions, we find large reductions in the likelihood of voting for Waxman-Markey with opposition contributions and large increases with contributions from supporting organizations.

The results with respect to campaign contributions are further supported when we consider how the policies differ with respect to their incidence across consumers and different types of producers. Consumer surplus losses are largest under CAT at approximately $65 billion per year. However, this ignores the $59 billion of potential revenue if the permits were auctioned and the revenue returned to consumers. Under the RFS and LCFS, consumer surplus falls by $27 and $29 billion per year, respectively. Consumer surplus remains unchanged under subsidies.

Producer surplus increases under *all* policies (even ignoring any free allocation of permits under CAT), but the increases vary considerably both across policies and across types of ethanol producers.[4] The $2.5 billion increase in producer surplus under CAT comes from changing the marginal fuel from gasoline to ethanol. By doing so, the price increase more than offsets the increase in costs associated with fuel production under CAT. In the public discourse surrounding Waxman-Markey and other cap & trade bills at the national and state levels, firms argued that free permits were required to "make them whole" in the presence of rising costs; this argument ignores the change in equilibrium prices arising from increases in costs, that can in principle, more than offset the aggregate increase in costs.

These arguments underscore one of the other major differences between cap & trade and its alternatives. Under the cap & trade programs that have been either proposed or implemented, including WM, allocation of free permits in the transportation sector have gone to gasoline refiners, since they are able to point to higher costs under the legislation. Ethanol producers cannot make such arguments. Therefore, while we simulate that producers gain under all policies, which *types* of producers gain varies dramatically across policies

Under subsidies, the RFS and the LCFS, producer surplus increases by approximately $20 billion per year. Therefore, the alternatives to cap & trade not only alter the distribution of net gains and losses, but they also redirect gains to ethanol producers at the expense of consumers.

Our results add to a large literature analyzing the relationship between policy and the gains of stakeholders. Both Seltzer (1995) and Kroszner and Strahan (1999) model Congressional voting behavior as function of both ideology and the interests of legislator's constituents. Both papers find strong evidence that both stakeholder gains and ideology correlate with voting behavior. Also related are papers that model the outcomes of policy changes. For example, Wright (1974) and

[4] By assumption, gasoline producers receive no surplus in our model.

Fleck (2008) correlate state-level expenditures in the New Deal with Senator influence and economic variables. They find that the power of the states' Senators explains gains even when conditioning on the states' need. Knittel (2006) models the adoption of state-level electricity regulation during the beginning of the 20th century and finds that interest group strength explains adoption. More recently, Cragg and Kahn (2009) correlate voting behavior on anti-carbon legislation with political ideology and per capita emissions and finds that higher emissions are correlated with a lower probability of voting for carbon-reducing legislation. Similarly, we find that stakeholder gains are correlated with voting.

More fundamentally, our analysis relates to research on the private-interest theory of regulation. This theory characterizes the regulatory process as one in which well-organized groups capture rents at the expense of more dispersed groups (see Stigler (1971), Peltzman (1976), Becker (1983), and Kroszner and Strahan (1999)). This theory has been effective in explaining regulations (e.g., regulatory barriers to entry) that are difficult to rationalize with the public-interest theory of regulation in which government interventions correct market failures and maximize social welfare (see Joskow and Noll (1981)). Kroszner and Strahan (1999) provide evidence that the private-interest theory also helps explain the removal of regulations in the banking sector. However, in each of these cases, the test of the private-interest theory rests on correlating whether or not a regulation is adopted or removed with *proxies* of interest group gains and losses.

In contrast, our analysis compares Congressional voting behavior with simulated interest group gains and losses from two *alternative* regulations with the same public-interest goals: reducing greenhouse gas (GHG) emissions. This provides a much more direct test of the private-interest theory since we control for the level of environmental benefit of the two regulations. Our analysis shows strong support for the private-interest theory. We find that the regulation with more concentrated private benefits is maintained over the competing regulation with higher social benefits but with less concentrated private benefits. Moreover, we show evidence that the well-organized groups are able to use their influence (i.e., campaign contributions) in a manner consistent with the private-interest theory.

There is considerable uncertainty about the GHG emissions of biofuels. Recent studies argue that ethanol from corn or herbaceous energy crops has lower lifecycle GHG emissions than gasoline Liska et al. (2009).[5] Others are more cautious, Farrell et al. (2006) and Fargione et al. (2009), citing the importance of understanding how cultivating energy crops for ethanol production shifts agricultural activity, so-called indirect land use changes. The magnitudes of these effects are highly

[5]Throughout this paper, "GHG emissions" refers to lifecycle greenhouse gas emissions.

uncertain. In an influential paper, Searchinger et al. (2008) argue that once indirect land use changes are taken into account, GHG emissions for ethanol may exceed the GHG emissions of gasoline. This result is not without controversy. For example, some authors Tyner et al. (2010) argue that once changes in both international trade and crop yields are accounted for, corn ethanol results in fewer GHG emissions than gasoline, despite indirect land use changes.

Given the uncertainty in the relative GHG emissions of gasoline and ethanol, policies that promote biofuel production *may* inadvertently increase GHG emissions. Importantly, the indirect land use effects, and thus the uncertainty associated with the actual GHG emission reductions from a given policy, depend crucially on the direct land use effects. We show that land-use effects may differ substantially for different carbon policies. The alternatives to CAT also result in large shifts in agricultural activity and land use. Other unintended consequences may result from policies with substantial shifts in agricultural activity. For example, nutrient run-off, soil erosion, groundwater contamination, habitat destruction, and aquifer depletion are likely to be exacerbated as biofuel production increases, especially for feedstocks using cultivated lands. Finally, an increase in cultivated lands devoted to biofuels puts upward pressure on prices for food-related crops, increasing the regressivity of biofuel policies. Incorporating these additional costs increases average abatement costs by \$1 to \$6 per $MTCO_2e$ for the CAT alternatives, but essentially does not increase average abatement costs for CAT. Furthermore, the risks associated with underestimating biofuel emissions are substantial for CAT alternatives.

These calculations assume that the lifecycle GHG emissions of the different varieties of ethanol are regulated at their true values. Difficulty in measuring emissions of biofuel production processes, and the politics of setting emissions rates, creates the possibility of errors in the assigned carbon intensities. This situation can lead to "uncontrolled emissions" if for example indirect land use effects are larger than assigned. In this case, policies that result in larger land-use changes may have emissions that exceed the intended level. To quantify these effects, we model a scenario where the actual carbon intensity of corn ethanol is 10% higher than assigned. Under the LCFS, uncontrolled emissions are approximately 5% of the stated policy goal. Under the RFS, the fraction grows to 8%. In contrast, uncontrolled emissions under CAT are only 1% of the target level. This highlights a desirable feature of carbon trading, namely that emissions are less sensitive to errors in assigning emissions factors relative to alternative policies.

The remainder of the paper is organized as follows. Section 2 summarizes the current set of transportation-related GHG policies. Sections 3 & 4 describe our theoretical framework, data and simulation methodology. Sections 5, 6, 7, & 8 present our main results. Section 9 describes a number of robustness checks and Section 10 concludes.

2 Policy background

A variety of policies exist that either directly or indirectly promote biofuels at both the federal and state levels. The most relevant direct subsidy is the Volumetric Ethanol Excise Tax Credit (VEETC). Under this policy, fuel blenders receive a 45 cent tax credit per gallon of ethanol sold. The VEETC was established in 2004 as a 51 cent tax credit under the JOBS Creation Act and extended in 2008 via the Farm Bill, dropping the rate to 45 cents once annual sales of ethanol exceed 7.5 billion gallons, which they now do. Prior to the VEETC ethanol received an implicit subsidy (relative to gasoline) as it was exempt from the federal fuel-excise tax beginning in 1978. The 2008 Farm Bill establishes a subsidy for producers of cellulosic ethanol of $1.01 per gallon tax credit minus the applicable VEETC collected by the blender of the cellulosic ethanol. In addition, producers with less than 60 million gallons of production capacity are entitled to a Small Ethanol Producer Tax Credit of $0.10 per gallon.

We note that these figures actually understate the subsidy level because they are on a per-gallon basis, not on a per-energy basis. One gallon of ethanol has roughly 66 percent of the energy content of a gallon of gasoline; implying, it requires 1.52 gallons of ethanol to displace one gallon of gasoline. Therefore, on a per gallon of gasoline equivalent (gge) basis, corn-based ethanol receives a 68 cent per gge subsidy; 84 cents for a small producer. Cellulosic ethanol receives a $1.53 per gge subsidy.

The other major federal ethanol policy is the Renewable Fuel Standard (RFS). The first RFS was adopted as part of the Energy Policy Act of 2005. The 2005 RFS required 7.5 billion gallons of ethanol by 2012.[6] The Energy Independence and Security Act (EISA) of 2007 expanded the RFS considerably, known as RFS-2. Not only does the new RFS increase the minimum ethanol requirements, it also differentiates ethanol by its feedstock and lifecycle greenhouse gas content; biomass-based diesel is also included. Four categories are created. Each of the four categories qualifies as renewable fuel, defined as ethanol and bio-diesel with lifecycle emissions at least 20 percent below those of gasoline. However, the 20 percent requirement only holds for renewable fuel facilities that commenced construction after December 19, 2007. Existing facilities are grandfathered, therefore, the actual greenhouse gas savings from these facilities are unknown. The second category is "Advanced Biofuel," defined as renewable fuel with lifecycle emissions at least 50 percent below those of gasoline. "Biomass-based" diesel is bio-diesel with emissions at least 50 below petroleum-based diesel. Finally, cellulosic biofuel is a renewable fuel with lifecycle emissions at least 60 percent below gasoline or petroleum-based diesel. When fully implemented in 2022, the new

[6] Current gasoline consumption is approximately 138 billion gallons per year. Because of the lower energy content of ethanol, 7.5 billion gallons displaces roughly 5 billion gallons of gasoline.

RFS calls for 36 billion gallons of biofuel, with 21 billion gallons coming from advanced biofuels, where advanced biofuels have a lower GHG content than corn-based ethanol.

In contrast to the RFS and subsidy policies, a national cap & trade system would price the carbon emitted by all transportation fuels. The 2009 House of Representatives bill, H.R. 2454 or the "Waxman-Markey" bill would have established a broad national cap & trade system. The bill would have set legally binding limits on greenhouse gases with the goal of reducing emissions 17% below 2005 levels by 2020.[7] In addition, the bill contained specific provisions aimed at addressing leakage and deforestation and supporting research and development for low carbon technologies. H.R. 2454 would also have severely reduced the benefits to a large number of ethanol producers under the existing RFS by including indirect land use effects in the lifecycle emissions of ethanol. While the magnitudes of the EPA-assigned indirect land use effects for each of the ethanols are unknown, the figures used for recent Californian legislation imply that many corn-based ethanol producers would no longer qualify as having emissions that are 20 percent below gasoline.

Waxman-Markey's effect on the RFS-2 and agriculture was clearly in the consciousness of lawmakers. Just prior to the house vote, House Agriculture Committee Chairman Collin Peterson (D - MN) and House Energy and Henry Waxman (D - CA) agreed on an amendment to Waxman-Markey that would prohibit the EPA from imposing indirect land use change adjustments to the RFS-2 for 5 years. After that period, the Secretaries of Agriculture and Energy along with the EPA must agree on the indirect land use change calculations.[8] With this amendment, the bill passed the U.S. House of Representatives on June 26, 2009 by a margin of 219 for to 212 against. In July of 2009, H.R. 2454 was placed on the Senate calendar, though a vote never occurred. On July 22, 2010 Senate Majority Leader Harry Reid (D - NV) was cited as abandoning the original bill in favor of a scaled-down version without emissions caps, Chaddock and Parti (2010).

In addition to federal policies, a number of state-level policies exist. Many states have additional subsidies for biofuels, as well as minimum blend levels of ethanol in gasoline.[9] A more recent policy is the Low Carbon Fuel Standard, adopted in California in 2009 requiring the state to reduce the average carbon intensity of transportation fuels 10 percent by 2020. The California LCFS has also been influential at the Federal level. Early versions of the Waxman-Markey Energy Bill would have created a national LCFS similar to California's system.

[7] Also known as the "American Clean Energy and Security Act of 2009."

[8] http://www.greencarcongress.com/2009/06/peterson-20090626.html.

[9] For example, Iowa awards a retail tax credit of 6.5 cents per gallon for ethanol sales above a minimum percentage. Minnesota requires all gasoline sold contain at least 10% ethanol (E10). Many states have similar policies. For a full listing, the reader is referred to http://www.afdc.energy.gov/afdc/laws/state.

3 Theoretical framework

This section builds a common theoretical framework for analyzing the four policies studied in the paper: SUBs, RFSs, LCFSs, and CAT. Let $q_1, q_2 \ldots, q_{n-1}$ be quantities of ethanol fuels, *e.g.,* corn or cellulosic ethanol, and q_n be gasoline where $mc_i(q_i)$ is the marginal cost of producing the ith fuel (with $mc_i' \geq 0$) and β_i is its carbon emissions rate. Throughout we assume that all fuels are measured using energy equivalent units and that fuels are perfect substitutes after controlling for energy content.[10] Let p be the common price of all the substitute fuels, and let $D(p)$ be the market demand for fuel. For ease of exposition, as in Holland, Hughes, and Knittel (2009), we model a single, representative, price-taking firm which produces all types of fuels. These market results hold for heterogeneous firms under trading, which is allowed for by all currently proposed policies.

For welfare calculations, we follow the usual assumptions that consumer and producer surplus can be calculated from the demand and supply curves. Except for the externality from greenhouse gas emissions, we assume that there are no additional distortions.[11] In particular, for transfers from the general funds (only required for the ethanol subsidies), we assume that funds can be raised without additional costs; we also ignore any potential benefits from using permit revenues to reduce other, distortionary, taxes.[12]

3.1 Ethanol subsidies

Suppose ethanol fuel i receives an ethanol subsidy s_i. In an unregulated competitive market, the firm will produce until the marginal cost of each fuel equals the fuel price. However, the ethanol fuels are subsidized, and, as is well known, a subsidized firm produces until marginal cost less the subsidy equals the market clearing price. This implies:

$$p = mc_i(q_i) - s_i \tag{1}$$

for each ethanol fuel. For gasoline, the firm produces until marginal cost equals price. These n equations determine supply from each of the n fuels at a given price. The equilibrium price is

[10] Recent studies by Anderson (2010) and Salvo and Huse (2011) provide evidence that consumers may not treat high-level ethanol blends (e.g. E85 or E100) and gasoline as perfect substitutes. There is little evidence that consumers perceive low-level ethanol blends as substantially different from gasoline.

[11] Holland (2009) shows that the relative efficiency of policies may change in the presence of additional market distortions such as incomplete regulation or market power.

[12] See Goulder (1995) for a discussion of the double-dividend.

determined by market clearing:

$$D(p) = \sum_{i=1}^{n} q_i. \tag{2}$$

Solving for the equilibrium price and quantities involves solving a system of $n + 1$ equations. The equilibrium for a baseline without subsidies can be solved similarly by setting $s_i = 0$ for all fuels.

3.2 Renewable fuel standard

A renewable fuel standard (RFS) sets a minimum quantity (or proportion) of "renewable fuel" that must be produced in a given year, but does not explicitly consider the carbon emissions of the fuels. However, the current Federal RFS sets different standards for three types of renewable fuels (cellulosic, advanced, and total) in a manner that roughly reflects carbon emissions. Appendix Table 1 shows the current standards for 2010, 2015, and 2022. The three categories are additive, *i.e.,* cellulosic fuel is counted toward the advanced requirement and advanced fuel is counted toward the total requirement. The Federal RFS classifies ethanol produced from agricultural waste and energy crops, which are expected to have the lowest lifecycle GHG emissions, as cellulosic. Ethanol produced from food waste (municipal solid waste) is classified as advanced, and total renewable fuel captures other renewable fuels, *e.g.,* corn ethanol, which have higher emissions than advanced or cellulosic fuels.

To implement the policy, the EPA translates the volumetric targets into proportional targets (which we call *RFS ratios*) by projecting gasoline demand for the upcoming year. Each RFS ratio is then the volumetric renewable target divided by the projected gasoline demand.[13] Let σ_{RFSj} be the jth RFS ratio with $j \in \{\text{cellulosic, advanced, total}\}$. For each gallon of gasoline produced, the representative firm would be required to produce σ_{RFSj} gallons of gasoline equivalent (gges) of the jth type of ethanol. Note that whether or not the regulation meets the volumetric ethanol target will depend on the accuracy of the EPA's forecast of gasoline production.[14]

To allow ethanol production by the least cost firms, Renewable Identification Numbers (RINs) are created for each gge of renewable fuel.[15] These RINs are then freely traded and are used to demonstrate compliance with the RFS. The RINs (and their market prices) are differentiated by the three types of ethanol. Let p_{RINj} be the price of the jth type of RIN. Since an ethanol producer can sell a RIN with every gge of ethanol produced, the RINs act as a subsidy to ethanol production.

[13] See Federal Register Vol. 75, No. 58; Friday, March 26, 2010; Rules and Regulations.

[14] In the simulations, we endogenously update the ratios so that the volumetric targets are met.

[15] In practice, the RINS are for gallons of ethanol and energy volumes are adjusted later. For ease of exposition, we simply focus on gges.

Thus in the equilibrium:

$$p = mc_i(q_i) - p_{RINj}, \tag{3}$$

where ethanol i is of type j and p_{RINj} is the price of a RIN of type j. The RINs also are an implicit tax on the production of gasoline since production of each gge of gasoline increases the renewable obligation of each type of ethanol. Thus, in equilibrium, the optimality condition for gasoline is:

$$p = mc_n(q_n) + \sum_{j \in \{cellulosic, advanced, total\}} \sigma_{RFSj} p_{RINj}. \tag{4}$$

These n equations define the quantities of each fuel for given fuel and RIN prices. The equilibrium fuel and RIN prices are determined by market clearing for fuel as in Equation 2 and for each type of ethanol, *e.g.,* $\sigma_{RFStotal} q_n = q_1 + \cdots + q_{n-1}$. Note that the market clearing conditions for the other two ethanol types need not hold with equality due to the additive nature of the constraints. For example, if cellulosic ethanol is cheap to produce on the margin relative to advanced ethanol, then the cellulosic constraint might not hold with equality. In this case, the RIN prices would be equal for these two types of ethanol. Note that since the constraints are additive, the RIN prices must be such that $p_{RINcellulosic} \geq p_{RINadvanced} \geq p_{RINtotal}$.

3.3 Low carbon fuel standard

Under an LCFS, the average emissions intensity, defined as emissions divided by total energy output, may not exceed the standard σ_{LCFS} Holland, Hughes, and Knittel (2009).[16,17] This constraint is given by:

$$\frac{\beta_1 q_1 + \beta_2 q_2 + \cdots + \beta_n q_n}{q_1 + q_2 + \cdots + q_n} \leq \sigma_{LCFS}. \tag{5}$$

Firms adjust total fuel output and the relative quantities of fuel produced to comply with the regulation. The first order condition for profit maximization for fuel i is:

$$p = mc_i(q_i) + \lambda_{LCFS}(\beta_i - \sigma_{LCFS}), \tag{6}$$

where λ_{LCFS} is the shadow value of the constraint in Equation 5 (or equivalently, the price of carbon under a LCFS). Notice that if the emission intensity β_i is greater than the standard, the last term in Equation 6 is positive. This implies that fuel i faces an implicit tax equal to $\lambda_{LCFS}(\beta_i - \sigma_{LCFS})$. On the other hand, if the fuel's emission intensity is below the standard, fuel i faces an implicit

[16] A LCFS has been adopted by California and is currently under development by various federal and state policy-makers.

