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The Rise and Fall of Bioenergy

Abstract

If bioenergy has a less negative impact on the climate than fossil energy, it may be optimal to have a significant increase in the use of bioenergy over time. Due to the difference in the way the climate is affected by the two types of energy, the future time path of the use of bioenergy may be non-monotonic: It may be optimal to first have an increase in its use, and later a reduction. Optimal taxes and subsidies are derived both for the first-best case and for the case of a constraint on the size of the fossil tax.

JEL-Codes: Q420, Q480, Q540, Q580.

Keywords: bioenergy, renewable energy, climate policy, carbon tax, second best, subsidies.

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1 Introduction

In many countries there are various forms of direct and indirect subsidies to biofuels and other types of bioenergy. Such policies are often justified by an argument that bioenergy is "climate neutral", and that the production and use of bioenergy gives a reduction in the use of fossil energy. There are two problems with these arguments. First, recent contributions have questioned whether the production and use of bioenergy is climate neutral in the sense that it has no climate impact. Moreover, even if the production and use of bioenergy had no climate impact, the argument for subsidizing it is questionable. It is widely recognized among economists that a price on carbon emissions, through a carbon tax or a price on tradeable emission permits, is the most important policy instrument to reduce such emissions. Standard economic reasoning also implies that in the absence of other market failures, an appropriately set carbon price is the *only* instrument needed to achieve an efficient climate policy. If bioenergy had no direct climate impact, it should therefore be neither taxed nor subsidized. A possible reason for subsidizing bioenergy could be that tax on fossil energy is "too low", i.e. lower than the Pigovian rate (equal to the marginal environmental cost of carbon emissions).

To study these issues, this paper considers a simple model where fossil fuels (henceforth called fossil energy) and bioenergy are perfect substitutes. The climate effects of the two types of energy are discussed in Section 2. Unlike fossil energy, bioenergy is climate neutral in the sense that it is possible to have a constant positive use of bioenergy without this giving any change over time in the carbon concentration in the atmosphere. This implies that in a long-run steady state, we will (under conditions specified in section 3) have positive bioenergy production and zero fossil energy production.

Although bioenergy is climate neutral in the sense given above, it has a negative climate impact in the sense that for any given time path of fossil energy, the carbon in the atmosphere is higher the higher is the level of the time path (constant or varying over time) of the production of bioenergy. Hence, both fossil energy and bioenergy have a negative climate impact, but the dynamics of these impacts differ. In section 3 the first-best optimum is derived, and it is shown that fossil energy production is zero in the long run, while bioenergy production is positive and constant. Due to the difference in how the climate is affected by the two types of energy, the time path of bioenergy production towards its steady-state level may be non-monotonic. Particular attention is given to the case in which marginal climate costs have an inverse L property: zero (or small) for carbon contents in the atmosphere below some threshold, and rapidly rising after the threshold is reached. In this case bioenergy production will first rise, and later decline towards its steady-state level.

To achieve the first-best optimum, bioenergy must have a non-negative tax. In the limiting case of zero marginal climate costs for low levels of carbon in the atmosphere the tax will be zero initially, but will eventually become positive.

As mentioned above, the tax on fossil energy could for some reason be constrained to be lower than its optimal value. The implications of such a constraint for bioenergy production and bioenergy policies are studies in section 4. In particular, it is shown that in this case it may be optimal to subsidize bioenergy for all or some of the time. For the inverse L climate cost function, it is optimal to subsidize bioenergy as long as carbon in the atmosphere is below the threshold. Moreover, during this phase the subsidy is increasing over time. However, once the threshold is reached the subsidy will start to decline. In the long run the tax on bioenergy may be negative (i.e. a subsidy) or positive, depending on parameters of the model.

Section 5 discusses the climate dynamics of bioenergy production in more detail, before Section 6 concludes.

1.1 Related literature

While the present study focuses on taxes and subsidies as policy instruments, there are several studies on the effects of a renewable portfolio standard for bioenergy. A renewable portfolio standard in this case means that a certain politically determined minimum percentage of the total energy use must come from bioenergy. Such a renewable portfolio standard is equivalent to a revenue neutral combination of a tax on fossil energy and a subsidy to bioenergy, see e.g. Amundsen and Mortensen (2001) and Eggert and Greaker (2012). A combination of a tax on fossil energy and a subsidy may be (second-best) optimal if there is a constraint on the tax on fossil energy (see Section 4), but this combination will generally not be revenue neutral.

De Gorter and Just (2009) find that a renewable fuel standard may lead to a decrease in the total use of fuel (oil and biofuel). This happens if the elasticity of biofuels supply is lower than the elasticity of oil supply. The effect of the policy is in this case not only to replace oil with biofuels, but also to reduce total consumption of transport fuels, which by itself will reduce climate costs. 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.

If a renewable fuel standard is in place, adding a subsidy or a tax rebate for biofuels will increase climate costs, even if there were no negative climate effects from bioenergy. The reason is that if the ratio between fossil energy and bioenergy is fixed due to the renewable portfolio standard, a subsidy to bioenergy works as an implicit support to oil and, hence, GHG emissions increase (see DeGorter and Just, 2010). The effects of combining several policies related to bioenergy have also been studied by Eggert and Greaker (2012) and Lapan and Moschini (2012).

Lapan and Moschini (2012) compare a renewable fuel standard with a subsidy to biofuels, and find that the former welfare dominates the latter. This result follows directly from the fact that a renewable fuel standard is identical to a revenue neutral combination of a tax on oil and a subsidy to biofuels, since there is an emission externality from the use of fossil fuels.

There are some contributions in the literature that analyze bioenergy policies in models with dynamic oil supply, see e.g. Chakravorty et al. (2008), Chakravorty and Hubert (2013), Grafton et al. (2012), and Fischer and Salant (2012). However, none of these studies includes negative climate effects from the use of bioenergy, which seems to be crucial when assessing the effect of bioenergy policies on climate costs.

Climate effects from bioenergy are included in the analysis of Greaker et al. (2014), where cumulative oil extraction depends on the policies used. An important result is that whereas a non-declining tax on oil or a non-declining subsidy to biofuel reduces cumulative oil extraction, a blending share has no effect on cumulative oil extraction (as long as the implied share of fossil is bounded away from zero). Such a blending mandate may nevertheless contribute to lower GHG emissions, as this policy will increase consumer prices and hence reduce the total fuel use at any time.

While most studies of bioenergy consider bioenergy from fuel crops, an alternative is to use the harvest from standing forest to produce bioenergy. Hoel and Sletten (2016) study climate policies for this type of bioenergy when it is assumed to be a perfect substitute for fossil energy (as assumed in the present study). However, unlike the present study they assume that the relative climate impact of the two types of energy are constant over time. Moreover, their main focus is on the long-run steady state, where there is no production of fossil energy.

