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### Summary

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**Keywords:** Blending Mandate, Renewable Fuel Standard, Biofuels, Climate Costs

**JEL Classification:** Q27, Q41, Q54

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

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## Abstract

Recent literature on biofuels have questioned whether biofuels policies are likely to reduce the negative effects of climate change. In this paper we make two contributions to the literature. First, we study the market effects of a renewable fuel standard in a dynamic model taking into account that oil is a non-renewable resource. Second, we model emissions from land use change explicitly when we evaluate the climate effects of the renewable fuel standard.

We find that global 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. Furthermore, we find that the standard also tends to reduce 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 have beneficial climate effects.

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# 1 Introduction

More than 20% of energy-related CO<sub>2</sub> 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, Greaker and Potter, 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 (2010) 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 et al, 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.

In this paper we make two contributions to the literature. With very few exceptions the literature studying the market effects of biofuels policies have treated oil as a traditional commodity in unlimited supply. In this paper we introduce forward looking, competitive suppliers, and we explicitly take into account that oil is a non-renewable natural resource.<sup>1</sup> Furthermore, to our knowledge no previous studies have combined new knowledge on emissions from land use change with market effects of biofuels policies, assessing the effects on climate costs, that is, the discounted sum of damage costs from climate change. This also requires a dynamic model since policies affect the time profiles of emissions from both sources.

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

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<sup>1</sup>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.

may lead to a decrease in total fuel sales. This happens if the elasticity of biofuels supply is lower than the elasticity of oil supply. The effect of the policy is then not only to replace oil with biofuels, but also to reduce total consumption of transport fuels, which by itself will reduce climate costs. Note that this result is reversed if the elasticity of biofuels supply is higher than the elasticity of oil supply, or if a biofuels subsidy is imposed rather than a renewable fuel standard (DeGorter and Just, 2009).

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. Two such examples are Crafton et al. (2012) and Chakravorty et al. (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.<sup>2</sup> 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.

First, we find that the extraction period of the oil resource is extended by the in-

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<sup>2</sup>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.

roduction 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. Second, it occurs both in the case with constant extraction cost and in the case with increasing extraction cost. Finally, we show that a biofuels subsidy 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, taking into account the effects of biofuels usage on land use changes. 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.

The paper is laid out as follows. In Section 2 we study the effects of a blending mandate in a one region model. In Section 3 we extend the model to include the two region case, increasing cost of extraction and increasing marginal costs of biofuels. In Section 4 we introduce climate costs from oil and biofuels, respectively. In Section 5 we provide a

numerical illustration of the model. Finally, in Section 6 we conclude.

## 2 Market effects of a blending mandate for biofuels

We consider a market with oil ( $x$ ) and biofuels ( $y$ ), which are assumed to be perfect substitutes.<sup>3</sup> The stock of oil ( $S$ ) is fixed, and there are no costs of extracting this stock. Unit costs of producing biofuels ( $b$ ) are fixed. Then irrespective of the blending mandate, the oil price is  $p(t) = p_0 e^{rt}$  until  $p(T) = b$  is reached at  $T$ , when a complete switch to biofuels occurs.

The assumption that oil is given in a fixed supply with constant unit costs of extraction might seem very restrictive. As shown by e.g. Gerlagh (2011) and Hoel (2011) the effects of a carbon tax are quite different for this case and the more realistic case in which extraction costs increase with accumulated extraction. However, our focus is not on a carbon tax, but on a blending mandate. Total extraction (but not the timing of extraction) is independent of a blending mandate. This will become apparent in the next section in which we look at the case of increasing extraction cost.

The assumption of a fixed unit cost for biofuels can also be criticized. It greatly simplifies the analysis, and it may not be too far from reality for so-called second generation biofuels, which to a large extent can be grown on pastures and currently unused land (IEA, 2011b). But in order to check the robustness of our results to this assumption, we consider the case of increasing marginal cost of biofuels both analytically (next section) and in the simulations (Section 5).

Assume that fuel consumers are required to use at least a share  $\alpha$  of biofuels in the total fuel use. We coin  $\alpha$  a renewable fuel standard (RFS). Let the consumer price of fuels

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<sup>3</sup>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.



be given by  $p^C(t)$ . We then have  $p^C(t) = \alpha b + (1 - \alpha)p_0 e^{rt}$ . Further, let the demand for fuel be given by  $D(p^C)$ , with  $D' < 0$ . The demand for oil and biofuels is then:

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

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

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

where  $T$  is determined by:

$$p_0 e^{rT} = b \quad (4)$$

Finally, we have the equilibrium condition:

$$\int_0^T x(t) dt = S \quad (5)$$

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  $\alpha$  affects the market equilibrium.

## 2.1 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  $\alpha$ . 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 initial price of the resource falls.*

Proof: See the Appendix.

Obviously, the proposition also holds if we introduce an RFS, i.e., increase  $\alpha$  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. We can then show:

**Proposition 2** *Assume that fuel demand is concave or linear. If the share of biofuels in an RFS system is increased, extraction of oil will decline for all  $t < \hat{t}$ , and increase for all  $t > \hat{t}$ .*

Proof: See the Appendix.

This proposition is also quite intuitive. As the resource extraction is extended, average extraction per period until the "old"  $T$  must come down. The proposition states that extraction declines at every point of time until some  $\hat{t}$ . Moreover, between the "old" and the "new"  $T$ , extraction obviously increases.

If fuel demand is convex, we cannot rule out the possibility that initial extraction increases. The explanation is that with convex demand, demand may be more price elastic at low prices. Thus, if the initial consumer price ( $p^C$ ) decreases in line with lower oil price ( $p_0$ ), fuel demand may be stimulated substantially so that even demand for oil increases.

## 2.2 Effects on fuel consumption and biofuels production

In order to investigate the effects on total fuel consumption, we assume that demand is a linear function of the consumer price. We can show the following:

**Proposition 3** *Assume that fuel demand is linear. If the share of biofuels in an RFS system is increased, the consumer price will increase (decrease) and fuel consumption will decrease (increase) for all  $t < (>)\hat{t}$ , where  $0 < \hat{t} < T$ .*

Proof: See the Appendix.<sup>4</sup>

The consumer price is pulled in both directions. On the one hand, the oil price  $p$  decreases. On the other hand, a higher  $\alpha$  increases the weighted price  $p^C = \alpha b + (1 - \alpha)p$ . According to the proposition, the latter effect is dominating initially, at least if the demand function is linear. Note that this holds whether the demand function is steep or not, as long as the choke price  $p_{\max}^C \geq b$ .

When  $t$  approaches  $T$ , both the oil price and the consumer price approaches  $b$ . Thus, for  $t$  sufficiently close to the "old"  $T$ , the consumer price must decrease when  $\alpha$  is increased (since  $p$  drops). Hence, for linear demand, 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  $\alpha$  is increased:

**Proposition 4** *If the share of biofuels in an RFS system is increased, production of biofuels will increase if either i)  $\alpha$  is sufficiently small initially, ii) demand is sufficiently inelastic, or iii)  $t$  is sufficiently close to  $T$ . On the other hand, biofuels production will decrease initially if  $\alpha$  is already sufficiently close to 1 and demand is linear and sufficiently elastic.*

Proof: See the Appendix.

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<sup>4</sup>Note that the value of  $\hat{t}$  is generally not the same in Propositions 2, 3 and subsequent propositions where this symbol is used.

The first result, i.e., that biofuels production expands if at least one of three conditions is fulfilled, is as expected. The last result, i.e., that biofuels production could in fact decrease, may seem counter-intuitive at first. We know from above that the initial consumer price increases when  $\alpha$  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  $\alpha$ , 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. If demand is concave or linear, oil production will decrease initially, and increase in later periods so that total extraction is unchanged. Finally, if demand is linear, 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, but could decrease initially if demand is sufficiently elastic and  $\alpha$  is already high.

