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The Green Paradox and the importance of endogenous resource exploration*

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It has been proposed that climate policies aimed at reducing greenhouse gas emissions from fossil fuel use may actually worsen the problem of global warming. Such a Green Paradox could occur if fossil fuel resource owners exploit their resources more rapidly due to the expectation of stricter climate policies in the future. This article shows that the emergence of the Green Paradox is less plausible if exploration activities are taken into account. An extraction model that incorporates exploration investments finds that an increasing cash flow tax is effective in dealing with climate change depending upon the specific formulation of the tax scheme. For example, the higher the initial tax level, the more effective is the tax scheme in mitigating climate change and hence a Green Paradox can be avoided. A very low growth rate is also beneficial for the climate as it leads to a small temporal redistribution of extraction to earlier periods. A very high growth rate leads to faster extraction; however, it also coincides with a significant decrease in total emissions that is inconsistent with a Green Paradox.

Key words: climate policy, exhaustible resources, exploration, green paradox, supply-side dynamics.

1. Introduction

With the establishment of the United Nations Framework Convention on Climate Change, the challenge to mitigate global warming has been on the agenda of governments from around the world since the early 1990s. As a result, a variety of policy measures to limit greenhouse gas emissions has been implemented over the past two and a half decades. Prominent examples include the World's first carbon tax adopted in Finland in 1990 and the European Trading Scheme that has been in place since 2005. Most of the policies that are currently in place are aimed at reducing emissions from fossil fuels, including coal, oil and gas (Sinn 2008). This is reasonable as the combustion of fossil fuels represents the major contributor to the increase of atmospheric greenhouse gas concentration, the principal driver of global warming (Ciais *et al.* 2013).

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There are a variety of feedback mechanisms that may be related to climate policies; these include leakage and rebound effects, which mostly undermine their effectiveness, and in rare cases, reinforce them (Fölster and Nyström 2010). This article focuses on one specific kind of feedback mechanism that is triggered by the non-renewable character of fossil fuel resources, known as the Green Paradox (Sinn 2008). A body of literature related to the Green Paradox has studied the potential for a situation where climate policies actually worsen the problem of global warming based on the reaction of the fossil fuel owners to climate policy measures. In particular, if resource owners expect that climate policies will become stricter over time and relate this to a gradual reduction in demand for fossil fuels, they may decide to accelerate the extraction of their resources to maximise their profits. Consequentially, the accumulation of atmospheric greenhouse gases occurs faster and worsens the problem of climate change. To show this formally, Sinn (2008) employs a model based on Hotelling's theory of exhaustible resource extraction (1931) with a given fossil fuel stock. He shows that increasing taxes over time may generate a Green Paradox.

Using a standard resource extraction model that has been expanded to incorporate the exploration of fossil fuels, this article reviews the conditions under which a Green Paradox occurs. A key driver for the emergence of the Green Paradox in the framework presented in Sinn (2008) is the assumption that fossil fuel extracting firms are endowed with the resource stock. In reality, fossil fuels are stored underground and their identification (through exploration) is necessary, as are development activities to prepare the site for extraction (Bohi and Toman 1983). Tools to identify fossil fuels include geographical studies and exploratory drilling which involve significant costs and a high risk regarding the success of finding resources (Bhattacharyya 2011). A tax or another fossil fuel demand-reducing policy measure, such as a subsidy on low-carbon energy sources, would decrease the value of a mining project through diminishing revenues from fossil fuel sales. As a result, incentives to invest in mining projects are lowered, and since some may become unprofitable, the total amount of fossil fuels available decreases and this generates a positive impact on the climate. In the context of the Green Paradox discussion, this implies that when exploration activities are taken into account, a Green Paradox may not occur and, accordingly, demand-reducing policy measures may result in effective climate change mitigation. To assess this formally, this article proposes an extended Hotelling model that includes the characteristic that a competitive firm has to invest in exploration activities prior to the extraction phase. It should be noted that the model developed utilises assumptions that are consistent with those in Sinn (2008) and that concurrently allow for an incorporation of exploration investments and an analytical solution.

The earliest contribution that links the theory of exhaustible resource extraction to climate policy is provided by Sinclair (1992), who finds that an *ad valorem* carbon tax could be redundant or even damaging for climate change issues. An *ad valorem* carbon tax is levied on the fossil fuel sales, while a *specific* carbon tax is levied in proportion to the CO_2 emissions generated through the combustion of fossil fuels. Within a standard Hotelling model with no extraction costs, Sinclair (1992) shows that an *ad valorem* carbon tax is only effective in postponing extraction if it is decreasing over time. As extraction costs are assumed to be zero in Sinclair (1992), this tax corresponds to a cash flow tax, or in alternative words a tax levied on net revenue. Within the literature, it has been often stated that a constant cash flow tax does not affect the extraction path, while a decreasing tax leads to slower extraction (Dasgupta *et al.* 1981). Following this, Sinn (2008) applies a Hotelling model similar to Sinclair's framework, but with stock-dependent extraction costs to assess different cash flow and *ad valorem* carbon tax schemes with regard to their effectiveness in achieving climate change mitigation. Note that a cash flow tax differs from an *ad valorem* carbon tax only insofar as extraction costs are not tax exempt. Sinn (2008) shows that an increasing cash flow tax and an *ad valorem* carbon tax with a growth rate larger than $(r - \dot{P})$ (r being the market interest rate and $\dot{P}$ the growth rate of the price) generate a Green Paradox. While total fossil fuel supply is not impacted by these tax schemes, their implementation leads to a change in the expected (producer) price path such that it is optimal for fossil fuel owners to extract faster. On the other hand, a decreasing cash flow tax and an *ad valorem* carbon tax with a growth rate smaller than $(r - \dot{P})$ is effective in postponing extraction. On the basis of these results, Sinn (2008, p. 388) concludes that 'measures to reduce carbon demand, ranging from taxes on fossil fuel consumption to the development of alternative energy sources [...] will not mitigate the problem of global warming'.