2 The climate effects of carbon energy and bioenergy

The climate is affected by the amount of carbon in the atmosphere, and burning of fossil fuels (i.e. the use of fossil energy) adds carbon to the atmosphere. As we shall see below, this is true also for bioenergy, although the mechanism is somewhat different. For both types of energy, the model I use gives a very crude and simple description of how the atmospheric carbon is affected. The following quotation from Millner (2015) might help to justify the somewhat drastic simplifications I use: "Like many economic models, our is a fable in which reality is pushed to absurdly simplistic extremes in order to cleanly illustrate a mechanism that may help explain real world policy outcomes."

2.1 Atmospheric carbon from fossil energy

Using carbon energy gives an immediate release of carbon to the atmosphere. Over time, some of this carbon is transferred to the ocean and other sinks. However, 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 this paper I simply assume that *all* the carbon released remains in the atmosphere for ever. This simplification is of no importance for the long-run steady state, but the details of the dynamics towards the steady state would be slightly different if I had taken the partial depreciation into account.

In my model, $x(t)$ measures the yearly production of fossil energy, and $S_x(t)$ measures the stock of carbon in the atmosphere caused by the production of fossil energy. The relationship between the two is simply $\dot{S}_x(t) = x(t)$. The dynamics of carbon in the atmosphere from fossil energy production is illustrated in Figure 1. In this figure we first have constant production, then production jumps up to a higher level, and finally it drops to low level. The important point (to be contrasted with bioenergy production below) is that as long as fossil energy production is positive, carbon in the atmosphere grows; it is only the rate of growth that depends on the size of fossil energy production.

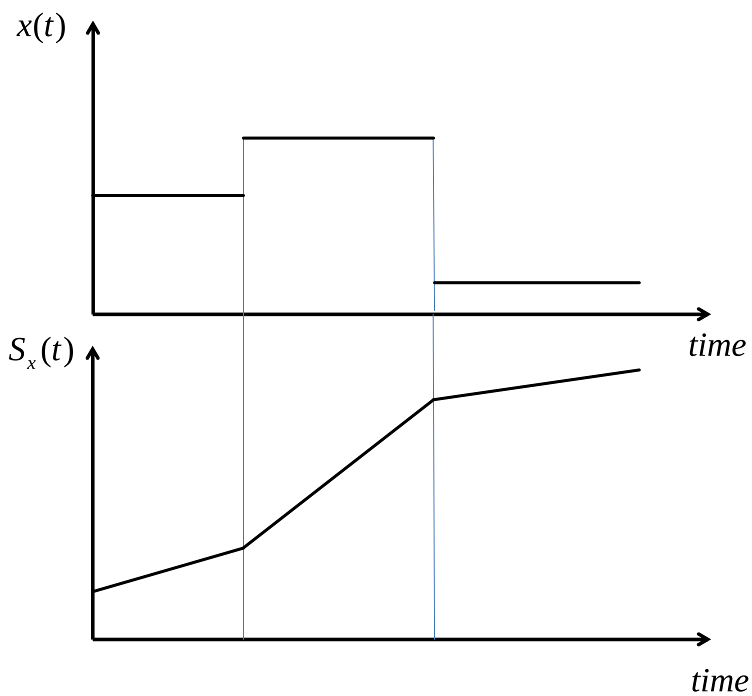

Figure 1

2.2 Atmospheric carbon from bioenergy

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). Even if these emissions related to the production and transportation of bioenergy are positive, one must be careful about what conclusions one draws from this.

There are, after all, emissions related to practically all economic activity. It is only if the emissions related to production and transportation of bioenergy are larger per unit of general resources used (labor, capital etc.) than the emissions related to these resources being used elsewhere in the economy that one can conclude that increased use of bioenergy contributes to increased climate costs.

Perhaps the most important source of greenhouse gas emissions from bioenergy is related to land use changes. As pointed out by e. g. Fargione et al. (2008), converting forests, peatlands, savannas, or grasslands to produce crop-based bioenergy will give a large immediate release of carbon from plant biomass and soils to the atmosphere.

In many cases bioenergy crops are grown on existing agricultural land, so that there is little or no direct effect on carbon emissions. However, increasing the production of bioenergy crops at the expense of food production raises other concerns: Food prices may increase, with negative consequences for low-income households world wide (see e.g. Chakravorty et al., 2008, and Chakravorty et al., 2009). Moreover, reduced land for food production may cause indirect land use changes: The increased value of land used for food production may lead to forest clearing to convert land for food production. This forest clearing will have the immediate effect of releasing carbon to the atmosphere, and thus increase climate costs. 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 my model I treat direct land-use change and indirect land-use change together. In particular, I assume that each unit of bioenergy production requires ℓ units of land, and that each unit of land converted to bioenergy production will reduce the carbon sequestered on this land by an amount σ. Increasing the yearly production of bioenergy by one unit hence gives a one-off increase in the amount of carbon in the atmosphere by $\sigma\ell \equiv \beta$ units.

In the model, fossil energy and bioenergy are measured in the same units, with 1 unit being equal to the amount of fossil energy that releases 1 unit of carbon to the atmosphere. Hence the denomination of y is tons of carbon per year. The denomination of ℓ is land units per y, and the denomination of σ is tons of carbon per land unit. Hence, the denomination of β is tons of carbon per y, i.e. tons of carbon/(tons of carbon per year), i.e. "years". Using this approach, Greaker et al. (2014) show that estimates in the literature of ℓ and σ suggest that β typically will be in the range of about 9-24 years.

In the reasoning above it has been implicitly assumed that bioenergy is based on fuel crops. An alternative to converting grazing land or forest land into land for growing suitable crops for bioenergy production is to use the harvests from standing forests to produce bioenergy. However, wood-based bioenergy from standing forests is not unproblematic from a climatic point of view. The carbon stored in the forest is highest when there is little or no harvest from the forest, see e.g. van Kooten et al. (1995), or more recently, Hoel et al. (2014) and the literature cited there. Hence, increasing the harvest from a forest in order to produce more bioenergy may conflict with the direct benefit of the forest as a sink of carbon.

Wood-based bioenergy may take many forms, including e.g. raw firewood, processed charcoals, and pellets. The possibility of producing liquid bioenergy from cellulosic biomass may also be a promising alternative to using fuel crops, see e.g. Hill et al. (2006). To the extent that bioenergy is produced from residuals that otherwise would gradually rot and release carbon, the climate impact of this type of bioenergy is limited. If increased production of bioenergy implies increased harvesting from the forest, the time path of the carbon in the forest biomass will be shifted downwards, giving an unambiguously negative climate effect (i.e. increased climate costs). This is illustrated in figure 2, where $g(F)$ is a standard biological growth function showing the growth of the forest as a function of its volume F (measured in tons of carbon). With harvesting h the net growth is hence $g(F) - h$.