[17] In our simulations, σ_{LCFS} is set to produce the same reduction in emissions as the RFS and CAT systems.

subsidy equal to $\lambda_{LCFS}(\beta_i - \sigma_{LCFS})$. Note that, under very general conditions, it is impossible to design a LCFS which results in the efficient allocation of energy production and emissions since each fuel with positive carbon emissions should be taxed (not subsidized) Holland, Hughes, and Knittel (2009).

To solve for the equilibrium, the system of equations includes the n first order conditions in Equation 6, demand equal to supply in the fuel market, and market clearing in LCFS credits (Equation 5).

3.4 Carbon trading

Consider a cap (σ_{CAT}) on the total emissions of carbon.[18] Since the total emissions summed over all fuels produced must not exceed the cap, the constraint is:

$$\beta_1 q_1 + \beta_2 q_2 + \cdots + \beta_n q_n \leq \sigma_{CAT}, \tag{7}$$

which simply states that the sum of emissions associated with each fuel type cannot exceed the carbon cap. The first order conditions of the firm's profit maximization problem are:

$$p = mc_i(q_i) + \lambda_{CAT}(\beta_i), \tag{8}$$

where λ_{CAT} is the shadow price of the carbon constraint (or equivalently, the price of a carbon permit). Note that the carbon cap implicitly taxes production of each carbon-emitting fuel in proportion to its carbon emissions. By taxing dirtier fuels more, carbon trading achieves a target level of carbon emissions at least cost, *i.e.,* is cost effective.

To solve for the equilibrium, the system of equations includes the n first order conditions in Equation 8, demand equal to supply in the fuel market, and market clearing in carbon permits (Equation 7).

4 Modeling assumptions

To compare the effects of these four policies, we use detailed data on projected U.S. ethanol supply to simulate the long-run market equilibria. This section outlines the modeling assumptions and methods. See Appendix A for more details.

[18] In our simulations, the cap (σ_{CAT}) is set to produce the same *total* emissions as the RFS.

We use ethanol supply curves for corn ethanol and for six different cellulosic ethanol feedstocks: agricultural residues, orchard and vineyard residues, forest biomass, herbaceous energy crops, municipal solid waste, and municipal solid waste from food. We construct county-level supply curves using estimates of biomass feedstock availability and aggregate county production to the national level for our policy simulations. For a given price of ethanol, the model selects optimal biorefinery locations to minimize costs of feedstock collection, ethanol production, and ethanol distribution. Reoptimizing the model for a range of ethanol prices provides an estimate of the long-run supply for each of the seven different types of ethanol.

The supply side of the model is completed by aggregating the supply from each type of ethanol with supply of conventional gasoline. We assume that the long-run gasoline supply is perfectly elastic at $2.75 in our baseline. The market supply depends on the policy since each policy may differentially affect the producer price of each of the types of fuel.

The producer prices under CAT and the LCFS depend directly on the carbon emissions of the fuels. We use lifecycle carbon emissions for each of the fuels including estimates of indirect land use effects where appropriate. In light of the great uncertainty and controversy over lifecycle emissions, we explore the robustness of our results to a variety of assumptions about lifecycle emissions.

The demand side of the model assumes that ethanol and gasoline are perfect substitutes after adjusting for their differential energy content. We model fuel demand with a constant elasticity which we set at 0.5 in our baseline case. The level of demand is calibrated to the U.S. EIA estimate of annual fuel consumption in 2022 of 140 billion gge and our baseline gasoline price of $2.75.

For each of the policies, we calculate the vector of consumer and producer prices which equates supply and demand. For BAU, the equilibrium price of $2.75 is determined by the long-run supply of gasoline. We next simulate the RFS, which requires us to use a series of loops to calculate the equilibrium fuel price and RIN prices for each of the three types of ethanol.

To compare all policies equally, we calibrate the CAT and LCFS so that each policy attains the same level of carbon emissions as the RFS. For CAT, we simply set the cap at this level and calculate the equilibrium price vector which now includes a carbon price. For the LCFS, the equilibrium price vector also includes a carbon price, and we adjust the carbon intensity required by the LCFS so that in equilibrium the LCFS leads to the same carbon emissions as the RFS and CAT.

At the national level, we calculate and compare the surplus gains and cost of carbon under each of the policies. Additionally, we construct estimates of producer surplus at the county-level using our disaggregate supply curves and the equilibrium prices under each policy. Producer surplus gains at the Congressional district-level are the weighted sum of county-level gains where each county is assigned an equal weight.

The county-level ethanol production also allows us to calculate and compare the land use changes required under each of the policies. We then compare the land-use intensities under the various crops and analyze the net environmental harm from the land-use changes which result under the different policies.

5 Simulation results

We discuss a variety of equilibrium outcomes from our simulations. We begin by comparing equilibrium fuel prices, quantities, and carbon emissions. Then, we estimate the relative efficiencies of the policies. Our measure is the average social cost per unit of GHG abated, which we refer to as "average abatement costs," reflecting the impact on consumer and producer surplus and the social costs associated with changing the fuel mix. We compare these costs to recent estimates for the social cost of carbon.

5.1 Energy prices, quantities, and emissions

Table 1 below presents energy prices, energy production and emissions under business as usual (BAU) and the RFS, LCFS, CAT, and subsidy (SUBs) policies. In the preferred specification we assume a BAU fuel price of $2.75 per gasoline gallon equivalent. Under the RFS, fuel prices increase to approximately $2.94 per gge and total fuel consumption decrease by approximately 5 billion gge per year to 135.31 billion gge. We find the RFS leads to a 10.2% reduction in GHG emissions, relative to BAU. The lower emissions under the RFS are a result of lower total fuel consumption and greater share of lower carbon cellulosic ethanol required by the advanced and cellulosic RFS rules.

In our simulations the LCFS and CAT are designed to produce the same reduction in carbon emissions as the RFS. The two policies differ in the mechanisms by which these reductions are achieved. Under the LCFS, fuel prices increase to $2.96 per gallon, total fuel consumption is approximately 134.99 billion gge per year of which approximately 20.07 billion gge are ethanol. Under CAT, fuel prices are higher at $3.23 per gallon, resulting in lower total fuel consumption of approximately 129.09 billion gge per year. As a result, less ethanol is required to achieve the desired 10.2% emissions reduction. We come back to this in Section 5.2.

Finally, we also simulate the equilibrium under the current set of subsidies. Under direct subsidies, fuel prices are unchanged.[19] Ethanol production increases from approximately 5.16 billion gge per year to 23.38 billion gge per year. Carbon emissions fall by approximately 6.9% relative to BAU.

Table 1 also summarizes ethanol production by three broad categories and by policy. SUBs and the RFS result in the largest shifts in corn ethanol production, increasing from 0.96 billion gge per year in the BAU scenario to approximately 9.25 and 9.86 billion gge per year, respectively. Corn ethanol production is lower at approximately 5.58 billion gge per year under the LCFS with a larger share coming from waste and cellulosic feedstocks. CAT results in no increase in corn ethanol production with nearly all the increase utilizing waste feedstocks.

5.2 Costs and relative efficiencies

Table 1 summarizes abatement costs under each policy calculated as the sum of changes in consumer and producer surplus net of any carbon market revenue or subsidy payments. An intuitive metric for comparison is the average abatement cost calculated as abatement cost divided by the total reduction in emissions. The average abatement cost for a 10.2% reduction in emissions under CAT is approximately $19.52 per metric ton of carbon dioxide equivalent ($MTCO_2e$). The marginal cost, or price of an emissions permit, at this level is approximately $40.83 per $MTCO_2e$ as shown in the bottom panel of Table 1. We note that while consumer surplus falls under CAT by roughly $65 billion, this calculation ignores the roughly $59 of potential revenue that could be cycled back to consumers if permits were auctioned. We find that total producer surplus increases even in the absence of free permit allocation. The intuition behind this result stems from shifting the price-setting marginal firm from the lower cost gasoline producers to higher cost ethanol firms.

Abatement costs under the alternative policies are much higher; however, producers benefit more from these policies, while consumers are harmed relative to a CAT program that recycles revenues from permits back to consumers. Under the RFS, average abatement costs are $57.90 per $MTCO_2e$. Producer surplus increases by $17.12 billion per year. Average abatement costs under the LCFS are $48.58 per $MTCO_2e$.[20] Finally, the average abatement costs under the subsidy programs are the highest at $82.30 per $MTCO_2e$ despite the fact that abatement is roughly 30 percent lower. Consumers are unharmed by a SUBs since fuel prices do not change Producer surplus increases by nearly $18.89 billion. Total government outlays exceed $28 billion.

[19] This is a consequence of the perfectly elastic supply curve for gasoline.

[20] We note that this figure is below many of the results in Holland, Hughes, and Knittel (2009) reflecting the long run nature of our ethanol supply curves.

Greater substitution to ethanol under the alternatives to CAT creates inefficiency in terms of higher abatement costs and results in larger changes in agricultural production. To see this, Figure 1 shows marginal abatement costs and emissions reduction mechanisms for CAT and a LCFS when we vary abatement levels. The heavy black line shows the marginal abatement cost under each policy calculated by running our simulation model for range of carbon prices and determining the level of carbon emissions. The light line depicts marginal abatement costs assuming zero fuel substitution.[21] For a 10.2% reduction in emissions, the marginal abatement costs under CAT and the LCFS are \$40.83 per $MTCO_2e$ and \$189.70 per $MTCO_2e$, respectively. Under CAT, a substantially larger portion of the emissions reduction comes from reduced fuel demand. Under the LCFS, a much larger share of abatement comes from fuel substitution, *i.e.* the horizontal distance between the light and heavy curves in Figure 1. This finding highlights the main difference between CAT and the other policies under consideration, namely that emissions reductions under CAT come from reduced fuel consumption while direct subsidies, the RFS and LCFS result in more substitution towards ethanol.

The large variation in average abatement costs brings up the possibility that, for given levels of marginal damage estimates, some of the policies may reduce welfare. A number of estimates of the externalities associated with GHGs exist. Tol (2008) provides a meta-study of 211 estimates of the "social cost of carbon" (SCC). He reports the points of the distribution of estimates after fitting the results to a parametric distribution. Across the three assumed distributions, for studies written after 2001, the median SCC ranges from \$17 to \$62 per $MTCO_2e$, while the mean ranges from \$61 to \$88 per $MTCO_2e$ (in 1995 dollars). More recently, Interagency Working Group on Social Cost of Carbon, United States Government (2010) estimates the SCC for a variety of assumptions about the discount rate, relationship between emissions and temperatures, and models of economic activity. Appendix Table 4 summarizes their results (in 2007 dollars). Because our analysis represents conditions in 2022, we focus on the 2020 estimates. For all but the most pessimistic set of assumptions, the RFS and LFCS reduce welfare relative to business-as-usual; the current sets of subsidies reduce welfare even 95th percentile of estimates using a 3 percent discount rate. In contrast, CAT increases welfare for all of the reported results with discount rates below 5 percent.

[21] We calculate this curve by assuming ethanol has the same emissions intensity as gasoline. In this case, carbon reductions come only from reductions in fuel consumption due to increased fuel prices and the elasticity of fuel demand.

6 The political economy of climate change policy

The obvious question that leads from our results is, given how much more efficient CAT is relative to the other policies, why have policy makers chosen the VEETC and Renewable Fuel Standard over CAT? We investigate the distributional impacts of the different policies as a potential answer.[22] We do this in a number of ways. We first calculate net private surplus changes for each county and analyze the distributions of these across the different policies.[23] We then aggregate these to the Congressional district level and correlate these changes with Congressional voting behavior on H.R. 2454, better known as the Waxman-Markey Climate Bill (WM). To investigate one potential mechanism through which private surplus changes affect Congressional behavior, we correlate our measures of private surplus changes with political contributions from organizations either supporting or opposing WM. Finally, we take our estimates from the House vote and predict the outcome of WM had it gone to vote in the Senate.

Figure 2 graphically illustrates the geographic variation in net changes in per capita surplus changes for each policy. Under CAT, the number of counties that benefit from the policy is small as are the benefits. However, the losses are also small, predominantly coming from the consumer surplus losses associated with higher fuel prices.[24] To see this, Table 2 reports different points in the distribution of county-level and Congressional district-level gains and losses for each of the policies. Note that because these are not weighted by county populations, the county mean values will not coincide with our aggregate loss calculations above. Congressional districts on the other hand, are created with roughly equal populations, and therefore coincide more closely with the aggregate measures.[25]

Beginning with the county-level statistics for CAT in Panel A, the largest mean annual county per capita loss is \$20.33, while no county gains more than \$1,015 per capita. The median county loses \$14.87, while the county mean is a gain of \$2.98. Furthermore, 24 percent of the counties have a net-positive gain from the policy.

The results from the other policies contrast greatly with the CAT results. The average county gains considerably across these policies. These average gains range from \$160 per capita under the

[22]Other possible reasons include the higher fuel prices which would result under CAT; the perception that CAT is a "tax"; ideological opposition to efficient regulations; and opposition to environmental regulations in general and climate policy in particular.

[23]See Section 4 for a discussion of the aggregation methodology.

[24]In determining the consumer surplus loss under CAT, we assume that carbon market revenue is returned to consumers in a lump sum fashion.

[25]Unfortunately, we cannot calculate the distribution of gains within a county.

RFS to over \$209 per capita under the LCFS. The distribution of gains and losses are quite skewed as well, as the median county loses in all cases but the LCFS where, the median county gains substantially less than the mean. No county loses more than \$100 under the SUBs, but one county gains over \$6,600 per capita. Under the RFS, the average county gains \$160, while 43 percent of counties gain something. The right tail of the distribution under the RFS is also long. 10 percent of counties gain over \$530 per capita, per year, while 5 percent gain over \$1,100. Figure 2 shows that the gains from these other policies are concentrated in the Midwest, with additional gains in forest areas and areas that might grow crops such as switchgrass on marginal lands. The positive mean, despite the negative weighted-mean, and right skew of these distributions suggest that the gains from these policies are concentrated, but the costs are diffuse. This may lead to political dynamics that lend themselves to passing such policies despite their overall inefficiency.

The trends in the district-level data in panel B are quite similar to those discussed above. The median district loses under every policy, though the magnitude of the loss is greater under the alternatives to CAT. While the district-level distribution is somewhat less skewed the RFS, LCFS and SUBs still exhibit a long right tail relative to CAT. Five percent of districts gain around \$100 or more per capita under the RFS, LCFS or SUBs, compared with less than \$8 under CAT. Furthermore, gains in the highest gaining district are an order of magnitude larger compared with CAT suggesting that the gains under these policies are still quite concentrated when measured at the district level.

6.1 Determinants of voting in the House

To motivate our empirical work, Table 3 reports a number of points in the distribution of our private surplus changes and contributions across Democrats and Republicans and their votes on WM.[26] The top two panels report district-level per capita annual gains and losses from CAT and the RFS, respectively. The simple cross-tabs suggest that Democrats who voted against WM tended to be in districts where the private surplus changes where larger under RFS than under CAT, especially in the right tail. The gains from the RFS are larger for Republicans that voted against, but we note statistical power is an issue because only eight Republicans voted for WM.

Contributions also show variation across votes, within a party. We discuss the data on contribution in detail below, but the third panel suggests that Democrats that voted against WM received,

[26] The p-values for the median, 75th and 90th percentiles are computed using qreg in Stata and are the p-values associated with the dummy variable for whether the Congressman voted for WM. Because we have never seen this reported, we verified that this dummy replicates the actual differences in these points in the distributions across the two samples, but have not verified the standard error.

on average, nearly $13,000 more from organizations opposing WM, while Republicans voting against received nearly $6,000 more. The tail of the Democrats' distribution is also much longer with the 75th and 90th percentiles over $23,000 and $28,000 larger, respectively, for Democrats that voted against. The tail of this distribution is less clear for Republicans. The contributions from organizations supporting WM do exhibit differences across Republicans that voted for and against, however. Those Republicans voting for WM received, on average, over $64,000 more dollars in supporting contributions. The Republican at the 90th percentile among those that voted for WM received more than $425,000 more than the Republican at the 90th percentile that voted against WM.[27]

We next investigate whether our measures of gains and losses have explanatory power for Congressional voting behavior and political contributions. Our cleanest voting "experiment" is for cap & trade legislation. An LCFS has never come up for a House vote, and the bill that extended the VEETC was a hodgepodge of disparate legislation. Indeed, the name was "Tax Relief, Unemployment Insurance Reauthorization, and Job Creation Act of 2010". Similarly the bill that established the most recent RFS contained numerous energy related measures. Therefore, we focus on correlating our gain and loss measures with votes on Waxman-Markey (WM)—H.R. 2454, "The American Clean Energy and Security Act of 2009"—which focused almost exclusively on a CAT program to reduce GHG emissions. Given these considerations, it seems plausible that Congressional Members viewed WM and the RFS as substitutes. We center our analysis on these two policies.

The substitutability of CAT and the RFS comes from a controversial provision in WM. Under WM, so-called indirect land use effects would be included in the lifecycle emissions of ethanol under both the cap & trade program and the RFS. At current indirect land use estimates, ethanol from many corn-based ethanol plants would have no longer counted toward the RFS requirements. As evidence of the importance of this provision, a last-minute compromise between Senators Henry Waxman and Collin Peterson, the House Agriculture Committee Chairman, delayed this provision for five years.[28]

Table 4 shows the marginal impacts of a probit model of whether a House Member voted for WM.[29] Model 1 includes an indicator for whether the Member is a Democrat and our estimated per capita district-level gain from CAT in natural logarithms.[30] We report the marginal effects at

[27]The 90th percentile may be driven by outliers since only eight Republicans voted against.

[28]see, http://www.greencarcongress.com/2009/06/peterson20090626.html

[29]Results from a linear probability model are qualitatively similar.

[30]Because many of the districts experience losses, we shift the district-level gains under each policy by a common factor of $100 per capita so that the natural logarithm is defined. Since we do not separately value welfare gains due to reduced carbon emissions, one may interpret this shift as a benefit of $100 per capita from reduced climate change damages.

the means of the continuous variables. The Democrat indicator is positive and large suggesting the probability a Democrat voted for WM is nearly 78 percentage points higher. Without controlling for gains from the RFS, the coefficient associated with per capita gains from CAT is negative. If Congressional members viewed WM and RFS as substitutes, insofar as the gains from CAT and the RFS are correlated, the CAT gain variable is confounding two countervailing effects.

Model 2 includes both the gains from CAT and the gains from the RFS. Once we account for both, greater gains from CAT are correlated with voting for WM, though the coefficient is not precisely estimated.[31] In contrast, greater gains from the RFS are correlated with a lower likelihood of voting for WM; this correlation is statistically significant. Model 3 allows for level shifts in voting behavior due to unobserved factors that vary at the state-level by including state fixed-effects. The point estimates are consistent with Model 2, though the results are somewhat nosier as a result of having to omit states where all of the House members either voted for or against WM. Models 4 and 5 investigate the correlation between the relative gains under CAT versus the RFS. Larger CAT gains, relative to the RFS, are correlated with an increased likelihood of voting for WM even accounting for state fixed-effects.

