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**Working Paper**

## Carbon Taxes, Oil Monopoly and Petrodollar Recycling

ifo Working Paper, No. 204

**Provided in Cooperation with:**

Ifo Institute – Leibniz Institute for Economic Research at the University of Munich

*Suggested Citation:* Marz, Waldemar; Pfeiffer, Johannes (2015) : Carbon Taxes, Oil Monopoly and Petrodollar Recycling, ifo Working Paper, No. 204, ifo Institute - Leibniz Institute for Economic Research at the University of Munich, Munich

This Version is available at:

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# **ifo** Working Papers

## Carbon Taxes, Oil Monopoly and Petrodollar Recycling

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Ifo Working Paper No. 204

September 2015

An electronic version of the paper may be downloaded from the Ifo website  
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## Carbon Taxes, Oil Monopoly and Petrodollar Recycling

### Abstract

We analyze the effects of an announced future carbon tax increase on the extraction behavior of a monopolistic supplier of a scarce fossil energy resource like oil in a two country, two period general equilibrium model with symmetric and homothetic preferences and no extraction costs. Based on the monopolist's strategic consideration of the interplay between the resource and the capital market, and especially of the effects of the extraction decision on the return on petrodollar financed capital investments we identify and analyze a new channel for the reversal of the green paradox, a major concern regarding carbon taxation. We employ a numerical simulation and a sensitivity analysis with regard to the model parameters to evaluate the prevalence of such a reversal of the green paradox and find that it robustly arises under a wide range of reasonable parameter settings.

**JEL codes:** D90; H20; Q31; Q38

**Keywords:** green paradox, monopoly, fossil energy resources, general equilibrium, capital market

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# 1 Introduction

The climate policy debate has seen the development of a whole literature which focuses on the supply side of fossil energy resources, and particularly oil, since the contribution of Sinn (2008). It has been acknowledged that taking into account the reaction of fossil energy resource exporters to climate policy and technology policy measures in the importing countries can be important for the effectiveness and the consequences of these policies. In particular, it has been pointed out that the introduction or credible announcement of climate policies such as a unilateral carbon tax on imported fossil fuels in the future, which might even rise over time, could very well cause the opposite of the intended climate relief: The dire revenue perspective in the future would lead the fossil fuel exporters to accelerate extraction in the present and thereby to increase cumulative climate damages. In most cases, the analysis of whether such a green paradox outcome arises or not is based on partial equilibrium models of the fossil resource market. For a very recent overview over the literature on the green paradox see for example Jensen et al. (2015) and van der Ploeg and Withagen (2015).

A general equilibrium perspective, however, yields additional insights into the supply behavior in resource markets, as work by Hillman and Van Long (1985), Hassler et al. (2010) and Moussavian and Samuelson (1984) confirms. Van der Meijden et al. (2015) show that general equilibrium feedback effects over a bond and a capital market can affect the supply side reaction to an announced carbon taxation for the case of perfectly competitive resource markets and that the green paradox can be reversed for asymmetric preferences in the importing and the exporting country. The importance of the general equilibrium feedback effects for the green paradox is also pointed out by van der Ploeg (2015). Van Long (2015) takes a slightly different perspective by discussing leakage effects from unilateral climate policies or generally effects from trade in final goods or production factors which may lead to climate policy outcomes adverse to the intentions of policy makers or may counteract such green paradox results (see also e.g. Eichner and Pethig (2011)).

We are interested in the interaction of the market for physical capital and the resource market in a general equilibrium framework and its consequence for the supply behavior of fossil resource owners as van der Meijden et al. (2015). But in contrast to their contribution we consider a single resource owner with market power. In Marz and Pfeiffer (2015) we use the same basic model framework as in the present paper (without a carbon tax) to show that the interaction of the capital and the resource market already

has implications for the supply decision of a resource owner with market power if the monopolist is aware of the general equilibrium structure and of the more widespread effects of resource supply in such a general equilibrium setting (cf. also Bonanno (1990)). More specifically, additional supply motives arise from the interaction of these markets in general equilibrium and from the complementarity of physical capital and the fossil resource in final goods production in particular: The monopolist takes into account the influence of resource supply on the return of his own capital assets and on capital accumulation with resulting feedbacks on capital and resource demand. In the conventional view market power does not alter profoundly the intertemporal supply decision compared to fully competitive suppliers (cf. Stiglitz (1976)). In the special case of a constant elasticity of resource demand and no extraction costs the resulting supply paths are even identical. But the arising general equilibrium supply motives mentioned above additionally affect the optimal supply path of a monopolist and lead it to deviate from the competitive outcome even given a constant demand elasticity and no extraction costs. The present paper builds upon this analysis and shows that these general equilibrium supply motives of a monopolist, the capital asset motive in particular, give rise to a new channel for a reversal of the green paradox, even without asymmetric preferences and without stock-dependent or other extraction costs: The expected income loss through future resource taxation leads the resource-rich country to increase its savings, which in turn boosts the monopolist's capital asset motive in the second period and creates an incentive to postpone oil extraction that can dominate the conventional green paradox effect. In fact, in a numerical simulation of the model framework the reversal of the green paradox can be observed for a wide range of plausible parameter settings.