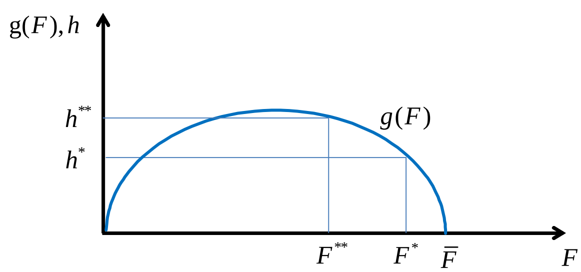

Figure 2

If yearly harvesting increases from a constant value h^* to a new constant value h^{**}, the forest volume will eventually decline from $F^* = g^{-1}(h^*)$ to $F^{**} = g^{-1}(h^{**})$. Assume that one unit increased bioenergy production implies ϕ units increased harvest, implying that one unit permanent increase of bioenergy production will give a permanent reduction of the volume of the forest equal to $-\phi(g')^{-1}(h)$. Moreover, assume that a fraction ξ of the carbon released from the forest is permanently added to the carbon in the atmosphere. Then one unit permanent increase of bioenergy production will give an immediate and permanent increase in the carbon in the atmosphere equal to $-\xi\phi(g')^{-1}(h) \equiv \beta$. Also in this case, β is measured in years, and in this case it will depend strongly on how intensively the forest initially is harvested. If the initial harvest h is close to the maximal sustainable yield value (i.e. close to $\max g(F)$), $-g'$ will be small and hence $-(g')^{-1}$ and β will be large.

In my model, $y(t)$ measures the yearly production of bioenergy, and $S_y(t)$ measures the stock of carbon in the atmosphere caused by the production of carbon energy. The relationship between the two is simply $S_y(t) = \beta y(t)$. Although such a relationship might be reasonable in the long run, it is of course quite a drastic simplification in the short run. The relationship is illustrated by the heavily drawn curve in Figure 3, with a similar time pattern of energy production as for fossil energy production in Figure 1. The level of carbon in the atmosphere depends on the size of bioenergy production, but as long as bioenergy production is constant, carbon in the atmosphere is also constant. This is in sharp contrast to the case of fossil fuel illustrated in Figure 1, where carbon in the atmosphere was growing for any positive production level.

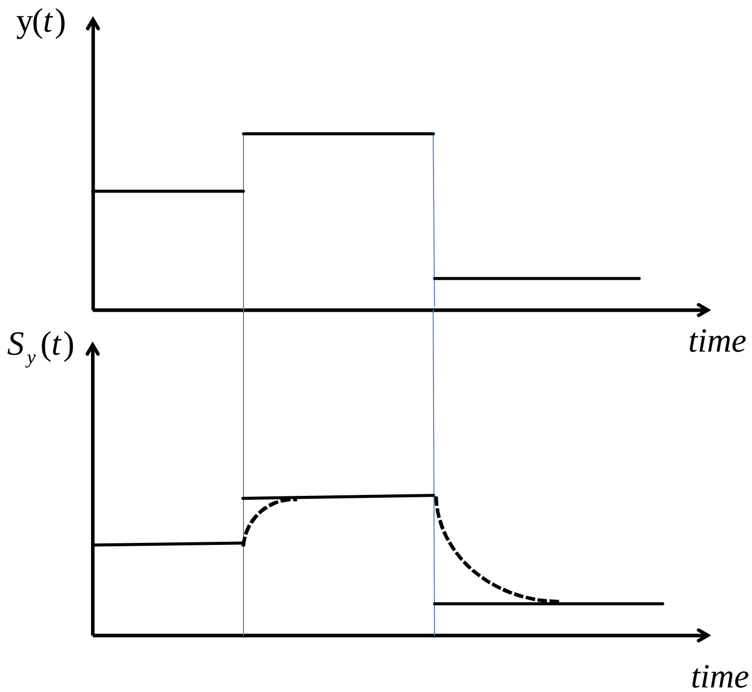

Figure 3

In the formal model, and in Figure 3, a change in $y(t)$ from one constant level y^1 to a new constant level y^2 will immediately change $S_y(t)$ from βy^1 to βy^2. In reality, the change in the amount of carbon to a new long-run level will not be immediate. Hence, the adjustment is likely to look more like the case illustrated by the dashed lines in Figure 3. I return to this issue in Section 5, and discuss when the differences between the two cases (solid and dashed curves in Figure 3) may be qualitatively important.

3 The optimal use of bioenergy

3.1 The model

Let x and y denote the production and use of fossil energy and bioenergy, respectively. I assume they are perfect substitutes so the gross benefit of using these two types of energy is $u(x+y)$, which is strictly increasing and concave. In some of the reasoning I assume that $u'(0)$ is finite, although this is not a crucial assumption. One interpretation of the function $u(x+y)$ is that there is also a third type of energy, assumed to have no climate impact (hydro, wind, solar, nuclear) and to be an imperfect substitute for $x+y$. Let z denote the output of this energy and let its cost be $\psi(z)$. Then $u(x+y)$ is defined as $u(x+y) = \max_z[U(x+y,z) - \psi(z)]$, where U is the gross benefit of energy use.

Production costs for fossil energy and bioenergy are given by the strictly convex cost functions $c(x)$ and $b(y)$, respectively. I disregard a resource constraint on the production of fossil energy. An obvious interpretation is that the resource reserves are so large that they due to climate considerations do not imply a binding constraint on the production of carbon energy.

To insure an interior solution in the absence of climate costs I assume $c'(0) = b'(0) < u'(0)$, although the equation $c'(0) = b'(0)$ is is not important for the main results.[1] Climate costs are given by an increasing and convex function of the total amount of carbon in the atmosphere, $D(S)$. Unless otherwise stated, I assume that this function is strictly convex.

The objective function in the social optimization problem is standard:

$$W = \int_0^\infty e^{-rt}\left[u(x(t)+y(t)) - c(x(t)) - b(y(t)) - D(S(t))\right]dt \qquad (1)$$

where r is the discount rate. In addition to the non-negativity constraints

[1] If e.g. $c'(0) < b'(0)$, it might be optimal to have an initial period of zero bioenergy production before a phase with simultaneous use of fossil energy and bioenergy.

on x and y, we have the following constraints (explained in section 2):

$$S(t) = S_x(t) + S_y(t) \tag{2}$$
$$\dot{S}_x(t) = x(t) \tag{3}$$
$$S_y(t) = \beta y(t) \tag{4}$$

Notice that with this formulation we have implicitly chosen units of fossil fuel and carbon in the atmosphere in the same units, e.g. tons of carbon, while the units of bioenergy are such that one unit of bioenergy is equally useful to the user as one unit of fossil energy.