The effects from the RFS and CAT are also politically significant. Using Model 2, if a district moves from the 25th percentile to 75th percentile in terms of RFS gains, the probability its member votes for WM falls by 13 percentage points. Moving from the minimum to the maximum in RFS gains, the likelihood of voting for WM falls by 62 percentage points. Using Model 4, if a district moves from the 25th percentile in terms of the relative gains from the RFS to CAT, to the 75th percentile, the probability its member votes for WM increases by 60 percentage points.

We next investigate the linearity assumption. Table 5 splits districts into quartiles in terms of their gains and losses. The results suggest that the relationship may be non-linear. Model 1 again includes only the gains from CAT. Model 2 includes the quartiles from the RFS and Model 3 adds state fixed-effects. When we include the RFS quartiles, the CAT quartiles are positive, though only the coefficient on the third quartile is statistically significant. The RFS quartiles, in contrast, suggest the negative correlation in the linear model is being driven by the large winners from the RFS with the parameter estimate increasing in magnitude for the higher quartiles. The estimated effects are substantial. Holding a district's gains under CAT constant, a House member's likelihood of voting for Waxman-Markey falls by 18 percentage points if the district is in the second quartile of gains from the RFS relative to if they were in the bottom quartile. However the probability falls

[31] A regression of the net gains from CAT on the net gains from the RFS yields a slope of 0.09 and an R-squared of 0.61. Identification of the two coefficients is obviously coming from deviations in the linear fit.

by over 39 percentage points moving from the first to the fourth quartile.[32]

Of course, the transportation sector was not the only sector to be regulated under WM. The effect of WM on for example, electricity generation, may also have influenced voting behavior. Furthermore political ideology, either party affiliation or ideology more broadly defined, may help explain Representative's votes. Indeed, Cragg and Kahn (2009) find that district-level per capita GHG emissions is strongly correlated with Congressional voting on GHG-reducing legislations more broadly. To investigate the influence of these factors, Table 6 presents estimates of the base model controlling for those variables included in Cragg and Kahn (2009)—various measures of district carbon emissions and the political ideology of the district's Representative. Model 1 adds indicator variables for whether the Member is a Democrat and whether the district is in a top-10 coal producing state.[33] Model 2 replaces the Democrat indicator variable with DW-nominate, a measure of political ideology based on a comparison of roll-call votes of House members.[34] A higher score indicates a more conservative voting record. Model 2 also adds district-level per capita carbon dioxide emissions and average power plant carbon emissions rate. Model 3 adds corn production and Model 4 adds state-fixed effects.

The results in Table 6 are remarkably similar to the base model. Increasing RFS gains conditional on CAT gains are associated with a lower likelihood of the Member voting for WM all else equal, though the estimated coefficients by quartile are generally smaller in magnitude. The emissions per capita and ideology controls have the appropriate signs and are in general statistically significant. In Model 1, the probability that a Democratic Member voted for WM is 75 percentage points higher. The probability that a Member in a top-10 coal producing state voted for WM is approximately 7 percentage points lower, though this parameter is imprecisely estimated. In Models 2 through 4, the coefficient on DW-nominate indicates that Representatives with more conservative voting records were less likely to vote for WM as were Members from districts with higher per capita emissions. Controlling for district-level gains and per capita carbon emissions, neither the coefficients on electricity plant emissions nor corn production are statistically significant. The parameters of interest do not change substantially with the addition of state fixed-effects.

We next investigate one of the mechanisms of these correlations—political contributions. We collected data on donations to Representatives from MapLight.org (2011). MapLight reports contributions for individual donors giving $200 or more to one candidate collected from Federal Election

[32]The quartiles across CAT and RFS are obviously correlated, however 8 percent of the districts in the upper RFS quartile are in the bottom two CAT quartiles. Appendix Figure 2 illustrates the source of identification.

[33]Similar results are obtained for top-5 coal producing states or controlling for coal consumption.

[34]DW-nominate is the voteview.org measure of political ideology based on all roll-call votes, not simply votes on environmental issues.

Committee filings. Donors are categorized into political interest groups according to the industry or occupation of the donor. For major pieces of legislation, MapLight.org researchers classify political interest groups as being in support of or opposed to a bill using Congressional hearing testimony, news databases and trade association web sites to assign interests.[35] We assume that donors from a given interest group share this group's position on H.R. 2454. Because political donation patterns follow election cycles, we focus on donations during a two-year period from January 1, 2009 to December 31, 2010.[36] One may worry that this period is too broad to capture donations specific to H.R. 2454. As a robustness check, we limit our data to a 60-day window around the House vote. These results are qualitatively similar to those presented below.

Table 7 shows the results of a linear regression of contributions from organizations opposing and supporting WM on party affiliations, our CAT and RFS quartiles and in columns 2 and 4, state fixed-effects. We measure contributions in logs.[37] The first two columns focus on contributions from opposing donors. Greater district-level gains from CAT are correlated with less contribution dollars from donors opposing WM. Moving from the 1st to the 4th quartile is associated with a 1.97 reduction in the log of contributions. In contrast, higher RFS gains are correlated with more money from opposition donors. A move from the 1st to the 4th quartile is associated with a 4.74 increase in the log of opposition contributions. These results are qualitatively similar with state fixed effects. There is less evidence that contributions from donors *supporting* WM are correlated with our simulated gains and losses.

Next, we include the contribution variables in the voting model to see whether the correlations between voting and gains/losses are working through contributions or through gain/losses more generally. Column 1 of Table 8, which includes only the contributions data, shows that greater contributions from donors supporting WM are correlated with an increase in the probability of voting for WM and that greater contributions from donors opposing WM are correlated with a decrease in the probability of voting for WM. When we include both the contribution variables and our gain/losses variables we find that the RFS quartile indicators still have explanatory power and are still politically significant. This is true even when we include fixed state effects in Model 3. Taking the Model 2 point estimates, a one standard deviation increase in the log of contributions supporting WM is associated with an 3 percentage point increase in the likelihood of voting for WM, while a one standard deviation increase in the log of contributions opposing WM is associated with a 3 percentage point decrease in the likelihood of voting for WM. Models 4 and 5 add the additional

[35] A list of opposing and supporting organizations, as well as the documentation of this categorization by Maplight.org is available at: http://maplight.org/us-congress/bill/111-hr-2454/371786/total-contributions.table

[36] Recall the House vote on H.R. 2454 occurred on June 26, 2009.

[37] We add one to allow us to account for observations with zero contributions.

ideology, carbon emissions controls and state fixed-effects. The point estimates for contributions in support of and opposed to WM decrease in magnitude slightly but remain statistically significant, but so do the RFS quartile dummies. We note that the RFS, Quartile 4 coefficient in Model 4 is statistically significant, but loses significance when we calculate the marginal effect.[38] Based on these results, it appears as though the gains and losses from the policies affect voting through more than just the contribution channel.

6.2 Predicting voting in the Senate

We next use our estimates from the House vote to predict how the Senate would have voted. This requires a number of assumptions. Because the relationship between gains and voting may change considerably between the House and the Senate, we focus on the specifications that include the gains and losses quartiles and indicators for Democrat, "Top 10 Coal State" (Model 1 in Table 6). By doing so, we categorize Senators into 64 bins. We aggregate up the gains and losses to the state level and then reconstruct these variables.

We present the results in two ways. First, we calculate the fitted probability of voting for WM and assume each Senator votes for WM if their predicted value is greater than 0.5 to predict positive votes. Second, we simulate 1,000 different votes using the fitted values. In particular, we take the fitted value of the latent variable and bootstrap the error term, which by definition has a normal distribution with mean zero and standard deviation of one. For each bootstrap, we calculate the number of votes and plot the distribution of votes across all bootstraps.

Using only the fitted probability and the 0.5 rule, we end up with 53 votes. Interestingly, this is enough votes to pass WM, if it were to go to a vote. However, during this time period many bills that would have had a majority did not make it to vote because of filibustering. The 0.5 voting rule suggests that WM would not have had enough votes to break a filibuster.

Figure 3 plots the distribution of voting probabilities. This distribution is as we would expect given the large coefficient associated with party affiliation, and all 53 of the Senators with voting probabilities greater than 0.5 are Democrats. We do, however, find that five Democrats have probabilities less than 0.5. These are all in high corn and coal states—Illinois (Dick Durbin and Roland Burris—Barack Obama's former seat), Indiana (Evan Bayh), and North Dakota (Kent Conrad and Byron Dorgan). The Senators have fitted probabilities of 0.45 coming from being in a state in the 4th quartile of RFS and CAT gains and in a coal mining state.

[38]The p-value for the point estimate is 0.08.

On the other side of the 0.5 cut-off are 5 Senators with fitted probabilities of 0.62. These are all Democrats—two from Arkansas, one from Iowa, one from Maine and one from South Dakota. These states are all in the 4th quartiles of RFS and CAT gains, but not in coal mining states. In addition, there are 4 Democratic Senators from Montana and New Mexico with fitted probabilities of 0.67. Both states are in the 2nd quartile of RFS gains and the 1st quartile of CAT gains but are top-10 coal states. As Figure 3 illustrates, there is little hope that WM could have passed filibuster and our simulations bear this out. While it is conceivable for the five Democrats to change their votes, the next highest fitted probability is 0.23. Indeed, we find that the maximum number of votes WM receives across our 1,000 draws is 59; this occurred one time. Figure 4 plots the distribution of these draws. Interestingly, on average WM garners 50 votes in the Senate. The reason why this is below our estimated number is that while the change in voting probabilities are symmetric, because we are adding a normal draw to the fitted $X\beta$, the change in votes is not symmetric. Basically, it is easier to get Senators to switch their votes from Yay to Nay than it is to switch from Nay to Yay. To see this, we point to the nine Senators with fitted probabilities of 0.62 and 0.67, but there are only five Senators close to this on the other side of the 0.5 cut-off (each with a probability of 0.45).

7 Environmental outcomes

Next, we turn to environmental outcomes under each policy. We begin by comparing land use changes across the policies. Because we have information on the *type* of land used, we also report this separately for cultivated and uncultivated lands. Given estimates of the externalities associated with land use changes, we calculate what these changes imply for non-GHG externalities. We report the land use externalities on a per GHG-abated basis allowing the reader to adjust the average-abatement-cost measure to include the additional externalities. Finally, we investigate the robustness of each policy to errors in assigning carbon emission intensities to each fuel.

7.1 Land use and non-carbon costs

The land-use impacts largely mirror the distributional results. Land area used in agricultural production of crops for ethanol are illustrated in Appendix Figures 3 and 4. Appendix Figure 3 shows the total land use under the 2022 RFS, LCFS, CAT, and SUBs systems that each reduce GHG emissions 10.2% relative to BAU. We plot the county-level "land-use intensity," calculated as the total acreage in energy crop production, herbaceous energy crops and corn, divided by total land area. The CAT system uses relatively little land in energy crop production, primarily in the Midwest.[39] In stark contrast, the LCFS and RFS result in substantial amounts of land dedicated to energy crop production. Land area used under direct subsidies is quite similar to the RFS, though the emissions reduction is considerable smaller.

Perhaps a more important metric than *total* area is land area used in the production of *cultivated* energy crops. Cultivated crops, such as corn, are more likely to result in negative impacts due to increased fertilizer use, irrigation, and competition for agricultural land compared to herbaceous crops grown on marginal land with few inputs. Appendix Figure 4 shows the land intensity for the production of corn under each policy. The RFS shows the largest number of acres of corn dedicated to ethanol production due to substantial ethanol production in the Midwest. The LCFS also results in large areas dedicated to corn production. In contrast, the CAT system results in relatively little land used in corn production.

The land-use changes relative to BAU, for each policy, are summarized in Table 9. The 2022 RFS results in 39.0 million additional acres of energy crop production relative to BAU. Approximately 27.7 million additional acres are used for corn production. Under SUBs, the land use change are quite similar at 37.8 million addition total acres and 25.7 additional corn acres relative to BAU. For comparison, total cropland in the U.S. is approximately 442 million acres Lubowski et al. (2006). The land use changes under the LCFS are smaller, though still substantial. Land-use changes are smallest under the CAT system, with approximately 1.2 million addition energy crop acres and essentially no increase in corn production relative to BAU.

Finally, we estimate the additional costs due to land use changes under each of the policies. We use lower and upper bounds of \$10 and \$25 per additional acre of corn production. Additional information on the calculation of these costs is discussed in Section A.8. We estimate costs per ton of CO_2e in order to compare with our average abatement cost estimates. Under CAT, land use change costs are approximately zero. Under the RFS, LCFS and SUBs systems, costs range between \$0.89 and \$2.31 per $MTCO_2$e for the low cost scenario and between \$2.22 and \$5.77 per $MTCO_2$e for the high cost scenario . While these effects are modest in size, they further increase the cost disparity between CAT and the alternative policies.

7.2 Mistakes in carbon intensities

As discussed in Section 4, the life-cycle emissions of advanced ethanol production technologies are highly uncertain. In addition, carbon emissions associated with direct and indirect land use

[39]Land use under BAU is quite similar to that which results under CAT.

changes resulting from shifts in agriculture are controversial. This situation creates the possibility of errors in estimating the carbon intensities of different biofuel pathways. Furthermore, emissions intensities under any transportation sector carbon policy are likely to be set as part of a political process. In light of this, we investigate the sensitivity of actual emissions under each policy to errors in the emissions intensity.

We focus on emissions related to corn ethanol production and associated land use changes. As shown in Appendix Table 2, recent estimates of the emissions intensity range from 0.79 to greater than those of conventional gasoline at 1.04. Because corn is a food crop and because land used for the cultivation for corn is also a substitute for other crops, direct and indirect land use effects are also likely to be large. Imagine a scenario where the emissions intensity of corn ethanol is larger than expected. Specifically, assume a value of $\sigma_{corn} = 0.90$ compared to the baseline value of $\sigma_{corn} = 0.80$.[40] We then re-run our simulations to estimate fuel production and emissions under for each policy using the new emissions intensity.

Table 10 summarizes carbon emissions under each scenario. Consider "uncontrolled" emissions as the additional carbon emitted because the true emissions intensity is larger than the emissions intensity specified by policy makers. An intuitive metric of environmental effectiveness then is the quantity of uncontrolled emissions as a fraction of the stated reduction in carbon. The effect of the higher emissions intensity is smallest under CAT at approximately 0.7%. Under the RFS, LCFS, and SUBs the effects are 7.1%, 4.0%, and 9.9%, respectively. As this example illustrates, errors or biases in the true greenhouse gas content of biofuels are exacerbated when relying on performance standards and subsidies, compared to more efficient policies.

8 Innovation incentives

Without new technologies for producing low-carbon fuels, reducing carbon emissions will be quite costly. Thus one of the key features of any carbon policy will be how well it provides incentives for innovation. Unfortunately innovation incentives can be insufficient since consumers generally receive some of the benefits from innovation (through lower prices) but producers must pay for the innovation through licensing or funding of R&D. If consumers receive a substantial portion of the benefits from innovation, then producers may not receive sufficient surplus to fund socially efficient

[40] For simplicity we imagine an error which underestimates emissions. From a welfare perspective, an overestimate could also be costly if it resulted in a level of ethanol production that was inefficiently too low. However, given the existence of other negative externalities associated with land use changes, the welfare implications are likely to be asymmetric.

innovation. In this section, we analyze the distribution of the gains from innovation between consumers and producers under the different policies.

The importance of innovation is highlighted by the fact that the primary low-carbon fuels analyzed in this paper, cellulosic ethanols, are not currently produced on a commercial scale. To estimate the benefits from innovation in cellulosic ethanol, we analyze the counterfactual in which these technologies are not available. The gain from innovation is the additional social surplus when the technology is available. Since the additional social surplus depends on the carbon policy, we calculate the gains from innovation under each of the carbon policies. Finally, we analyze the distribution of those gains across consumers and producers to estimate the incentive to innovate.

Table 11 shows the results of calculating surplus with and without our six types of cellulosic ethanol under BAU, LCFS, CAT, and SUBs.[41] To make the carbon policies comparable, we set the LCFS and CAT such that they each result in the same carbon emissions (1453 $MMTCO_2e$) as the RFS.

The first column of Table 11 shows that the benefits from innovation with no carbon policy are \$0.91 billion. This benefit arises because we estimate that some cellulosic ethanol would be produced even in the absence of carbon policy. Note that the entire benefit accrues to the producers of cellulosic ethanol since the additional ethanol simply displaces gasoline and does not lower the price of fuel. In his case, private innovation incentives exactly match the social incentives.

With a carbon policy the story is quite different. For the LCFS (shown in the second column of Table 11) the fuel price would need to rise to \$3.48 to reduce carbon sufficiently in the absence of innovation. However, with innovation in cellulosic ethanol, the fuel price would only rise to \$2.96. Thus consumers as well as cellulosic ethanol producers benefit from innovation. However, corn ethanol producers are harmed by innovation under the LCFS. Recall that the LCFS has an implicit subsidy to fuels with relatively low carbon intensities. In the absence of innovation in cellulosic ethanol, corn ethanol is *the* low carbon fuel and as such receives a subsidy. Corn ethanol loses this subsidy when cellulosic ethanol is commercialized.[42]

The gains from innovation to cellulosic ethanol producers under the LCFS are quite substantial (\$20.56 billion). Note that this implies that cellulosic ethanol producers would be willing to pay (e.g., in licensing fees) more than the entire social benefit from innovation (\$2.61 billion). Thus the private innovation incentives under the LCFS are too large and could result in investment beyond

[41] We cannot analyze the RFS since the RFS explicitly requires production of cellulosic ethanol.

[42] It is worth noting that corn ethanol producers gain under the LCFS even with innovation (see Table 1) they just don't gain as much as they would have in the absence of innovation.

the socially efficient level.[43]

The social benefits from innovation are largest ($4.38 billion) under the efficient carbon policy, CAT. Since with innovation the fuel price does not need to increase as much, consumers also benefit. However, much of the increase in consumer surplus is offset by a loss in carbon market revenue (which drops from $102 billion to $59 billion). Even if we assume producers receive none of the carbon market revenue, cellulosic ethanol producers capture all of the social benefits of innovation. Producer surplus to corn ethanol producers decreases with innovation due to lower fuel prices. Thus the private incentive to innovate for cellulosic ethanol producers may be too small, but the gap between the private and socially efficient incentives is relatively small.

Under the subsidy policy (SUBs), the benefits from innovation accrue entirely to the producers of cellulosic ethanol. The subsidies provide quite a strong private incentive for innovation, but it would be cheaper to give the cellulosic ethanol producers the $17.29 billion directly since the subsidy payments exceed this amount by $4.45 billion.

Comparing the average abatement costs shows that an efficient carbon policy benefits greatly from innovation. For the CAT, the abatement costs are reduced by over a third through commercialization of cellulosic ethanol. This result highlights again the importance of innovation for successful carbon policy.[44]

9 Robustness

Appendix B investigates the robustness of our results to changes in the preferred scenario parameters. Specifically we vary: the baseline fuel price; the emissions intensities of corn and cellulosic ethanol; and the elasticity of fuel demand. Finally, we relax our assumption that corn prices are not substantially affected by shifts in ethanol production. We briefly summarize the results of these robustness checks here. The reader is referred to the Appendix for a more detailed discussion.

