Does a renewable fuel standard for biofuels reduce climate costs?*

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Abstract

Recent literature on biofuels has questioned whether biofuels policies are likely to reduce the negative effects of climate change. Our analysis explicitly takes into account that oil is a non-renewable natural resource. A blending mandate has no effect on total cumulative oil extraction. However, extraction of oil is postponed as a consequence of the renewable fuel standard. Thus, if emissions from biofuels are negligible, the standard will have beneficial climate effects. The standard also reduces total fuel (i.e., oil plus biofuels) consumption initially. Hence, even if emissions from biofuels are non-negligible, a renewable fuel standard may still reduce climate costs. In fact our simulations show that even for biofuels that are almost as emissions-intensive as oil, a renewable fuel standard has beneficial climate effects.

Key words: Renewable fuel standard, Blending mandate, Biofuels, Climate costs, Petroleum extraction profile

JEL Codes: Q3, Q4, Q5

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*We thank two anonymous referees, the editor of JAERE, Charles F. Mason and Bjart Holtsmark for valuable comments and suggestions. Furthermore, we than the Research Council of Norway and the Swedish research foundation Mistra for financial support. While carrying out this research we have been associated with CREE - Oslo Center for Research on Environmentally friendly Energy. CREE is supported by the Research Council of Norway.

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1 Introduction

More than 20% of energy-related CO_2 emissions come from the transport sector, and governments are therefore looking for alternatives to oil in this sector. Biofuels are currently the most employed alternative, accounting for 2-3 percent of global transport-related energy use (IEA, 2011a).

The advantage of biofuels is that they are relatively easy to introduce into the transport sector. While hydrogen and battery driven cars at the moment imply both more expensive and somewhat inferior technologies, cars that run on biofuels have approximately the same performance as cars that run on oil, and can use the same infrastructure. The US and a number of European countries have introduced various support schemes for deployment of biofuels, leading to strong growth in global biofuels production and use. The support to biofuels has not only been driven by a concern for greenhouse gas (GHG) emissions, but also by a concern for "energy security" in both the EU and the US.

Current support schemes involve the use of a myriad of policies. The EU has imposed a biofuels target of 10% in 2020, and many EU countries have already introduced blending mandates for biofuels together with excise tax rebates to biofuels and subsidies to growing biofuels crops (Eggert, Greaker and Potter, 2011). The US has a renewable fuel standard (RFS), which is similar to a blending mandate, in addition to various tax reliefs (Eggert et al, 2011). The complex support schemes have spurred an emerging literature analyzing the combined effect of these schemes, see, e.g., DeGorter and Just (2010), Lapan and Moschini (2012) and Eggert and Greaker (2012).

Recent contributions have also questioned whether first generation biofuels actually lead to any real GHG reductions. Obvious sources of emissions from biofuels include the use of fertilizer when growing biofuels crops (Crutzen et al, 2008), and the use of fossil energy in the harvesting and processing of biofuels (Macedo, Seabra and Silva, 2008). Land use change can lead to additional GHG emissions if the area of arable land is increased to accommodate increasing use of biofuels. Fargione et al. (2008) introduced the concept of carbon debt, and hold that in the worst case scenario it may take up to several hundred years to reach climate neutrality after such conversion.

There are two strands of literature that study the effects of biofuels policies. One strand studies GHG emissions from increased use of biofuels without taking into account the interaction with the oil market. Examples of this literature are Searchinger et al (2008) and Lapola et al. (2010). They both find that increased use of biofuels may lead to increased GHG emissions due to land use change. In these analyses it is implicitly assumed that biofuels will replace oil on a one-to-one basis (based on energy content).

The second strand of literature emphasizes that one should also analyze the market effects of biofuels policies. DeGorter and Just (2009) find that a renewable fuel standard may lead to a decrease in total fuel sales. Thus, the effect of the policy is not only to replace oil with biofuels, but also to reduce total consumption of transport fuels, which by itself will reduce climate costs.[1] This result may change if we look at a multi-region world. Drabik and De Gorter (2013) study the effect of introducing a renewable fuel standard in the US, and identify a significant leakage effect to the rest of the world due to decreased global oil prices.

Introducing several instruments complicates the picture even further. If a renewable fuel standard is in place, adding a tax rebate for biofuels can only make things worse with respect to climate costs. The subsidy then works as an implicit support to oil and, hence, GHG emissions increase (see DeGorter and Just, 2010). Lapan and Moschini (2010) compare a renewable fuel standard to a price based consumption subsidy, and find that the former welfare dominates the latter. A renewable fuel standard is identical to a revenue neutral combination of a tax on oil and a subsidy to biofuels (Eggert and Greaker, 2012). It follows that a blending mandate outperforms a pure subsidy as long as there is an emission externality.

The robustness of these results should be analyzed in a model with dynamic oil supply. In

[1] This happens if the elasticity of biofuels supply is lower than the elasticity of oil supply. The result is reversed if the elasticity of biofuels supply is higher than the elasticity of oil supply.

this paper we introduce forward looking, competitive suppliers of oil, and we explicitly take into account that oil is a non-renewable natural resource. Two such examples are Crafton, Kompas and Van Long (2012) and Chakravorty, Magne and Moreaux (2008). On the other hand, whereas Chakravorty et al. consider a cap on the stock of emissions and Crafton et al. (2012) considers a subsidy to biofuels, we include a renewable fuel standard which is used in both the EU and the US.[2] Moreover, neither Crafton et al. (2012) nor Chakravorty et al. (2008) include emissions from biofuels which seems to be crucial when assessing the effect of biofuels policies on climate costs.[3]

An important result is that unlike a carbon tax or a subsidy to biofuels, a blending mandate has no effect on total cumulative oil extraction. However, the blending mandate does have an effect on the time path of oil extraction. We find that the extraction period of the oil resource is extended by the introduction of a renewable fuel standard. This happens also if only a subset of countries introduces the standard, while the rest of the world continues without. We also show that a biofuels subsidy combined with a renewable fuel standard speeds up oil extraction and, hence, GHG emissions increase, confirming the findings from static models.

Given that we know the market effects of a renewable fuel standard, we can also study the effects upon climate costs. A biofuels standard has two opposing effects: It reduces climate costs due to the postponement of oil extraction, but increases climate costs due to higher accumulated emissions (because of more biofuels production that also involves emissions). In order to evaluate the relative strengths of these effects, we calibrate a numerical model of oil extraction and demand. We find that even for biofuels that are almost as emissions-intensive as oil, a blending mandate may have a beneficial climate effect. The reason is that the blending mandate reduces total fuel demand over the first few decades. Thus, even though cumulative fuel demand and emissions are increased, emissions are postponed, which reduces the discounted sum of damage costs from climate change.

Despite the beneficial climate effect, a renewable fuel standard is welfare inferior to a tax on oil. A renewable fuel standard implies a subsidy to biofuels alongside a tax on oil. A subsidy to biofuels is welfare reducing since there are no other externalities than the climate externality in our model.

A renewable fuel standard is also analyzed in Fischer and Salant (2012). They include a theoretical model with multiple pools of oil with different extraction costs. As in this paper, they find that the extraction period of the oil resource is extended by the introduction of a renewable fuel standard. Chakravorty et al. (2012) uses a numerical model to study the effect on food prices of biofuel mandates, but they also report results for GHG emissions, and find that a blending mandate combined with tax rebates to biofuels increases global GHG emissions. This is in line with our theoretical result that a biofuels subsidy combined with a renewable fuel standard may increase emissions. On the other hand, neither Fischer and Salant (2012) nor Chakravorty et al. (2012) include an analysis of climate costs.

The paper is laid out as follows. In section 2 we show that static analyses of blending mandates may give misleading conclusions. In particular, such analyses conclude that total oil production will decline as a consequence of the blending mandate. With a dynamic analysis that takes into account that oil is a non-renewable resource with extraction costs increasing with cumulative extraction, we show that total cumulative extraction is unaffected by a blending mandate. In Section 3 we show that a blending mandate nevertheless may have an important impact on the time profile of oil extraction. In Section 4 we discuss climate costs of a renewable fuel standard, and in Section 5 we provide a numerical illustration of the model. Finally, in Section 6 we

[2] In our paper a renewable fuel standard is identical to a blending mandate as both policies require that biofuels constitute a given share of total fuel use in the transport sector.