The current value Hamiltonian corresponding to the maximization of W subject to (2)-(4) is (ignoring the time references)

$$H = u(x+y) - c(x,y) - D(S_x + \beta y) + (-\lambda)x \tag{5}$$

and the conditions for the optimum are

$$u'(x+y) - c'(x) - \lambda \leq 0 \; [= 0 \text{ for } x > 0] \tag{6}$$
$$u'(x+y) - b'(y) - \beta D'(S) \leq 0 \; [= 0 \text{ for } y > 0] \tag{7}$$
$$\dot{\lambda} = r\lambda - D'(S) \tag{8}$$
$$Lim_{t\to\infty} e^{-rt}\lambda(t) = 0 \tag{9}$$

3.2 Policy

The costate variable $\lambda(t)$ may be interpreted as the optimal tax tax on fossil energy in a market economy. From (8) and (9) we can derive

$$\lambda(t) = \int_0^\infty e^{-r\tau} D'(S(t+\tau))d\tau \tag{10}$$

This well-known formula for the optimal fossil tax, or social cost of carbon, has a straightforward interpretation: The optimal fossil tax at time t is equal to the discounted value of the marginal climate cost caused at all future dates from one unit of fossil use at time t.

The term $\beta D'$ may be interpreted as the optimal tax on bioenergy. Clearly this is always positive (or at least non-negative, but zero for any t when $D'(S(t)) = 0$).

Using the taxes above, the first-best optimum will be achieved in a market economy within the context of my model. In reality, it will be considerably more difficult to achieve the first-best optimum. One reason for this is that the parameter β in reality will differ considerably between different types of bioenergy. This suggests heterogeneous tax rates across different types of bioenergy. However, in practise it likely to be difficult to obtain accurate information about the parameter β for all types of bioenergy.

An alternative, and in principle better, instrument to regulate the production of bioenergy follows from standard principles: The social optimum may be achieved by setting a Pigovian tax on all net carbon emissions to the atmosphere. This tax should be equal to the climate cost given by (10), and should be applied both to the emissions from fossil energy use and to *net* emissions from using bioenergy (gross emissions minus growth of the forests or bioenergy crops; i.e. a tax on gross emissions and a subsidy to growth). With such a tax scheme the first-best outcome would in principle be achieved (see e.g. Tahvonen, 1995, and Hoel and Sletten, 2016, for a further discussion). However, in practice the government lacks detailed and verifiable information about the net carbon flows from bioenergy at the micro level (i.e. level of the individual farmer or forest owner), and it will therefore in practice not be possible to reach the first-best solution using only a tax on net carbon emission. Even without detailed and verifiable information about volumes and growth at the *micro* level, the regulator may have reasonably good data of volumes and growth at the aggregate level, and hence be able to calculate an average β, and use this to calculate a tax on bioenergy. As mentioned above, although this gives a first-best outcome in the my simple model, this policy will in reality give a sub-optimal outcome.

In the rest of the paper I disregard the heterogeneity of β across different types of bioenergy, and hence assume that the first best may be achieved by appropriate energy taxes. In Section 4 I consider the possibility of constraints on the taxes so that the first best nevertheless may not be achieved, and calculate second-best policies.

As will be shown below, the optimal value of $S(t)$ is non-declining, implying that the value of D' is non-declining. From (10) this implies that

$$\lambda(t) \geq \frac{D'(S(t))}{r}$$

It follows that the tax $\beta D'$ on bioenergy is always lower than the tax on fossil energy provided $r\beta < 1$. This seems a reasonable assumption: If e.g. $\beta = 10$ (see section 2) and the interest rate is $r = 0.02$, we have $r\beta = 0.2$. With these numbers, the tax on bioenergy should therefore be much lower than the tax on fossil energy.

Without more assumptions about the function $D(S)$ and the parameter β it is not possible to say much about the relative sizes or relative growth rates of the two energy taxes (λ and $\beta D'$), at least outside of steady state.

3.3 Steady state

Assuming $D'' > 0$, there are two possible types of steady states. In the first there is positive production of bioenergy, i.e. $y^* > 0$. This steady state follows directly from the equations in the previous subsection. For $\dot{\lambda} = \dot{S}_x = 0$

we have

$$
\begin{aligned}
x^* &= 0 && (11)\\
u'(y^*) &= c'(0) + \lambda^* && (12)\\
u'(y^*) &= b'(y^*) + \beta D'(S_x^* + \beta y^*) && (13)\\
\lambda^* &= \frac{1}{r} D'(S_x^* + \beta y^*) && (14)
\end{aligned}
$$

In the long run, the optimal fossil tax is constant and exactly so high that fossil energy production is zero. This level of the fossil tax is achieved by cumulative fossil energy production giving so much carbon in the atmosphere that discounted future damages are equal to this tax rate. Bioenergy will be produced at the level that is privately optimal given a tax equal to $\beta D'$. The ratio between this tax and the carbon tax is hence βr.

Since $c'(0) < b'(y^*)$ for $y^* > 0$, these equations can only be valid if $\beta D' < \lambda^*$, i.e. if $r\beta < 1$. As mentioned above, this seems a reasonable assumption, and if this inequality holds we hence have a steady state with positive bioenergy production.

In Appendix A I show that if the initial value of S_x is sufficiently small, this steady state is reached asymptotically with monotonically rising values of $\lambda(t)$, $S_x(t)$, and $S(t)$.

If $r\beta > 1$ the production of both fossil energy and bioenergy will be zero in the steady state. Equations (11)-(14) remain valid, except that $y^* = 0$, and $=$ is replaced by $<$ in (13). Notice that even if $y^* = 0$, it may be optimal to have $y(t) > 0$ for some t. To see this, assume $y(t) = 0$ for all t. With positive production of fossil energy $\lambda(t)$ will be be positive and rising for $D'' > 0$ (see (10)). However, it may well be the case that D' is small or even zero for low values of S_x, implying that we may have $\beta D'(S(t)) < \lambda(t)$ for some t even if $r\beta > 1$. But if this is the case it follows immediately from (6) and (7) that $x(t) > 0$ and $y(t) = 0$ cannot be optimal. This contradiction proves that even if $r\beta > 1$, it may be optimal to have positive production of bioenergy for some t, although this production must go to zero in the long run.

In the remainder of this paper I restrict myself to the case of $r\beta < 1$. I now give an analysis both of the steady state and the dynamics for two limiting cases.

3.4 Linear climate costs

If the climate cost function is linear, D' is independent of S. In this case the fossil tax is constant and given by $\lambda = D'/r$, and the optimal tax on bioenergy is also constant, equal to $\beta D'$. The ratio between the tax on bioenergy and fossil energy is βr, as in the steady-state situation for the general climate cost function.