The cost advantage of CAT over the alternative policies is very robust to changes in the modeling parameters. Across all scenarios, average abatement costs are at least 2 times as large as CAT and can be nearly 7 times greater. Average abatement costs under the LCFS and RFS are consistently

[43] This result is akin to the business-stealing effect which can lead to excess entry beyond the socially optimal level of entry.

[44] It is surprising that average abatement costs increase with innovation under the LCFS. This is likely an artifact of our assumption that the supply of corn ethanol is perfectly inelastic at high prices. In future work, we plan to extend the corn ethanol supply beyond the current sample of prices.

around 2.5 to 4 times greater than CAT. Average abatement costs under subsidies are 3 to 7 times larger than CAT.

Our political economy results are most sensitive to changes in the gains to ethanol producers across policies. While net gains depend on both surplus gains to producers and loses to consumers, consumer surplus changes are relatively small and spread across all the counties in the sample. Producer surplus gains, and gains to corn ethanol producers in particular, can be quite concentrated as shown in Table 2 and Figure 2. We find that across our scenarios, the relative gains to ethanol producers under the RFS compared with CAT are fairly constant. A possible exception to this trend is the case of high baseline fuel prices. Higher prices result in higher levels of ethanol production absent policy intervention. In our high baseline fuel price ($3.25 per gallon) scenario, surplus gains to corn ethanol producers fall from approximately $3.2 billion per year to approximately $2 billion, relative to our $2.75 baseline fuel price scenario. Gains to corn ethanol producers increase slightly under CAT. We note that fuel prices at the time of the final vote on H.R. 2454 were approximately $2.60 per gallon, and *below* our preferred baseline fuel price of $2.75.[45] Nevertheless, we may worry that expectations of higher fuel prices may change the incentives to lobby for one policy versus another. We test this hypothesis by rerunning our empirical model using results for the high baseline fuel price scenario.

With high baseline fuel prices, gains to producers under the RFS fall from approximately $17 billion per year to approximately $12.5 billion per year. However, county-level gains under the alternatives to CAT are still large and concentrated. Under the RFS and subsidies, the top 5% of counties gain more than $953 and $2,076 per capita, respectively. No county loses more than $105 per capita. Under CAT, the 95th percentile of gains is $146 per capita. No county gains more than $788. Correlations between gains, loses, voting behavior, and contributions are qualitatively similar to results using our preferred simulation parameters, though less precisely estimated.

10 Conclusion

We analyze equilibrium outcomes for carbon cap & trade and three alternative policies aimed at promoting low carbon transportation fuels. To do this we numerically simulate the market for transportation fuel for the U.S. in 2022. Our simulations exploit feedstock-specific ethanol supply

[45] Recent research by Anderson, Kellogg, and Sallee (2010) suggests that current fuel prices are a reasonable proxy for consumers' expectations about future fuel prices. It seems reasonable to extend this result to the constituents of Congressional districts.

curves developed from detailed agricultural feedstock data and engineering ethanol production models.

We find that the 2022 Federal RFS reduces carbon emissions by approximately 10.2% relative to BAU levels. Our analysis shows that the alternatives to CAT are quite costly. Average abatement costs range from \$49 per $MTCO_2e$ for the LCFS to \$82 per $MTCO_2e$ for subsidies, compared with only \$20 per $MTCO_2e$ under CAT. The RFS, LCFS and subsidies all results in larger shifts in agricultural activity and land use compared to CAT. The RFS results in large shifts in agricultural production including approximately 24 billion gge of ethanol production and 39 million acres of addition land for energy crop production relative to the BAU scenario. The LCFS and subsidies result in similar shifts. In contrast, an equivalent CAT system results in only 9 billion gge per year of ethanol production and increases land used to grow energy crops by only 1 million acres. Accounting for environmental cost due to the land use changes further increases the cost disparity among policies, adding an additional \$0.89 to \$5.77 per $MTCO_2e$ to the average abatement cost for the alternative to CAT. These results are robust to a variety of assumptions about the modeling parameters including: business as usual fuel prices, the elasticity of fuel demand and the emissions characteristics of the various fuel pathways.

Overall, producer surplus increases under each of the policies, with the largest changes occurring under direct subsidies at approximately \$19 billion per year. Consumer surplus decreases under the RFS, LCFS and CAT systems relative to BAU. The change in consumer surplus is largest under the CAT system at approximately \$65 billion per year. However, auctioning of permits would create nearly \$59 billion in carbon market revenue which could be distributed to consumers. Under subsidies, consumer surplus in unchanged.

Given the higher costs of alternatives to CAT, we investigate one possible explanation for the popularity of ethanol subsidies and the RFS. Specifically, we generate county-level estimates for the producer and consumer surplus changes under each policy. These estimates suggest an unequal distribution of the gains and loses. Under the alternative to CAT, the median county experiences a small gain or loss. However, gains in some counties can be greater than \$6,600 per capita. Under the RFS, five percent of counties gain more the \$1,100 per capita and no county loses more than \$95 per capita. In contrast, under CAT fewer counties experience gains as result of the policy and these gains are smaller in magnitude than under the alternatives policies. The 95th percentile surplus change under CAT is \$73 per capita per year and no county gains more than \$1,015 per capita.

We test whether these results translate into political incentives by correlating surplus changes at the Congressional district level with voting behavior on the Waxman-Markey H.R. 2454 cap & trade bill. We argue that under this bill, the RFS and CAT are likely viewed as substitutes. Conditional on a Representative's party affiliation and the district's predicted gains under the RFS, gains under CAT are positively correlated with voting for Waxman-Markey. Similarly, greater RFS gains are negatively correlated with a vote for Waxman-Markey.

We provide evidence that political contributions are the mechanism by which these political incentives are translated into voting behavior. Greater district level gains are associated with fewer donations by groups opposed to H.R. 2454. Higher RFS gains are associated with more contributions from groups opposed to WM. Contributions from groups who support WM are associated with an increased probability of a yes vote. Contributions from groups opposed to the bill are associated with a decreased probability of a yes vote.

Taken together, these results strongly support the private-interest theory of regulation. We find that regulation with more concentrated private benefits, the RFS, is maintained over a CAT system which would offer larger social benefits but with less concentrated private benefits. The pattern of campaign contributions around the vote on H.R. 2454 is consistent with political interest groups effectively influencing carbon regulation in a manner consistent with private interest theory.

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Figures

Figure 1: Marginal abatement cost curves and emissions reduction mechanisms for CAT and LCFS systems.

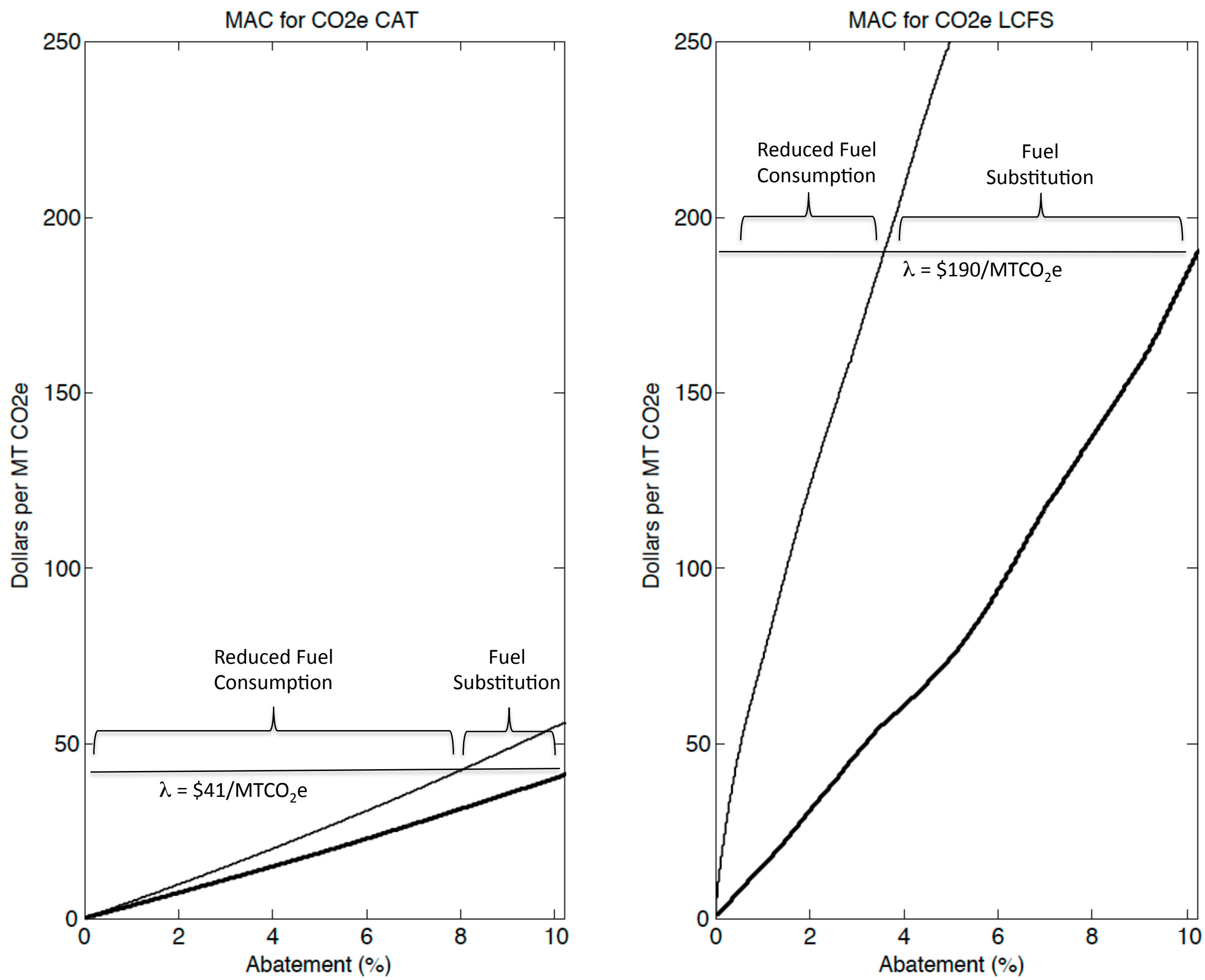


Figure 2: County-level surplus changes ($\Delta PS + \Delta CS$) under a CAT, a LCFS, the 2022 RFS and subsidies.

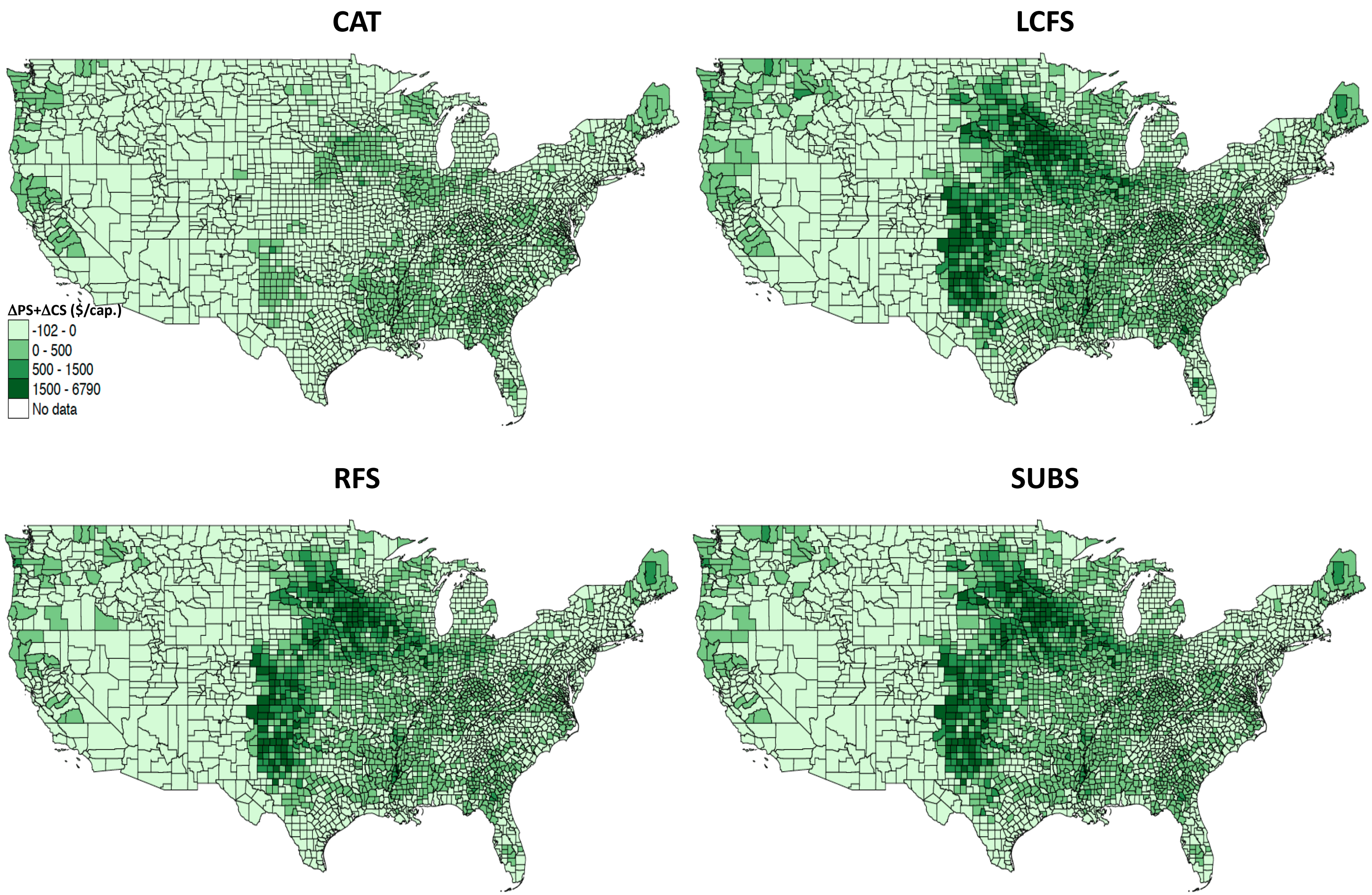


Figure 3: Distribution of the Senate-vote probabilities.

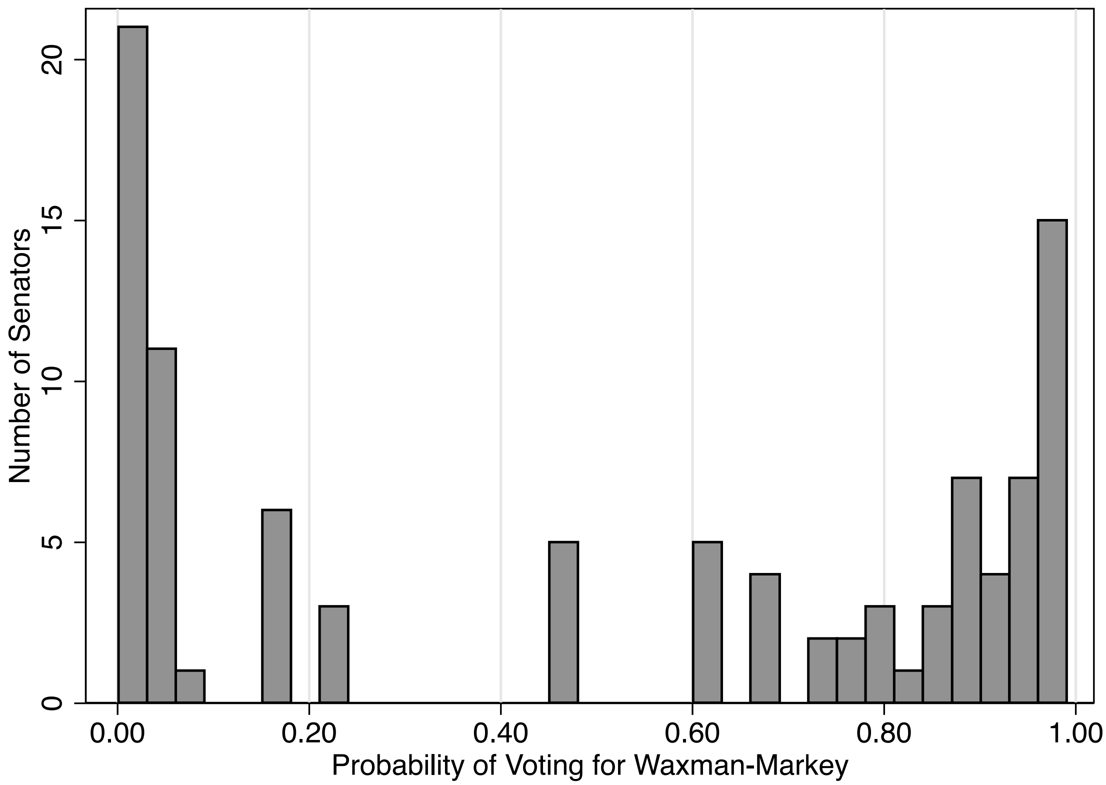
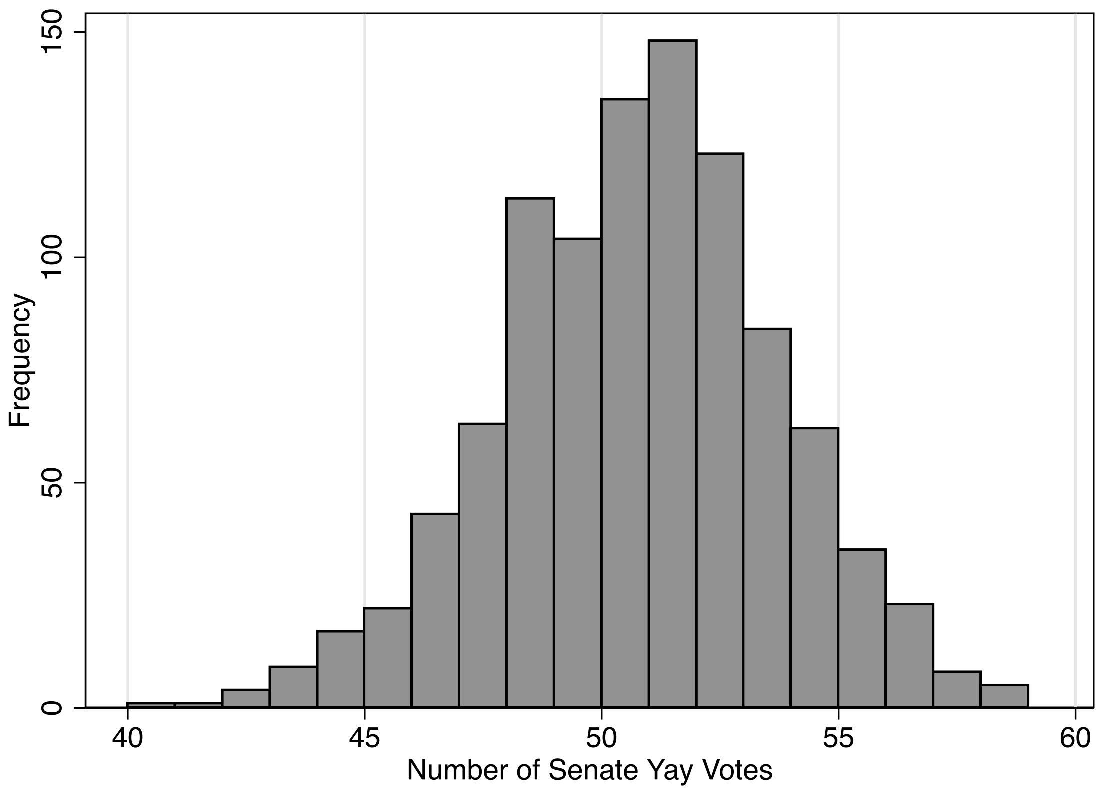


Figure 4: Histogram of simulated Senate-vote outcomes.