[3] We do not consider market power in the oil market. This has been studied by Hochman et al. (2011) and Kverndokk and Rosendahl (2013), who consider the effects of biofuels policies taking into account OPEC behaviour. However, both these studies use static analysis.

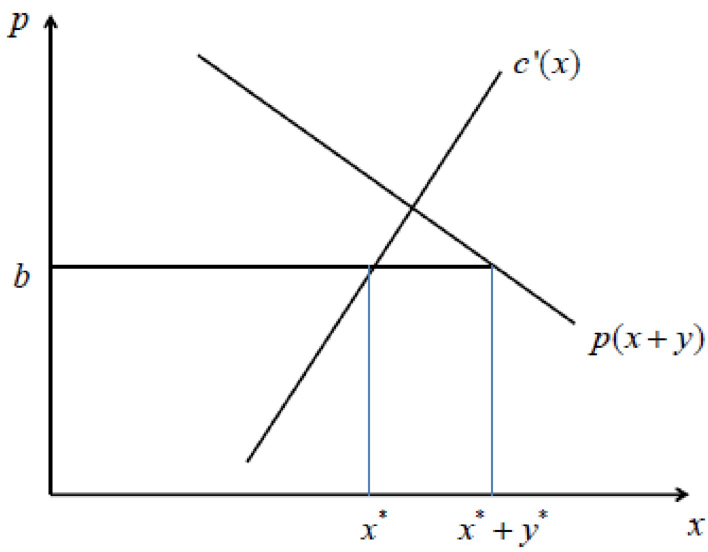
conclude.

2 Static and dynamic analyses of a biofuel mandate

We consider a market with oil (x) and biofuels (y), which are assumed to be perfect substitutes.[4] The inverse demand function for fuel is given by $p(x + y)$ where p is the consumer price of fuel. We assume that unit costs of biofuel are fixed and denoted by b.[5] For our static analysis we assume that the marginal cost of oil extraction is increasing, i.e. $c'(x) > 0$ where $c(x)$ denotes total extraction costs.

The market equilibrium for the unregulated economy in illustrated in Figure 1 for the static case. Equilibrium output levels of oil and biofuel are given by x^* and y^*, respectively. We next consider three alternative climate policies and see how they affect these equilibrium policies.

Figure 1 "Market equilibrium without RFS"



Consider first a carbon tax, i.e. a tax on oil production equal to τ. This will shift the upward sloping supply curve for oil upwards from $c'(x)$ to $c'(x) + \tau$, implying a reduction in x^* and an increase in y^*. Total fuel output $x^* + y^*$ and the price $p^* = b$ will be unaffected by the carbon tax; this result would be modified if we instead had assumed increasing marginal costs of biofuel production.

Consider next a subsidy σ on biofuel production. This will shift the horizontal supply curve for biofuel downwards from b to $b - \sigma$, implying a reduction in x^* and an increase in y^*. In this case total fuel output $x^* + y^*$ will increase and the equilibrium price p^* will decline from b to $b - \sigma$.

Finally, consider a blending mandate. It is well known that a biofuel mandate is equivalent to a revenue neutral combination of a carbon tax and a subsidy on biofuel production (see e.g. Eggert and Greaker, 2012). From the analysis above we can therefore conclude that the effect of such a mandate is to reduce x^* and increase y^*. Moreover, for the case of a constant unit cost of biofuel production total output must increase and the equilibrium price must decline.

To summarize, the output of oil (and hence carbon emissions) can be reduced using any one of the three policies discussed above. However, the analysis above ignores the fact that oil is

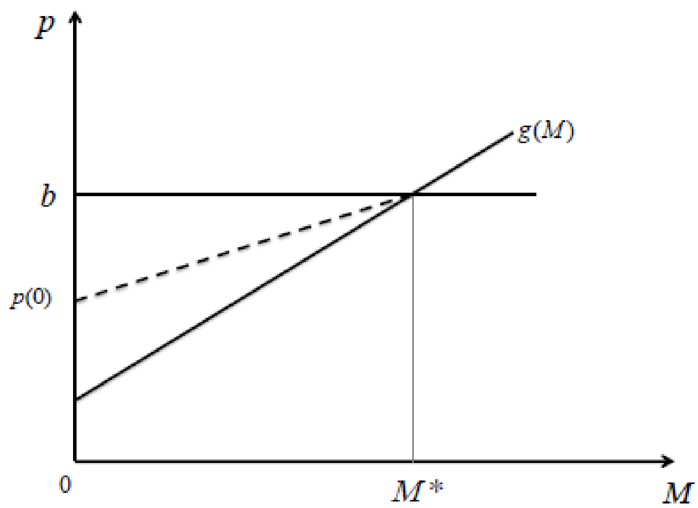
[4] We may think of fossil fuels as oil here, as we are interested in the transport sector and the competition from biofuels. Thus, we implicitly abstract from oil use in other sectors, as well as other substitutes to oil in the transport sector such as electric cars, which may become important in the future.

[5] This assumption is used, and discussed, in our subsequent dynamic analysis.

non-renewable resource. To take this fact into consideration we must replace the static supply function used above with an alternative dynamic formulation. In the literature it is common to assume that unit costs of oil extraction are given by $g(M)$, where M is cumulative extraction and $g'(M) > 0$.[6] Modifying the supply side of oil in this way obviously makes the analysis considerably more complicated. Previous literature (e.g. Gerlagh (2011) and Hoel (2011)) has studied the effects of taxes and subsidies. We briefly consider this before turning to a blending mandate.

In Figure 2 the cumulative extraction M is measured along the horizontal axis, while price and costs are as before measured along the vertical axis. Without any regulation, all oil with extraction costs below b will eventually be extracted, giving total extraction equal to M^* in Figure 2. The equilibrium price will be increasing over time, and will always lie between the extraction cost $g(M)$ and the substitute cost b, as illustrated by the dashed line in Figure 2 (see e.g. Hoel and Kverndokk, 1996, for details).

Figure 2 "Cumulative extraction"



A carbon tax at the rate τ will will shift the cost curve from $g(M)$ to $g(M) + \tau$. This shift in the extraction cost function implies that the intersection with the b-line in Figure 2 will occur at a lower level of cumulative extraction. Total cumulative extraction (M^* in Figure 2) will hence decline. Subsidizing biofuel has a similar effect on total extraction: A shift in the horizontal supply curve for biofuel from b to $b - \sigma$ implies that the intersection with the extraction cost curve $g(M)$ in Figure 2 will occur at a lower level of cumulative extraction.

Since both a constant tax and a constant subsidy give lower total extraction, we might expect that also a biofuel mandate would give lower total extraction. However, this is not the case. Any biofuel mandate that is bounded away from 100%, constant or time-variant, will have no effect on total cumulative extraction. Whatever the blending mandate is, oil producers will sooner or later extract all oil that has a price above extraction costs. Since an equilibrium fuel price below b is impossible unless we have positive oil extraction, it follows that the equilibrium total extraction M^* is unaffected by a blending mandate.[7]

[6] The simple Hotelling case of constant extraction costs and a fixed resuorce supply is a special case of this, with c having the shape of an inverse L in this case.

[7] Any biofuel mandate that is bounded away from 100% corresponds to a tax and subsidy combination with both rates approaching zero as extraction declines towards zero. Taxes and subsidies that approach zero as extraction approaches zero have no effect on the total extraction.

From the discussion above we can conclude that a static analysis of a blending mandate can give very misleading conclusions. Hence, in the rest of this paper we give a dynamic analysis of a blending mandate where we explicitly take into account that oil is a non-renewable natural resource.

3 Market effects of a blending mandate for biofuels

Since total fuel extraction is unaffected by a blending mandate, we assume that the stock of oil (S) is fixed. Moreover, as long as total extraction is given (equal to the initial stock) the details about the cost structure are unimportant. We therefore set these costs equal to zero in the theoretical analysis to simplify notation.

As in the previous section, oil (x) and biofuels (y) are assumed to be perfect substitutes, and unit costs of producing biofuels (b) are fixed. Allowing for increasing marginal cost of biofuels does not change our main results, but complicates the analysis (see the working paper version of this paper; Greaker, Hoel and Rosendahl, 2014, which considers the case of increasing marginal cost of biofuels both analytically and in simulations).