With a linear climate cost function, production of fossil energy and bioenergy are constant over time. Provided fossil energy production is positive, this means that the stock of carbon in the atmosphere is continuously increasing. However, if there is a resource constraint on the production of fossil energy the equilibrium would be different. In addition to production costs and the fossil tax there would now be a term reflecting the resource scarcity, rising at the rate of interest in the standard Hotelling manner. With this modification of the model, fossil fuel production would gradually decline and eventually reach zero. With a constant tax $\beta D'$ on bioenergy, the production of bioenergy would increase monotonically over time as a response to the decline in fossil energy production.

3.5 A binding threshold on carbon in the atmosphere

Linear climate costs do not seem particularly realistic. The opposite limiting case seems to be more in line with the climate goals that were agreed upon in the Paris agreement. These goals might be interpreted as what we might call an "inverse L" cost function, with negligible costs for carbon concentrations (or temperature) below some threshold, and "infinitely" high costs above the threshold. Hence, we therefor consider this case below. Assume now that $D' = 0$ for $S < \bar{S}$ and $D' =$ "∞" for $S > \bar{S}$. (Our results would not be changed much if we instead assumed a small and constant marginal cost for values of S below the threshold $\bar{S}$.). The interpretation of D' for this case is that it is an endogenous shadow price associated with the constraint $S \leq \bar{S}$.

Provided $S_x(0)$ is small enough, it follows from the monotonicity result above that the solution will have two phases: First (before t_1 in Figure 4) $S(t) < \bar{S}$ and rising, and then a phase with $S(t) = \bar{S}$.

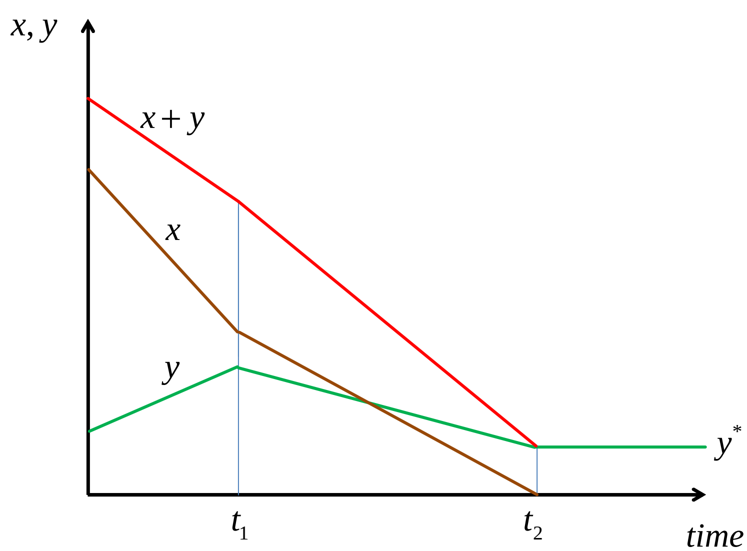

Figure 4

Consider first the phase where $S(t) < \bar{S}$. In this phase the carbon tax $\lambda(t)$ rises at the rate of interest, while the bioenergy tax $\beta D'$ is zero. This gives (from (6) and (7)) a declining $x(t)$, a rising $y(t)$, and a declining $x(t) + y(t)$, as illustrated in Figure 4.

When $S(t)$ reaches its upper limit $\bar{S}$, the term D' becomes positive, reducing $y(t)$. As long as $x(t)$ is positive, $y(t)$ must be declining, since $S_x(t)+\beta y(t)$ is constant during this phase. In Figure 4 this phase lasts till t_2, after which we have the steady-state outcome $(x, y) = (0, y^*)$. (In reality this phase is reached only asymptotically; i.e. $t_2 = "\infty"$).

The reason we get the "the rise and fall of bioenergy" as illustrated in Figure 4 is the following. As long as carbon in the atmosphere is below the threshold, there is no negative climate impact of using bioenergy, and since its marginal utility increases as fossil energy production declines, the production of bioenergy increases. However, once the threshold $\bar{S}$ is reached, the production of bioenergy must be reduced to "make room for" the carbon released from the fossil energy use. In practise, this comes about by reconverting land used for bioenergy production to forest land, and from less intensive harvesting of standing forests, so the volume, and hence stored carbon, of such forests increases.

4 Second-best policy

Assume that the energy taxes are $\theta_x(t)$ and $\theta_y(t)$, so that an interior market equilibrium is given by

$$u'(x(t)+y(t)) = c'(x(t)) + \theta_x(t) \tag{15}$$

$$u'(x(t)+y(t)) = b'(y(t)) + \theta_y(t) \tag{16}$$

As discussed previously, this equilibrium will coincide with the social optimum if the taxes $\theta_x(t)$ and $\theta_y(t)$ are equal to the $\lambda(t)$ and $\beta D'(S)$ derived in section 3. Assume now that, for whatever reason, $\theta_x(t)$ is exogenously set at a level satisfying

$$\theta_x(t) < \int_0^\infty e^{-r\tau} D'(S(t+\tau))d\tau \tag{17}$$

In other words, there is an exogenous carbon tax that is lower than the social cost of carbon.

For a given time path of $y(t)$, (15) and (16) determine the time path of $x(t)$ (and of $\theta_y(t)$). We write this relationship as $x = x(y, \theta_x)$. Choosing $y(t)$ to maximize our objective function (5) gives the following Hamiltonian (ignoring the time references):

$$H = u(x(y,\theta_x) + y) - c(x(y,\theta_x)) - b(y) - D(S_x + \beta y) + (-\lambda)x(y,\theta_x) \quad (18)$$

The conditions for an interior optimum are

$$\begin{aligned} u'(x+y) &= b'(y) + \beta D'(S) + \left[(\lambda + c' - u')\frac{\partial x(y,\theta_x)}{\partial y}\right] && (19) \\ \dot{\lambda} &= r\lambda - D'(S) && (20) \\ Lim_{t\to\infty} e^{-rt}\lambda(t) &= 0 && (21) \end{aligned}$$

The costate variable $\lambda(t)$ may as in the first-best case be interpreted as the social cost of carbon. From (20) and (21) we can derive

$$\lambda(t) = \int_0^{\infty} e^{-r\tau} D'(S(t+\tau))d\tau \quad (22)$$

Define

$$k = -\frac{\partial x(y,\theta_x)}{\partial y} \quad (23)$$

From (15) and (16) it follows that $k = \frac{u''}{u''-c''}$, implying that $k \in (0,1)$.