Tables

Table 1: Equilibrium outcomes under alternate policies.

	BAU	RFS	LCFS	CAT	SUBS
Fuel Price ($/gge)	$2.75	$2.94	$2.96	$3.23	$2.75
Fuel Quantity (bn. gge)	140	135.31	134.99	129.09	140
Gasoline Quantity (bn. gge)	134.84	111.64	114.92	120.11	116.62
Ethanol Quantity (bn. gge)	5.16	23.67	20.07	8.98	23.38
Corn Ethanol	0.96	9.86	5.58	0.96	9.25
Herb. Energy Crops	0.09	4.43	4.62	0.59	4.57
Waste Feedstocks	4.11	9.37	9.87	7.43	9.57
Emissions (MMTCO$_2$e)	1619	-10.2%	-10.2%	-10.2%	-6.9%
ΔCS ($ bn.)		-$26.69	-$28.59	-$65.07	$0.00
ΔPS ($ bn.)		$17.12	$20.56	$2.49	$18.89
ΔPS Corn Ethanol ($ bn.)		$3.19	$0.91	$0.09	$2.50
Carbon Market Revenue ($ bn.)				$59.35	
Subsidy Payments ($ bn.)					$28.05
Carbon Permit Price ($/MTCO2e)			$189.70	$40.83	
Abatement Cost ($ bn.)		-$9.57	-$8.03	-$3.23	-$9.16
Avg. Abatement Cost ($/MTCO$_2$e)		$57.90	$48.58	$19.52	$82.30

Table 2: The distribution of county- and district-level gains and losses across the different policies.

Panel A: County-level distributions

	CAT	LCFS	RFS	SUBS
Mean	$2.98	$209.42	$159.85	$186.83
Percentage>0	24%	49%	43%	46%
Minimum	-$20.33	-$101.60	-$94.85	-$99.67
25th Percentile	-$20.33	-$68.07	-$71.93	-$72.03
Median	-$14.87	$11.26	-$16.30	-$5.12
75th Percentile	$0.14	$209.70	$133.19	$166.53
90th Percentile	$34.98	$688.43	$537.34	$625.59
95th Percentile	$73.21	$1,363.58	$1,109.67	$1,252.99
Maximum	$1,015.28	$6,786.71	$6,596.38	$6,618.38

Panel B: District-level distributions

	CAT	LCFS	RFS	SUBS
Mean	-$11.49	-$29.10	-$34.33	-$32.97
Percentage>0	9%	18%	14%	15%
Minimum	-$20.33	-$101.60	-$94.85	-$99.67
25th Percentile	-$17.22	-$82.03	-$80.30	-$82.86
Median	-$15.04	-$68.79	-$70.09	-$71.49
75th Percentile	-$11.05	-$25.87	-$39.29	-$36.28
90th Percentile	-$1.72	$50.86	$24.27	$33.09
95th Percentile	$7.69	$134.07	$97.45	$111.81
Maximum	$110.44	$1,080.16	$1,101.95	$1,129.85

Table 3: Points of the distribution for key co-variates across party and voting on Waxman-Markey, H.R. 2454.

		Democrats				Republicans			
Variable	**Statistic**	**Voted For (211)**	**Voted Against (43)**	**+Against**	**P-value of Difference**	**Voted For (8)**	**Voted Against (171)**	**+Against**	**P-value of Difference**
Gains from CAT	Mean	-13.40	-8.58	4.82	0.003	-16.95	-9.56	7.39	0.200
($/per capita)	Median	-15.85	-11.46	4.39	0.000	-17.07	-14.08	2.99	0.129
	75th	-12.99	-1.65	11.34	0.000	-14.63	-9.69	4.94	0.238
	90th	-7.42	5.50	12.92	0.067	-14.43	-0.44	13.99	0.359
Gains from RFS	Mean	-51.73	-20.02	31.71	0.039	-78.81	-13.63	65.18	0.239
($/per capita)	Median	-76.65	-37.81	38.84	0.000	-81.87	-56.67	25.20	0.165
	75th	-60.61	11.71	72.32	0.000	-74.05	-28.23	45.82	0.230
	90th	-13.53	60.27	73.80	0.115	-68.25	60.22	128.47	0.289
Political	Mean	3.46	16.14	12.68	0.000	10.25	16.03	5.78	0.559
Contributions	Median	0.50	12.00	11.50	0.000	1.00	7.55	6.55	0.195
Against ($1,000s)	75th	3.35	26.60	23.25	0.000	9.50	18.85	9.35	0.284
	90th	9.00	36.95	27.95	0.000	64.85	36.45	-28.40	0.077
Political	Mean	90.69	90.25	-0.44	0.971	143.65	79.48	-64.17	0.071
Contributions	Median	70.51	74.84	4.33	0.690	137.25	58.03	-79.22	0.000
For ($1,000s)	75th	112.65	104.95	-7.70	0.731	143.35	90.40	-52.95	0.051
	90th	156.41	182.55	26.14	0.397	581.86	156.76	-425.10	0.000

Notes: This table lists points in the distribution across Democrats and Republicans that voted for and against H.R. 2454. 211 Democrats voted for the policy, while 43 voted against. 8 Republicans voted for the policy, while 169 voted against. The standard errors are calculated via Stata's req and qreg commands and are the standard errors associated with the indicator variable for whether the member voted for the policy. Gains from CAT is average per capita benefits across the district from a cap & trade program that reduces GHG emissions by 10 percent. Gains from RFS is average per capita benefits across the district from the current federal RFS program in 2022. Political Contributions Against is the amount of political contributions received by the House member from organizations opposing H.R. 2454, measured in $1000s. Political Contributions For is the amount of political contributions received by the House member from organizations supporting H.R. 2454, measured in $1000s.

Table 4: Probit model correlating voting behavior for Waxman-Markey with estimated gains and losses: Linear terms.

	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**
Democrat	0.777***	0.749***	0.720***	0.752***	0.720***
	(0.028)	(0.019)	(0.019)	(0.019)	(0.019)
ln(Per Capita Benefits from CAT)	-0.530***	0.319	0.154		
	(0.137)	(0.222)	(0.249)		
ln(Per Capita Benefits from RFS)		-0.114***	-0.110***		
		(0.026)	(0.031)		
ln(Benefits from CAT) - ln(Benefits from RFS)				0.094***	0.105***
				(0.016)	(0.021)
State Fixed Effects	No	No	Yes	No	Yes
Observations	431	431	394	431	394
Chi-Square Statistic	315.11	334.66	340.56	333.64	340.52
P-Value	0.000	0.000	0.000	0.000	0.000
Log-Likelihood	-141.13	-131.36	-102.64	-131.87	-102.66
Pseudo-R2	0.53	0.56	0.62	0.56	0.62

Notes: The dependent variable equals one if the House member voted for H.R. 2454. The reported coefficients are the average of marginal coefficients taken at each observations level of the righthand side variables. For indicator variables, the coefficient represents the average change in the probability of voting yes from changing the indicator from zero to one. Democrat is an indicator equal to one if the House member is a Democrat. Per Capita Benefits from Cap & Trade is average per capita benefits across the district from a cap & trade program that reduces GHG emissions by 10 percent. Per Capita Benefits from RFS is average per capita benefits across the district from the current federal RFS program in 2022. We simulate that this leads to a 10 percent reduction in GHG emissions. Natural logarithms are calculated by adding $100 per capita to gains under each policy. ***, **, and * denotes statistical significance at the 1, 5, and 10 percent levels, respectively. Standard errors are in parentheses.

Table 5: Probit model correlating voting behavior for Waxman-Markey with estimated gains and losses: Quartile indicators.

	Model 1	**Model 2**	**Model 3**
Democrat	0.774***	0.755***	0.724***
	(0.029)	(0.031)	(0.037)
Per Capita Benefits from Cap & Trade, Quartile 2	-0.0230	0.0510	0.095**
	(0.042)	(0.042)	(0.047)
Per Capita Benefits from Cap & Trade, Quartile 3	-0.0270	0.111**	0.124**
	(0.043)	(0.045)	(0.056)
Per Capita Benefits from Cap & Trade, Quartile 4	-0.191***	0.0710	0.0730
	(0.050)	(0.057)	(0.066)
Per Capita Benefits from RFS, Quartile 2		-0.182***	-0.165***
		(0.050)	(0.053)
Per Capita Benefits from RFS, Quartile 3		-0.254***	-0.264***
		(0.060)	(0.067)
Per Capita Benefits from RFS, Quartile 4		-0.393***	-0.358***
		(0.069)	(0.080)
State Fixed Effects	No	No	Yes
Observations	431	431	394
Chi-Square Statistic	322	351	355
P-Value	0.000	0.000	0.000
Log-Likelihood	-137.60	-123.15	-95.37
Pseudo-R2	0.54	0.59	0.65

Notes: The dependent variable equals one if the House member voted for H.R. 2454. The reported coefficients are the average of marginal coefficients taken at each observations level of the righthand side variables. For indicator variables, the coefficient represents the average change in the probability of voting yes from changing the indicator from zero to one. Democrat is an indicator equal to one if the House member is a Democrat. The Per Capita Benefits from Cap & Trade quartile indicators are the quartiles of the average per capita benefits across the district from a cap & trade program that reduces GHG emissions by 10 percent. Per Capita Benefits from RFS quartile indicators are the quartiles of the average per capita benefits across the district from the current federal RFS program in 2022. We simulate that this leads to a 10 percent reduction in GHG emissions. ***, **, and * denotes statistical significance at the 1, 5, and 10 percent levels, respectively. Standard errors are in parentheses.

Table 6: Correlating voting behavior for Waxman-Markey with estimated gains and losses, other GHG-related variables, and political ideology: Quartile model.

	Model 1	Model 2	Model 3	Model 4
Democrat	0.752***			
	(0.031)			
Per Capita Benefits from Cap & Trade, Quartile 2	0.043	0.007	0.017	0.047
	(0.042)	(0.039)	(0.041)	(0.050)
Per Capita Benefits from Cap & Trade, Quartile 3	0.106**	0.033	0.042	0.065
	(0.045)	(0.043)	(0.045)	(0.057)
Per Capita Benefits from Cap & Trade, Quartile 4	0.065	0.002	0.014	0.04
	(0.057)	(0.054)	(0.057)	(0.067)
Per Capita Benefits from RFS, Quartile 2	-0.174***	-0.123***	-0.130***	-0.145***
	(0.049)	(0.044)	(0.046)	(0.052)
Per Capita Benefits from RFS, Quartile 3	-0.234***	-0.120**	-0.136**	-0.183**
	(0.061)	(0.054)	(0.061)	(0.073)
Per Capita Benefits from RFS, Quartile 4	-0.383***	-0.150**	-0.177**	-0.219**
	(0.070)	(0.076)	(0.089)	(0.101)
Top 10 Coal Producing State	-0.068*	-0.032	-0.035	
	(0.036)	(0.030)	(0.031)	
DW-Nominate		-0.426***	-0.427***	-0.421***
		(0.014)	(0.015)	(0.021)
ln(Per Capital CO2 Emissions)		-0.097***	-0.101***	-0.090***
		(0.023)	(0.024)	(0.029)
ln(Average Power Plant CO2 Rate)		0.035	0.034	0.03
		(0.028)	(0.027)	(0.038)
ln(Corn Production)			0.002	0.001
			(0.003)	(0.004)
State Fixed Effects	No	No	No	Yes
Observations	431	424	424	386
Chi-Square Statistic	354.90	408.00	408.47	390.94
P-Value	0.000	0.000	0.000	0.000
Log-Likelihood	-121.24	-89.77	-89.54	-72.00
Pseudo-R2/R2	0.59	0.69	0.70	0.73

Notes: The dependent variable equals one if the House member voted for H.R. 2454. The reported coefficients are the average of marginal coefficients taken at each observations level of the righthand side variables. For indicator variables, the coefficient represents the average change in the probability of voting yes from changing the indicator from zero to one. The Per Capita Benefits form Cap & Trade quartile indicators are the quartiles of the average per capita benefits across the district from a cap & trade program that reduces GHG emissions by 10 percent. Per Capita Benefits from RFS quartile indicators are the quartiles of the average per capita benefits across the district from the current federal RFS program in 2022. We simulate that this leads to a 10 percent reduction in GHG emissions. DW-nominate is the voteview.org measure of political ideology for the House member. Per capita CO2 emissions is the Purdue University Vulcan estimate of district's annual per capita CO2 emissions. Average power plant CO2 rate is the EIA measure of the average CO2 emission rate of power plants within the district. Corn production is the district's total corn production in 2007. ***, **, and * denotes statistical significance at the 1, 5, and 10 percent levels, respectively. Standard errors are in parentheses.

Table 7: Correlating campaign contributions by groups in support of or opposed to Waxman-Markey with estimated gains and losses: Quartile model.

	ln(Contributions Opposing WM)	ln(Contributions Opposing WM)	ln(Contributions Supporting WM)	ln(Contributions Supporting WM)
Democrat	-2.180***	-1.746***	0.372***	0.399***
	(0.347)	(0.360)	(0.122)	(0.125)
Per Capita Benefits from Cap & Trade, Quartile 2	-1.508***	-1.914***	0.213	0.321
	(0.525)	(0.611)	(0.185)	(0.213)
Per Capita Benefits from Cap & Trade, Quartile 3	-1.679***	-1.960***	0.134	0.330
	(0.627)	(0.720)	(0.221)	(0.251)
Per Capita Benefits from Cap & Trade, Quartile 4	-1.966**	-2.488***	-0.055	0.082
	(0.764)	(0.882)	(0.269)	(0.307)
Per Capita Benefits from RFS, Quartile 2	1.574***	1.568***	0.016	-0.129
	(0.552)	(0.585)	(0.195)	(0.204)
Per Capita Benefits from RFS, Quartile 3	2.819***	3.081***	0.061	-0.131
	(0.638)	(0.718)	(0.225)	(0.250)
Per Capita Benefits from RFS, Quartile 4	4.741***	5.004***	0.3690	0.276
	(0.773)	(0.898)	(0.272)	(0.313)
State Fixed Effects	No	Yes	No	Yes
Observations	430	430	430	430
R2	0.23	0.37	0.03	0.23

Notes: All models are estimated via OLS. The dependent variable in the first two columns is the amount of political contributions received by the House member from organizations opposing H.R. 2454, measured in \$1000s. The dependent variable in the columns three and four is the amount of political contributions received by the House member from organizations supporting H.R. 2454, measured in \$1000s. Democrat is an indicator equal to one if the House member is a Democrat. The Per Capita Benefits form Cap & Trade quartile indicators are the quartiles of the average per capita benefits across the district from a cap & trade program that reduces GHG emissions by 10 percent. We simulate that this leads to a 10 percent reduction in GHG emissions. Per Capita Benefits from RFS quartile indicators are the quartiles of the average per capita benefits across the district from the current federal RFS program in 2022. ***, **, and * denotes statistical significance at the 1, 5, and 10 percent levels, respectively. Standard errors are in parentheses.

Table 8: Correlating voting behavior for Waxman-Markey with estimated gains and losses, other GHG-related variables, and contributions: Quartile model.

	Model 1	Model 2	Model 3	Model 4	Model 5
Democrat	0.689***	0.670***	0.640***		
	(0.042)	(0.043)	(0.051)		
Per Capita Benefits from Cap & Trade, Quartile 2		0.024	0.056	0.013	0.038
		(0.041)	(0.047)	(0.042)	(0.050)
Per Capita Benefits from Cap & Trade, Quartile 3		0.081*	0.094*	0.027	0.057
		(0.044)	(0.054)	(0.046)	(0.057)
Per Capita Benefits from Cap & Trade, Quartile 4		0.027	0.047	0.003	0.037
		(0.057)	(0.066)	(0.057)	(0.067)
Per Capita Benefits from RFS, Quartile 2		-0.154***	-0.142***	-0.122***	-0.134***
		(0.047)	(0.051)	(0.045)	(0.052)
Per Capita Benefits from RFS, Quartile 3		-0.185***	-0.201***	-0.110*	-0.152**
		(0.056)	(0.064)	(0.057)	(0.069)
Per Capita Benefits from RFS, Quartile 4		-0.256***	-0.246***	-0.131	-0.159*
		(0.077)	(0.086)	(0.081)	(0.095)
ln(Contributions Supporting Waxman-Markey)	0.034**	0.036***	0.033**	0.020*	0.025*
	(0.014)	(0.014)	(0.016)	(0.012)	(0.015)
ln(Contributions Split on Waxman-Markey)	0.005	0.001	-0.002	0.005	0.003
	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)
ln(Contributions Opposing Waxman-Markey)	-0.031***	-0.023***	-0.021***	-0.009**	-0.010**
	(0.005)	(0.004)	(0.005)	(0.004)	(0.005)
Top 10 Coal Producing State				-0.031	
				(0.030)	
DW-Nominate				-0.409***	-0.395***
				(0.020)	(0.025)
ln(Per Capital CO2 Emissions)				-0.088***	-0.072**
				(0.024)	(0.030)
ln(Average Power Plant CO2 Rate)				0.036	0.041
				(0.026)	(0.044)
ln(Corn Production)				0.001	0.000
				(0.003)	(0.004)
State Fixed Effects	No	No	Yes	No	Yes
Observations	427	427	391	420	383
Chi-Square Statistic	349.32	375.89	373.20	412.59	394.75
P-Value	0.000	0.000	0.000	0.000	0.000
Log-Likelihood	-121.26	-107.97	-84.27	-84.71	-68.04
Pseudo-R2/R2	0.59	0.64	0.69	0.71	0.74

Notes: The dependent variable equals one if the House member voted for H.R. 2454. The reported coefficients are the average of marginal coefficients taken at each observations level of the righthand side variables. For indicator variables, the coefficient represents the average change in the probability of voting yes from changing the indicator from zero to one. The Per Capita Benefits form Cap & Trade quartile indicators are the quartiles of the average per capita benefits across the district from a cap & trade program that reduces GHG emissions by 10 percent. Per Capita Benefits from RFS quartile indicators are the quartiles of the average per capita benefits across the district from the current federal RFS program in 2022. We simulate that this leads to a 10 percent reduction in GHG emissions. DW-nominate is the voteview.org measure of political ideology for the House member. Political Contributions Opposing is the amount of political contributions received by the House member from organizations opposing H.R. 2454, measured in \$1000s. Political Contributions Supporting is the amount of political contributions received by the House member from organizations supporting H.R. 2454, measured in \$1000s. Per capita CO2 emissions is the Purdue University Vulcan estimate of district's annual per capita CO2 emissions. Average power plant CO2 rate is the EIA measure of the average CO2 emission rate of power plants within the district. Corn production is the district's total corn production in 2007. ***, **, and * denotes statistical significance at the 1, 5, and 10 percent levels, respectively. The coefficient for Per Capita Benefits from RFS, Quartile 4 in Model 4 is significant at the 10 percent level, but the marginal effect p-values are slightly greater than 0.10.