Assume that fuel consumers are required to use at least a share α of biofuels in the total fuel use. We coin α a renewable fuel standard (RFS). Let the consumer price of mixed fuel be given by $p^C(t)$. Demand for fuel is given by $D(p^C)$, with $D' < 0$. In our formal analysis we assume that this demand function is linear. However, we show in Greaker et al (2014) that our results hold for a considerably broader set of demand functions.

The consumer price of (mixed) fuel follows from the producer price of the two types of fuel; $p^C(t) = \alpha b + (1-\alpha)p(t)$ where $p(t)$ is the price of oil. The oil price increases over time according to the Hotelling Rule, i.e. $p(t) = p_0 e^{rt}$ until $p(T) = b$ is reached at T, when a complete switch to biofuels occurs.

With the assumptions above the demand for oil and biofuels is:

$$x(t) = (1-\alpha)D(\alpha b + (1-\alpha)p_0 e^{rt}) \quad \text{for } t < T \tag{1}$$

$$y(t) = \alpha D(\alpha b + (1-\alpha)p_0 e^{rt}) \text{ for } t < T \tag{2}$$

$$x(t) = 0 \quad \text{ and } \quad y(t) = D(b) \text{ for } t \geq T \tag{3}$$

where T is determined by:

$$p_0 e^{rT} = b \tag{4}$$

Finally, we have the equilibrium condition:

$$\int_0^T x(t)dt = S \tag{5}$$

The endogenous variables in equations (1)-(5) are $x(t)$, $y(t)$, T and p_0. If p_0 is known, the whole price path is known from $p(t) = p_0 e^{rt}$.

We are now ready to investigate how an increase in α affects the market equilibrium.

3.1 Effects on resource extraction

First, we examine how the extraction time T and the initial resource price p_0 are affected by a change in α. We can show the following proposition:

Proposition 1 *If the share of biofuels in an RFS system is increased, the oil resource will last longer. Moreover, the intial price of the resource falls.*

Proof: See the Appendix.

Obviously, the proposition also holds if we introduce an RFS, i.e., increase α from zero. The intuition of this proposition is quite clear: If the resource price didn't fall, demand for oil would have to decrease in every period, which subsequently implies that there are resources left in the ground at time T when the oil price reaches the backstop price b.

Next, we examine the effects on the extraction path. Let T and $\hat{T}$ denote the extraction time before and after a policy change, respectively. We can then show:

Proposition 2 *If the share of biofuels in an RFS system is increased, there exists a time $\hat{t} < T$ so that extraction of oil will decline for all $t < \hat{t}$, and increase for all $\hat{t} < t < \hat{T}$.*

Proof: See the Appendix.

Quite intuitively, the proposition states that a renewable fuel standard will reduce initial extraction of fossil fuels. This is also consistent with Proposition 1, i.e., that resource extraction is extended - hence average extraction per period until T must come down. Eventually, however, since accumulated extraction is unchanged, output of fossil fuels must increase at some future time (compared to without the RFS). Obviously, between T and $\hat{T}$, extraction must increase. According to the proposition, extraction first declines until some time $\widehat{t}$ and then increases until the resource is depleted (again compared to without the RFS).

3.2 Effects on fuel consumption and biofuels production

Next, we consider the effects on total fuel consumption:

Proposition 3 *If the share of biofuels in an RFS system is increased, there exist a time $\hat{t} < T$ so that the consumer price increases and fuel consumption decreases for all $t < \hat{t}$, while the consumer price decreases and fuel consumption increases for all $\hat{t} < t < \hat{T}$.*

Proof: See the Appendix.[8]

According to this proposition, a renewable fuel standard will increase the initial consumer price of fuel. Hence, not only fossil fuel consumption but also total fuel demand (including biofuels) will decline initially. The consumer price is pulled in both directions. On the one hand, the oil price p decreases. On the other hand, a higher α increases the weighted price $p^C = \alpha b + (1-\alpha)p$. According to the proposition, the latter effect dominates initially. Note that this holds whether the demand function is steep or not, as long as the choke price $p^C_{\max} \geq b$.

When t approaches T, both the oil price and the consumer price approaches b. Thus, for t sufficiently close to the T, the consumer price must decrease when α is increased (since p drops). Hence, total fuel consumption declines at early dates, and increases at later dates.

The RFS is introduced to stimulate the use of biofuels. The following proposition states how biofuels production (and consumption) is affected when α is increased:

Proposition 4 *If the share of biofuels in an RFS system is increased, production of biofuels will increase if either i) α is sufficiently small initially, ii) demand is sufficiently inelastic, or iii) t is sufficiently close to T.*

Proof: See the Appendix.

This proposition is quite intuitive. The opposite result, i.e., reduced biofuels production, is however also possible if α is already sufficiently large and demand is sufficiently elastic. However, this requires that α is at least higher than 0.5, which is not a very likely policy scenario.[9]

[8] Note that the value of $\hat{t}$ is generally not the same in Propositions 2, 3 and subsequent propositions where this symbol is used.

[9] The explanation for this result is the following: We know from above that the initial consumer price increases when α is increased. If demand is very elastic, fuel consumption may then drop quite substantially. Furthermore, if there is already a significant biofuels consumption due to a high α, it is possible that the effect of demand reduction dominates the effect of a higher share of biofuels. Similar results have been found in static analysis of Renewable Portfolio Standards (RPS) (or tradable green certificate markets), see e.g. Amundsen and Mortensen (2001).

To summarize, we have shown that introducing or strengthening an RFS system will lead to lower oil prices, and prolonged extraction period. Oil production will decrease initially, and increase in later periods so that total extraction is unchanged. Finally, the consumer price will increase initially, implying lower initial fuel consumption, but in later periods the price will drop and fuel consumption increase. Biofuels production will most likely increase.

3.3 Effects of a biofuels subsidy in addition to RFS

A number of countries, including the U.S. and the EU, have or have had subsidies to biofuels production in addition to an RFS. Such subsidies will stimulate biofuels production and subsequently consumption, but due to the binding relationship between oil and biofuels consumption given by the RFS, fossil consumption will also be stimulated. We can show this formally, and have the following proposition:

Proposition 5 *If a binding RFS is in place, a subsidy to biofuels production will reduce the extraction time for the oil resource. Further, there exist a time $\hat{t} < T$, so that the use of oil increases for all $t < \hat{t}$, and decreases for all $\widehat{t} < t < \hat{T}$.*

Proof: See the Appendix.

Thus, introducing subsidies to biofuels production may have quite the contrary effect of what is the purpose, at least if the subsidy is introduced for environmental reasons. In reality, such subsidies may be temporary. Nevertheless, given a binding RFS, any policy that stimulates biofuels use will also stimulate the use of oil.

3.4 Effect of introducing two regions

In reality not all regions have a RFS, and regions do not synchronize their use of RFS. With more regions one would expect carbon leakage to occur. That is, regions not tightening their RFS may increase their use of oil as a result of a stronger RFS in other regions. It is straight forward to extend our model to include two regions (see the Appendix). We can then show that the extraction time will be extended, and the initial price of oil declines independent of which region that tightens its RFS. In particular, we prove the following proposition:

Proposition 6 *In a two region world, if one of the regions increases the share of biofuels in its RFS system, the global oil resource will last longer. Moreover, the intial price of the resource falls, and there exist a time $\hat{t} < T$ so that extraction of oil will decline for all $t < \hat{t}$, and increase for all $\hat{t} < t < \hat{T}$.*

Proof: See the Appendix.

When one of the regions increases the share of biofuels in its RFS system, the global price of oil falls. Then according to (4) it will take longer time for the price of oil to reach the price of biofuels. Consequently, the resource will last longer. Note that the consumer price on transportation fuels in the region not changing its RFS must fall at all dates due to the lower oil price. Hence, we will have carbon leakage as this region will use more oil at each date due to the increased RFS rate in the other region. If the former region also has an RFS in place, it follows that it will also increase its use of biofuels. If fossil extraction declines in the initial periods, oil consumption in the region with increased RFS must fall in these periods. It is more ambiguous what happens to biofuels consumption in this region, and to oil consumption after time $\widehat{t}$.

Note that the our analysis of two regions also carries over to the case in which only a part of the oil consumption is covered by the RFS e.g. the RFS covers road transport but not gasoline and diesel used for air and sea transport. Then an increase in the blending mandate for road transport will induce a "leakage" to air and sea transport, but all the same, the extraction period will be prolonged.