Using the definitions above, it follows from (15) that (19) may be rewritten as

$$u'(x+y) = b'(y) + \beta D'(S) - k[\lambda(t) - \theta_x(t)]$$

Using (16) the second-best optimal tax on bioenergy follows:

$$\theta_y(t) = \beta D'(S) - k[\lambda(t) - \theta_x(t)] \quad (24)$$

To interpret (24), it is useful to rewrite it as $\theta_y = \beta D'(S) - k\lambda + k\theta_x$. The first term in this expression, $\beta D'(S)$, measures the direct climate cost of producing and using bioenergy. The second term, $-k\lambda$, represents the reduced climate costs from fossil energy caused by the increased use of bioenergy. The final term, $k\theta_x$, represent a non-environmental indirect cost of increasing the use of bioenergy: By increasing the use of bioenergy the use of fossil energy declines. This reduction gives a social cost (ignoring the climate effect, since this is taken care of by the second term), since the marginal benefit of using fossil energy exceeds the marginal cost of supplying it. This difference is due to the carbon tax, since the carbon tax is identical to the difference between the user and producer price.

4.1 Steady state

Without any assumptions about the exogenous carbon tax $\theta_x(t)$, we cannot know whether a steady state exists. Hence, we assume that $\theta_x(t)$ in the long run is equal to (or approaches asymptotically) a constant value θ_x^*. If this is the case and $D'' > 0$ there is a steady state given by

$$x^* = 0 \quad (25)$$

$$u'(y^*) = c'(0) + \theta_x^* \quad (26)$$

$$u'(y^*) = b'(y^*) + \theta_y^* \quad (27)$$

$$\lambda^* = \frac{1}{r} D'(S_x^* + \beta y^*) \quad (28)$$

$$\theta_y^* = r\beta\lambda^* - k[\lambda^* - \theta_x^*] \quad (29)$$

Since $c'(0) < b'(y^*)$ for $y^* > 0$, these equations can only be valid if $\theta_y^* < \theta_x^*$. From the equations above it is clear that this inequality is identical to $r\beta < k + (1-k)\theta_x^*/\lambda^*$. For $\theta_x^* < \lambda^*$ the r.h.s. of this inequality is smaller than 1. Hence the condition for $y^* > 0$ is stricter in the second-best case than in the first-best optimum, and is stricter the larger is the relative fossil tax distortion (i.e. the smaller is θ_x^*/λ^*). In the remainder of this section I assume that the inequality $r\beta < k + (1-k)\theta_x^*/\lambda^*$ holds. In other words, I only consider cases where bioenergy production is positive in a steady state.

From the equations above we see that the sign of θ_y^* is ambiguous. It is positive (i.e. we have a tax on bioenergy in the long run) if $r\beta > k\,(1-\theta_x^*/\lambda^*)$, and negative (i.e. a subsidy to bioenergy in the long run) if $r\beta < k\,(1-\theta_x^*/\lambda^*)$. In other words, with a small carbon tax distortion (θ_x^*/λ^* close to 1) bioenergy should be taxed in the long run (as in the first-best case), while bioenergy should be subsidized in the long run if the tax distortion is sufficiently high (θ_x^*/λ^* close to 0).

I assumed above that $\theta_x(t)$ in the long run was equal to (or approaches asymptotically) a constant value θ_x^*. Without more assumptions on the time path of $\theta_x(t)$ is is of course not possible to say anything about the dynamics toward the steady state. In the next section I shall nevertheless briefly consider the dynamics of the second-best equilibrium for the case of an inverse L damage function and a particular assumption about the time path of $\theta_x(t)$.

4.2 A binding threshold on carbon in the atmosphere and a constant parameter of tax distortion.

Assume that the exogenous carbon tax develops in a manner that makes the variable $\frac{\theta_x(t)}{\lambda(t)}$, which is a measure of the tax distortion, constant over time, denoted α. As in the first-best optimum, the equilibrium will have two phases. First $S(t) < \bar{S}$, and then a phase with $S(t) = \bar{S}$.

Consider first the phase where $S(t) < \bar{S}$. In this phase the fossil tax $\alpha\lambda(t)$ rises at the rate of interest. Since D' is zero in this phase, it follows from (24) that $\theta_y = -k(1-\alpha)\lambda$. Hence, bioenergy is subsidized, and the subsidy is increasing over time. This gives a declining $x(t)$ and a rising $y(t)$, as in the first-best case.

When $S(t)$ reaches its upper limit $\bar{S}$, $y(t)$ is declining for $x(t) > 0$, since $S_x(t) + \beta y(t)$ is constant during this phase. This is achieved trough a gradual reduction in the subsidy to bioenergy (as D' increases), which might even eventually turn into a tax.

We assumed above that the fossil tax was exogenous and below the level giving the social optimum. This type of assumption is quite often made in various studies of second-best climate policies. One reason for such a constraint on the fossil tax could be distributional concerns. Even if the government intends to fully recycle the revenues from a carbon tax, each voter may focus on the visible tax increase and not trust that the revenue from the carbon tax will be recycled in a way compensating him or her. Moreover, some persons will be hurt more by the carbon tax than others; this will typically be those who consume more than the average share of fossil fuels due to their current preferences or earlier investments (e.g. a large house with a long commuting distance). On the production side, some industries will bear a disproportionately high share of the total costs from the carbon tax. Consumers with a high use of fossil fuels as well as workers and owners in such high emission sectors will often be successful in lobbying against a carbon tax.

In contrast, the costs of subsidizing renewable energy are likely to be less visible to the typical voter and also be more evenly shared by everyone in the economy. Sectors in the economy producing renewable energy or inputs to this production will gain from a subsidy to renewable energy, and might thus engage in lobbying for the use of such subsidies instead of a carbon tax. These arguments suggest that it might be easier to obtain political support for a subsidy to renewable energy than for a carbon tax.

Since fossil energy production in the long run is zero, there is no revenue from the fossil energy tax in the long run. The only purpose of the tax in the long run is to make it prohibitively expensive to produce fossil energy, and hence avoid any fossil energy production. In such a situation, it can obviously not be the fossil tax itself, and the distributional issues related to the revenue from it, that raises political concerns. There may however be distributional concerns related to the user cost of energy (be it fossil or bio), and political objections to high energy prices. From (13) it immediately follows that the long-run energy price $u'(y^*)$ is higher the higher is the fossil tax θ_x^*. Hence, there are political arguments for a constraint on the fossil tax even if there are no tax revenues collected and redistributed.

5 The climate effects of bioenergy

So far we have assumed $S_y = \beta y$, implying that any change in the level of bioenergy production immediately gives a corresponding change of carbon in the atmosphere. As mentioned in section 2.2, the change in the amount of carbon to a new long-run level will not be immediate, and we will instead get an adjustment as illustrated by the dashed lines in Figure 3.

A simple way to model a gradual adjustment as illustrated by the dashed lines in Figure 3 would be to assume that $S_y(t)$ develops according to

$$\dot{S}_y(t) = \delta\left(\beta y(t) - S_y(t)\right) \tag{30}$$

where δ is a positive parameter.