### **2.3 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, and increase (decrease) the use of oil for all  $t < (>)\hat{t}$ , where  $0 < \hat{t} < T$ .*

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 Extensions**

As already mentioned some of our simplifying assumptions in our base case may be questioned. In this section we show that Proposition 1 still holds even if these are relaxed. Moreover, we have considered a closed one region model. Although many countries have implemented an RFS for biofuels, policies are not synchronized, and several large countries such as China do not at present have any mandate at all. The question then arises whether the results obtained so far also hold for a single region trading with other regions with no or weaker mandates.

#### **3.1 Stock dependent extraction costs**

So far we have assumed fixed extraction costs (set to zero to simplify notation). It is more reasonable that extraction costs depend on the remaining stock of oil. Let the cost of extraction  $c$  be given by:

$$c = \theta(S(t))x(t)$$

with  $\theta' < 0$ , and where  $S(t)$  denotes the remaining stock and  $x(t)$  denotes extraction. Extraction will stop when the marginal extraction cost reaches the price of the backstop i.e.  $\theta(S(T)) = b$  in which  $T$  denotes the time at which extraction stops. The amount of stock that will be extracted is hence given by:  $\bar{S} = S(0) - \theta^{-1}(b)$  in which  $\theta^{-1}$  is the inverse of  $\theta$ .

Note that  $\bar{S}$  is independent of the biofuels mandate  $\alpha$ . This is an important difference between a biofuels mandate and some other climate policies. With a constant carbon tax  $\tau$  we get  $\bar{S}^{tax} = S(0) - \theta^{-1}(b - \tau)$ , which is lower the higher is  $\tau$ . Similarly, with a constant subsidy  $\sigma$  of biofuels we get  $\bar{S}^{subsidy} = S(0) - \theta^{-1}(b - \sigma)$ , which is lower the higher is  $\sigma$ . 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. Since both a constant tax and a constant subsidy give lower total extraction, we therefore might expect that also a biofuel mandate would give lower total extraction. However, any biofuel mandate that is bounded away from 100%, constant or time-variant, 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.

As before, we have

$$\int_0^T x(t) dt = \bar{S}. \quad (6)$$

Consider an increase in  $\alpha$  - the biofuels share. The price of oil  $p(t)$  must then decrease, because if not, equation (6) cannot hold. Further, at time  $T$  the price of oil must have reached  $b$ . Hence, if the rate of change in the price of oil stays constant or decreases, the extraction time  $T$  must increase.

The Hotelling equation for the case of stock dependent extraction costs tells us:

$$\frac{d[p(t) - \theta(S(t))]}{dt} = r[p(t) - \theta(S(t))] + \theta'(S(t))x(t) \quad (7)$$

(See for instance Crafton et al.,2012)

We rewrite (7) using  $\dot{S} = -x(t)$  where dots over variables denote time derivatives:

$$\dot{p}(t) + \theta'x(t) = rp(t) - r\theta(S(t)) + \theta'x(t)$$

which simplifies to:

$$\frac{\dot{p}(t)}{p(t)} = r \left( 1 - \frac{\theta(S(t))}{p(t)} \right) \quad (8)$$

If  $\alpha$  is increased at time  $t$ , and the price  $p(t)$  decreases, the rate of change in the price must decrease ( $\theta(S(t))$  does not change). Consequently, if  $\alpha$  is increased, the extraction time  $T$  is extended.

### 3.2 Increasing marginal costs of biofuels

We return to the case of zero extraction costs, but introduce increasing marginal costs of biofuels. Let the costs of biofuels be given by  $c(y)$  with  $c' > 0$  and  $c'' > 0$  (instead of  $c' = b$  being constant as we previously assumed). As before, when the fuel price is sufficiently high biofuel production will serve all of the demand. Previously, this price  $p(T)$  was equal to  $b$ . With increasing marginal costs of biofuel  $p(T)$  is determined by fuel demand being equal to the supply of biofuels; this equilibrium can be written as  $c'(D(p(T))) = p(T)$ .

As before, the Hotelling rule implies that the oil price is rising at the rate of interest until oil is completely exhausted, i.e.  $p(t) = e^{r(t-T)}p(T)$  for  $t < T$ . Without a biofuel mandate, we will first have a phase with only oil production if  $c'(0)$  is sufficiently high (so  $p(0) < c'(0)$ ). Once  $p(t)$  reaches  $c'(0)$ , biofuel production starts, and will increase over

time since the fuel price is rising. Total fuel demand is declining over time, and since oil production covers the difference between total demand and biofuel supply, oil production is declining over time. This decline continues until  $t = T$ , after which biofuel production is constant and equal to  $D(p(T))$ . Without a biofuel mandate, the main difference from the case of constant marginal costs is that the transition from oil to biofuel now is gradual, with a phase of simultaneous production of both fuel types.

With constant marginal costs of biofuel production, a blending mandate is always binding until oil is fully exhausted. This is not the case with increasing marginal costs of biofuel: For any blending mandate of  $\alpha$  there is a threshold price  $p_\alpha$  such that the mandate is not binding for  $p(t) > p_\alpha$ , where  $p_\alpha$  is determined by  $c'^{(-1)}(p_\alpha) = \alpha D(p_\alpha)$ . In words,  $p_\alpha$  is the price making the unregulated supply of biofuels equal to the a share  $\alpha$  of total demand.<sup>5</sup> Hence, for the period for which  $p(t) \in (p_\alpha, p(T))$  the biofuel mandate is not binding, and the equilibrium is as described above.

The price path  $p(t)$  must be lower with a blending mandate than without. To see this, consider oil demand with a mandate at the equilibrium price path when there was no mandate. Prior to the date at which  $p(t) = p_\alpha$  is reached, oil demand is lower with the mandate than without. Hence, there would be unextracted oil at the date  $T$  at which biofuel production covers all of the fuel demand. To restore equilibrium, the price path  $p(t)$  therefore must decline as a response to the biofuel mandate. A lower price path for oil also means that the exhaustion date  $T$  is postponed, just as in the case with constant marginal costs of biofuel production.

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<sup>5</sup>Clearly,  $p_\alpha < p(T)$  since  $p(T)$  is defined by  $c'^{(-1)}(p(T)) = D(p(T))$ .



### 3.3 Two regions

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. In the Appendix we analyze a two region version of our model. We show that the extraction time will be extended independent of which region that tightens its RFS, and the initial price of oil declines. Moreover, if the demand functions in the two regions are linear, oil extraction will decline for all  $t < \hat{t}$ , and increase for all  $t > \hat{t}$  (for some  $0 < \hat{t} < T$ ). If one or both demand functions have second order derivatives unequal to zero, the effects on the extraction path are ambiguous. Thus, Proposition 1 carries over to the case with two regions, while Proposition 2 only partly carries over.

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  $\hat{t}$ .

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

We will now consider the effect of the RFS on the costs of climate change. The use of oil leads to flow emissions, while emissions from use of biofuels potentially include both flow emissions and emissions from stock changes (related to land use changes). We first discuss the climate costs of oil and biofuels separately, before we combine them and look at the effects of an RFS on climate costs.

### 4.1 Climate costs from using oil

Burning oil releases carbon to the atmosphere, which will gradually decline over time, as it is transferred to other sinks. We model this in the "standard" way, assuming that the carbon in the atmosphere (beyond preindustrial level) depreciates at a constant rate  $\delta$ .<sup>6</sup> The amount of 1 unit of carbon emissions at time  $t$  remaining in the atmosphere  $z$  years after the emission date is thus  $e^{-\delta z}$ .