4 Climate costs of an RFS

Once we have derived time paths for $x(t)$ and $y(t)$ we can calculate total discounted climate costs C as follows:

$$C = \int_0^\infty e^{-rt}\left[q_x(t)x(t) + q_y(t)y(t)\right] dt \tag{6}$$

where in this expression oil and biofuel is measured in units that make 1 unit of oil give 1 ton of CO_2, so that the climate cost of oil ($q_x(t)$) is simply the social cost of carbon. Moreover, the climate cost of biofuel ($q_y(t)$) is assumed to be proportional to the social cost of carbon, i.e. $q_y(t) = \gamma q_x(t)$ where γ is a positive parameter. The parameter γ is crucial for the effect on climate costs of a RFS. If γ is equal to unity, the use of biofuels has identical climate costs to oil. On the other hand, for the limiting case of $\gamma = 0$ the only effect on climate costs will be through the change in the time profile of oil extraction.

Theoretical and numerical models that derive optimal climate policy typically find that the social cost of carbon rises at a rate lower than the rate of interest, provided high carbon concentrations in the atmosphere are considered bad also when the carbon concentration is below some exogenously given upper limit.[10]. With $e^{-rt}q_x(t)$ declining over time, climate costs will go down if extraction is delayed. By continuity, the following proposition hence follows from Proposition 2:

Proposition 7 *If γ is sufficiently small, climate costs will decline as a consequence of the introduction of an RFS for biofuels.*

For larger values of γ it is not obvious how climate costs are affected by an RFS, even if oil use is postponed. There are two opposing effects: Reduced climate costs due to the postponement of oil extraction, and increased climate costs due to advancement in time of biofuels production. Which effect is strongest will depend on γ, and the latter effect will dominate if γ is sufficiently large. The effects of an RFS on climate costs is hence an empirical issue. In the next section we give some estimates of parameter determining γ from existing literature, and compare the effects of an RFS policy with the effects of an optimal tax policy.

5 Numerical illustrations

5.1 Model calibration

We calibrate our model to real world data in the following way: Our point of reference is the global oil market today with no carbon tax or RFS in place. We consider a linear fuel demand function with initial price elasticity equal to -0.4. The elasticity is increasing over time (due to higher price and linear demand).[11] The demand functions are calibrated so that initial fuel demand equals global oil consumption in 2011 if the initial price equals the average crude oil price in 2011 (BP, 2012). Fuel consumption growth (for given price) is set to 1.3% p.a., which is slightly more than what the IEA (2011a) assumes until 2035 in combination with higher oil prices.

The stock of oil (S) is set equal to remaining global oil reserves at the end of 2011, according to BP (2012). This may underestimate the ultimate recoverable amount of oil, but on the other hand we will assume constant unit extraction costs. Unit costs of biofuels are set to two times the crude oil price in 2011. Biofuels can be produced at lower costs today, but remember that we consider biofuels as a backstop technology with unlimited supply at constant unit costs. We

[10] This result may be found in several contributions to the literature, an example is Hoel and Kverndokk (1996). On the other hand, Fischer and Salant (2012) cite work that do not support this result.

[11] Estimated long-run price elasticities of oil vary quite a lot, see e.g. the database developed by Carol Dahl http://dahl.mines.edu/courses/dahl/dedd/. According to Dahl's summary statistics, the median long-run price elasticities are -0.55 and -0.33 for gasoline and diesel, respectively. In our working paper we also present results for a demand function with initial elasticity equal to -0.1. The qualitative results are quite similar.

may think of this as e.g. cellulosic ethanol. The unit cost of oil is calibrated so that the initial oil price and consumption are consistent with the 2011 data. This leaves us with unit cost of 84% of the oil price, which seems fairly reasonable.

The initial social cost of carbon is set to \$50 per ton of CO_2, which is within the range of CO_2 prices suggested to reach ambitious climate targets (e.g., IPCC, 2007; Stern, 2007; IEA, 2011a).[12] Converted to oil, the initial carbon cost (q_x) amounts to 19% of the initial oil price. Further, we assume a discount rate of $r = 4\%$, and a yearly growth in the social cost of carbon of 2%.

Land use change emissions are probably critical for the climate costs of biofuels, see e.g. Khanna and Crago (2012). The US EPA reports the GHG-reducing effect of different biofuels based on life cycle analyses (US EPA, 2009). They use a 30 year horizon, no discounting and include indirect effects such as emissions from land use change. As noted by Rajagopal, Hochman and Zilberman (2011), they do not include market effects of policies, but for our purpose this is good as the market effects are covered by our model.

Cellulosic bioethanol is by far the most promising biofuel according to the EPA: The GHG emission reduction potential is 124%, while other biofuels such as sugarcane and the best performing corn ethanol only has a 26% GHG reduction potential. Based on this we use an average value of γ of 0.3 in our simulations (see the Appendix). However, as there is large variation across different biofuels, as well as significant uncertainties, we will start by considering which levels of γ that make the RFS policy climate neutral (compared to the BaU scenario).[13]

5.2 Simulation results

How large must γ be before the RFS becomes counter-productive, i.e., increases climate costs? This could clearly depend on the stringency of the RFS policy. We consider levels of α in the range $10 - 20\%$, which is in line with the EU targets. Our simulations suggest that the RFS policy reduces climate costs if γ is below 0.99 in the case of $\alpha = 10\%$, and 0.93 if $\alpha = 20\%$. That is, even for biofuels that are almost as emissions-intensive as oil, the RFS policy may have some beneficial climate effects. The reason is that the RFS policy reduces total fuel demand over the first few decades. Thus, even though cumulative fuel demand and emissions are increased, emissions are postponed which gives a beneficial climate effect.

Second, we compare the effects of the RFS policy with the effects of an optimal climate policy scenario, which in our model can be implemented by imposing a Pigovian tax on the use of oil and biofuels. We now assume that $\gamma = 0.3$ (cf. the discussion above), in which case the RFS policy clearly reduces climate costs. We search for the level of α that gives the same present value of reduced climate costs as the Pigovian tax. This turns out to be $\alpha = 0.52$, given the calibrated model as described above.[14]

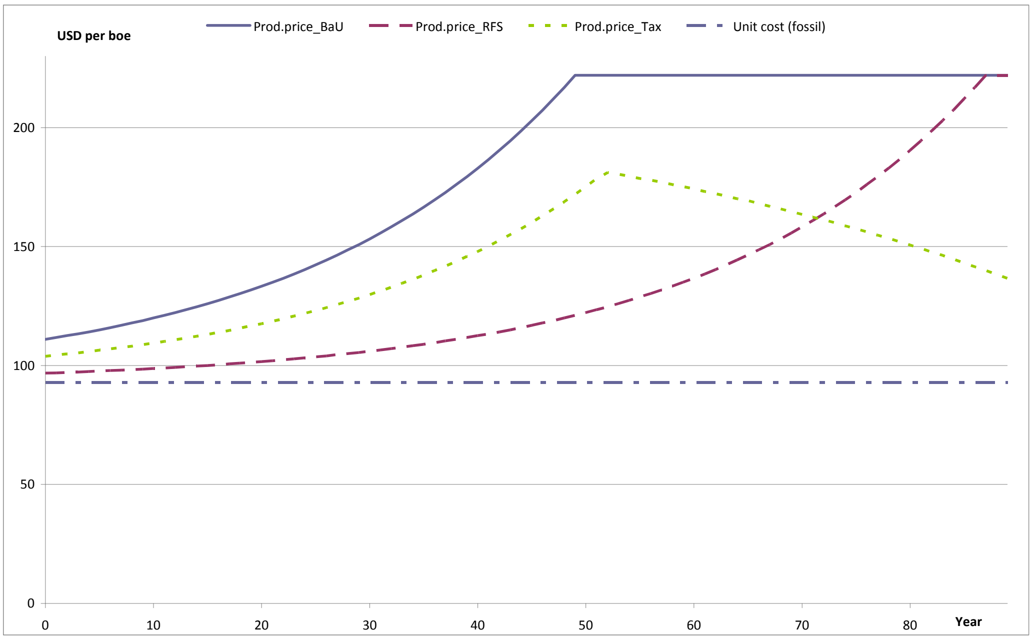
The two policies give very different market and welfare effects. Total welfare, measured as the sum of consumer, producer and government surplus, is reduced by one third when choosing the RFS instead of the tax. The RFS scenario is also reducing welfare compared to the BaU scenario.