In recent years, a range of papers has focused on the contribution of Sinn (2008) and has reviewed the conditions for the occurrence of a Green Paradox. These papers have utilised different climate policy approaches and model formulations (e.g. Strand 2007; Hoel 2010; Chakravorty *et al.* 2011; Edenhofer and Kalkuhl 2011; Gerlagh 2011; Grafton *et al.* 2012; Van der Ploeg and Withagen 2012). Several contributions introduce a backstop technology within a Hotelling resource extraction framework to assess the effect of climate policies (e.g. Gerlagh 2011; Grafton *et al.* 2012; Van der Ploeg and Withagen 2012). It should be noted that a backstop technology is a perfect substitute to the fossil fuel resource and is not constrained by exhaustibility (Nordhaus 1973). The existence of a backstop technology together with stock-dependent extraction costs means that suppliers stop supplying fossil fuels once the producer price reaches the price of the backstop technology (Perman *et al.* 2003). As a result, some of the resources remain in the ground as it is no longer profitable for the firm to extract them. It has been shown that the existence of a backstop technology in conjunction with stock-dependent extraction costs makes the appearance of a Green Paradox less plausible. Hoel (2010) finds that under these assumptions, the implementation of a carbon tax leads to lower total emissions irrespective of the time profile of the tax. Moreover, a carbon tax that increases at a rate that is less than or equal to the interest rate generates reduced emissions at each point in time. Similarly, the implementation of an *ad valorem* tax leads to reduced total emissions. For example, with a backstop technology, an *ad valorem* tax that increases with a growth rate equal to $(r - \dot{P})$ generates a reduction in emissions at each point in time and is effective as a climate policy (Österle 2012). In comparison, this specific tax scheme has no effect on the extraction path within a framework where there is no backstop technology, as assumed within Sinn (2008).

Focusing on exploration, Pindyck (1978) presents a model consistent with Hotelling (1931) where a competitive firm decides how much to produce and how much to invest in exploratory activities at each point in time across a finite time horizon with firms facing stock-dependent extraction costs. Several studies provide useful insights into the effects of taxes by drawing on Pindyck's (1978) seminal paper and these may be applied to assess climate policies (e.g. Yücel 1986; Deacon 1993; Kunce *et al.* 2003). While most of the articles focus on national taxes, Yücel (1986) examines the impact of a constant global sales tax (which is consistent with an *ad valorem* carbon tax) on fossil fuel supply in a competitive economy with a backstop technology. Within this framework, extraction and exploration activities are reduced at each point in time compared to the scenario where no tax is applied. Berg *et al.* (2002) analyses the effects of different carbon tax schemes within an exhaustible resource model where a competitive fringe can invest in costly exploration activities, while the resource base of a cartel is fixed. The article finds that a constant and an increasing carbon tax lead to an initial increase in production and exploration activities by the competitive fringe, because in both cases, the firms react more slowly to increasing price paths compared to the reference scenario. Even though the competitive fringe increases production initially, global production from all suppliers is lowered at all points in time and hence no Green Paradox occurs. The frameworks used in Yücel (1986) and Berg *et al.* (2002) do not isolate the effect of costly exploration activities on total extraction and the appearance of a Green Paradox. This is due to the assumptions of a backstop technology in conjunction with stock-dependent extraction costs, which, as shown above, imply that not all resources are depleted. In particular, the implementation of a carbon tax in Berg *et al.* (2002) leads to a decrease of the total amount of fossil fuels produced, independent of the existence of exploration costs. Venables (2011) extends the standard Hotelling model (with no backstop technology) to incorporate capital expenditures required for development activities. Within this model, he uses simulation to analyse the effect of a permanent reduction in the growth rate of the price path, a situation comparable to an increasing fossil fuel tax. The results show a temporary increase in fossil fuel extraction in the short term, but a decrease in overall extraction, which indicates that the occurrence of a Green Paradox is less plausible with exploration activities.

The study presented within this article presents an extended Hotelling model without a backstop technology that includes *a priori* investment in exploration and is applied to the context of climate change policy. In this model, a competitive firm invests in exploration activities during an initial phase and, in a second phase, extracts the amount of available resources without extraction costs. The size of the resource stock depends on the amount of exploration activities undertaken before extraction starts and thereby draws on the contributions of Lasserre (1991) and Heaps and Helliwell (1985). The article explores the impact of an increasing cash flow tax on the supply decision in order to shed light on the effectiveness of the tax in relation to climate change mitigation. Under the assumptions adopted within the model presented, an *ad valorem* carbon tax is equivalent to a cash flow tax because there are no extraction costs. As a prelude to the results of the analysis, this study finds that an increasing cash flow tax (and equivalently, an increasing sales tax) tends to mitigate climate change when exploration is modelled endogenously. While it may generate an increase in short-term emissions, a positive effect on the climate will be triggered by a decrease in overall emissions.