Table 9: Land use changes under alternate policies.

	BAU	RFS	LCFS	CAT	SUBS.
Land Use Changes (1000s of Acres)					
Total Acres	3,121	+38,979	+27,479	+1,158	+37,779
Corn Acres	2,892	+27,708	+14,708	+8	+25,708
Land Use Change Cost ($/MTCO2e)					
Low Scenario ($10 per corn acre)		$ 1.68	$ 0.89	< $0.01	$ 2.31
High Scenario ($25 per corn acre)		$ 4.19	$ 2.22	< $0.01	$ 5.77

Table 10: Uncontrolled emissions due to errors in estimating carbon intensity.

	RFS	**LCFS**	**CAT**	**SUBS**
Measured Emissions (MMTCO$_2$e)	1454	1454	1454	1508
Actual Emissions (MMTCO$_2$e)	1465	1460	1455	1519
Uncontrolled as % of stated reduction	7.1%	4.0%	0.7%	9.9%

Notes: "Measured emissions" assumes the emissions intensity for corn ethanol is sest.= 0.80. "Actual emissions" assumes regulators set corn emissions at sest.= 0.80, while the true emissions intensity is sact.= 0.90. This error results in "uncontrolled emissions" above the level targeted by the policy.

Table 11: Innovation incentives under alternate policies.

	BAU	LCFS	CAT	SUBS
Δ Social Surplus ($ bn.)	$0.91	$2.61	$4.38	-$4.43
Δ CS	$0.00	$67.08	$43.44	$0.00
Δ PS	$0.91	-$64.47	$3.24	$17.29
Δ PS (Corn Ethanol)	$0.00	-$85.03	-$0.07	$0.00
Δ PS (Cellulosic Ethanol)	$0.91	$20.56	$3.31	$17.29
Fuel Price ($/gge)				
Without Innovation	$2.75	$3.48	$3.58	$2.75
Base Case (With Innovation)	$2.75	$2.96	$3.23	$2.75
Avg. Abatement cost ($/MT$CO_2$e)				
Without Innovation		$47.43	$32.66	$194.45
Base Case (With Innovation)		$48.58	$19.52	$82.30

Notes: The change in surplus is the additional surplus from including our six types of cellulosic ethanol (With Innovation) relative to the counterfactual which excludes cellulosic ethanol (Without Innovation).

Appendices

A Modeling assumptions

Using data on biofuel supply and emissions intensity, we simulate fuel production, emissions, and land use in the U.S. under ethanol subsidies, RFS, LCFS, CAT, and SUBs systems. The simulation model captures the key characteristics of the market for transportation fuels in a simple framework that enables us to iteratively solve for market outcomes under each policy. In the sections that follow we describe our simulation model, key assumptions, and data.

A.1 Simulation methodology and data

We limit our analysis to a transportation fuel market consisting of gasoline and ethanol fuels. Because ethanol, and to a lesser extent gasoline, are likely to have very different emissions characteristics based on the feedstocks and technologies used in fuel production, we define a unique fuel as the combination of feedstock and production technology leading to a finished transportation fuel. For example, gasoline, ethanol produced by fermentation of corn, and ethanol produced from lignocellulosic forest biomass are considered distinct fuels.[46] It is worth noting that while our biofuel supply data focus on the U.S., other nations such as Brazil are likely to be important suppliers of biofuels in the future. Because we lack reliable data on these regions, we focus our analysis on domestic production.

We assume that on an energy basis these fuels are perfect substitutes and can be represented by a single demand equation for transportation fuel. This approach can be thought of as combining gasoline and ethanol fuels into a single blended fuel where the volume fraction of ethanol depends on the relative aggregate supply of each fuel. This simplification seems reasonable since modern gasoline vehicles can operate on blends containing up to, perhaps, 20% ethanol by volume and fuel economy, once adjusted for energy content, does not vary substantially for gasoline and ethanol fuels.[47]

[46] Similarly, gasoline produced from light sweet crude and gasoline produced from tar sands would be considered distinct fuels. However, since the focus of this paper is on biofuel production, we limit our analysis to gasoline produced from conventional oil resources.

[47] One limitation of this approach is that it ignores any utility consumers have for fuels that have environmental benefits, i.e. "warm glow."

A.2 Fuel demand

Baseline consumption of 140 billion gge per year is taken from the U.S. Department of Energy estimate for motor fuel consumption in 2022 U.S. Energy Information Administration (2010). This estimate includes the effect of policies such as the new Corporate Average Fuel Economy standards on future fuel consumption. We use a BAU retail price of \$2.75 per gallon.[48] Because future fuel prices are uncertain, we rerun our simulations using high and low price scenarios with retail prices of \$2.25 per gallon and \$3.25 per gallon. To put these numbers in perspective, the mean retail U.S. average price for gasoline in 2005 dollars from 2005 - 2009 was approximately \$2.45 per gallon with 25th and 75th percentiles of approximately \$2.20 and \$2.85 per gallon. Compared with recent prices, our base case BAU price is relatively high. However, this value is conservative in the sense that it favors higher BAU ethanol production and smaller changes in ethanol production and land use due to the adoption of carbon policy.

For our main analysis we assume that demand has constant elasticity, *i.e.,* $D(p) = Ap^{-\epsilon}$, where the elasticity ϵ is 0.5 and A is determined by the baseline consumption of 140 billion gge at a price of \$2.75. In our sensitivity analysis, we solve for different As at fuel prices of \$2.25 per gallon and \$3.25 per gallon. This long-run elasticity of 0.5 is consistent with recent estimates from the literature, for example Small and Winston (1999). The long-run demand elasticity is meant to capture both the short-run (*e.g.*, driving less) and long-run (*e.g.*, purchasing a more fuel efficient vehicle) behavior of consumers in response to changes in the price of fuel. We test the sensitivity of our results to the demand elasticity assumption below.

A.3 Gasoline supply

We assume that gasoline supply is perfectly elastic in the long run. Gasoline supply is primarily limited by refinery capacity in the short-run. Since each policy studied here serves to reduce gasoline consumption, it is unlikely that capacity constraints will be important in the long run. Violations of this assumption would come from an upward sloping long run average cost curve. This could occur, for example, if the refinery locations vary in their quality in terms of either access to inputs or demand.

The assumption of perfectly elastic supply at \$2.75 per gallon (retail) means that gasoline is always the marginal fuel and the fuel price is always determined by the effects of the policies on

[48] We convert ethanol wholesale prices to retail prices by adding \$0.63 per gge to the wholesale price. This figure, meant to capture fuel taxes and distribution costs, is taken from the average difference between retail and wholesale gasoline prices from 2000 to 2009.

the cost of gasoline production. Furthermore, the assumption of perfectly elastic supply implies that gasoline production is determined by the demand for transportation fuel and the total level of ethanol production as discussed previously.

Finally, we assume that real state and federal fuel excise taxes in 2022 are unchanged from today's levels and that no additional taxes are levied on transportation fuel. The net U.S. average state and federal gasoline tax is approximately \$0.48 per gallon. Taking the average difference between retail and wholesale prices of \$0.63 described above, implies distribution and retail costs (and, possibly, mark ups) of approximately \$0.15 per gallon. This approach assumes that gasoline and ethanol are treated the same on a energy equivalent basis. However, this assumption implies changes in the structure of fuel taxes to take the energy content of fuels into account.

A.4 Ethanol supply curves

We construct ethanol supply curves using cost estimates for biomass feedstocks, conversion, and ethanol distribution. We consider grain and lignocellulosic ethanol produced from: corn (grain); agricultural residues, such as rice straw and corn stover; orchard and vineyard waste; forest biomass, including waste and farmed trees; herbaceous energy crops, such as switchgrass; and municipal solid waste.[49] Feedstock costs are based on county-level geographic information system (GIS) data on agricultural production in the United States. Conversion costs are based on engineering models for ethanol production facilities. Transportation costs are based on GIS data for existing truck, rail, and marine facilities.

These data are combined with a simplified model for the biofuel refining industry in a mixed integer linear optimization program. The industry is modeled as a set of competitive firms with perfect information. Firms choose plant location and plant size (output) to maximize profit conditional on the price of fuel, biomass resources, and transportation costs. The model explicitly accounts for the trade-off between economies of scale in the conversion of biomass to fuels and the feedstock collection costs. Supply curves are constructed by varying the price of fuel and calculating the profit maximizing level of biofuel production. Different prices correspond to different levels of plant production as well as different industry configurations in terms of the number, size and location of production facilities. Therefore, the supply curves represent estimates of long-run biofuel supply. The resulting supply curves are shown in Appendix Figure 1.

[49]Given that ethanol and gasoline are substitutes for low level ethanol blends, we focus on ethanol production pathways. Future work may explore implications of carbon policy on diesel and biodiesel supply.

Biomass resource estimates are constructed as follows. National corn production and price projections Office of the Chief Economist, World Agricultural Outlook Board, United States Department of Agriculture (2010) are disaggregated to county level by assuming future production matches the historical geographic distribution of production National Agricultural Statistics Service (2009). Total corn ethanol production is constrained at 15 billion gallons per year in compliance with the RFS.

Herbaceous energy crop resource (switchgrass) estimates are take from Wullschleger et al. (2010). We assume that herbaceous energy crop production is limited to marginal land, defined as cropland that was idle or in pasture (not pastureland) in the 2007 Census of Agriculture National Agricultural Statistics Service (2009). In this case, our results can be interpreted as a lower bound on the projected land use changes. In reality, high energy prices may cause farmers to switch production of herbaceous energy crops to land previously used for other types of agriculture.

Sustainably removable quantities of agricultural residues − corn stover, wheat straw, orchard and vineyard prunings − are estimated based on historical yields, land areas, and production practices with binding constraints on wind erosion, water erosion and organic matter in the soil Graham et al. (2007); Nelson (2010). The cost of harvesting, storing and transporting agricultural residues comes from a feedstock logistics model developed by Idaho National Laboratory Idaho National Laboratory (2010).

Forest residue resource assessments are taken from Biomass Research and Development Board (2009). Production of biomass from farmed trees is modeled using pulpwood supply curves obtained from the U.S. Forest Service.[50] Finally, the municipal solid waste resource is estimated by projecting the organic fraction of municipal solid waste using state-level per capita waste production statistics Simmons et al. (2006) and the composition of wastes currently landfilled U.S. Environmental Protection Agency (2007). A fraction of the gross waste landfill is assumed to be available for fuels production. The cost of sorting waste biomass for use in an ethanol production facility is assumed to be $30/ton.

We model grain and cellulosic ethanol production technologies. The engineering economic models represent future technology costs in the year 2017. Given that new ethanol plants operating in 2022 will include a mix of facilities built both immediately prior to 2022 and a number of years before, 2017 seems a reasonable approximation for plant vintage.

For grain ethanol, both wet and dry-mill corn ethanol technology are considered. Production costs are taken from Gallagher, Brubaker, and Shapouri (2005); Gallagher and Shapouri (2005);

[50]Obtained via personal communication with Ken Skog at the USFS.

Butzen and Hobbs (2002). All dry mill facilities are modeled with natural gas for process heat and dry distillers grains as a co-product. We assume conversion efficiencies of 2.8 gallons per bushel for dry mill facilities and 2.5 gallons per bushel for wet mill facilities. Existing ethanol plants are modeled with zero capital cost. The locations and capacities of existing plants are fixed Renewable Fuels Association (2009). Due to the relative cost of the technologies, all new facilities use dry mill technology.

The conversion of cellulosic feedstocks to ethanol uses a dilute acid enzymatic hydrolysis and fermentation technology. Cost and performance are taken from Wooley et al. (1999); Hamelinck, Hooijdonk, and Faaij (2005); Aden et al. (2002); McAloon et al. (2000). The technology cost and performance reflect *nth* of a kind facilities and represent significant advances from the current state of the industry. Conversion efficiencies are dependent on composition of the feedstock and range from 70 gallons per dry ton to 90 gallons per dry ton. For all technologies, capital cost are converted to levelized costs of conversion using a 20-year economic life and a 12.3% annual discount rate.

Finally, finished ethanol fuel is distributed to existing gasoline distribution terminals Oil Price Information Service (2007) in proportion to the fraction of national vehicle miles traveled (VMT) within each terminal service area Hu et al. (2007). Distribution costs are based on the highway distance between ethanol plants and gasoline distribution terminals.

A.5 GHG emissions intensities

The distinguishing feature of biofuels, compared to other fuels, is the fact that growing plants remove carbon dioxide from the atmosphere. The combustion of fuel produced from biomass feedstocks releases this carbon back into the atmosphere, where in principle, a roughly equivalent quantity is absorbed by the next generation of biomass. Therefore, overall carbon emissions can be limited within this cycle. In practice however, the cultivation, collection, conversion, and distribution of biomass feedstock and ethanol fuel create additional carbon emissions. Unfortunately, for many developing technologies, production scale facilities do not currently exist. As a result, engineers rely on techniques of life-cycle analysis to estimate the average emissions characteristics of different ethanol pathways.

Life-cycle analysis assigns emissions factors to the various stages of ethanol production such as feedstock collection, conversion, and fuel combustion. Differences in emissions for fuel pathways arise from variation in ethanol yield and energy input requirements for alternate feedstocks and production processes. In addition to direct process emissions, the cultivation of biomass feedstocks may result in carbon emissions due to indirect land use changes. The emissions intensities used here are intended to capture both direct and indirect emissions.

Recent work Searchinger et al. (2008); California Air Resources Board (2009); Fargione et al. (2009) suggests that switching land to energy crop production emits large quantities of sequestered carbon. The argument is that increased biofuel consumption can lead to new land being put into production either directly, by growing energy crops, or indirectly by displacing other agricultural activity. Carbon sequestered in the soil and in existing vegetation is released into the atmosphere when the new land is cleared and tilled. While considerable uncertainties exist, one recent study estimated that accounting for these effects increases the emissions associated with corn and cellulosic ethanol production by 30 g/MJ and 18 g/MJ, respectively California Air Resources Board (2009). Effects of this magnitude represent increases of approximately 44% and 98% of model estimates for corn and cellulosic ethanol emissions excluding land use changes.[51]

Unfortunately, there is no single study or research group that provides estimates of life-cycle GHG emissions for all the fuels considered here and, as noted, for studies that overlap, there is substantial variation in the parameter values. Appendix Table 2 summarizes the life-cycle GHG estimates for various subsets of the ethanol fuels in this paper. The results are presented as normalized emissions intensities where the intensity of each ethanol fuel is divided by the emission intensity of gasoline. This leads to a more intuitive interpretation. For example, a normalized intensity of 0.90 means that GHG emissions are 90% of GHG emissions of conventional gasoline.

Due to the considerable variability in these estimates, we adopt baseline values that fall conservatively in the range of those presented in Appendix Table 2. We construct a series of scenarios to gauge the sensitivity of our results to changes in these parameters. The base case emissions intensities and scenario parameters are presented in Appendix Table 3.

A.6 County-level surplus calculations

To understand the distributional impacts of transportation carbon policies across the U.S., we first estimate changes in consumer and producer surplus under each policy at the county level. To do this we calculate the change in producer surplus relative to BAU for corn ethanol, the seven cellulosic fuels, and gasoline for each county using the equilibrium producer fuel prices from our national model and our county-level ethanol supply curves. Because we lack detailed data on fuel consumption or driving at the county level, we assign changes in consumer surplus to counties based

[51] In the case of corn ethanol, indirect land use effects of this magnitude would result in CO_2e emissions exceeding those of conventional gasoline.

on population.[52] County-level surplus changes are then calculated as the difference in producer and consumer surplus changes under each policy. Because counties may be of substantially different size, we report changes per capita.

Our analysis of Congressional voting behavior requires aggregating the county-level surplus data to Congressional Districts. We assign counties to Congressional districts based on the 110th Congress. When a district contains more than one county, each county's contribution to the district surplus change is weighted equally by one $1/n_j$, where n_j is the number of counties in district j.

Despite the concentration of agricultural activity in the U.S. Midwest, there is substantial variation in county-level gains and loses across policies. Appendix Figure 2 compares county-level gains under the RFS and CAT. Deviations for the dotted line identify the RFS and CAT gains parameters in Tables 4 through **??**.

A.7 Land use calculations

The land areas used to grow energy crops for ethanol production are calculated using county-level geographic information system (GIS) data on biomass resources. In our data, the feedstocks with the largest potential for large land-use shifts are corn and herbaceous energy crops. For simplicity, we assume that there are no land use effects associated with the use of waste biomass for ethanol production.[53] This assumption seems reasonable given collection costs and the relatively small quantity of waste biomass available.

Each ethanol supply curve is based on production at discrete plants optimally sited across the U.S. by our linear optimization model. The quantity of biomass required to produce a gallon of ethanol is determined by ethanol conversion efficiency factors assigned to each production technology described above. For each ethanol plant and each fuel type, the total quantity of biomass consumed is known for every point on the supply curve. To calculate the total amount of land required to supply biomass to each plant, we use county-level crop yield data to convert biomass tons to acres planted.

Corn yields are estimated by increasing the current county-level yields National Agricultural Statistics Service (2009) uniformly at the rate projected for the national average Office of the Chief Economist, World Agricultural Outlook Board, United States Department of Agriculture (2010). Switchgrass yields were modeled by Oak Ridge National Laboratory for both lowland and upland

[52]Weights were derived based on population from the 2000 U.S. Census.

[53]For example, farmers that sell orchard and vineyard waste to ethanol plants do not expand their orchards as a result of the reduced cost of waste disposal.

varieties of switchgrass. Our calculations use upland yields as these more closely approximate yields for switchgrass grown on marginal lands.

To graphically illustrate land use shifts we calculate “land use intensities” for both corn and total energy crop production, corn plus herbaceous energy crops and corn alone. Herbaceous energy crops are assumed to be grown on land not used for production of food or other cultivated crops. This distinction is useful for two reasons. First, farmland used for corn production is a substitute for land used for food crops. Therefore, one would expect food price and indirect land use effects to be larger than for crops grown on marginal land. Second, corn may be raised using more intensive farming practices leading to more fertilizer use, irrigation, erosion, etc., compared to herbaceous crops.

We define land use intensity as the total number of acres used in energy crop production divided by total land area in a given county. This approach provides a consistent basis for comparison across counties and highlights the regions where land use shifts are occurring. Using total land area as the basis for comparison also illustrates the tradeoffs that occur when marginal lands are put into production.[54]

A.8 Environmental costs per acre of cropland

Land-use changes have important implications for indirect carbon emissions, food prices, run-off, erosion and habitat loss. Because different transportation carbon policies are likely to result in vastly different land-use changes, we consider these costs an important part of any policy evaluation. We incorporate indirect carbon emissions directly in our baseline emissions intensity parameters. Because fuel price effects are controversial, for example see Roberts and Schlenker (2010), we leave food price effects for future analysis. Instead, we focus on environmental costs due to erosion and habitat loss.