[12] Ideally, the shadow cost of carbon should be based on a global cost-benefit analysis. One prominent example of a CBA study is the Stern Review (2007). Their findings suggest that the present social cost of carbon is around \$85 per ton CO_2 if the world continues on the BaU path, and \$25–30 if the concentration of CO_2-equivalents stabilises between 450–550 ppm CO_2e. Most other CBA studies seem to find lower shadow costs of carbon. Both these studies and the Stern Review have been much critized for various reasons, see, e.g., Weitzman (2007, 2011) who in particular emphazises the role of uncertainty.

[13] For instance, a recent paper in Nature Climate Change claims that cellulosic ethanol made from corn residue may have nearly the same life cycle emissions as gasoline, see Liska et al (2014).

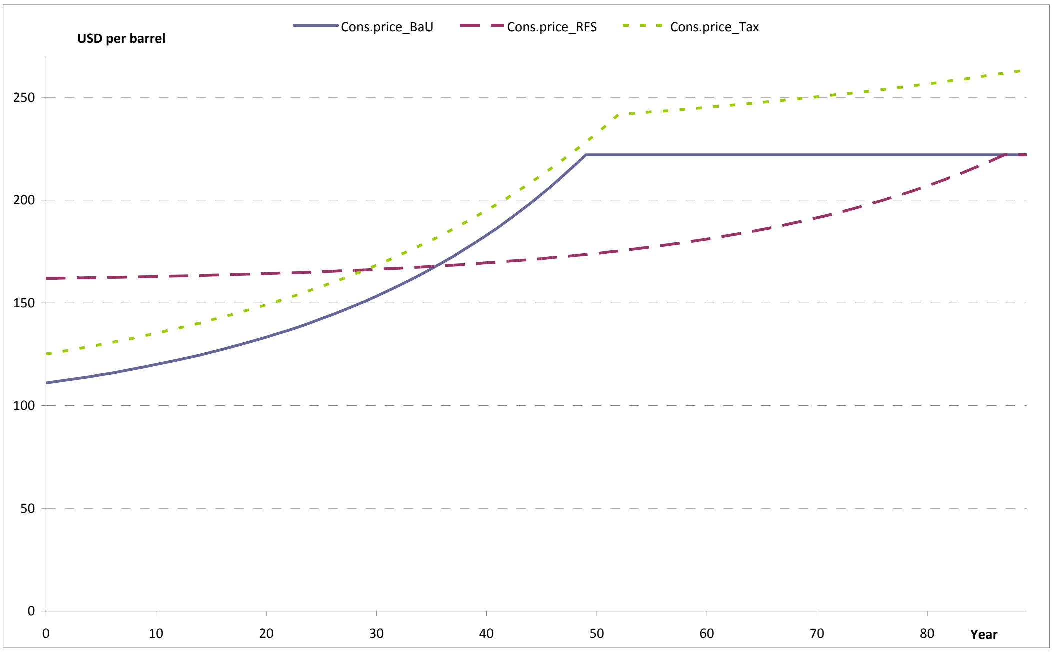
[14] Such a high value of α will of course require an enormous growth in biofuels production, which will lead to substantial land use changes and presumably siginficant interactions with other parts of the economy (e.g., agriculture). Moreover, it is not realistic that such a large increase in the use of biofuels may take place on short notice. Conventional autos cannot use fuels containing more than a certain amount of ethanol - some say 15% at the most. There exist technologies that would allow cars to run at far higher blends, but that requires making changes to the engines etc. which of course takes time. Thus, this part of the numerical simulations is mainly illustrative.

Figure 3 Producer price of fossil fuel under different scenarios. USD per barrel of oil equivalent (boe) (real prices)



The RFS policy is particularly detrimental for oil producers, see Figure 1 which shows how the real price of oil develops over time in the three scenarios. Whereas the Pigovian tax reduces profits of these producers by almost 40% (compared to BaU), profits are reduced almost 80% under the RFS policy. The initial price of oil is reduced by 13% in the latter case (cf. Table 1).

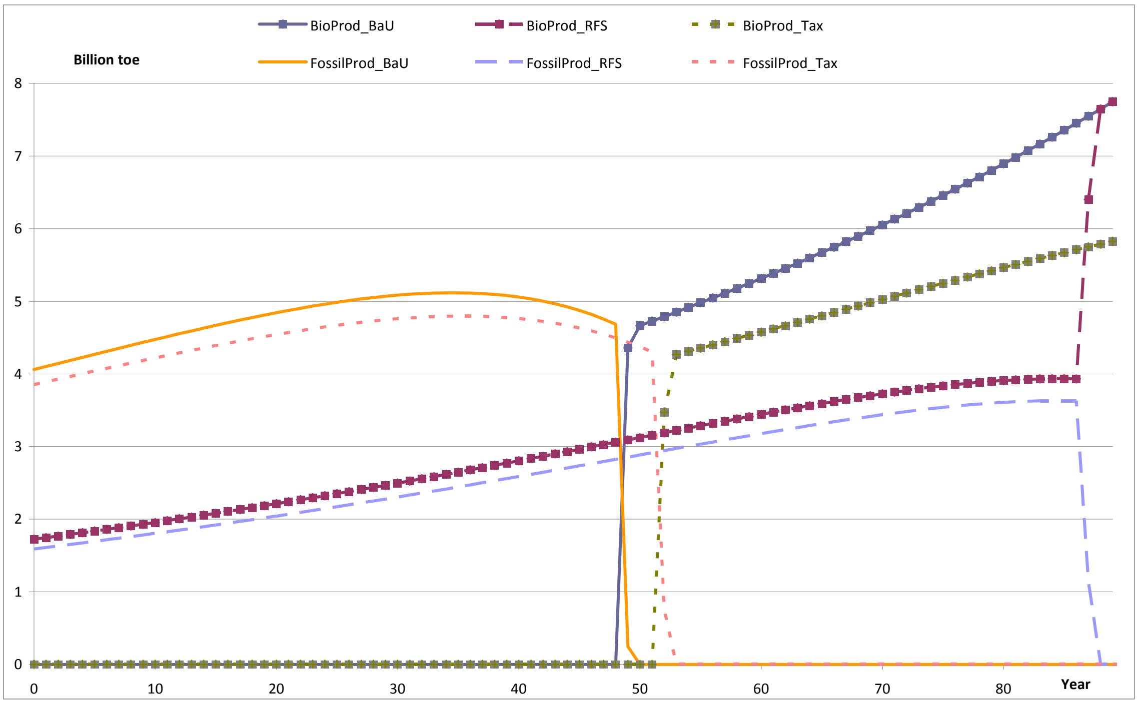
Figure 4 Consumer price of transport fuel under different scenarios. USD per barrel of oil equivalent (boe) (real prices)



Consumer surplus is marginally lower in the tax scenario than under the RFS policy, but not if the emission tax revenues are allocated back to the consumers. Thus, consumers might prefer the RFS policy if they are ignorant about public revenues, which may partly explain the popularity of blending mandates over emission taxes. On the other hand, the initial consumer price increases much more under the RFS policy than with a tax (cf. Figure 2), as the high level of α requires a large share of expensive biofuels. Thus, total fuel use is reduced much more initially under the RFS than under the tax. After about 30 years, the consumer price becomes higher under the tax policy, as the consumer price is more stable under the RFS policy due to the smaller resource rent.

Another possible explanation for the popularity of RFS might be that biofuels are thought to be environmentally friendly, or almost climate neutral, and that a blending mandate of α is assumed to reduce climate costs by close to α%. This is clearly not the case. In the optimal tax scenario, climate costs are reduced by more than 15%, while we have seen above that a similar reduction under RFS policy requires an α of around 50%. This is partly because emissions from biofuels are far from negligible, and partly because the RFS policy does not reduce cumulative use of oil over time. Over the first 40 years, however, oil production is approximately halved, but the extraction period is extended from about 50 years in the BaU and Tax scenarios to almost 90 years in the RFS scenario (cf. Figure 3).