The removal of extraction costs within the proposed model allows for an analytical solution of the framework. In addition, Livernois and Uhler (1987) point out that a stock-dependent extraction cost function with the properties assumed in Sinn (2008) might be misspecified if it is used in extraction models where the size of the resource stock depends on discoveries. In these models, including Pindyck's (1978) formulation of a resource extraction framework, a convex and decreasing stock-dependent cost function loses its validity if new discoveries do not have characteristics that lower extraction costs.

It should be acknowledged that any issues that arise from the modelling of exploration occurring in the period where $t \leq 0$, as opposed to occurring simultaneously with extraction, are not investigated within this article. This assumption is utilised as the aim of the article is to find an analytical solution and to study how different parameters affect the Green Paradox under conditions that are similar to the framework of Sinn (2008). Nevertheless, Venables (2011), who incorporates simultaneous exploration into an otherwise similar model, finds consistent results with respect to the appearance of the Green Paradox. As a result, without the assumption that exploration becomes cheaper over time (i.e. due to technological improvements), incorporating exploration when discussing the existence of the Green Paradox under Sinn's (2008) framework is more important than the timing of the cost of exploration.

The article is structured as follows: Section 2 presents the extraction-exploration model, which is used in Section 3 to highlight the conditions for the occurrence of a Green Paradox when exploration is endogenously accounted for. Section 4 reviews the conclusions of the article.

2. The extraction-exploration model

The model assumes a representative firm that extracts a resource stock over time without extraction costs in a competitive economy where no backstop technology exists. Note that these assumptions are consistent with those in Sinn (2008), except for the assumption of the existence of extraction costs. The size of the extractable resource base depends on the firm's effort in exploration activities undertaken prior to extraction. Within this framework, the optimal supply paths with and without an increasing cash flow tax are derived and compared to assess the effectiveness of the policy in terms of climate change mitigation.

The assumptions regarding the timing of extraction and exploration activities as well as the exploration process are based on the contribution of Lasserre (1991). In a first phase, the firm undertakes costly exploration activities to accumulate a stock of fossil fuels. The length of the exploration phase and the size of exploration expenditure at each point in time are optimally chosen by the firm. Extraction starts as soon as the exploration process is over. The beginning of the extraction activity is fixed at the date $t = 0$ without any loss of generality. Cumulative exploration expenses are expressed by $C(S_0)$ with S_0 being the total amount of fossil fuels discovered during the exploration period. Following Lasserre (1991), total discovery costs are expressed by the following continuous function of time t

$$C(S_0) = \min \int_{-T_x}^{0} e^{-rt} c(s_{-t}, S_{-t}) \mathrm{d}t \tag{1}$$

subject to

$$\dot{S}_{-t} = s_{-t}. \tag{2}$$

Note that subscripts refer to time periods. The time $-T_x$ denotes the initial period of the exploration process with $-T_x < 0$. At the starting point, there are no discoveries given that $S_{-Tx} = 0$. With no initial resource allocation, the firm invests at any time an amount of $c(s_{-t}, S_{-t})$ to build up a natural capital stock. Marginal discovery costs increase with both the amount of discoveries, s_{-t}, and the total amount of discoveries made in previous periods, S_{-t}, reflecting a standard assumption of the exploration literature (refer to Pindyck 1978). From this, it follows that $C(S_0)$ is convex and rising. To reflect the alternative possibility of investing within the capital market, the expenditures for exploration are valued by the interest rate r. Given these constraints, the firm chooses an optimal exploration path to minimise costs to obtain an initial amount of fossil fuels, S_0. If the firm minimises exploration costs as specified in Equation (1) by choosing an optimal exploration path, total exploration costs can be expressed as a function that is convex in S_0. This is captured by the following expression.

$$C(S_0) = \beta \cdot S_0^{\alpha} \tag{3}$$

with $\alpha > 1$ and $\beta > 0$.

The formulation of exploration costs as in Equation (3) allows for an analytical solution of the firm's maximisation problem. Extraction activities start as soon as the exploration process is finished. The extraction amount at time t is denoted by R_t. The firm can sell a unit of fossil fuel for the competitive price P_t that leads at each point in time to a market equilibrium. Demand for fossil fuels is given by $D(P_t)$ with $D'(P_t) < 0$ and the elasticity of demand is bounded from above due to R_t decreasing to zero to reflect the non-existence of a backstop technology. To simplify the analysis, the properties of demand are further specified by introducing a specific demand function that ensures that the elasticity of demand is constant for any R_t. This demand function is defined as

$$D(P_t) = P_t^{-\gamma}, \tag{4}$$

with $\gamma > 0$. Dasgupta and Heal (1979) present this demand function to express fossil fuel demand in a simple Hotelling framework. The property of the demand leads to an optimal time horizon for extraction that is equal to infinity. An increasing cash flow tax can be imposed with a factor given by $\theta_t = \theta_0 \cdot e^{\hat{\theta} t}$ where $\hat{\theta}$ is a constant. Note that $\theta_t = (1-\tau_t)$ with τ_t denoting the tax rate. There exists a limited amount of fossil fuels in the ground, representing the real-world physical finiteness of fossil fuel resources; it is assumed that the complete discovery of the resource is not profitable for the firm.

Under these assumptions, the firm selects the optimal investment in exploration in the first phase and in the second phase selects its optimal extraction plan so that total discounted profits from extraction (net of eventual taxes and cumulative expenditures in exploration) are maximised. Formally, this is expressed as

$$\max \int_0^{\infty} P_t \cdot R_t \cdot \theta_t \cdot e^{-rt} \mathrm{d}t - C(S_0), \tag{5}$$

s.t.

$$\dot{S}_t = -R_t \text{ with } R_t \geq 0, S_0 \text{ endogenous} \tag{6}$$

and $C(S_0)$ as defined by Equation (1).