At any time  $t$ , climate costs are  $e^{mt}C(A(t))$ , where  $A(t)$  is carbon in the atmosphere. The term  $e^{mt}$  (where  $m \geq 0$ ) captures the reasonable assumption that the value of climate damages increases over time due to income and production growth. Consider the climate damage caused by 1 unit of emissions from burning oil at time  $t$ . The total additional damage caused by 1 unit of carbon emissions at time  $t$  is the sum of additional damages at all dates from  $t$  to infinity caused by the additional stocks from  $t$  to infinity. To get from additional stocks at  $t + z$  to additional damages at  $t + z$  we must multiply the additional stocks at  $t + z$  by the marginal damage at  $t + z$ , which is  $e^{m(t+z)}C'(A(t+z))$ . The marginal damage of 1 additional unit of emissions at  $t$ , often denoted the social cost of carbon, is

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<sup>6</sup>This is a major simplification of the properties of the true carbon cycle. In reality, a significant portion (about 25% according to e.g. Archer, 2005) remains in the atmosphere for ever (or at least for thousands of years). In the last part of the Appendix we show that our main results in this section remain valid even if the carbon cycle is modeled as in Farzin and Tahvonen (1996), allowing some of the carbon emission to remain in the atmosphere for ever.

thus given by

$$q_x(t) = e^{mt} \int_0^\infty e^{-(r+\delta-m)z} C'(A(t)) dz \quad (9)$$

For  $C'' > 0$  the social cost of carbon will change over time at a varying growth rate. For the special case of  $C'' = 0$ , i.e. that damages are linear in the atmospheric stock, (9) may be rewritten as

$$q_x(t) = e^{mt} \frac{C'}{r - m + \delta} \quad (10)$$

which rises over time at the constant rate  $m$ .

## 4.2 Climate costs from using biofuels

Growing and processing biofuels entails greenhouse gas (GHG) emissions, but to what extent is a controversial topic. According to life-cycle analyses the emission sources can be grouped into the following categories: (I) oil usage for harvesting, transporting and production, (II) N<sub>2</sub>O emissions from fertilizer usage and the crop itself, (III) direct land-use change, and (IV) indirect land-use change (see e.g. Macedo et al. 2008, Khanna and Crago, 2011).

It seems reasonable that the renewable fuel standard encompasses oil used for harvesting and transporting in the agricultural sector. Thus, source (I) is to some degree included in our model already.<sup>7</sup> With respect to energy for biofuels production, this is in many cases provided from the biofuel crop itself. For instance, sugarcane ethanol production

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<sup>7</sup>Ideally, source (I) could be incorporated into our model by taking into account that total fuel demand is an increasing function of  $y(t)$ . This could alter the extraction path of  $x(t)$ , but obviously not  $S$ . As the RFS policy implies that this extra fuel demand would be proportional to  $x(t)$ , it seems unlikely that the extraction path would be much altered either. Moreover, harvesting and transporting biofuels crops probably make up a rather small share of total transportation fuel demand.

often supplies electricity, too. To our knowledge such possibilities also exist for second generation biofuels (Schmer et al., 2008).

Furthermore, according to Crutzen et al. (2008) source (II) may be significant for some kinds of first generation biofuels, but not so much for second generation biofuels based on energy crops. Hence, in the following we will disregard source (I) and (II), and focus on emissions due to land use changes, i.e., (III) and (IV). This is of course a simplification, and it is straightforward to add flow emissions to the expressions below.

Emissions from direct land-use change are treated by Fargione et al. (2008). Their study shows that converting different types of virgin land to crop land may give high initial emissions, coined by Fargione et al. as *carbon debt*. Biofuels crops are however often grown on existing agricultural land. Indirect land use change then refers to changes in land use that occurs through changes in the market prices for food and land. Both Searchinger et al. (2008) and Lapola et al. (2010) analyze indirect land-use change, and show that the effect upon emissions may be of great significance.

In our model we treat direct land-use change and indirect land-use change together. In particular, we assume that the global area for food crop is kept constant, and thus that a certain production level of biofuels have led to a one time boost in emissions as the growing of every new non-food crop must increase the total area of cultivated land globally. We will now turn to how this can be modeled.

### 4.3 Climate costs from land use changes

Assume that each unit of  $y$  requires  $\ell$  units of land, and that each unit of land converted to biofuels production will reduce the carbon sequestered on this land by an amount  $\beta$ .<sup>8</sup>

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<sup>8</sup>Note that  $\beta$  will depend on the type of initial land and on the type of biofuels production. For some types (barren land transformed to an energy forest)  $\beta$  may be negative. In the subsequent discussion we assume  $\beta > 0$ . The parameter  $\ell$  will also vary across types of biofuels. Alternatively, the biofuel crop is

Producing  $y(t)$  units of biofuel hence increases the amount of carbon in the atmosphere by  $\beta\ell$  units. The marginal climate cost of producing  $y(t)$  is therefore equal to  $\beta\ell e^{mt}C'(A(t))$ . However, there is also a climatic benefit of the extra carbon in the atmosphere: When the carbon stock is increased by an amount  $\beta\ell$ , there is an additional flow of  $\delta\beta\ell$  from the atmosphere to other carbon sinks. This carbon flow *from* the atmosphere has a value that is equal to the social cost of carbon for flows of carbon *into* the atmosphere, i.e. equal to  $q_x(t)$ . The net marginal climate cost of producing biofuels, denoted  $q_y(t)$ , is therefore given by

$$q_y(t) = \beta\ell [e^{mt}C'(A(t)) - \delta q_x(t)] \quad (11)$$

Combining this with (9) gives

$$\frac{q_y(t)}{q_x(t)} = \beta\ell \left[ \frac{C'(A(t))}{\int_0^\infty e^{-(r+\delta-m)z} C'(A(t)) dz} - \delta \right] \quad (12)$$

Notice that in the derivation above it is implicitly assumed that any increase in  $y$  will immediately release carbon to the atmosphere. This is not an unreasonable assumption. However, the formulation also implies that any reduction in  $y$  immediately sequesters carbon from the atmosphere. This is obviously unrealistic; in reality, the sequestration takes time. Hence, our formulation makes biofuels production more climate friendly than it is in reality if we have a declining  $y(t)$ .<sup>9</sup>

For the special case of  $C'' = 0$ , i.e. that damages are linear in the atmospheric stock

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grown on already developed agricultural land. We then assume that virgin land must be converted some other place to upkeep the production of the replaced agricultural products.

<sup>9</sup>Note that in our simulations presented in Section 5 biofuels use increases over time.

the two equations above may be rewritten as

$$q_y(t) = e^{mt} \beta \ell \frac{r - m}{r - m + \delta} C' \quad (13)$$

$$\frac{q_y(t)}{q_x(t)} = \beta \ell (r - m) \equiv \gamma \quad (14)$$

The parameter  $\gamma$  is crucial for the effect on climate costs of a RFS. If  $\gamma$  is equal to unity, the use of biofuels has identical climate costs to oil.