Figure 5 Fossil and biofuel production under different scenarios



Even if the RFS policy is welfare deteriorating, it clearly reduces climate costs given our assumed value of $\gamma = 0.3$ (i.e., $q_y/q_x = 0.3$). In Table 1 we take a closer look at what happens the first 20 years:

Table 1 Market effects in $t = 0$ and $t = 20$ in the RFS and Tax scenarios. Percentage changes from the BaU scenario

	RFS		Tax	
	t= 0	*t*= 20	*t*= 0	*t*= 20
Producer price	-13%	-24%	-6%	-12%
Consumer price	46%	23%	13%	12%
Fossil output	-61%	-58%	-5%	-6%
Fuel consumption	-18%	-12%	-5%	-6%

Note the dramatic effect on fossil output of an RFS compared to a tax. The effect on producer prices of oil and fuel consumption is also far more drastic with an RFS compared with a tax.

5.3 Two regions

In Section 3 we considered a model with two regions, and discussed the effects of implementing RFS in only one of the regions. One important implication is that there will be emissions leakage to the other region. We have simulated a model version identical to the one above, except that we have split the demand region into two identical demand regions. When one region imposes an RFS with 20% biofuels, and the other region has no RFS policy, we find a leakage rate increasing from 5% initially to above 100% in the last years of extraction. Thus, global emissions are postponed, and decline vis-a-vis BaU-levels over the first 45 years. Climate costs are also reduced compared to BaU-levels despite leakage and an accumulated increase in emissions over time (due to more biofuels consumption). The reduction in climate costs amounts to 2%, versus 4.5% if both regions implement a 20% RFS share.

6 Discussion and conclusion

We have found that the extraction period of the oil resource is extended by the introduction of a renewable fuel standard. This happens even if only a subset of countries introduces a renewable fuel standard, while the rest of the world continues without. Extraction of oil will then decline initially. Thus, a renewable fuel standard will decrease climate costs as long as biofuels involves negligible emissions of GHG and the social cost of carbon increases by less than the interest rate. In fact, according to our numerical simulations even for biofuels that are almost as emissions-intensive as oil, a standard may reduce climate costs. The reason is that it tends to reduce total fuel consumption over the first decades.

Note, however, that despite the beneficial climate effect, a renewable fuel standard always reduces total welfare in our numerical model runs. A renewable fuel standard implies a subsidy to biofuels alongside a tax on oil. A subsidy to biofuels hampers welfare in our model since there are no other externalities than the climate externality.

In our base case we treat biofuels as a backstop technology with constant unit costs. As shown by Chakravorty et al.(2008), this is a reasonable assumption as long as land is abundant. IEA (2011b) predicts that biofuels may provide 27% of total transport fuel in 2050. Biofuels crops must then increase from 2% of total arable land today to around 6% in 2050. Much of this increase, however, will take place on pastures and currently unused land, which is suitable for second generation biofuels. Furthermore, Schmer et al. (2008) conjecture that large improvements in both genetics and agroeconomies will increase yields dramatically. Thus, the rate of technological progress within second generation biofuels could overcome the problem with land scarcity.

In our base case we also assume that biofuels can fully replace oil when all oil is extracted. Whether a total replacement of oil is possible at reasonable costs seems to depend on the rate of technological development, for instance, if the experiments with algae based biofuels will be successful (IEA, 2011b).

Our paper should be seen as a first attempt to include both dynamic optimization and emission from land use change when looking at biofuels policies. Later contributions should consider replacing the constant unit cost of biofuels assumption with more realistic biofuels supply schedules, among other taking into account that land quality may vary. One would then also likely let the carbon sequestered on the converted land vary with total production.

Our study has focused on the transport sector, and implicitly disregarded oil used in other sectors. Thus, future research should also consider incorporating fuel demand in other sectors. Our analysis of the two region model can in fact be alternatively interpreted as a simple representation of a two sector model, where Region 2 represents demand in non-transport sectors where the RFS policy does not apply. The numerical results above then indicate that the climate costs of the RFS policy will still be reduced, especially as the higher use of oil in Region 2 will lead to less use of other energy goods.

In the analysis above we have considered a time invariant blending mandate. It could be argued that a more realistic scenario would be to introduce a gradually increasing share of biofuels, i.e., that α is increasing over time. If so, fossil producers could find it profitable to enhance their initial extraction as future policies are (expected to be) even more detrimental to them than current policies. We have briefly tested this in our numerical model, considering linear increases in the blending rate.[15] The simulations suggest that initial extraction and emissions (including those from biofuels) tend to increase if demand is elastic, but decrease if demand is inelastic. Accumulated climate costs decline in all our simulations, given our benchmark assumptions. Thus, using the terminology used by Gerlagh (2011), there may be a weak green paradox if a blending mandate is gradually introduced (if demand is sufficiently elastic), but probably not a strong green paradox.

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[15] That is, $\alpha = kt$, $\alpha \leq \widehat{\alpha}$ for different values of k and $\widehat{\alpha}$.

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7 Appendix

Proof of Proposition 1:

We first differentiate (4) with respect to α:

$$\frac{dp_0}{d\alpha}e^{rT} + rp_0e^{rT}\frac{dT}{d\alpha} = 0 \Leftrightarrow \frac{dp_0}{d\alpha} = -rp_0\frac{dT}{d\alpha} \tag{7}$$

Next, we insert from (1) into (5) and differentiate:

$$-\int_0^T D(p^C(t))dt + (1-\alpha)\int_0^T \left(b - p_0e^{rt} + (1-\alpha)e^{rt}\frac{dp_0}{d\alpha}\right)\bar{D}'dt + (1-\alpha)D(b)\frac{dT}{d\alpha} = 0$$

where $\bar{D}' < 0$ is the (constant) derivative of the demand function (given linear demand). We notice that the first term equals $-S/(1-\alpha)$. Inserting for $\frac{dp_0}{d\alpha}$ then gives:

$$-\frac{S}{(1-\alpha)}+(1-\alpha)\int_0^T\left[\left(b-p_0e^{rt}\right)\bar{D}'\right]dt-(1-\alpha)^2rp_0\frac{dT}{d\alpha}\int_0^T\left[e^{rt}\bar{D}'\right]dt+(1-\alpha)D(b)\frac{dT}{d\alpha}=0$$

$$\frac{dT}{d\alpha}\left[(1-\alpha)D(b)-(1-\alpha)^2rp_0\int_0^T\left[e^{rt}\bar{D}'\right]dt\right]=\frac{S}{(1-\alpha)}-(1-\alpha)\int_0^T\left[\left(b-p_0e^{rt}\right)\bar{D}'\right]dt$$

$$\frac{dT}{d\alpha}=\frac{1}{(1-\alpha)^2}\frac{S-(1-\alpha)^2\Gamma}{D(b)-(1-\alpha)rp_0\Lambda}>0 \tag{8}$$

where $\Gamma=\int_0^T\left[\left(b-p_0e^{rt}\right)\bar{D}'\right]dt<0$ and $\Lambda=\int_0^T\left[e^{rt}\bar{D}'\right]dt<0$.
This further gives:

$$\frac{dp_0}{d\alpha}=\frac{-rp_0}{(1-\alpha)^2}\frac{S-(1-\alpha)^2\Gamma}{D(b)-(1-\alpha)rp_0\Lambda}<0 \tag{9}$$

Hence, we have proved the proposition.■

Proof of Proposition 2:
We differentiate $x(t)$ with respect to α:

$$\begin{aligned}\frac{dx(t)}{d\alpha}&=-D(p^C(t))+(1-\alpha)\left(b-p_0e^{rt}\right)\bar{D}'-e^{rt}rp_0\frac{S-(1-\alpha)^2\Gamma}{D(b)-(1-\alpha)rp_0\Lambda}\bar{D}'\\&=-D(p^C(t))+\left[(1-\alpha)\left(b-p_0e^{rt}\right)-p_0e^{rt}r\frac{S-(1-\alpha)^2\Gamma}{D(b)-(1-\alpha)rp_0\Lambda}\right]\bar{D}'\end{aligned} \tag{10}$$

The first term is negative and increasing over time (since $p^C(t)$ increases over time). The second term can be either positive or negative, and is also increasing over time (remember that $\bar{D}'<0$ is constant due to linear demand). Hence, if the sum of the two terms is positive at $t=0$, the expression will be positive for all t, which is not possible (accumulated resource extraction over the whole time horizon cannot increase). Thus, the expression must be negative initially, i.e., $x(0)$ decreases when α increases. We know from Proposition 1 that extraction will increase at least after $t=T$. Since the whole expression is increasing over time, the proposition follows.■