The solution to this dynamic optimisation problem, which is presented in detail in Section 3 and the Appendix shows that the overall impact of an increasing cash flow tax on the climate is not clear because the tax exerts two countervailing effects on fossil fuel supply. On the one hand, it modifies the temporal distribution of extraction by making it more profitable to extract the fossil fuel stock faster. On the other hand, it reduces the total amount extracted because exploration incentives are lowered. As a result, the optimal extraction path may start from a higher or a lower level in the policy scenario compared to the business-as-usual scenario. These two possible solutions are captured by the concept of the *weak* Green Paradox introduced in Gerlagh (2011).

Definition 1: *A weak Green Paradox arises when the implementation of an increasing cash flow tax increases current and near term extraction compared to the business-as-usual extraction path, formally, if* $R_0^{tax} > R_0$.

The implication of a policy scenario for the climate where no *weak* Green Paradox occurs is straightforward. Because extraction levels are lower at each point in time compared to the business-as-usual scenario, the climate is clearly better off with an increasing cash flow tax. There is no clear implication for the climate, however, when a *weak* Green Paradox occurs as higher emissions in the initial periods may be compensated by the decrease of total emissions. This makes it necessary to adopt the concept of the *strong* Green Paradox (Gerlagh 2011). A *strong* Green Paradox captures the long-term effect of climate policies and is equivalent to the issue raised by Sinn (2008). It is manifested in the case where the policy worsens the climate change problem. To measure the long-term effect on the climate, this framework utilises a function of present value climate damages proposed by Gerlagh (2011), who defines the net present value of climate damages with

$$\Gamma = \int_0^\infty e^{-rt} \cdot \chi_t \cdot R_t \, \mathrm{d}t. \tag{7}$$

Based on this climate damage function, the occurrence of a *strong* Green Paradox can be defined as follows.

Definition 2: *A strong Green Paradox arises if an increasing cash flow tax leads to higher cumulative net present value climate damages compared to the business-as-usual scenario, formally, if* $\Gamma^{tax} > \Gamma$.

Climate change damages as formulated in Equation (7) are captured through a shadow price on fossil fuel emissions, χ_t with $\chi_t = \chi_o \cdot e^{\hat{\chi} \cdot t}$ and $\hat{\chi} > 0$, reflecting an increasing shadow price over time. Fossil fuel emissions are assumed to be equal to the amount of fossil fuels extracted, while in reality, the amount of CO_2 emissions per unit of fossil fuel are proportional to the carbon content of the type of fossil fuel used. An increasing shadow price can be interpreted as being a result of increasing greenhouse gas concentration in the atmosphere, which in turn implies growing marginal damages from emissions. This is a standard assumption in the literature (refer to Ulph and Ulph 1994; Hoel and Kverndokk 1996). However, in line with Gerlagh (2011), the present value of marginal damages, $e^{-rt}\cdot\ x_t$, decreases over time, that is early extraction (emissions) causes higher net present value damages than delayed extraction. That is, marginal damage from extraction increases by a lower amount than the discount rate, such that $\hat{x} < r$. This reflects the assumption of the Green Paradox theory (Sinn 2008) that postponing extraction is beneficial for the climate. As a result, the damage function used in this paper has been chosen for its consistency with the Green Paradox formulation (refer to Hoel 2009 for a similar approach). In his paper, Gerlagh (2011) notes that 'the assumption does not require marginal damages to follow a hump-shaped curve; it only requires marginal damages not to grow too fast'. While this does not conform to the standard approach to specifying climate damage functions (refer to Hoel and Kverndokk 1996; Nordhaus 2007), it does replicate a major characteristic of the Green Paradox as formulated in Sinn (2008).

3. Results

This section presents the conditions under which the optimal decision of the fossil fuel extracting firm leads to a *weak* and a *strong* Green Paradox. To derive these conditions, the following subsections derive the fossil fuel extraction paths that emerge under the business-as-usual and tax scenarios.

3.1. The optimal supply decision

The dynamic optimisation problem formulated in Equations (3–5) is solved through a Hamilton function (refer to the Appendix for the Hamiltonian function and the necessary conditions). As a result, optimal extraction activities within the business-as-usual scenario follow the Hotelling rule,

$$\dot{P}_t = r \cdot P_t, \tag{8}$$

while the optimal price path within the policy scenario is given by

$$\dot{P}_t^{tax} = (r - \hat{\theta}) \cdot P_t^{tax}. \tag{9}$$

Recall from above that the tax factor θ_t equals to $(1-\tau_t)$ with τ_t denoting the tax rate. This implies that an increasing cash flow tax corresponds to $\hat{\theta} < 0$. Comparing the two price paths, it clearly follows that the growth rate of the price is greater in the policy scenario, indicating a steeper extraction path. Hence, the firm extracts in the early periods a higher fraction of the initial fossil fuel stock compared to the fraction that is optimal in the business-as-usual scenario. This is intuitive as a notable growth rate of the tax creates a higher tax burden in the farer future such that it is optimal for the firm to reallocate extraction activities to earlier periods where the tax rate is lower.