#### 4.4 The effects of an RFS on climate costs

In Section 2 we showed how the introduction of an RFS for biofuels affects the time paths for the use of oil and biofuels. The effect on climate costs of the introduction of an RFS will depend on the size of  $\gamma$  defined by (14). 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. If extraction is delayed climate costs will go down, since  $e^{-rt} q_x(t)$  is declining over time. By continuity, the following proposition hence follows from Proposition 2:

**Proposition 6** *If  $\gamma$  defined by (14) is sufficiently small and demand for fuel is linear or concave, climate costs will decline as a consequence of the introduction of an RFS for biofuels.*

For larger values of  $\gamma$  it is not obvious how climate costs are affected by an RFS, even if oil use is postponed. The reason for this is that biofuels use increases for low values of  $t$ , but declines for higher values of  $t$  (until the date at which oil use is zero both with and without the RFS), see Propositions 1 and 4. The isolated effect of this is to increase climate costs. There are thus 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  $\gamma$ , and the latter effect will dominate if  $\gamma$  is sufficiently large. We therefore have the following proposition:

**Proposition 7** *If  $\gamma$  defined by (14) is sufficiently large, climate costs will increase as a consequence of the introduction of an RFS for biofuels.*

The effects of an RFS on climate costs is hence an empirical issue. In the next section we give some numerical estimates of the parameters determining  $\gamma$  defined by (14), 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 the model to real world data in the following way: We consider two alternative linear fuel demand functions, with either elastic or inelastic demand. The initial price elasticities in the two cases are respectively  $-0.4$  and  $-0.1$ , but the elasticities are increasing with the price (due to linear demand). 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 may think of this as e.g. cellulosic ethanol. The unit costs of oil is calibrated so that the initial oil price and consumption are consistent with the 2011 data. This leaves us with unit costs of respectively 83% and 79% of the oil price under elastic and inelastic demand, which seems fairly reasonable.

The initial shadow 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).<sup>10</sup> Converted to oil, the initial carbon cost ( $q_x$ ) amounts to 19% of the initial oil price. Further, we assume a discount rate of  $r = 4\%$ , an income growth of  $m = 2\%$ , and a depreciation rate of  $\delta = 0.013$ .<sup>11</sup>

Based on the discussion above, we only consider emissions from land use change for the climate costs of biofuels. We have found figures for second generation biofuels of which cellulosic ethanol based on perennial grasses seems to be the most promising (Eggert, Greaker and Potter, 2011). From Sanderson (2006) we have that on average 0.052 hectares of land is needed to produce 1 barrel of oil equivalent (boe) cellulosic ethanol.<sup>12</sup> This corresponds to the parameter  $\ell$  in our theoretical model, but measured in ha/boe instead of in ha/tonne $CO_2$  as in the theoretical model. Emissions from oil are 0.44 tonne  $CO_2$ /boe. The parameter  $\ell$  measured in ha/tonne $CO_2$  is hence  $0.052/0.44 = 0.118$ .

Further, according to Plevin et al (2010) the emission factor for converted grassland is 75 – 200 tonne  $CO_2$ /ha. This corresponds to the variable  $\beta$  in our theoretical model. The

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<sup>10</sup>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  $CO_2$ e. Most other CBA studies seem to find lower shadow costs of carbon. Both these studies and the Stern Review have been much criticized for various reasons, see, e.g., Weitzman (2007, 2011) who in particular emphasises the role of uncertainty.

<sup>11</sup>Note that in the simulation model we use the slightly more complicated climate model of Farzin and Tahvonen (1996) in which  $\theta = 0.25$  denotes the amount of emitted carbon staying in the atmosphere "forever", see Appendix.

<sup>12</sup>For comparison, Plevin et al (2010) reports the average corn ethanol yield to be 0,07 ha/boe, while IEA (2011b) reports the sugarcane ethanol yield to be 0,056 ha/boe.



land use change emissions from ethanol (i.e.  $\ell\beta$ ) is hence given as  $8.9 - 23.6$ .<sup>13</sup> For the relationship  $q_y/q_x \equiv \gamma = (r - m)\ell\beta$  we then get a value in the range  $[0.18, 0.47]$  (cf. (14)). In our simulations we mainly use  $\gamma = 0.33$ , i.e., the average of this interval. However, as there is large variation across different biofuels, as well as significant uncertainties, we will start by considering which levels of  $\gamma$  that make the RFS policy climate neutral (compared to the BaU scenario).

## 5.2 Simulation results

How large must  $\gamma$  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  $\alpha$  in the range  $10 - 20\%$ , which is in line with the EU targets. The answer is that the RFS policy is climate-neutral if  $\gamma$  is in the range  $0.93 - 1$ . 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 search for the level of  $\alpha$  that gives the same present value of reduced climate costs as the Pigovian tax. This turns out to be  $\alpha = 0.48$  (0.61) in the case with inelastic (elastic) demand, given the calibrated model as described above.<sup>14</sup> Here

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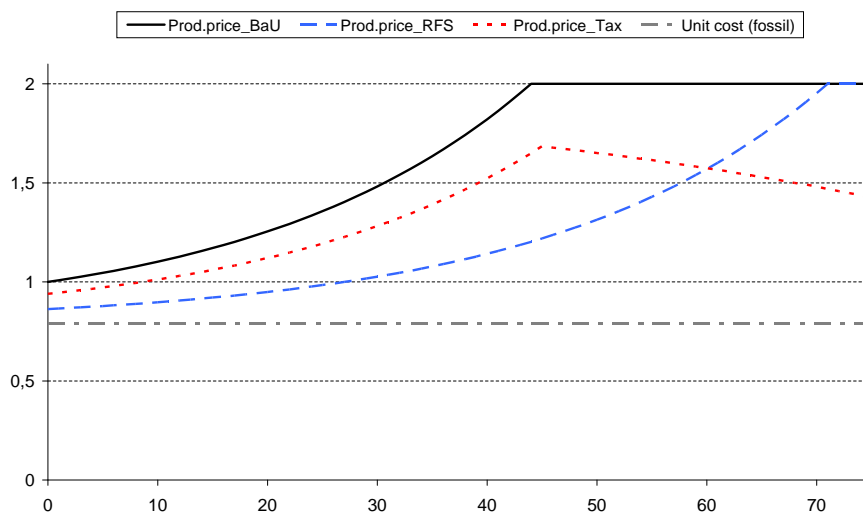
<sup>13</sup>In our theoretical model we measure oil in units  $CO_2$  that are released by combustion. Thus, to get the product  $\ell\beta$  in tonnes  $CO_2$  per  $CO_2$ -units of oil, we must divide our figures with the emission factor for oil in tonnes  $CO_2$ /boe.

<sup>14</sup>Such large values of  $\alpha$  will of course require an enormous growth in biofuels production, which will lead to substantial land use changes and presumably significant interactions with other parts of the economy (e.g., agriculture). Moreover, it is not realistic that such a large production growth may take place on short notice. Thus, this part of the numerical simulations is mainly illustrative.

we discuss the case with inelastic demand only – the qualitative results are the same with elastic demand.

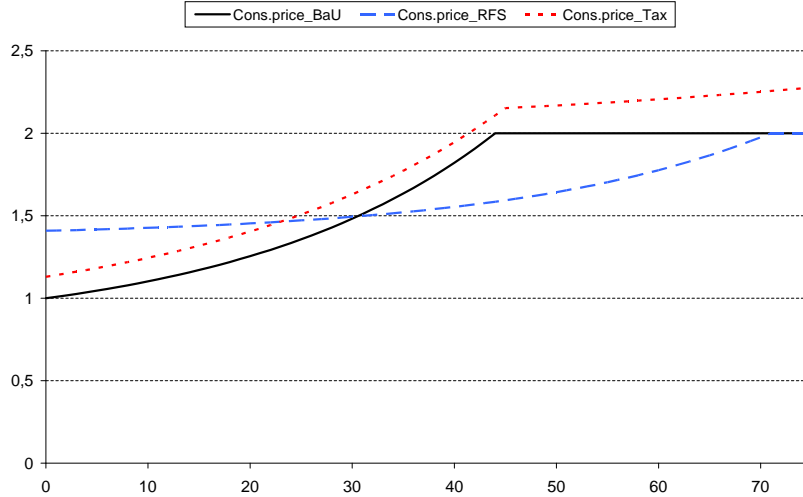
The two policies give very different market and welfare effects. Total welfare is reduced by 6% when choosing the RFS instead of the tax, and the RFS scenario is also reducing welfare compared to the BaU scenario.