One of the potential benefits of herbaceous energy crops, such as switchgrass, are the low environmental costs of cultivation. Our supply curves assume switchgrass is grown on marginal agricultural lands without irrigation or application of chemical fertilizers. We imagine that these farming practices do not substantially increase, and potentially reduce, erosion. Furthermore, we assume that when land is converted to switchgrass farming, these fields offer similar wildlife habitat to the fallow land being replaced. Under these circumstances, we conservatively estimate the environmental costs of additional lands devoted to herbaceous energy crop production as zero.

[54]As opposed to comparisons based on the number of arable acres within the county, for example.

Cultivated crops such as corn are likely to have more serious environmental costs. Land used for increased corn production comes from a combination of existing agricultural land previously used for other cultivated crops, and new lands being brought into production. To a first approximation, we assume the environmental costs of corn and other cultivated crops are similar. Therefore, we ignore the fraction of land coming from crop substitution. To model new lands, we assume any additional acres come from the Conservation Reserve Program (CRP). Hansen (2007), studies the benefits of CRP in terms of reduced erosion and habitat preservation. He estimates an annual benefit of approximately $1.3 billion for the approximately 36 million acres in CRP for an average annual benefit of approximately $36 per acre per year. Benefits vary substantially by region. In the nation's corn belt, Hansen (2007) estimates CRP benefits of over $80 per acre. We use $36 per acre and $80 per acre as lower and upper bounds on the range of potential costs.

To estimate the fraction of new acres planted per additional acre of corn produced we refer to previous work on land use changes due to biofuel production. Searchinger et al. (2008) model global land-use changes under the Federal RFS. The authors find that for a 56 billion liter (15 billion gallon) increase in U.S. corn ethanol production, corn acreage increases by approximately 7,864 thousand hectares and total cropland increases by 2,245 thousand hectares (29%). In our analysis, we assume that 30% of all additional corn acres come from CRP land. Based on these assumptions, we model a range of environmental costs due to land-use change in a range between $10 and $25 per additional acre of corn production.

A.9 Numerical simulation algorithm

Given the theoretical framework described above, the equilibrium under each of the four policies could be solved analytically for continuous functional forms. However, our detailed ethanol supply curves are discontinuous, which necessitates a numerical simulation. The code for the calculations is available on the web. Here we briefly describe the algorithm.

In the baseline case with no carbon policy, the fuel price is simply determined by the marginal cost of gasoline. Fuel demand is then found from the demand curve, and supply of each type of ethanol is determined by the ethanol supply curves. Gasoline production is simply the residual after subtracting total ethanol production from the quantity demanded.

For the case with ethanol subsidies, the calculation is quite similar except now supply of each type of ethanol is determined by Equation 1. As above, the price is determined by the marginal cost of gasoline.

The RFS simulation is somewhat more complicated since the fuel price is now determined by the optimality condition for gasoline in Equation 4 which in turn depends on the RIN prices. The equilibrium is calculated with a series of nested loops. For a given vector of RIN prices, the supply of each type of ethanol can be calculated from Equation 3. Since the fuel price is determined by Equation 4, the fuel demand is determined and again gasoline fills the residual demand. However, given these prices, the cellulosic RIN price may not satisfy the RFS ratio for cellulosic ethanol. By raising the cellulosic RIN price if there is too little cellulosic ethanol and lowering it if there is too much cellulosic ethanol, the cellulosic RIN price can be adjusted so that the RFS ratio for cellulosic ethanol is exactly satisfied.[55] However, now the RFS ratio for advanced ethanol may not hold. By using a nested loop, the RIN prices can be adjusted so that both the cellulosic and advanced RFS ratios hold. Adding another nested loop ensures that all three RFS ratios hold.[56]

For the LCFS, for a given λ_{LCFS}, the fuel price is determined by Equation 6 for gasoline. With this price and λ_{LCFS}, the quantities of each ethanol and of gasoline can be calculated. However, the LCFS constraint in Equation 5 may not be satisfied. By looping over λ_{LCFS}, the LCFS equilibrium can be calculated.

Finally for carbon trading, the fuel price is determined for a given λ_{CAT} by Equation 8 for gasoline. The supply of each type of ethanol can then be determined by Equation 8 for each type of ethanol. As above, the carbon price can be increased if carbon emissions exceed the cap or can be decreased otherwise until Equation 7 holds with equality. This yields the carbon trading equilibrium.

To make the policies comparable, the LCFS standard and carbon cap are set so that they each yield the same emissions reductions as the RFS.

B Robustness

In this section, we investigate the robustness of our results to changes in the preferred simulation parameters. In the following scenarios we vary; the baseline fuel price; the emissions intensities of corn and cellulosic ethanol; and the elasticity of fuel demand. Finally, we relax our assumption that corn prices are not substantially affected by shifts in ethanol production.

[55] Actually, the algorithm starts with upper and lower bounds for the price and then calculates new upper and lower bounds by evaluating the midpoint of the interval. Note that changing the cellulosic RIN price requires that all the equilibrium values be recalculated.

[56] We add three additional loops to ensure that the RFS ratios indeed hit the volumetric targets.

B.1 Gasoline price scenarios

The fuel price scenarios in Appendix Table 5 highlight the effect of our BAU fuel price assumption on equilibrium prices, average abatement costs, consumer and producer surplus changes. Because ethanol and gasoline are substitutes, we expect higher baseline levels of ethanol production during periods of high fuel prices. Therefore at higher BAU prices, the RFS results in lower changes in ethanol production and lower predicted emissions reductions. As a result, consumer and producer surplus changes as well as average abatement costs are lower with higher BAU fuel prices. Because the LCFS and CAT systems are designed to achieve the same reduction in emissions as the RFS, changes under these policies also decrease with higher baseline fuel prices.

Average abatement costs continue to vary substantially across policies. At $2.25 per gallon, abatement costs under the RFS are more than three times those under CAT, while abatement costs under the LCFS are more than two times greater. Increasing the baseline fuel price to $3.25 reduces average abatement costs for all of the policies, though the relative levels remain fairly constant. Abatement costs under the RFS and LCFS continue to be over two and a half times those of CAT.

Producer surplus gains to ethanol producers decreases with higher baseline fuel prices under the RFS, LCFS and CAT systems. However, the differences between gains under CAT and the alternatives remains large. Under subsidies, producer surplus gains increase with higher BAU fuel prices. Approximately half of this gain ($3.79) goes to corn ethanol producers.

Because the difference in producer surplus gains between the RFS and CAT systems decreases with high baseline fuel prices, we re-estimate our empirical model with data from the high fuel price scenario. With high baseline fuel prices, gains to producers under the RFS fall from approximately $17 billion per year to approximately $12.5 billion per year. However, county-level gains under the alternatives to CAT are still large and concentrated. Appendix Table 6 shows points on the distribution of gains and loses under each of the policies. Under the RFS and subsidies, the top 5% of counties gain more than $953 and $2,076 per capita, respectively. No county loses more than $105 per capita. Under CAT, the top 5% of counties gain more than $146 per capita. No county gains more than $789. Correlations between gains, loses, voting behavior, and contributions are very similar to results using our preferred simulation parameters.

B.2 GHG emissions intensities scenarios

In our baseline simulation, we used emissions intensities for the different ethanol feedstocks that fall conservatively in the range of those presented in Appendix Table 2 and conduct a series of scenarios to gauge the sensitivity of our results to changes in these parameters. The base case emissions intensities and scenario parameters are presented in Appendix Table 3. The "High Indirect Land Use" scenario is meant to capture the case where emissions due to indirect land use changes are higher than initially estimated. "Waste Zero Emissions" captures the case where ethanol produced from waste biomass is assigned zero emissions.[57] Finally, the "Existing Corn" scenario represents the case where future corn ethanol technologies fail to realize fewer emissions than current technology.

Appendix Table 7 presents simulation results under the base case and the three emissions intensity scenarios. Fuel prices and production are unchanged under the RFS and subsidies as these policies do not take into account the carbon emissions characteristics of fuels. Similarly, producer and consumer surplus changes under the RFS and subsidies are unaffected by changes in emissions parameters. Under the LCFS and CAT systems, energy prices and consumer surplus loses decrease, and producer surplus gains increase, under the high indirect land use scenario. Producer surplus gains to ethanol producers are largest under the scenario where waste biomass is assigned an emissions intensity of zero.

Abatement costs also move in expected ways. Under the "High Indirect Land Use" and "Existing Corn" scenarios average abatement costs increase for the RFS and SUBs policies. This is because the higher emissions intensities of fuels in these scenarios decreases the total emissions reduction under policies that don't take carbon production into account. The mechanism varies by policy, however. In the scenarios where emissions intensities increase, under the RFS and SUBs the change in private surplus from the regulations is unaltered, but abatement is reduced, leading to an increase in average abatement costs. Under the LCFS and CAT, there are two competing effects. For one, the required abatement under these policies is reduced since this is set by abatement under the RFS. Second, because the emission intensities of some fuels has increased, it is more costly to meet a given level of abatement. We find the first effect dominates, leading to an decrease in abatement costs. Under the "Waste Zero Emissions" scenario, the availability of "zero carbon" fuels results in lower average abatement costs in all scenarios. In all cases the relative abatement cost differences across policies remains large.

[57] Though in reality these feedstock may generate emissions, due to the uncertainty in estimating emissions policy makers may be inclined to give these fuels a "free pass."

B.3 Fuel demand price elasticity scenarios

Appendix Table 8 presents simulation results for a range of price elasticities of gasoline demand. Our base case simulations use a price elasticity of -0.50. In addition, we simulate less elastic and more elastic demand with elasticities of -0.30 and -0.70, respectively. The land use estimates are very robust to changes in the demand elasticity. There are no changes in equilibrium outcomes under subsidies as fuel prices under the policy are unchanged. Under CAT, fuel price increases are smaller with more elastic demand. Fuel price changes under the RFS and LCFS are essentially unchanged across the scenarios. Under CAT, consumer surplus loses decrease substantially when demand is assumed to be more elastic. Surplus to gains to ethanol producers vary slightly depending on the assumed demand elasticity, though the large differences across policies remain. In particular, the large gains to corn ethanol producers under the RFS compared with CAT are essentially unchanged.

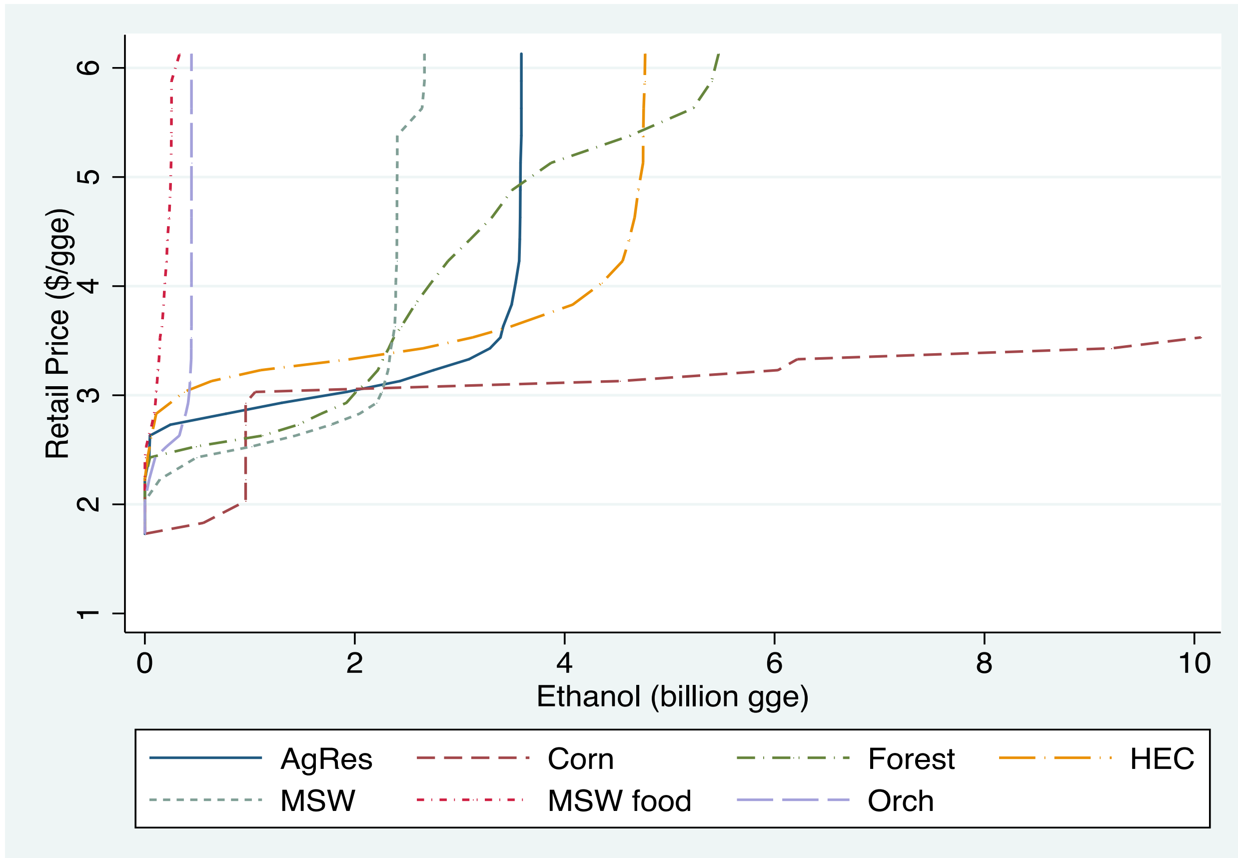
B.4 Corn price elasticity scenario

Corn represents a substantial fraction of the cost of producing corn ethanol, in our simulations approximately $2.00 per gasoline gallon equivalent. We set corn prices under the 2022 RFS to $3.64 per bushel, consistent with production of 10 billion gge per year of corn ethanol Office of the Chief Economist, World Agricultural Outlook Board, United States Department of Agriculture (2010). At these levels, corn used in ethanol production represents a substantial share of U.S. corn production. However, substantially less corn ethanol is produced under BAU and CAT. In these cases, we may expect lower prices reflecting a decreased demand for corn. To gauge the sensitivity of our results to endogenous changes in corn prices, we adjust our corn ethanol supply curve using a elasticity of corn prices with respect to corn consumption for ethanol production of 0.12 (Gardner (2007)). Supply curves for corn ethanol with and without corn price effects are shown in Appendix Figure 5. The upper supply curve is our base case. The lower supply curve shows the adjustment to marginal costs from decreased corn prices at lower production levels. The horizontal line in Appendix Figure 5 shows the marginal cost of production plus the carbon charge under CAT. The intersection of the horizontal line with the supply curves gives the levels of ethanol production in each case. Because corn supply is relatively elastic, small shits in prices result in large changes in corn ethanol production.

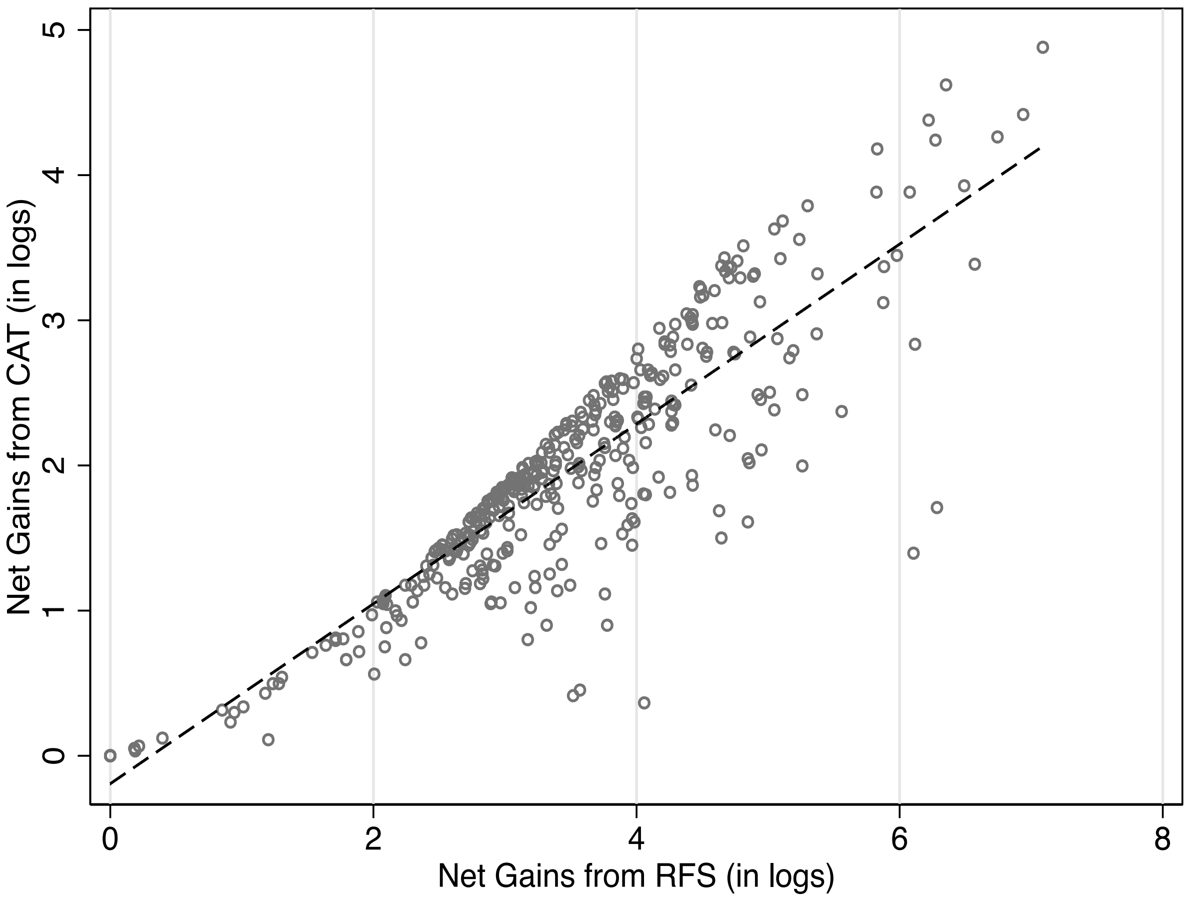
Appendix Table 9 shows the simulation results for each policy in the base case and accounting for corn price effects. Equilibrium outcomes are quite similar to the base case. Energy price increases are essentially unchanged under the RFS, LCFS and CAT policies when changes in corn prices are taken into account. Producer surplus gains for corn ethanol producers are slightly larger under all policies with endogenous corn prices. As a result, average abatement costs decrease modestly. However, the overall cost difference across policies remains large.