The assumption regarding a competitive economy [formally, $R_t = D(P_t)$ and $R_t^{tax} = D(P_t^{tax})$] as well as the fact that it is optimal for the firm to extract completely the explored resource stock over an infinite time horizon, results in the following equation formulations.

$$\int_0^\infty P_t^{-\gamma}\,\mathrm{d}t = S_0 \tag{10}$$

and

$$\int_0^\infty P_t^{tax-\gamma}\,\mathrm{d}t = S_0^{tax}. \tag{11}$$

Solving Equations (10) and (11) and again using the assumption regarding a competitive economy lead to the optimal extraction paths. Initial extraction levels are given by

$$R_0 = \gamma \cdot r \cdot S_0 \tag{12}$$

and

$$R_0^{tax} = \gamma \cdot (r - \hat{\theta}) \cdot S_0^{tax}. \tag{13}$$

Recall from Definition 1 that a *weak* Green Paradox occurs if initial extraction is higher in the policy scenario than in the business-as-usual scenario. The growth rate of the tax factor, $|\hat{\theta}|$, triggers an increase in the right hand side of Equation (13). On the other hand, it also impacts exploration incentives and hence extraction levels, S_0^{tax}, creating a decrease on the right hand side of Equation (13). This can be seen by comparing optimal exploration investments of the two scenarios. Consider the optimal level of exploratory activity in the business-as-usual scenario. According to Lasserre (1991), the firm's optimal investment in exploration must satisfy the following transversality condition at $t = 0$,

$$C'(S_0) = \lambda_0 = P_0. \tag{14}$$

The transversality condition requires that at $t = 0$, the cost of exploring a marginal unit of fossil fuel, $C'(S_0)$, must be equal to its additional benefit that is measured by its shadow value, λ_0 (both expressed in discounted value terms). The optimal exploration decision with an increasing cash flow tax is required to satisfy the following transversality condition

$$C'(S_0^{tax}) = \lambda_0^{tax} = P_0^{tax} \cdot \theta_0. \tag{15}$$

Equations (14) and (15) show that optimal investment in exploration is lower in the policy scenario thereby lowering the amount of fossil fuels discovered compared to the business-as-usual scenario, formally, $S_0 > S_0^{tax}$.

3.2. Conditions for a weak Green Paradox

A *weak* Green Paradox arises when initial emissions from fossil fuel extraction are higher in the policy scenario compared to the business-as-usual scenario, formally, if $R_0^{tax} > R_0$. A *weak* Green Paradox is generated if

$$\theta_0 > \left(1 + \frac{|\hat{\theta}|}{r}\right)^{1-\alpha}. \qquad (16)$$

To derive this result, the absolute value of the growth rate of the cash flow tax, $|\hat{\theta}|$, has been used to facilitate interpretation (refer to the Appendix for the derivation). The short-term effect on the climate is detrimental with increased emissions in early periods if the initial tax factor is greater than $\left(1 + \frac{|\hat{\theta}|}{r}\right)^{1-\alpha}$. The condition depicts clearly the drivers of a *weak* Green Paradox. The higher the initial tax factor θ_0 (equivalently, the lower the initial burden of the tax) and the higher the growth rate of the cash flow tax, $|\hat{\theta}|$, the more plausible a *weak* Green Paradox. This is illustrated in Figures 1a,b, 2a,b.

Figure 1a,b illustrates the effect of a cash flow tax with a low and a high growth rate (denoted as tax scenario 1 and 2, respectively) on extraction paths and this corresponds with the appearance of a *weak* Green Paradox. Figure 1a shows the initial resource amount available for extraction within the business-as-usual scenario and the policy scenarios. To do this, the graph depicts marginal exploration costs as defined by Equation (3) and the shadow values of all three scenarios as functions of total available resources, S_0. The optimal investment in exploration for each scenario, S_0^{bau}, S_0^{tax1} and S_0^{tax2}, is determined by the intersection of marginal exploration costs and shadow value curves. By imposing a cash flow tax, the initial shadow value of the fossil fuel resource decreases [refer to Equation (15)], thereby reducing optimal marginal exploration costs. As a result, total available resources within both tax scenarios are lower compared to the business-as-usual scenario. A high growth rate of the tax (tax scenario 2) leads to the lowest level of available resources. This volume effect leads to an upwards shift of the price path as less fossil fuels are supplied over the same time period. In addition to the volume effect, the increase of the tax over time triggers a temporal redistribution with relatively more resources being extracted in earlier periods. If the second effect predominates, a *weak* Green Paradox occurs. This is more plausible the higher the growth rate of the tax as can be seen in Figure 1b.

Figure 1b depicts the initial price levels associated with the three scenarios, P_0^{bau}, P_0^{tax1} and P_0^{tax2}, as functions of the amount of fossil fuel explored. Given the optimal initial resource levels, S_0^{bau}, S_0^{tax1} and S_0^{tax2} as determined in Figure 1a, it can be seen that a high growth rate of the tax (tax scenario 2) leads to a lower initial price level compared to the business-as-usual scenario