Figure 1 Producer price of transport fuel under different scenarios



The RFS policy is particularly detrimental for oil producers. Whereas the Pigovian tax reduces profits of these producers by 30%, profits are reduced by two thirds under the RFS policy. The initial price of oil is reduced by almost 15% in the latter case (cf. Figure 1), which means that the initial resource rent is reduced by two thirds. In the tax scenario, the initial oil price declines by 6%.

Figure 2 Consumer price of transport fuel under different scenarios

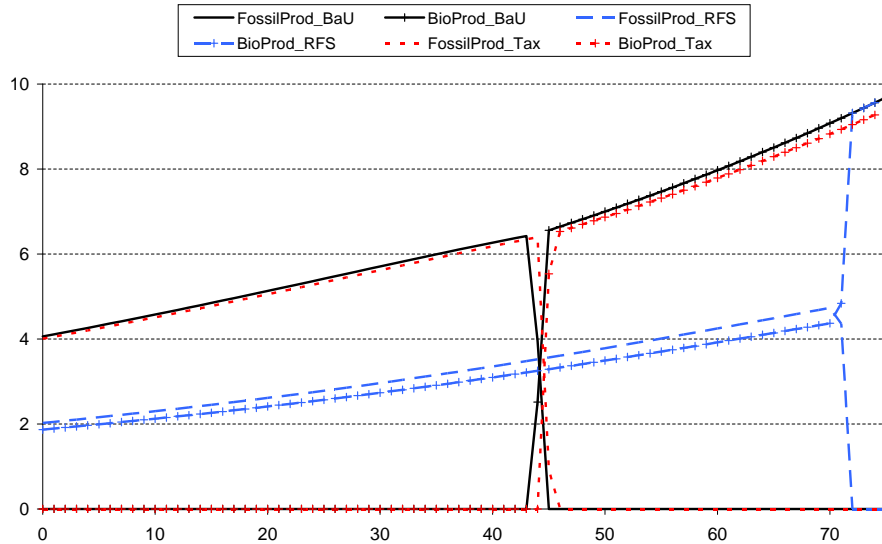


Consumer surplus is somewhat lower in the tax scenario than under the RFS policy, but not if the emission tax revenues are allocated back to the consumers. Thus, consumers might prefer the RFS policy if they are ignorant about public revenues, which may partly explain the popularity of blending mandates 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  $\alpha$  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 25 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  $\alpha$  is assumed to reduce climate costs by close to  $\alpha\%$ . This is clearly not the case. In the optimal tax scenario, climate costs are reduced by 10%, while we have seen above that a similar reduction under RFS policy requires an  $\alpha$  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 almost halved, but the extraction period is extended from 44-45 years in the BaU and Tax scenarios to 71 years in the RFS scenario (cf. Figure 3).

Figure 3 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  $\gamma = 0.33$  (i.e.,  $q_y/q_x = 0.33$ ).

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 12% initially to almost 35% just before the fossil resource is fully extracted.<sup>15</sup> Thus, global emissions are postponed, and decline vis-a-vis BaU-levels until the "old" depletion time period  $T$ . Climate costs are also

<sup>15</sup>These results refer to the inelastic demand function. With elastic demand, leakage is lower initially but higher later on.

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 1.5%, versus 3.3% if both regions implement a 20% RFS share.

### 5.3 Increasing marginal costs of biofuels

In the simulations above we have assumed constant biofuels costs. This is a fair assumption for moderate levels of biofuels, such as 10-30% of the global market (cf. IEA, 2011b). However, in our model biofuels eventually take over the whole market when the non-renewable oil resource is extracted. Then the marginal supply costs may be significantly higher, even in the long run. However, there is little information regarding this, which is why we have considered constant costs so far. Nevertheless, it is important to test the sensitivity of our results with respect to this (we only consider the inelastic case here). Thus, we have simulated the model with quadratic marginal costs of biofuels, i.e.,  $c'(y(t)) = b_1 + b_3(y(t))^2$ . We let  $b_1 = b$ , i.e., the constant unit cost applied above, and calibrate  $b_3$  so that marginal costs are respectively doubled (“Moderate”) or tripled (“Strong”) when  $y(t)$  is equal to total initial fuel demand (in BaU).<sup>16</sup> One implication of having increasing marginal costs of biofuels is that there will be a period when both oil and biofuels are consumed in the BaU scenario. In both the considered cases, this period lasts from around year 30 to around year 60.

We find that all our main results carry over when biofuels costs are increasing with supply. That is, when a proportional standard of 10-20% is imposed, initial fuel demand declines, climate costs are reduced, whereas overall welfare decreases. As before, implementing a Pigovian tax leads to even stronger reductions in climate costs; however, the

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<sup>16</sup>It then follows from the chosen functional form that marginal costs are respectively 9% and 18% above  $b_1$  when  $y(t)$  is 30% of total initial fuel demand. Hence, biofuels costs increase only gradually given moderate levels of biofuels (cf. the reference to IEA above).

level of  $\alpha$  that gives the same climate costs as the Pigovian tax decreases from 0.48 to 0.37 in both cases considered here. The explanation is that with higher costs of biofuels, total fuel demand is hit even harder when  $\alpha$  is increased.

Our benchmark assumption regarding emissions of biofuels is  $\gamma = 0.32$ . With constant biofuels costs, we concluded above that the RFS policy would be climate-neutral if  $\gamma$  is in the range  $0.93 - 1$ . With increasing marginal costs of biofuels, we find that an RFS policy with  $\alpha = 20\%$  is climate-neutral if  $\gamma = 0.74$  (“Moderate”) and  $\gamma = 0.69$  (“Strong”), respectively. The explanation is that higher biofuels costs postpone the extraction of non-renewable oil in the BaU scenario - hence, the additional postponement implied by the RFS policy has less importance than under a constant biofuels cost. Thus, emissions from biofuels cannot be too high if the RFS policy is to reduce climate costs.

## 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 likely decline initially. Furthermore, even for biofuels that are almost as emissions-intensive as oil, a standard may then 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  $\alpha$  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.<sup>17</sup> 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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<sup>17</sup>That is,  $\alpha = kt$ ,  $\alpha \leq \hat{\alpha}$  for different values of  $k$  and  $\hat{\alpha}$ .



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## 7 Appendix

### Proof of Proposition 1:

We first differentiate (4) with respect to  $\alpha$ :

$$\frac{dp_0}{d\alpha} e^{rT} + rp_0 e^{rT} \frac{dT}{d\alpha} = 0 \Leftrightarrow \frac{dp_0}{d\alpha} = -rp_0 \frac{dT}{d\alpha} \quad (15)$$

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

$$-\int_0^T D(p^C(t))dt + (1-\alpha) \int_0^T \left( b - p_0 e^{rt} + (1-\alpha) e^{rt} \frac{dp_0}{d\alpha} \right) D'(p^C(t))dt + (1-\alpha) D(b) \frac{dT}{d\alpha} = 0$$

We notice that the first term equals  $-S/(1-\alpha)$ . Inserting for  $\frac{dp_0}{d\alpha}$  then gives:

$$-\frac{S}{(1-\alpha)} + (1-\alpha) \int_0^T [(b - p_0 e^{rt}) D'(p^C(t))] dt - (1-\alpha)^2 r p_0 \frac{dT}{d\alpha} \int_0^T [e^{rt} D'(p^C(t))] dt + (1-\alpha) D(b) \frac{dT}{d\alpha} = 0$$

$$\frac{dT}{d\alpha} \left[ (1-\alpha) D(b) - (1-\alpha)^2 r p_0 \int_0^T [e^{rt} D'(p^C(t))] dt \right] = \frac{S}{(1-\alpha)} - (1-\alpha) \int_0^T [(b - p_0 e^{rt}) D'(p^C(t))] dt$$

$$\frac{dT}{d\alpha} = \frac{1}{(1-\alpha)^2} \frac{S - (1-\alpha)^2 \Gamma}{D(b) - (1-\alpha) r p_0 \Lambda} > 0 \quad (16)$$

where  $\Gamma = \int_0^T [(b - p_0 e^{rt}) D'(p^C(t))] dt < 0$  and  $\Lambda = \int_0^T [e^{rt} D'(p^C(t))] dt < 0$ .