Proof of Proposition 3:
We differentiate $p^C(t)$ with respect to α:

$$\frac{dp^C(t)}{d\alpha}=b-p_0e^{rt}+(1-\alpha)e^{rt}\frac{-rp_0}{(1-\alpha)^2}\frac{S-(1-\alpha)^2\Gamma}{D(b)-(1-\alpha)rp_0\Lambda} \tag{11}$$

We notice that $\frac{dp^C(t)}{d\alpha}$ is decreasing over time. We also know that $\frac{dp^C(t)}{d\alpha}<0$ for t sufficiently close to T, since T increases with α. Thus, if we can show that $\frac{dp^C(0)}{d\alpha}>0$, we have proved the proposition.
We have:
$\Gamma=\left[T-\frac{1}{r}(1-e^{-rT})\right]b\bar{D}'$ and $\Lambda=\frac{1}{r}(e^{rT}-1)\bar{D}'$.
Thus, we get:

$$\frac{dp^C(0)}{d\alpha}=p_0\left[e^{rT}-1-r\frac{S-(1-\alpha)^2\Gamma}{D(b)(1-\alpha)-(1-\alpha)^2rp_0\Lambda}\right] \tag{12}$$

Next, we derive the following expression for S, where we use that $D(p^C) = \bar{D}'\left(-p^C_{\max} + p^C\right)$ ($p^C_{\max}$ is the choke price, i.e., $D(p^C_{\max}) = 0$):

$$
\begin{aligned}
S &= \int_0^T x(t)dt = (1-\alpha)\int_0^T D(\alpha b + (1-\alpha)p_0 e^{rt})dt \\
&= (1-\alpha)\,\bar{D}'\int_0^T \left[-p^C_{\max} + \left(\alpha b + (1-\alpha)p_0 e^{rt}\right)\right]dt \\
&= (1-\alpha)\,\bar{D}'\left[\left(-p^C_{\max}T + \alpha bT\right) + (1-\alpha)\,\frac{b}{r}\left(1-e^{-rT}\right)\right] \qquad (13)
\end{aligned}
$$

We insert this and the expressions for Γ and Λ into (12) (note that $D(b) = \bar{D}'(b - p^C_{\max})$):

$$
\begin{aligned}
\frac{dp^C(0)}{d\alpha} &= p_0[e^{rT} - 1 \\
&\quad - r\frac{(1-\alpha)\,\bar{D}'\left[\left(-p^C_{\max}T + \alpha bT\right) + (1-\alpha)\frac{b}{r}\left(1-e^{-rT}\right)\right] - (1-\alpha)^2\left[T - \frac{1}{r}(1-e^{-rT})\right]b\bar{D}'}{\bar{D}'(b - p^C_{\max})(1-\alpha) - (1-\alpha)^2 r p_0 \frac{1}{r}(e^{rT}-1)\bar{D}'}] \\
&= p_0\left[e^{rT} - 1 - r\frac{\left(-p^C_{\max}T + \alpha bT\right) + (1-\alpha)\frac{b}{r}\left(1-e^{-rT}\right) - (1-\alpha)\left[T - \frac{1}{r}(1-e^{-rT})\right]b}{(b - p^C_{\max}) - (1-\alpha)b(1-e^{-rT})}\right] \\
&= p_0\frac{\Phi}{\alpha b + (1-\alpha)be^{-rT} - p^C_{\max}} = \frac{p_0}{b}\frac{\Phi}{\alpha + (1-\alpha)e^{-rT} - \frac{p^C_{\max}}{b}} \qquad (14)
\end{aligned}
$$

where

$$
\begin{aligned}
\Phi &= \alpha be^{rT} + (1-\alpha)b - p^C_{\max}e^{rT} - \alpha b - (1-\alpha)be^{-rT} + p^C_{\max} + p^C_{\max}rT - \alpha brT - (1-\alpha)b \\
&\quad + (1-\alpha)be^{-rT} + (1-\alpha)brT - (1-\alpha)b + (1-\alpha)be^{-rT} \\
&= b\left[\frac{p^C_{\max}}{b}\left(rT + 1 - e^{rT}\right) + \alpha\left(e^{rT} - 1 - rT\right) + (1-\alpha)\left(e^{-rT} + rT - 1\right)\right] \\
&\leq b\left[\left(rT + 1 - e^{rT}\right) + \alpha\left(e^{rT} - 1 - rT\right) + (1-\alpha)\left(e^{-rT} + rT - 1\right)\right] \\
&= b\,(1-\alpha)\left[\left(rT + 1 - e^{rT}\right) + \left(e^{-rT} + rT - 1\right)\right] = b\,(1-\alpha)\left[2rT - e^{rT} + e^{-rT}\right] < 0
\end{aligned}
$$

Here we have used that $p^C_{\max} \geqslant b$ and $2rT + e^{-rT} - e^{rT} < 0$ for any rT. We see that the denominator in (14) is negative. Hence, we have shown that the whole expression is positive for any $p^C_{\max} \geqslant b$, so that $\frac{dp^C(0)}{d\alpha} > 0$.■

Proof of Proposition 4:

We differentiate $y(t)$ with respect to α:

$$
\begin{aligned}
\frac{dy(t)}{d\alpha} &= D(p^C(t)) + \alpha\left(b - p_0 e^{rt} + (1-\alpha)e^{rt}\frac{dp_0}{d\alpha}\right)\bar{D}' \\
&= D(p^C(t)) + \alpha\left(b - p_0 e^{rt}\right)\bar{D}' - \alpha r p_0 e^{rt}\frac{S - (1-\alpha)^2\Gamma}{(1-\alpha)D(b) - (1-\alpha)^2 r p_0 \Lambda}\bar{D}' \qquad (15)
\end{aligned}
$$

The first term is positive. The second and third terms are zero if either $\alpha = 0$ or $\bar{D}' = 0$. Thus, if α is sufficiently low initially, or if demand is sufficiently inelastic, $y(t)$ will increase. Furhermore, if t is sufficiently close to T, we know from above that the consumer price falls, implying that $y(t)$ must increase. Hence, we have shown the first part of the proposition.

Next, let us show that $y(0)$ decreases if demand is sufficiently elastic, and α is sufficiently large initially. We use the derivations in (14), and insert for Γ, Λ and $D(p^C) = \bar{D}'\left(-p^C_{\max} + p^C\right)$. Then we get:

$$\begin{aligned}
\frac{dy(t)}{d\alpha} &= \bar{D}'[-p^C_{\max} + \alpha b + (1-\alpha)p_0 e^{rt} + \alpha b - \alpha p_0 e^{rt} \\
&\quad -\alpha r p_0 e^{rt} \frac{\left(-p^C_{\max}T + \alpha b T\right) + (1-\alpha)\frac{b}{r}\left(1 - e^{-rT}\right) - (1-\alpha)\left[T - \frac{1}{r}(1-e^{-rT})\right] b}{(b - p^C_{\max}) - (1-\alpha)b(1-e^{-rT})}] \\
&= \bar{D}'[-p^C_{\max} + 2\alpha b + (1-2\alpha) b e^{r(t-T)} \\
&\quad -\alpha b e^{r(t-T)} \frac{\left(-p^C_{\max} rT + \alpha b r T\right) - (1-\alpha)\left[rT - 2(1-e^{-rT})\right] b}{-p^C_{\max} + \alpha b + (1-\alpha) b e^{-rT}}]
\end{aligned} \tag{16}$$

If we letα go toward one, we get:

$$\frac{dy(t)}{d\alpha} \rightarrow \bar{D}'\left[-p^C_{\max} + 2b - b e^{r(t-T)}(1 + rT)\right] \tag{17}$$

If $p^C_{\max}$ is sufficiently close to b, we see that the bracket is positive for $t = 0$, and hence $\frac{dy(0)}{d\alpha}$ is negative.■

It is straightforward to show that the sign of $\frac{dy(t)}{d\alpha}$ is negative for $\alpha = 0.5$, as long as $p^C_{\max} \geq b$, implying that α has to be at least higher than 0.5 in order to get reduced biofuel supply when α is increased.