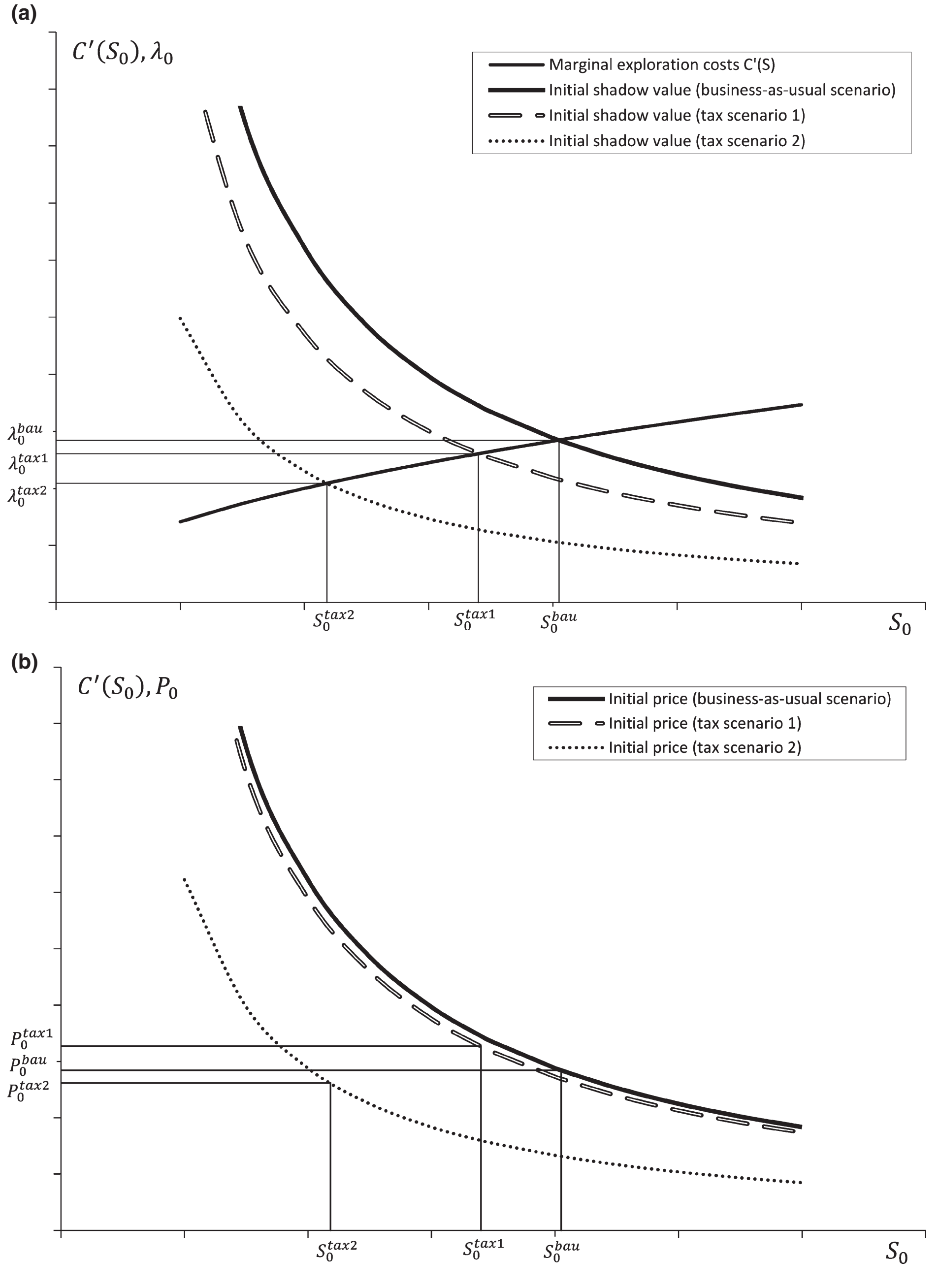

Figure 1 (a) The effect of different growth rates of the tax on the fossil fuels stock. (b) The effect of different growth rates of the tax on the initial price level.

and this generates a *weak* Green Paradox. The growth rate causes a reallocation of extraction to earlier periods that is sufficiently high to offset the volume effect and this results in a higher initial extraction level compared to the business-as-usual scenario. On the other hand, tax scenario 1 leads to a