This further gives:

$$\frac{dp_0}{d\alpha} = \frac{-r p_0}{(1-\alpha)^2} \frac{S - (1-\alpha)^2 \Gamma}{D(b) - (1-\alpha) r p_0 \Lambda} < 0 \quad (17)$$

Hence, we have proved the proposition. ■

### **Proof of Proposition 2:**

We differentiate  $x(t)$  with respect to  $\alpha$ :

$$\begin{aligned}
\frac{dx(t)}{d\alpha} &= -D(p^C(t)) + (1 - \alpha) (b - p_0 e^{rt}) D'(p^C(t)) - e^{rt} r p_0 \frac{S - (1 - \alpha)^2 \Gamma}{D(b) - (1 - \alpha) r p_0 \Lambda} D'(p^C(t)) \\
&= -D(p^C(t)) + \left[ (1 - \alpha) (b - p_0 e^{rt}) - p_0 e^{rt} r \frac{S - (1 - \alpha)^2 \Gamma}{D(b) - (1 - \alpha) r p_0 \Lambda} \right] D'(p^C(t)) \quad (18)
\end{aligned}$$

The first term is negative, whereas the last term can be either positive or negative. Notice that the bracket in front of  $D'(p^C(t))$  decreases over time. If the bracket is positive at  $t = 0$ , we obviously have that the whole expression is negative, i.e.,  $x(0)$  decreases when  $\alpha$  increases. If the bracket is negative at  $t = 0$  (and thus for all  $t$ ), the bracket will increase in absolute value over time. If the demand function is concave, i.e.,  $D''(p^C(t)) \leq 0$ , then  $D'(p^C(t))$  will also increase in absolute value over time (since  $p^C(t)$  increases over time). Thus, the second term will increase over time, and so will the first term, too. Hence,  $dx(t)/d\alpha$  will increase over time. But then we must have  $dx(0)/d\alpha < 0$  - otherwise accumulated resource extraction over time will increase, which is not possible. Moreover, if the demand function is concave, it follows that fossil extraction will decline for all  $t < \hat{t}$  and increase for all  $t > \hat{t}$  (for some  $0 < \hat{t} \leq T$ ). ■

### Proof of Proposition 3:

We differentiate  $p^C(t)$  with respect to  $\alpha$ :

$$\frac{dp^C(t)}{d\alpha} = b - p_0 e^{rt} + (1 - \alpha) e^{rt} \frac{-r p_0}{(1 - \alpha)^2} \frac{S - (1 - \alpha)^2 \Gamma}{D(b) - (1 - \alpha) r p_0 \Lambda} \quad (19)$$

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  $\alpha$ . Thus, if we can show that  $\frac{dp^C(0)}{d\alpha} > 0$ , we have proved the proposition.

With linear demand we have:

$$\Gamma = \left[ T - \frac{1}{r}(1 - e^{-rT}) \right] b \overline{D}' \text{ and } \Lambda = \frac{1}{r}(e^{rT} - 1) \overline{D}'.$$

Thus, we get:

$$\frac{dp^C(0)}{d\alpha} = p_0 \left[ e^{rT} - 1 - r \frac{S - (1 - \alpha)^2 \Gamma}{D(b)(1 - \alpha) - (1 - \alpha)^2 r p_0 \Lambda} \right] \quad (20)$$

Next, we derive the following expression for  $S$ , where we use that  $D(p^C) = \overline{D}'(-p_{\max}^C + p^C)$

( $p_{\max}^C$  is the choke price, i.e.,  $D(p_{\max}^C) = 0$ ):

$$\begin{aligned} S &= \int_0^T x(t) dt = (1 - \alpha) \int_0^T D(\alpha b + (1 - \alpha)p_0 e^{rt}) dt \\ &= (1 - \alpha) \overline{D}' \int_0^T [-p_{\max}^C + (\alpha b + (1 - \alpha)p_0 e^{rt})] dt \\ &= (1 - \alpha) \overline{D}' \left[ (-p_{\max}^C T + \alpha b T) + (1 - \alpha) \frac{b}{r} (1 - e^{-rT}) \right] \end{aligned} \quad (21)$$

We insert this and the expressions for  $\Gamma$  and  $\Lambda$  into (20) (note that  $D(b) = \overline{D}'(b - p_{\max}^C)$ ):

$$\begin{aligned} \frac{dp^C(0)}{d\alpha} &= p_0 [e^{rT} - 1 \\ &\quad - r \frac{(1 - \alpha) \overline{D}' [(-p_{\max}^C T + \alpha b T) + (1 - \alpha) \frac{b}{r} (1 - e^{-rT})] - (1 - \alpha)^2 [T - \frac{1}{r}(1 - e^{-rT})] b \overline{D}'}{\overline{D}'(b - p_{\max}^C)(1 - \alpha) - (1 - \alpha)^2 r p_0 \frac{1}{r}(e^{rT} - 1) \overline{D}'}] \\ &= p_0 \left[ e^{rT} - 1 - r \frac{(-p_{\max}^C T + \alpha b T) + (1 - \alpha) \frac{b}{r} (1 - e^{-rT}) - (1 - \alpha) [T - \frac{1}{r}(1 - e^{-rT})] b}{(b - p_{\max}^C) - (1 - \alpha)b(1 - e^{-rT})} \right] \\ &= p_0 \frac{\Phi}{\alpha b + (1 - \alpha)b e^{-rT} - p_{\max}^C} = \frac{p_0}{b} \frac{\Phi}{\alpha + (1 - \alpha)e^{-rT} - \frac{p_{\max}^C}{b}} \end{aligned} \quad (22)$$

where

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

Here we have used that  $p_{\max}^C \geq b$  and  $2rT + e^{-rT} - e^{rT} < 0$  for any  $rT$ . We see that the denominator in (22) is negative. Hence, we have shown that the whole expression is positive for any  $p_{\max}^C \geq b$ , so that  $\frac{dp^C(0)}{d\alpha} > 0$ . ■

#### Proof of Proposition 4:

We differentiate  $y(t)$  with respect to  $\alpha$ :

$$\begin{aligned}
\frac{dy(t)}{d\alpha} &= D(p^C(t)) + \alpha \left( b - p_0 e^{rt} + (1 - \alpha) e^{rt} \frac{dp_0}{d\alpha} \right) D'(p^C(t)) \\
&= D(p^C(t)) + \alpha (b - p_0 e^{rt}) D'(p^C(t)) - \alpha r p_0 e^{rt} \frac{S - (1 - \alpha)^2 \Gamma}{(1 - \alpha)D(b) - (1 - \alpha)^2 r p_0 \Lambda} D'(p^C(t)) \quad (23)
\end{aligned}$$

The first term is positive. The second and third terms are zero if either  $\alpha = 0$  or  $D' = 0$ . Thus, if  $\alpha$  is sufficiently low initially, or if demand is sufficiently inelastic,  $y(t)$  will increase. Furthermore, 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 linear and sufficiently elastic, and