With this modification it is straightforward to show that (5)-(10) remain valid with the exception of (7), which is replaced by

$$u'(x+y) - b'(y) - \gamma(t) \leq 0 \; [= 0 \text{ for } y > 0]$$

where

$$\gamma(t) = \delta\beta \int_0^\infty e^{-(r+\delta)\tau} D'(S(t+\tau)) d\tau$$

Notice that

$$\begin{aligned} Lim_{\delta \to \infty} \gamma(t) &= \beta D'(S(t)) \\ Lim_{\delta \to 0} \gamma(t) &= 0 \end{aligned}$$

Hence, if the speed of adjustment is sufficiently high (large δ), the results of our model will remain valid. On the other hand, with a very low speed of adjustment (δ close to zero), production of bioenergy will be almost without any climate impact, and the optimal tax on bioenergy will be close to zero.

Equation (30) implicitly assumed symmetry, in the sense that carbon is reduced from the atmosphere when bioenergy production is reduced just as fast as carbon in the atmosphere is increased when the production of bioenergy is increased. This is obviously not realistic. Cutting down a forest to make land available for bioenergy crops will give an immediate release of carbon to the atmosphere. Converting farm land to forest land will on the other hand only give a slow growth of carbon contained in the forest.

A limiting case of the asymmetry suggested above would be to replace $S_y(t) = \beta y(t)$ with $S_y(t) = \beta \max_{\tau \leq t} y(\tau)$. Clearly, with this assumption there will be no climate impact of bioenergy for any t when $y(t) < \max_{\tau \leq t} y(\tau)$, so that the optimal value of y is then given by $u'(x+y) = b'(y)$. This implies that we will never have $\dot{y}(t) < 0$. To see this, assume $\dot{y}(t) < 0$ for some t. It then follows from $u'(x+y) = b'(y)$ and the fact that $x(t)$ is declining (due to $\lambda(t)$ rising) that $y(t)$ must be rising. This contradiction proves that with the $S_y(t) = \beta \max_{\tau \leq t} y(\tau)$, the optimal outcome must satisfy $\dot{y}(t) \geq 0$ for all t. Replacing the assumption $S_y(t) = \beta y(t)$ with $S_y(t) = \beta \max_{\tau \leq t} y(\tau)$ is hence equivalent to keeping the assumption $S_y(t) = \beta y(t)$ but adding the constraint $\dot{y}(t) \geq 0$ for all t.

Assume that without the constraint $\dot{y}(t) \geq 0$ the optimal path of $y(t)$ is qualitatively as in Figure 4, i.e. that there is a period before the steady state is reached where y is larger than the steady-state level y^*. This equilibrium is not feasible with the constraint $\dot{y}(t) \geq 0$. One feasible outcome would be to simply keep $y(t)$ at its steady-state value y^* once this is reached. Compared with the unconstrained case, we would then get a loss in social welfare for the time period when $y(t) > y^*$ without the constraint. This loss could be reduced by letting $y(t)$ increase to some value $y^{**} > y^*$, as illustrated in Figure 5. Doing this would come at the cost of a long-run loss in social welfare, i.e. for all t where we would like to have $y(t) < y^{**}$ without the constraint. With a positive discount rate, it is optimal to accept some long-rune loss in order to make the near-term loss in social welfare smaller. This intuitive description of the optimum is confirmed by the formal analysis given in Appendix B.

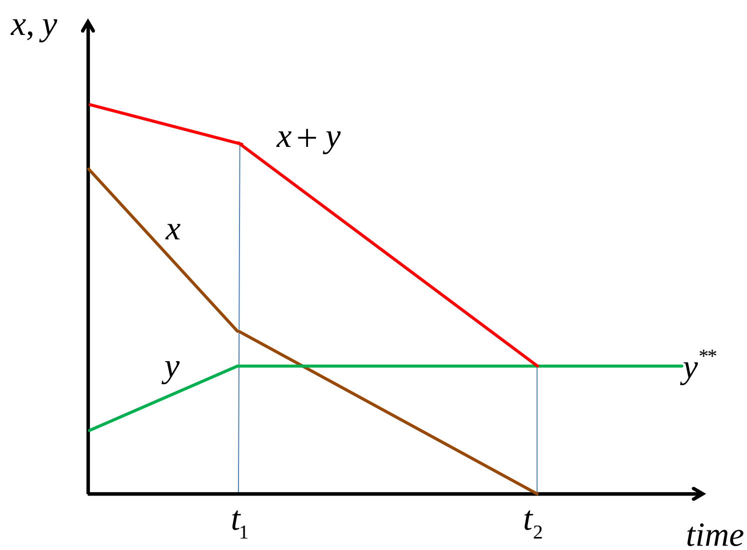

Figure 5

6 Concluding remarks

In recent years it has become clear that the production of bioenergy in most cases will have a negative direct climate impact. This suggests that contrary to what is the case in many countries, bioenergy ought to be taxed, and certainly not subsidized.

Ideally, all flows of carbon to the atmosphere should be taxed at the same rate, and this same rate should be used to subsidize flows of carbon from the atmosphere. For fossil energy this simply implies a uniform carbon tax, as in this case there is no flow of carbon from the atmosphere to the biosphere. However, for bioenergy there are generally flows of carbon between the biosphere and the atmosphere going in both direction. The ideal tax/subsidy scheme for bioenergy is likely to be difficult or impossible to achieve in practise. In the context of our simple model, the first-best social optimum may nevertheless be achieved by appropriate taxes on both types of energy. Due to the differences in dynamics of the climate impact of bioenergy and fossil energy, the optimal taxes of the two types of energy may have very different time paths.

If policy makers for some reason are not willing to tax carbon energy as high as the climate considerations require, it may be optimal to subsidize bioenergy. However, even if such a such a subsidy is (second-best) optimal in the short run, it may be optimal to eventually reduce the subsidy and perhaps tax bioenergy in the long run.

The difference in the dynamics of the climate impacts of bioenergy and fossil energy have an important implication for the dynamics of the production of the two types of energy. Both in the first-best and second-best case it may be optimal to have an initially rising, but later declining, production of bioenergy.

The present study has completely ignored the possibility of CCS (Carbon Capture and Storage). An interesting extension would be to include the possibility of CCS, both in a first-best and second-best setting.

Appendix A: The dynamics towards steady state.