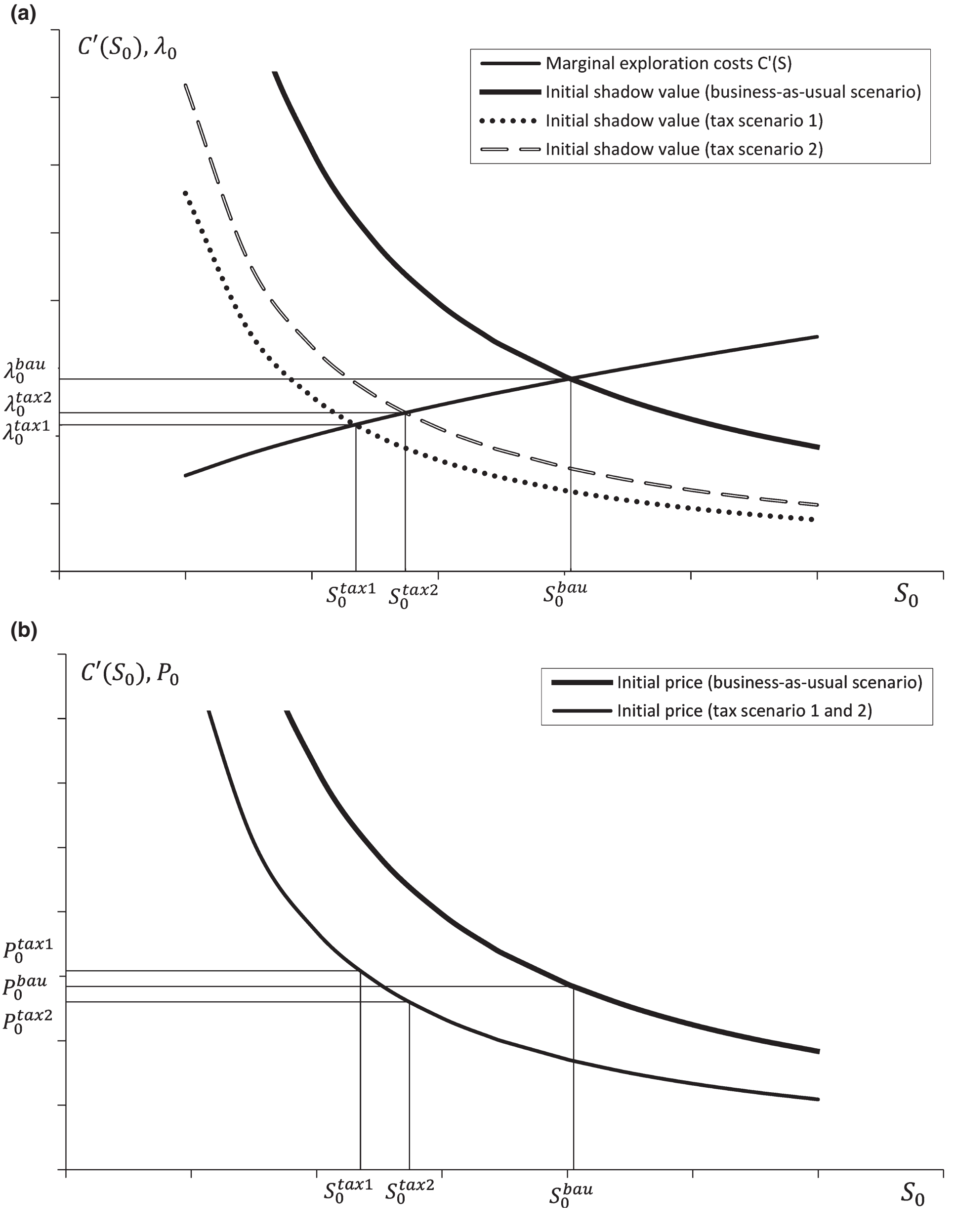

Figure 2 (a) The effect of different initial tax rates on the fossil fuel stock. (b) The effect of different initial tax rates on the initial fossil fuel price.

higher initial price compared to the business-as-usual scenario and hence no *weak* Green Paradox is generated.

Figure 2a,b shows two tax scenarios where a high initial tax rate (tax scenario 1) does not lead to a *weak* Green Paradox, whereas a low initial tax rate (tax scenario 2), *ceteris paribus*, does. In line with Figures 1a,1a. Figure 2a depicts the optimal amount of total resources based on the firms' exploration decisions, S_0^{bau}, S_0^{tax1} and S_0^{tax2}, while Figure 2b shows the initial price levels for each of the three scenarios. Figure 2a illustrates that a tax reduces the shadow value of the resource and hence it is optimal to decrease the total amount of fossil fuels available within the policy scenarios compared to the reference scenario. As a result, total extraction decreases and this leads to an upwards shift of the price path. However, this volume effect is too small to avoid a *weak* Green Paradox when there is a small initial tax level as in tax scenario 2. Under this scenario, the timing effect that results from the incentive to extract the resource faster (due to the increase of the tax over time) is stronger than the volume effect, thereby causing a *weak* Green Paradox.

3.3. Conditions for a strong Green Paradox

A *strong* Green Paradox occurs when net climate damages are greater in the policy scenario than in the business-as-usual scenario. Formally, this is specified as

$$\theta_0 > \left(1 + \frac{\gamma \cdot |\hat{\theta}|}{r \cdot (1+\gamma) - \hat{\chi}}\right)^{\alpha - 1 + \frac{1}{\gamma}} \left(1 + \frac{|\hat{\theta}|}{r}\right)^{1-\alpha}. \tag{17}$$

The Appendix provides the formal derivation of the conditions for the *strong* Green Paradox. It is more plausible that an increasing cash flow tax generates a *strong* Green Paradox, the lower the initial tax burden (associated with a high θ_0) for given values of $\hat{\theta}, r, \gamma, \hat{\chi}$ and α. This is intuitive as a lower initial tax level (and hence a lower tax level in all subsequent periods) assures a higher level of investment in exploratory activities and hence a higher total amount of extractable fossil fuels, while the temporal distribution of extraction remains the same for a given growth rate of the tax. In turn, more emissions enter the atmosphere at each point in time from 0 to infinity the lower the initial tax level.

3.3.1 Impact of the growth rate of the tax $|\hat{\theta}|$

The level of the growth rate of the tax has an ambiguous impact on the climate. A very low growth rate leads to a small temporal redistribution such that a *strong* Green Paradox is avoided. With a high growth rate, the incentive to extract the resources earlier increases; however, if the level of the tax grows significantly, it can reduce expected profits such that the investments in exploration activities shrink notably. In this case, a *strong* Green Paradox may be avoided if the reduction of the total amount of extraction is sufficiently high to offset the increase in initial extraction. As a result, there is a specific range of growth rates that generate a *strong* Green Paradox, *ceteris paribus*. In particular, the smaller the growth rate as well as the higher the growth rate, the less plausible is the generation of a *strong* Green Paradox.

3.3.2 Impact of the discount rate r

A higher discount rate r, *ceteris paribus*, leads to a smaller value of the right hand side in Equation (17) and hence makes a *strong* Green Paradox more plausible. Consistent with the climate change damage function stated in Equation (7), the greater r, the greater the discounted climate damage associated with the use of an additional unit of fossil fuels in early periods compared to later periods. Hence, it is intuitive that the reallocation of extraction to early periods in response to the implementation of a tax scheme is more harmful to the climate, the higher the value of r, making a *strong* Green Paradox more plausible.