$\alpha$  is sufficiently large initially. We use the derivations in (22), and insert for  $\Gamma$ ,  $\Lambda$  and  $D(p^C) = \bar{D}'(-p_{\max}^C + p^C)$ . Then we get:

$$\begin{aligned}
\frac{dy(t)}{d\alpha} &= \bar{D}'[-p_{\max}^C + \alpha b + (1 - \alpha)p_0 e^{rt} + \alpha b - \alpha p_0 e^{rt} \\
&\quad - \alpha r p_0 e^{rt} \frac{(-p_{\max}^C T + \alpha b T) + (1 - \alpha)\frac{b}{r}(1 - e^{-rT}) - (1 - \alpha)[T - \frac{1}{r}(1 - e^{-rT})] b}{(b - p_{\max}^C) - (1 - \alpha)b(1 - e^{-rT})}] \\
&= \bar{D}'[-p_{\max}^C + 2\alpha b + (1 - 2\alpha)be^{r(t-T)} \\
&\quad - \alpha be^{r(t-T)} \frac{(-p_{\max}^C rT + \alpha brT) - (1 - \alpha)[rT - 2(1 - e^{-rT})] b}{-p_{\max}^C + \alpha b + (1 - \alpha)be^{-rT}}] \tag{24}
\end{aligned}$$

If we let  $\alpha$  go towards one, we get:

$$\frac{dy(t)}{d\alpha} \rightarrow \bar{D}'[-p_{\max}^C + 2b - be^{r(t-T)}(1 + rT)] \tag{25}$$

If  $p_{\max}^C$  is sufficiently close to  $b$ , we see that the bracket is positive for  $t = 0$ , and hence

$\frac{dy(0)}{d\alpha}$  is negative. ■

### 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:

$$\frac{dT}{db} = -\alpha \frac{\int_0^T D'(p^C(t)) dt}{D(b) - (1 - \alpha)r p_0 \Lambda} > 0 \tag{26}$$

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

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



$$\frac{dx(t)}{db} = (1 - \alpha)D'(p^C(t)) \left[ \alpha - (1 - \alpha)\alpha r p_0 \frac{dp_0}{db} e^{rt} \right] \quad (27)$$

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  $\hat{t}$  where the paranthesis is equal to zero. Then we have that the whole expression must be negative for all  $t < \hat{t}$  and positive for all  $t > \hat{t}$ . In other words, a subsidy to biofuels increases (decreases) oil consumption and extraction for all  $t < (>)\hat{t}$ .

### The case of two regions

The RFS rate is now region-specific,  $\alpha_i$ . 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 then have:

$$S_1 + S_2 = S \quad (28)$$

We are now ready to look at the effects of an increase in  $\alpha_i$ . We insert from (1) into (5), and then into (28):

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

and differentiate with respect to  $\alpha_i$

$$-\int_0^T D_i(p_i^C(t)) dt + (1 - \alpha_i) \int_0^T \left( b - p_0 e^{rt} + (1 - \alpha_i) e^{rt} \frac{dp_0}{d\alpha_i} \right) D_i'(p_i^C(t)) dt + (1 - \alpha_i) D_i(b) \frac{dT}{d\alpha_i} +$$

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

Inserting for  $\frac{dp_0}{d\alpha}$  from (15), which still holds but is region-specific, gives:

$$0 = - \int_0^T D_i(p_i^C(t)) dt + (1 - \alpha_i) \int_0^T [(b - p_0 e^{rt}) D'_i(p_i^C(t))] dt +$$

$$\left[ (1 - \alpha_i) D_i(b) + (1 - \alpha_j) D_j(b) - (1 - \alpha_i)^2 r p_0 \int_0^T e^{rt} D'_i(p_i^C(t)) dt - r p_0 (1 - \alpha_j) \int_0^T e^{rt} D'_j(p_j^C(t)) dt \right] \frac{dT}{d\alpha_i}$$

which can be rearranged:

$$\frac{dT}{d\alpha_i} = \frac{1}{1 - \alpha_i} \frac{S_i - \Gamma_i}{(1 - \alpha_i) D_i(b) + (1 - \alpha_j) D_j(b) - \Lambda_i - \Lambda_j} > 0 \quad (29)$$

where  $\Gamma_i = (1 - \alpha_i)^2 \int_0^T [(b - p_0 e^{rt}) D'_i(p_i^C(t))] dt < 0$ ,  $\Lambda_i = (1 - \alpha_i)^2 r p_0 \int_0^T e^{rt} D'_i(p_i^C(t)) dt < 0$  and  $\Lambda_j = r p_0 (1 - \alpha_j) \int_0^T e^{rt} D'_j(p_j^C(t)) dt < 0$ . Note that  $\Gamma_i$ ,  $\Lambda_i$  and can all be treated as constants (given the new paths for  $p_i^C(t)$  and  $p_j^C(t)$  and the new  $T$ ). Since  $\frac{dp_0}{d\alpha_i} = -r p_0 \frac{dT}{d\alpha_i}$ , it follows that  $\frac{dp_0}{d\alpha} < 0$ .

For the change in total oil extraction we have:

$$\begin{aligned} \frac{dx_i(t)}{d\alpha_i} + \frac{dx_j(t)}{d\alpha_i} = & -D_i(p_i^C(t)) + (1 - \alpha_i) D'_i(p_i^C(t)) (b - p_0 e^{rt}) \\ & + [(1 - \alpha_i)^2 D'_i(p_i^C(t)) + (1 - \alpha_j)^2 D'_j(p_j^C(t))] e^{rt} \frac{dp_0}{d\alpha_i} \end{aligned} \quad (30)$$

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 transportation 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 (30) we obtain the following expression for  $\frac{dx_i(t)}{d\alpha_i} + \frac{dx_j(t)}{d\alpha_i}$ :

$$\begin{aligned}
& -D_i(p_i^C(t)) - r(1 - \alpha_j)^2 D_j'(p_j^C(t)) p_0 e^{rt} \frac{S_i - \Gamma_i}{(1 - \alpha_i)D_i(b) + (1 - \alpha_j)D_j(b) - \Lambda_i - \Lambda_j} \\
& + (1 - \alpha_i) \left[ b - p_0 e^{rt} - r p_0 e^{rt} \frac{S_i - \Gamma_i}{(1 - \alpha_i)D_i(b) + (1 - \alpha_j)D_j(b) - \Lambda_i - \Lambda_j} \right] D_i'(p_i^C(t)) \quad (31)
\end{aligned}$$

The first term is negative, and will become less negative over time since the consumer-price on transportation fuel  $p_i^C(t)$  must increase over time. The next term is positive, and it must increase 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 initially. 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  $[0, \bar{t})$  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 (31) 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  $t < \hat{t}$  and increase for all  $t > \hat{t}$  (for some  $0 < \hat{t} < T$ ). For the other cases  $\frac{dx_i(0)}{d\alpha_i} + \frac{dx_j(0)}{d\alpha_i}$  is ambiguous.