Appendix Figures

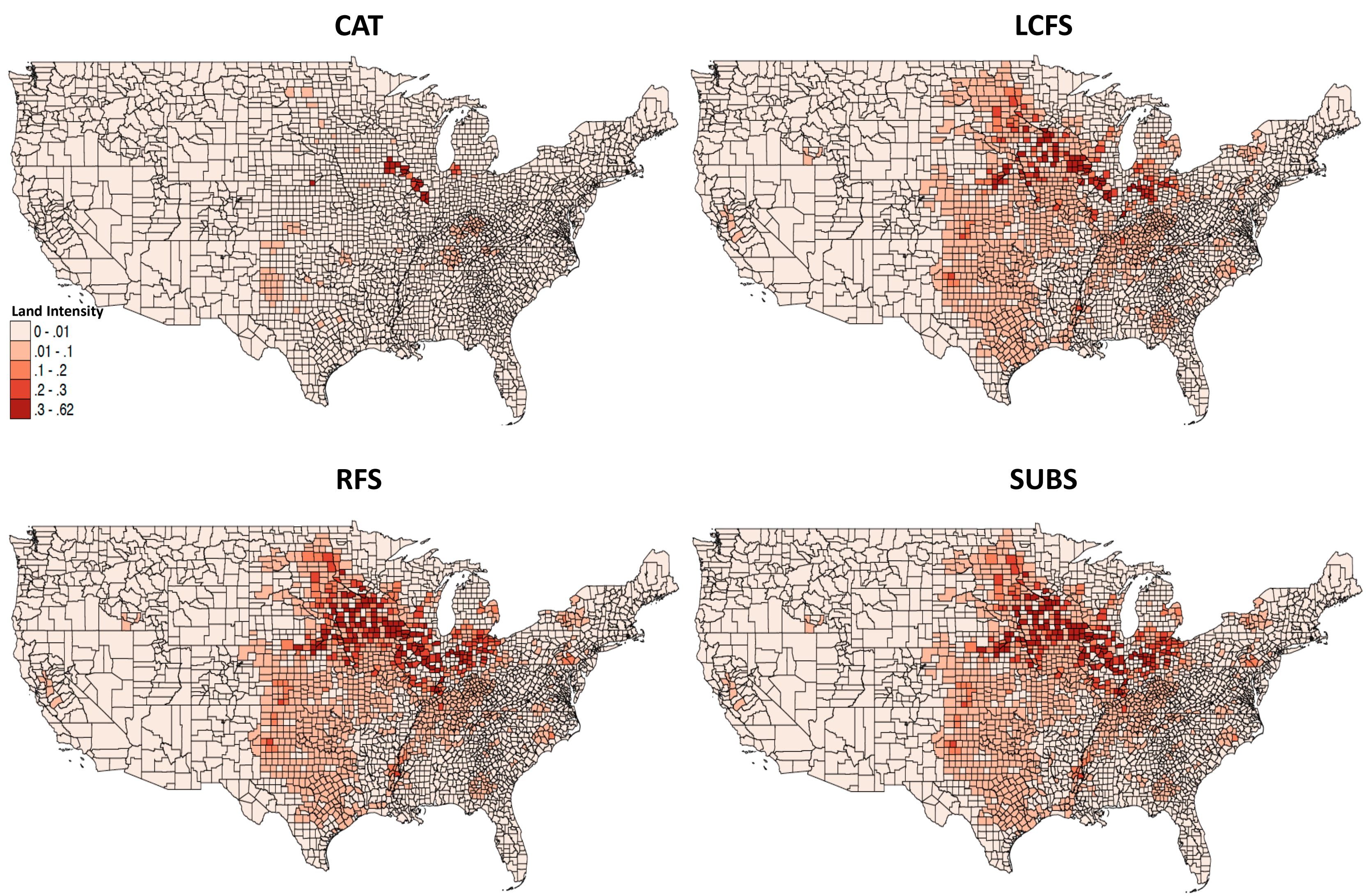
Appendix Figure 1: Biomass supply curves for corn based and cellulosic ethanol.



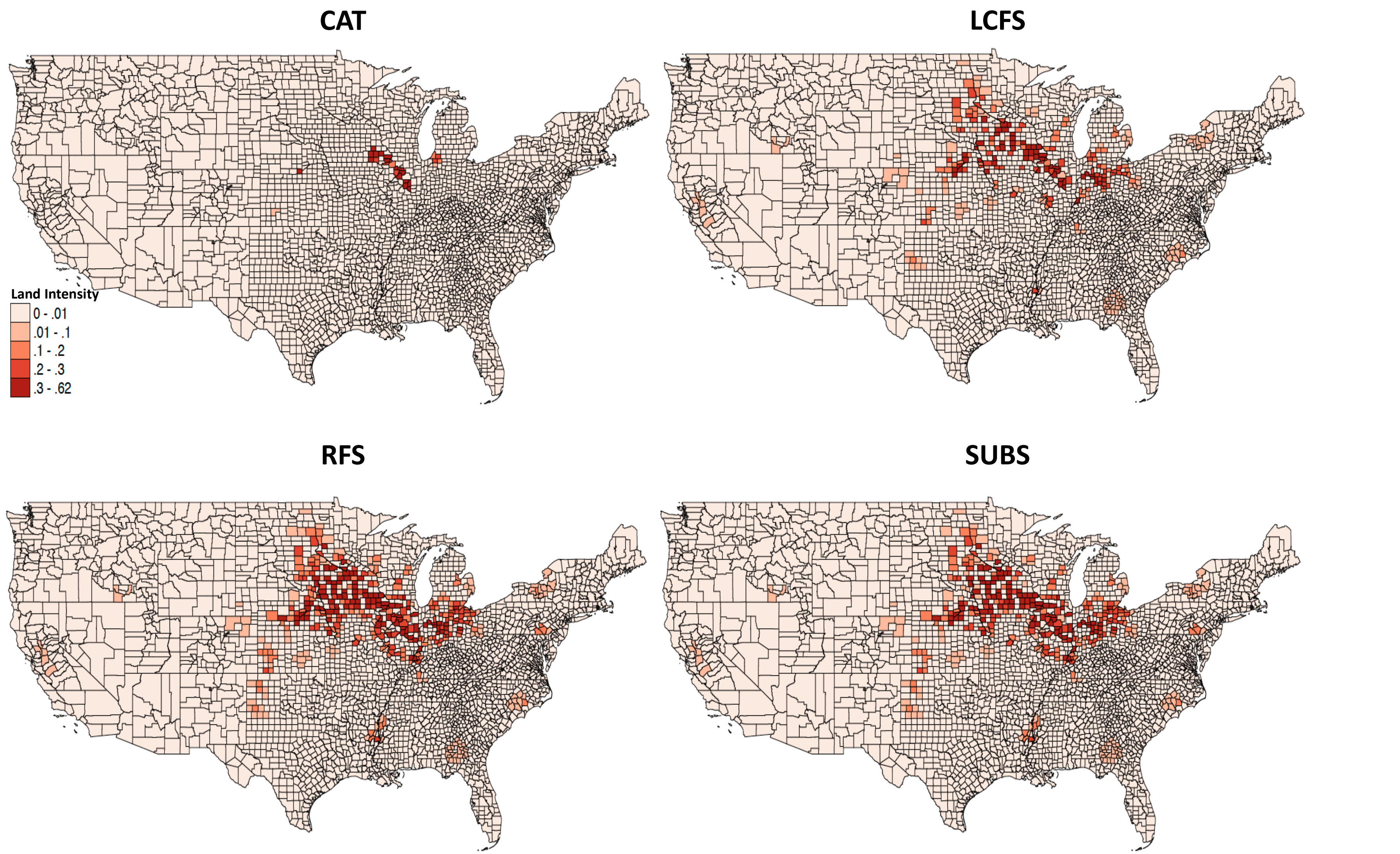
Appendix Figure 2: Comparison of net district-level gains from CAT and from the RFS.



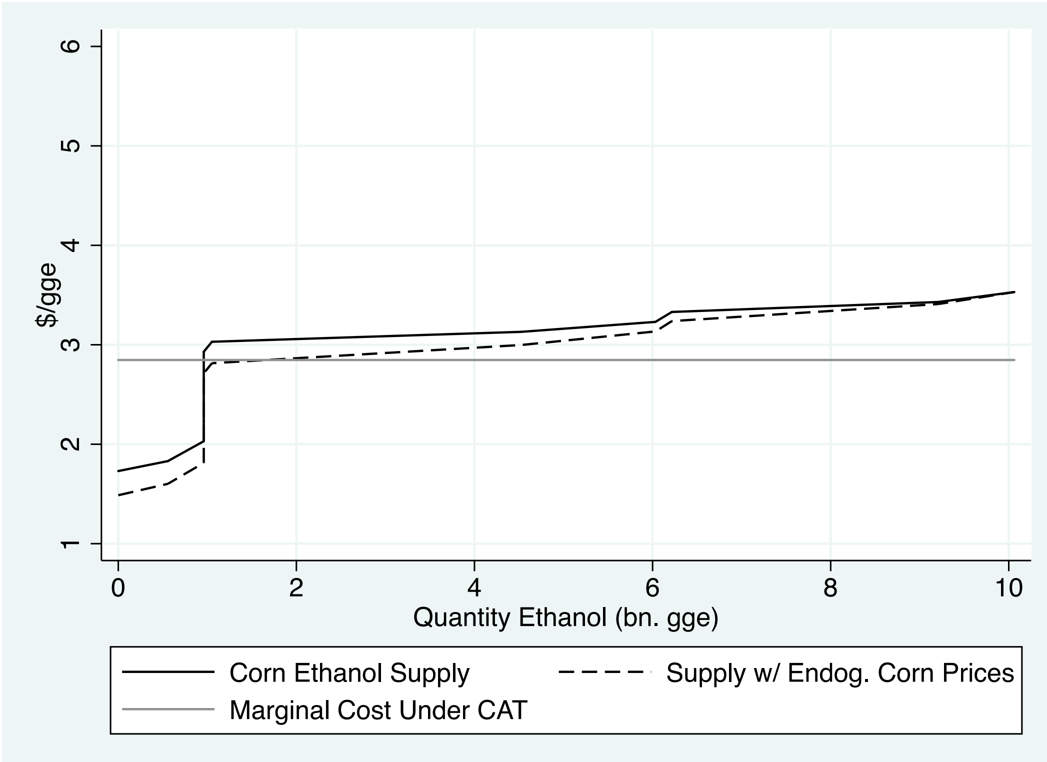
Appendix Figure 3: Total energy crop land intensity (% of total land) used in ethanol production from corn and switchgrass under CAT, a LCFS, the 2022 RFS and subsidies.



Appendix Figure 4: Corn land intensity (% of total land) used in ethanol production under CAT, a LCFS, the 2022 RFS and subsidies.



Appendix Figure 5: Corn ethanol supply curves with and without corn price effects.



Appendix Tables

Appendix Table 1: Federal Renewable Fuel Standard for 2010, 2015 and 2022.

	2010	2015	2022
Cellulosic (bn. gal./year)	0.1	5.5	16
Advanced (bn. gal./year)	1	3	21
Total Renewable Fuel (bn. gal./year)	12	20.5	36

Appendix Table 2: Lifecycle GHG emission estimates for corn and cellulosic ethanol pathways.

	CARB (2009)	EPA (2010)	Zhang *et al*. (2010)	Kalogo *et al*. (2007)	Spatari *et al*. (2005)
Corn	0.91 to 1.04	0.79	1.04		
Herb. Energy Crops		-0.10			0.24
Waste Biomass					
Ag. Residues		-0.29	-0.09 to 0.16		0.16
Orchard and Vineyard					
Forest	0.02 to 0.22		-0.06 to 0.19		
Muni. Solid Waste			0.042	0.16 to 0.35	

Appendix Table 3: Baseline emissions intensities and emissions scenario parameters.

	Base Case	High Indirect Land use	Waste Zero Emissions	Existing Corn
Corn	0.80	1.00	0.80	0.90
Herb. Energy Crops	0.25	0.40	0.25	0.25
Waste Biomass	0.20	0.20	0.00	0.20

Notes: Emission intensities are relative to gasoline.

Appendix Table 4: Externality estimates from the Interagency Working Group on Social Cost of Carbon (2010).

	Discount Rate			
	5%	3%	2.5%	3%
Year	Average	Average	Average	95th Percentile
2010	4.7	21.4	35.1	64.9
2015	5.7	23.8	38.4	72.8
2020	6.8	26.3	41.7	80.7
2025	8.2	29.6	45.8	90.9
2030	9.7	32.8	50.0	100.0
2035	11.2	36.0	54.2	109.7
2040	12.7	39.2	58.4	119.3
2045	14.2	42.1	61.7	127.8
2050	15.7	44.9	65.0	136.2

Appendix Table 5: Equilibrium outcomes under carbon policies for three fuel price scenarios.

	BAU	RFS	LCFS	CAT	SUBS
Fuel Price ($/gge)					
Low Fuel Price: $2.25	$ 2.25	$ 2.54	$ 2.57	$ 2.92	$ 2.25
Base Case: $2.75	$ 2.75	$ 2.94	$ 2.96	$ 3.23	$ 2.75
High Fuel Price: $3.25	$ 3.25	$ 3.35	$ 3.36	$ 3.49	$ 3.25
ΔCS ($ bn.)					
Low Fuel Price: $2.25		-$39.23	-$43.14	-$87.86	$0.00
Base Case: $2.75		-$26.69	-$28.59	-$65.07	$0.00
High Fuel Price: $3.25		-$14.52	-$14.63	-$33.18	$0.00
ΔPS Ethanol ($ bn.)					
Low Fuel Price: $2.25		$18.48	$27.96	$1.18	$11.11
Base Case: $2.75		$17.12	$20.56	$2.49	$18.89
High Fuel Price: $3.25		$12.53	$12.65	$2.26	$26.53
ΔPS Corn Ethanol ($ bn.)					
Low Fuel Price: $2.25		$3.67	$0.67	$0.13	$0.66
Base Case: $2.75		$3.19	$0.91	$0.09	$2.50
High Fuel Price: $3.25		$1.99	$1.71	$0.30	$6.29
Avg. Abatement Cost ($/MTCO$_2$e)					
Low Fuel Price: $2.25		$84.79	$62.08	$27.78	$79.95
Base Case: $2.75		$57.90	$48.58	$19.52	$82.30
High Fuel Price: $3.25		$25.92	$25.65	$9.85	$50.60

Appendix Table 6: Points in the distribution of net gains and losses from the different policies with baseline fuel price of $3.25 per gallon.

	CAT	**LCFS**	**RFS**	**SUBS**
Mean	$21.82	$150.18	$151.47	$339.58
Percentage>0	42%	52%	51%	52%
Minimum	-$10.71	-$51.97	-$51.61	-$105.13
25th Percentile	-$8.73	-$34.17	-$34.34	-$67.17
Median	-$1.97	$10.56	$9.10	$28.10
75th Percentile	$17.20	$128.07	$122.98	$276.93
90th Percentile	$61.98	$484.72	$496.12	$1,085.57
95th Percentile	$146.32	$937.57	$952.96	$2,076.31
Maximum	$788.92	$4,707.69	$5,019.16	$12,328.45

Appendix Table 7: Equilibrium outcomes under carbon policies for different emissions intensity scenarios.

	BAU	RFS	LCFS	CAT	SUBS
Fuel Price ($/gge)					
Base Case	$ 2.75	$ 2.94	$ 2.96	$ 3.23	$ 2.75
High Indirect Land use	$ 2.75	$ 2.94	$ 2.93	$ 3.15	$ 2.75
Waste Zero Emissions	$ 2.75	$ 2.94	$ 2.96	$ 3.23	$ 2.75
Existing Corn	$ 2.75	$ 2.94	$ 2.95	$ 3.20	$ 2.75
ΔCS ($ bn.)					
Base Case		-$26.69	-$28.59	-$65.07	$0.00
High Indirect Land use		-$26.69	-$24.30	-$53.46	$0.00
Waste Zero Emissions		-$26.69	-$28.54	-$64.82	$0.00
Existing Corn		-$26.69	-$28.11	-$60.56	$0.00
ΔPS Ethanol ($ bn.)					
Base Case		$17.12	$20.56	$2.49	$18.89
High Indirect Land use		$17.12	$18.27	$1.83	$18.89
Waste Zero Emissions		$17.12	$20.74	$3.22	$18.89
Existing Corn		$17.12	$21.43	$2.22	$18.89
ΔPS Corn Ethanol ($ bn.)					
Base Case		$3.19	$0.91	$0.09	$2.50
High Indirect Land use		$3.19	$0.00	$0.00	$2.50
Waste Zero Emissions		$3.19	$0.60	$0.09	$2.50
Existing Corn		$3.19	$0.23	$0.04	$2.50
Avg. Abatement Cost ($/MTCO$_2$e)					
Base Case		$57.90	$48.58	$19.52	$82.30
High Indirect Land use		$70.15	$44.24	$15.97	$109.49
Waste Zero Emissions		$53.84	$43.90	$19.09	$73.73
Existing Corn		$61.86	$43.14	$18.17	$90.28

Appendix Table 8: Equilibrium outcomes under carbon policies for different demand elasticity scenarios.

	BAU	RFS	LCFS	CAT	SUBS
Fuel Price ($/gge)					
Less Elastic: Elast. = -0.30	$ 2.75	$ 2.94	$ 2.96	$ 3.37	$ 2.75
Base Case: Elast. = -0.50	$ 2.75	$ 2.94	$ 2.96	$ 3.23	$ 2.75
More Elastic: Elast. = -0.70	$ 2.75	$ 2.95	$ 2.96	$ 3.17	$ 2.75
ΔCS ($ bn.)					
Less Elastic: Elast. = -0.30		-$26.51	-$29.04	-$84.19	$0.00
Base Case: Elast. = -0.50		-$26.69	-$28.59	-$65.07	$0.00
More Elastic: Elast. = -0.70		-$26.88	-$28.40	-$55.64	$0.00
ΔPS Ethanol ($ bn.)					
Less Elastic: Elast. = -0.30		$17.12	$21.08	$3.44	$18.89
Base Case: Elast. = -0.50		$17.12	$20.56	$2.49	$18.89
More Elastic: Elast. = -0.70		$17.12	$20.25	$2.07	$18.89
ΔPS Corn Ethanol ($ bn.)					
Less Elastic: Elast. = -0.30		$3.19	$0.95	$0.12	$2.50
Base Case: Elast. = -0.50		$3.19	$0.91	$0.09	$2.50
More Elastic: Elast. = -0.70		$3.19	$0.88	$0.08	$2.50
Avg. Abatement Cost ($/MTCO$_2$e)					
Less Elastic: Elast. = -0.30		$65.64	$55.78	$24.78	$82.30
Base Case: Elast. = -0.50		$57.90	$48.58	$19.52	$82.30
More Elastic: Elast. = -0.70		$51.90	$43.31	$16.87	$82.30

Appendix Table 9: Equilibrium outcomes under carbon policies incorporating corn price effects.

	BAU	RFS	LCFS	CAT	SUBS
Fuel Price ($/gge)					
Base Case	$ 2.75	$ 2.94	$ 2.96	$ 3.23	$ 2.75
Endogenous Corn Prices	$ 2.75	$ 2.94	$ 2.95	$ 3.23	$ 2.75
ΔCS ($ bn.)					
Base Case		-$26.69	-$28.59	-$65.07	$0.00
Endogenous Corn Prices		-$26.64	-$28.14	-$64.31	$0.00
ΔPS Ethanol ($ bn.)					
Base Case		$17.12	$20.56	$2.49	$18.89
Endogenous Corn Prices		$18.06	$20.76	$2.47	$19.87
ΔPS Corn Ethanol ($ bn.)					
Base Case		$3.19	$0.91	$0.09	$2.50
Endogenous Corn Prices		$4.14	$1.64	$0.11	$3.49
Avg. Abatement Cost ($/MTCO$_2$e)					
Base Case		$57.90	$48.58	$19.52	$82.30
Endogenous Corn Prices		$51.97	$44.68	$19.42	$74.16

Notes: The base case and ethanol supply reflect corn price effects.