3.3.3 Impact of the shadow price of emissions $\hat{\chi}$

The right hand term of Equation (17) increases with the shadow price of emissions, $\hat{\chi}$. This indicates that with a higher value for $\hat{\chi}$, a *strong* Green Paradox is less plausible because the timing of the emissions for climate damage is less relevant and hence a reallocation of extraction activities to earlier periods is less harmful for the climate.

3.3.4 Impact of the parameter α

The higher the value of α, the smaller becomes the right hand side of Equation (17), making a *strong* Green Paradox more plausible. A high α is associated with an exploration cost function with high marginal exploration costs. Any given decrease in optimal marginal exploration costs due to the implementation of a tax in this case results in a smaller decrease in the absolute amount of fossil fuel discovered. Hence, total discoveries are lowered, but by a smaller fraction. This results in a lower reduction in climate change damages and hence makes a *strong* Green Paradox more plausible.

3.4. Summary of the results and discussion

The results show that an increasing cash flow tax tends to reduce climate damages when exploration is modelled endogenously. The size of the initial fossil fuel stock depends on the expected profit from extraction activities. Under this assumption, any cash flow tax reduces the expected profit for a given amount of fossil fuels leading the competitive firm to reduce exploratory activities, thereby lowering the size of the overall stock available. In addition to the volume effect, a tax exerts a change in the temporal distribution of extraction with an increase of the fraction of the fossil fuel stock which gets extracted in the near term future in comparison with the no tax scenario. Hence, the extraction path under a tax scenario in comparison with the business-as-usual extraction path is unclear and depends on the exact tax scheme.

Three different results are possible. First, an increasing cash flow tax may be effective in climate change mitigation as it lowers emissions from fossil fuels at all points in time in comparison with the business-as-usual scenario. Second, an increase in initial extraction activity may occur, thereby leading to higher initial emissions and a *weak* Green Paradox. The review in Section 3.2 shows that the lower the initial burden of the tax and the higher the growth rate, the more plausible a *weak* Green Paradox. However, the tax may be an effective climate change mitigation policy in this situation and hence a *strong* Green Paradox is avoided. The occurrence of the third possible result, the appearance of a *strong* Green Paradox, depends on the specific tax scheme $[\theta_0, \hat{\theta}]$ given the development of marginal climate change damages over time, $\hat{\chi}$, the discount rate, r, and exploration costs, α [refer to Equation (17)]. In general, a tax scheme is more effective for climate change mitigation when the initial tax level is high and it is combined with a very high or a very low growth rate of the tax.

Note that the policy scenario studied within this paper may correspond to different climate change measures and commitment levels that are effective in decreasing global fossil fuel demand. For example, partial commitment and global mitigation strategies may lead to decreasing global demand. It should be noted, however, that there are several mechanisms that countervail the effectiveness of climate policy measures in terms of the global reduction of fossil fuels demand. For example, the effectiveness of partial commitment may be weakened by carbon leakage. This phenomenon occurs when emission reductions obtained by a subset of countries are offset by an increase in emissions in nonabating countries (Paltsev 2001). A main channel for carbon leakage is industrial migration, which is caused by a relative production cost increase in countries that enforce climate policies compared to other countries (Dröge 2009). In this case, fossil fuel owners may not be too concerned about a worldwide demand decrease because the policies in place are not effective to achieve this. While this article focuses on policy scenarios that are effective in decreasing the global price path of fossil fuels, Eichner and Pethig (2009) present a framework that studies the green paradox effect allowing for partial commitment and carbon leakage effects.

4. Conclusion

By including exploration activity in a standard resource extraction model, the article shows that an increasing cash flow tax may be an effective instrument to control climate change. This result is also valid for an increasing *ad valorem* carbon tax because it is identical to a cash flow tax as the model does not incorporate extraction costs. The tax leads to a temporal redistribution of extraction activities to earlier periods because firms expect the tax burden to increase over time. However, the total amount of resources extracted by the firm over the whole time horizon tends to be lower because of a reduction in exploratory activities following a decrease in expected profits from extraction. The results obtained within this article contrast with the well-known effect of an increasing cash flow tax within a basic Hotelling framework utilised within Sinn (2008). Sinn (2008) finds that an increasing cash flow tax worsens climate change due to the total amount of fossil fuels extracted remaining unchanged while resource owners hasten extraction.

The results of this paper are derived within a framework that extends the standard extraction model based on Hotelling (1931) by accounting for the reality that firms are not endowed with fossil fuels. To incorporate exploration, the approach of Heaps and Helliwell (1985) and Lasserre (1991) was applied. Both focus on the endogeneity of the reserve base and include exploration efforts that are undertaken prior to the extraction phase and depend on the expected profit from extraction. The assumptions surrounding the formulation of climate damages and extraction have been driven by a desire to maintain consistency with the assumptions of Sinn (2008) and the need to solve the model analytically. This is in contrast with utilising alternate approaches that more complex formulations would deem necessary.

To generate desirable results in terms of climate change mitigation within the proposed framework, a specific tax scheme is required. A higher initial tax rate with a steep or relatively flat growth rate makes it more plausible that climate change policy will be effective. The effectiveness of a specific tax scheme depends on the development of climate change damages from emissions over time, the interest rate and the exploration cost function.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1.