For the effects on the consumer price  $p_i^C(t)$  in Region  $i$  we have:

$$\frac{\partial p_i^C(t)}{\partial \alpha_i} = b - p_0 e^{rt} + (1 - \alpha_i) e^{rt} \frac{dp_0}{d\alpha_i}$$

Note that the sum of the two first terms are positive (for  $t < T$ ), while the last term is negative. We know that  $\frac{dp^C(t)}{d\alpha} < 0$  for  $t$  sufficiently close to  $T$ , since  $T$  increases with  $\alpha$ . What about the effect at  $t = 0$ ? Using that  $\frac{dp_0}{d\alpha_i} = -rp_0 \frac{dT}{d\alpha_i}$  and that  $p_0 = be^{-rT}$  we have:

$$\begin{aligned}
\frac{\partial p_i^C(0)}{\partial \alpha_i} &= b \left[ 1 - e^{-rT} - rT e^{-rT} \frac{(1 - \alpha_i)}{T} \frac{dT}{d\alpha_i} \right] \\
&= b \left[ 1 - e^{-rT} - r e^{-rT} \frac{S_i - \Gamma_i}{(1 - \alpha_i)D_i(b) + (1 - \alpha_j)D_j(b) - \Lambda_i - \Lambda_j} \right] \\
&> b \left[ 1 - e^{-rT} - r e^{-rT} \frac{S_i - \Gamma_i}{(1 - \alpha_i)D_i(b) - \Lambda_i} \right] > 0,
\end{aligned}$$

where we use the findings for one region in Section 1.4 (cf. (20)) in the last inequality. Hence, total fuel consumption in Region  $i$  declines initially. Initial consumption of oil in this region must then also decline.

For the region not changing its blending mandate, we have:

$$\frac{\partial p_j^C(t)}{\partial \alpha_i} = (1 - \alpha_j) e^{rt} \frac{dp_0}{d\alpha_i} < 0$$

It follows that Region  $j$  will use more of the resource at all times. Thus, we have:  $\frac{dS_j}{d\alpha_i} > 0$  and  $\frac{dS_i}{d\alpha_i} < 0$ . It also follows that Region  $j$  will use more biofuels in each period, given that  $\alpha_j > 0$ .

### A more realistic carbon cycle

The carbon in the atmosphere at any time  $t$  is artificially split into two components  $A_1(t) + A_2(t)$ : component 1 that remains in the atmosphere for ever and component 2 that gradually depreciates at a rate  $\delta$ . For each unit emitted the share that remains in the atmosphere for ever is denoted  $\theta$ . The amount of 1 unit of carbon emissions at time  $t$  remaining in the atmosphere  $z$  years after the emission date is thus  $\theta + (1 - \theta)e^{-\delta z}$ . If e.g.  $\delta = 0.013$  and  $\theta = 0.25$ , 45 % of the original emissions will remain in the atmosphere after 100 years, while 27 % still remains after 300 years. These numbers are roughly in line with what is suggested by Archer (2005) and others.

Consider the following simple optimization problem, where the resource constraint is ignored:

$$\max \int_0^{\infty} e^{-rt} [F(x(t), y(t)) - C(A_1(t) + A_2(t))] dt \quad (32)$$

where  $x$  and  $y$  stand for oil use and biofuel use, respectively. The net benefit (ignoring climate effects) function  $F$  is strictly increasing and concave, and the climate cost function  $C$  has the properties  $C' > 0$  and  $C'' \geq 0$ . Total carbon in the atmosphere is given by  $A_1 + A_2$ , and is a state variable in the optimization problem.

We assume that  $x$  can be chosen freely at any time. In order to avoid jumps in the state variables, we assume  $y$  is a state variable developing according to

$$\dot{y}(t) = u(t) \text{ where } u(t) \in [-\bar{u}, \bar{u}]$$

Any change in  $y$  must thus occur via the control variable  $u$  differing from zero. We assume  $\bar{u}$  is large, so that jumps in  $y$  are "almost possible".

Previously, we assumed that any jump in  $y$  was associated with a corresponding jump on the amount of carbon in the atmosphere. Now any change in  $y$  will be captured by the change in the atmosphere being gradual and proportional to  $u$ :

$$\dot{A}_1(t) = \theta [x(t) + \ell\beta u(t)]$$

$$\dot{A}_2(t) = (1 - \theta) [x(t) + \ell\beta u(t)] - \delta A_2(t)$$

Before proceeding, it is useful to consider the development of carbon in the atmosphere when  $x$  and  $y$  are constant equal to  $x^*$  and  $y^*$ . In this case the long-run equilibrium is

characterized by  $u = 0$  and  $A_2$  constant equal to

$$A_2^* = \frac{1 - \theta}{\delta} x^*$$

while  $A_1(t)$  will be given by

$$A_1(t) = A_1(0) + \theta \left\{ \int_0^t x(t) dt + \ell\beta (y^* - y(0)) \right\}$$

Hence,

$$A(t) = A_1(0) + \frac{1 - \theta}{\delta} x^* + \theta \left\{ \int_0^t x(t) dt + \ell\beta (y^* - y(0)) \right\}$$

which will be growing over time unless  $x^* = 0$ . If  $x^* = 0$ ,  $A^*$  will be higher the higher is the level of biofuel production.

Returning to the maximization problem (32), the current value Hamiltonian is (formulated with positive costate variables and ignoring time references)

$$\begin{aligned} H = & F(x, y) - C(A_1 + A_2) \\ & + \mu u - \lambda_1 \theta [x(t) + \ell\beta u(t)] - \lambda_2 \{(1 - \theta) [x(t) + \ell\beta u(t)] - \delta A_2(t)\} \end{aligned}$$

The optimal solution must satisfy

$$F_x(x(t), y(t)) - [\theta\lambda_1(t) + (1 - \theta)\lambda_2(t)] = 0 \text{ for } x(t) > 0 \quad (33)$$

$$\mu(t) - \ell\beta [\theta\lambda_1(t) + (1 - \theta)\lambda_2(t)] = 0 \text{ for } u(t) \in (-\bar{u}, \bar{u}) \quad (34)$$

$$\dot{\mu}(t) = r\mu(t) - F_y(x(t), y(t)) \quad (35)$$

$$\dot{\lambda}_1(t) = r\lambda_1(t) + C'(A_1(t) + A_2(t)) \quad (36)$$

$$\dot{\lambda}_2(t) = (r + \delta)\lambda_2(t) + C'(A_1(t) + A_2(t)) \quad (37)$$

$$\text{Lim}_{t \rightarrow \infty} e^{-rt} \mu(t) y(t) = 0 \quad (38)$$

$$\text{Lim}_{t \rightarrow \infty} e^{-rt} \lambda_i(t) A_i(t) = 0 \quad i = 1, 2 \quad (39)$$

The equations above imply that

$$\mu(t) = \int_0^\infty e^{-rz} F_y(x(t+z), y(t+z)) dz \quad (40)$$

$$\theta \lambda_1(t) + (1 - \theta) \lambda_2(t) = q_x(t) \text{ given by (9)}$$

For an interior solution at any time when  $y$  does not "jump" we thus have

$$F_x(x(t), y(t)) = q_x(t) \quad (41)$$

$$\mu(t) = \ell \beta q_x(t) \quad (42)$$

There is not much one can say about the ratio  $F_y/F_x$  for the general case of  $C'' > 0$ . We therefore restrict ourselves to the special case of the equilibrium value of  $C'$  rising at a constant rate  $m \in [0, r)$ . One interpretation of the case  $m > 0$  was given in Section 3. A second interpretation could be that the functions in the optimization problem are such that the solution gives a constant growth rate of  $C'$ .



Inserting  $C' = C'_0 e^{mt}$  into (9) gives

$$q_x(t) = \left[ \frac{\theta}{r-m} + \frac{1-\theta}{r+\delta-m} \right] C'_0 e^{mt} \quad (43)$$

From (42) it follows that  $\mu(t)$  must grow at the rate  $m$ , and from (40) this implies that  $F_y$  grows at the rate  $m$  and that

$$\mu(t) = \frac{F_y(x(t), y(t))}{r-m}$$

Together with (42) we thus get

$$F_y(x(t), y(t)) \equiv q_y(t) = (r-m)\ell\beta q_x(t)$$

and hence

$$\frac{q_y(t)}{q_x(t)} = (r-m)\ell\beta$$

■

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