Proof of Proposition 5:

Introducing (or increasing) a unit subsidy to biofuels production has the same market effect as reducing the size of b. Thus, we examine the effects of changing b. Following the same procedure as in the proof of Proposition 1, we get:

$$\frac{dT}{db} = -\alpha \frac{\int_0^T D'(p^C(t))dt}{D(b) - (1-\alpha) r p_0 \Lambda} > 0 \tag{18}$$

Thus, T decreases when b declines, or when a subsidy is introduced.

Next, differentiating (1) with respect to b, we get:

$$\frac{dx(t)}{db} = (1-\alpha) D'(p^C(t)) \left[\alpha - (1-\alpha)\alpha r p_0 \frac{dp_0}{db} e^{rt}\right] \tag{19}$$

The only variable that changes over time is e^{rt}. Thus, the paranthesis must decrease over time. We know that if $x(t)$ increases for some t, it must decrease at some other time (since S is fixed). Hence, there must be a $\widehat{t}$ where the paranthesis is equal to zero. Then we have that the whole expression must be negative for all $t < \widehat{t}$ and positive for all $t > \widehat{t}$. In other words, a subsidy to biofuels increases (decreases) oil consumption and extraction for all $t < (>) \widehat{t}$.

Proof of Proposition 6:

The RFS rate is now region-specific, α_i. Equations (1)-(3), as well as the consumer price, are also then region-specific, while (4) is unchanged. Let S_1 and S_2 denote accumulated resource use in the two regions, i.e., $S_1 = \int_0^T x_1(t)dt$ and $S_2 = \int_0^T x_2(t)dt$. We have:

$$S_1 + S_2 = S \tag{20}$$

We are now ready to look at the effects of an increase in α_i. We insert from (1) into (5), and then into (20):

$$\sum_i (1-\alpha_i)\int_0^T D_i(\alpha_i b + (1-\alpha_i)p_0 e^{rt})dt = S$$

and differentiate with respect to α_i

$$-\int_0^T D_i(p_i^C(t))dt + (1-\alpha_i)\int_0^T \left(b - p_0e^{rt} + (1-\alpha_i)e^{rt}\frac{dp_0}{d\alpha_i}\right) D_i'(p_i^C(t))dt$$

$$+(1-\alpha_i)D_i(b)\frac{dT}{d\alpha_i}+$$

$$(1-\alpha_j)\int_0^T (1-\alpha_j)e^{rt}\frac{dp_0}{d\alpha_i}D_j'(p_j^C(t))dt + (1-\alpha_j)D_j(b)\frac{dT}{d\alpha_i} = 0$$

Inserting for $\frac{dp_0}{d\alpha}$ from (7), which still holds but is region-specific, gives:

$$0 = -\int_0^T D_i(p_i^C(t))dt + (1-\alpha_i)\int_0^T \left[\left(b - p_0e^{rt}\right) D_i'(p_i^C(t))\right] dt +$$

$$\left[(1-\alpha_i)D_i(b) + (1-\alpha_j)D_j(b) - (1-\alpha_i)^2 rp_0\int_0^T e^{rt}D_i'(p^C(t))dt\right]\frac{dT}{d\alpha_i}$$

$$-\left[rp_0(1-\alpha_j)\int_0^T e^{rt}D_j'(p_j^C(t))dt\right]\frac{dT}{d\alpha_i}$$

which can be rearranged:

$$\frac{dT}{d\alpha_i} = \frac{1}{1-\alpha_i}\frac{S_i - \Gamma_i}{(1-\alpha_i)D_i(b) + (1-\alpha_j)D_j(b) - \Lambda_i - \Lambda_j} > 0 \tag{21}$$

where $\Gamma_i = (1-\alpha_i)^2\int_0^T \left[\left(b - p_0e^{rt}\right) D_i'(p_i^C(t))\right] dt < 0$, $\Lambda_i = (1-\alpha_i)^2 rp_0\int_0^T e^{rt}D_i'(p_i^C(t))dt < 0$ and $\Lambda_j = rp_0(1-\alpha_j)\int_0^T e^{rt}D_j'(p_j^C(t))dt < 0$. Note that Γ_i, Λ_i and can all be treated as constants for $D_i'(p_i^C(t)) = D'$. Since $\frac{dp_0}{d\alpha_i} = -rp_0\frac{dT}{d\alpha_i}$, it follows that $\frac{dp_0}{d\alpha_i} < 0$.

For the change in total oil extraction we have:

$$\begin{aligned}\frac{dx_i(t)}{d\alpha_i} + \frac{dx_j(t)}{d\alpha_i} &= -D_i(p_i^C(t)) + (1-\alpha_i)D_i'(p_i^C(t))(b - p_0e^{rt}) \\ &+ \left[(1-\alpha_i)^2D_i'(p_i^C(t)) + (1-\alpha_j)^2D_j'(p_j^C(t))\right]e^{rt}\frac{dp_0}{d\alpha_i}\end{aligned} \tag{22}$$

The two first terms are negative: Increasing the RFS decreases the use of oil for a given consumer price on transportation fuel and increases the consumer price on transporation fuel for a given price on oil. On the other hand, the last term is positive as the price on oil falls, having a downward effect on the consumer price in both regions. We know that extraction must increase at some point since extraction now last longer. It must then decline at other points since the amount of resource is given. To see what happens at $t = 0$, we rearrange (22) we obtain the following expression for $\frac{dx_i(t)}{d\alpha_i} + \frac{dx_j(t)}{d\alpha_i}$:

$$-D_i(p_i^C(t)) - r(1-\alpha_j)^2D_j'(p_j^C(t))p_0e^{rt}\frac{S_i - \Gamma_i}{(1-\alpha_i)D_i(b) + (1-\alpha_j)D_j(b) - \Lambda_i - \Lambda_j}$$

$$+(1-\alpha_i)\left[b - p_0e^{rt} - rp_0e^{rt}\frac{S_i - \Gamma_i}{(1-\alpha_i)D_i(b) + (1-\alpha_j)D_j(b) - \Lambda_i - \Lambda_j}\right]D_i'(p_i^C(t)) \tag{23}$$

The first term is negative, and will become less negative over time since the consumerprice on transportation fuel $p_i^C(t)$ must increase over time. The next term is positive, and it must increases over time as long as the demand function is concave, i.e., $D_j''(p^C(t)) \leq 0$. Hence, if the sum of the first and the second term is positive, the sum will stay positive and increase in value for all t until T.

The bracket in the last term decreases over time. If the bracket is negative at $t = 0$, the whole term is positive intially. Moreover, it will become more and more positive over time as long as $D_i''(p^C(t)) \leq 0$. If the bracket is positive at $t = 0$, the whole term is negative initially. At some time $\bar{t} < T$ the bracket will become negative, and then the second term will become more and more positive over time as long as $D_i''(p^C(t)) \leq 0$. In the time interval $[0, \bar{t}\rangle$ the terms in brackets will decrease towards zero, while the derivative $D_i'(p_i^C(t))$ will stay constant or become more negative (as long as $D_i''(p^C(t)) \leq 0$).

There are only two ways in which the whole expression in (23) can be positive for $t = 0$. The sum of the first and second term can be positive and the last term can be positive. However, then the whole expression will stay positive for all $t < T$. This is inconsistent with the fact that extraction time increases. Thus, this case can be ruled out.

The last term could be negative, but still the whole expression could be positive for $t = 0$. This implies that the sum of the first and second term is positive initially, and that this sum is larger than the absolute value of the second term. However, we know that the sum of the first and second term is increasing in t. Hence, in order for the whole expression to become negative at some point, the second term must become more negative. This cannot happen if $D_i''(p^C(t)) = 0$. Hence, it follows that if $D_i''(p^C(t)) = 0$, total fossil extraction will decline for all $t < \widehat{t}$ and increase for all $t > \widehat{t}$ (for some $0 < \widehat{t} < T$).■

The value of γ:

The following table is taken from the EPA (2009). We use this to guess the value on our γ.

Table A1 "The climate cost of biofuels relative to the climate costs of fossil fuels"

	Emission reduction potential	*Estimate "gamma"*
Corn ethanol (best case)	-26%	0.74
Soy-based biodiesel	+4%	1.04
Sugarcane ethanol	-26%	0.74
Switchgrass ethanol (cellulosic)	-124%	-0.24

If we assume that cellulosic ethanol constitute 50% of the biofuels, while the other three together constitute the rest, we get an average γ of 0.3 which we use in our base case.