For an interior solution it follows from (6) and (7) and the properties of the functions that

$$x = x(\underset{-}{\lambda}, \underset{+}{S_x}) \tag{31}$$

$$y = y(\underset{+}{\lambda}, \underset{-}{S_x}) \tag{32}$$

It follows that

$$S = S_x + \beta y(\lambda, S_x) = S(\underset{+}{\lambda}, \underset{+}{S_x}) \tag{33}$$

To see that S is increasing in S_x, assume the opposite. Then it would follow from (6) and (7) that an increase in S_x for given λ would make y higher or unchanged, and hence increase S. This contradiction proves the last sigh in (33)

The phase diagram in Figure 6 follows from (3) and (8). From (3) and (31) it is clear that the line for $x(\lambda, S_x) = 0$ is upward sloping, and that $\dot{S}_x$ is zero above this line and positive below.

When $\dot{\lambda} = 0$ it follows from (8) that

$$\lambda = \frac{1}{r} D'(S_x + \beta y(\lambda, S_x))$$

When $x = 0$ it follows from (7) that y is independent of λ, and since S and D' is higher the higher is S_x, the curve for $\dot{\lambda} = 0$ must be upward sloping above the line for $x(\lambda, S_x) = 0$. The slope below this line is not obvious, but is of no importance. In any case we must have $\dot{\lambda} = r\lambda - D'(S(\lambda, S_x)) > 0$ to the left of the curve giving $\dot{\lambda} = 0$.

If the initial value of S_x is higher than the steady-state value S_x^*, the optimal solution is trivial: We should have $x = 0$ for all t,and y constant and determined by (7) for all t.

If the initial value of S_x is lower than the steady-state value S_x^*, as in Figure 6, the dynamics are as illustrated: $S_x(t)$ and $\lambda(t)$, and hence also $S(t)$, rise monotonically and asymptotically towards their steady-state values.

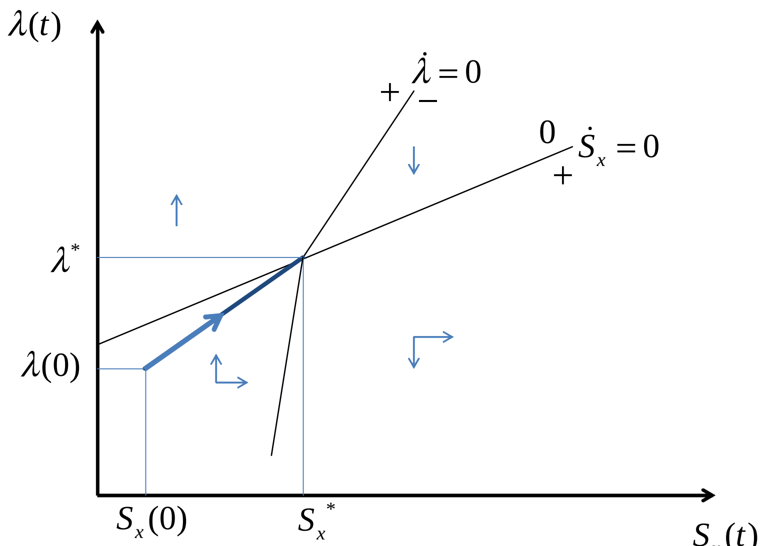

Figure 6

Appendix B: Non-declining bioenergy production

Consider the same problem as in Section 3.1, but now with the additional constraint $\dot{y}(t) \geq 0$. To analyze this problem, I treat $y(t)$ as a state variable and add a control variable $w(t)$, with the relationship between the two being $\dot{y}(t) = w(t)$. Moreover, we have the constraint that $w(t) \geq 0$.

The current value Hamiltonian is now (ignoring time references and written so the costate variables λ and σ are non-negative)

$$L = u(x + y) - c(x) - b(y) - D(S_x + \beta y) + (-\lambda)x + (-\sigma)w$$

Ignoring a possible initial jump upwards in y (with w being "very large" for a "very short" time), the conditions for an interior optimum are now

$$\begin{aligned}
u'(x + y) - c'(x) - \lambda &= 0 && (34)\\
\sigma &\geq 0 \; [= 0 \text{ for } w > 0] && (35)\\
\dot{\lambda} &= r\lambda - D'(S) && (36)\\
\dot{\sigma} &= r\sigma + [u' - b' - \beta D'] && (37)\\
Lim_{t\to\infty} e^{-rt}\lambda(t) &= 0 && (38)\\
Lim_{t\to\infty} e^{-rt}\sigma(t) &= 0 && (39)
\end{aligned}$$

It is immediately clear that $x(t)$ is determined as before by (6) and (10), i.e. $u'(x+y) = c'(x) + \lambda$, where λ is the social cost of carbon. Hence, also in this case x is monotonically declining.

The exact equilibrium for $y(t)$ will depend on the function $D(S)$. If the equilibrium without the constraint $\dot{y} \geq 0$ never has $\dot{y} < 0$ (e.g. as in the case of $D'' = 0$), the constraint $\dot{y} \geq 0$ is non-binding. In this case we will have $\sigma(t) = 0$ for all t, and the conditions above give the same outcome as in Section 3.1.

The interesting case is when it is optimal to have $\dot{y}(t) < 0$ for some t in the unconstrained case. For this case, the optimal solution for the constrained case has three phases (or only two, see below).

In the first phase $y(t)$ is increasing and $\sigma(t) = 0$. From the equations above this implies that y is determined as before by (7), i.e. $u'(x+y) = b'(x) + \beta D'(S)$. In the second phase y is constant and $\sigma > 0$. The phase starts with y being constant and $u'(x+y) - b'(y) - \beta D'(S)$ rising from zero due to x declining. From (37) this implies that σ will start to rise. Initially, $\dot{\sigma} > r\sigma$. However, as D' rises due to the increasing S, the term in brackets in (37) will eventually become negative, making $\dot{\sigma} < r\sigma$. This phase ends when σ stops growing so that its steady state σ^{**} is reached. From then on we are in phase three with $x = 0$ and

$$u'(y^{**}) = b'(y^{**}) + \beta D'(S^{**}) - r\sigma^{**} \tag{40}$$

Four properties of the equilibrium are worth mentioning. First, the existence of the first phase depends on the initial conditions; if e.g. the initial amount of fossil carbon in the atmosphere is sufficiently high we would only get the two last phases.

Second, the equilibrium described above relied on $u'(x+y)-b'(y)-\beta D'(S)$ changing from positive to negative as S increased. This will only occur if D is sufficiently convex. If D doses not have this property, the equilibrium will be unaffected by the constraint $\dot{y}(t) \geq 0$, as explained above.

Third, the third phase will generally only be reached asymptotically. However, with an inverse L damage cost function, a constant y and $u'(x+y) = c'(x) + \lambda$ must imply that x is reached in finite time since $\dot{\lambda} = r\lambda$ as long as the threshold $\bar{S}$ has not been reached.

Finally, it is clear that the steady-state value y^{**} given by (40) is larger than the corresponding value y^{*} in the unconstrained case (since $\sigma^{**} > 0$). The intuition of this result is explained in the main text.

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