We present our two period, two country model framework in section 2 and briefly summarize how the additional effects of resource supply in this general equilibrium setting modify the extraction decision of an omniscient monopolist, in particular by the capital asset motive, in section 3. In section 4 we theoretically identify and interpret the mechanism which may lead to a reversal of the green paradox. The theoretical analysis is complemented by a numerical simulation and sensitivity analysis in section 5 to evaluate the prevalence of the reversal of the green paradox and the role of the most important parameters for the outcome. We analyze how the parameters of the production technology, the initial factor endowments and the consumption preferences of households determine the direction of the extraction shift in reaction to a future tax increase. Finally, section 6 concludes.

## 2 Model

We consider a general equilibrium framework with two countries  $m = E, I$  and a finite time horizon of two periods  $t = 1, 2$ . In each country, there is a representative household deriving utility from consuming a final good which we choose as numeraire. Households have symmetric homothetic preferences represented by the life-time utility function

$$U(c_{1m}, c_{2m}) = u(c_{1m}) + \beta_m u(c_{2m}) = \begin{cases} \frac{c_{1m}^{1-\eta}}{1-\eta} + \beta_m \frac{c_{2m}^{1-\eta}}{1-\eta} & \text{for } \eta \neq 1, \eta > 0 \\ \ln c_{1m} + \beta_m \ln c_{2m} & \text{for } \eta = 1 \end{cases} \quad (1)$$

where  $1/\eta$  equals the constant elasticity of intertemporal substitution and  $\beta_m < 1$  denotes the utility discount factor for country  $m = E, I$ . For symmetric countries, we have  $\beta_E = \beta_I$ .

### 2.1 Resource Extraction

Country  $E$  owns the entire global stock of a fossil resource  $\bar{R}$  which is costless to extract, just as in the very basic textbook model of resource economics. Resource extraction is controlled by some authority which we call the “sheikh” who benevolently distributes resource income

$$\pi_{tE}^\tau = \tilde{p}_t R_t \quad (2)$$

to his constituency, i.e. to the representative household in country  $E$ , where  $R_t$  denotes resource supply and  $\tilde{p}_t$  the resource producer price.

We assume the resource to be scarce so that the sheikh has to obey the resource constraint and aggregate supply cannot exceed the given resource stock

$$R_1 + R_2 = \bar{R} \quad (3)$$

### 2.2 Final Goods Production

In the block of resource-importing countries  $I$ , there is a competitive final goods production sector. Final goods are produced by use of three input factors, capital  $K_t$ , resources  $R_t$  and labour  $L_t$  which is in constant supply from the representative household. We

assume a CES production technology

$$F_t = F(K_t, R_t) = A [\gamma K_t^\alpha + \lambda R_t^\alpha + (1 - \gamma - \lambda)L^\alpha]^{\frac{1}{\alpha}} \quad (4)$$

where  $-\infty < \alpha < 1$ . The parameter  $A > 0$  measures total factor productivity, and the constant elasticity of substitution between the two variable input factors is given by

$$\sigma = -\frac{d \ln \left( \frac{K_t}{R_t} \right)}{d \ln \left( \frac{F_{tK}}{F_{tR}} \right)} = \frac{1}{1 - \alpha} > 0$$

The CES technology has constant returns to scale but decreasing returns to scale with respect to the only variable production inputs capital and oil so that<sup>1</sup>

$$\Gamma_t = F_{tRR}F_{tKK} - F_{tKR}^2 > 0 \quad (5)$$

and firms earn zero profits in the competitive market equilibrium.

With profit maximizing competitive final goods producers the first-order conditions for optimal factor use (implicitly) define the market demand for the resource

$$R_t^d = R_t^d(p_t, i_t) \quad \text{with} \quad dR_t^d = \frac{F_{tKK}}{\Gamma_t} dp_t - \frac{F_{tKR}}{\Gamma_t} di_t \quad (6)$$

and capital

$$K_t^d = K_t^d(i_t, p_t) \quad \text{with} \quad dK_t^d = \frac{F_{tRR}}{\Gamma_t} di_t - \frac{F_{tKR}}{\Gamma_t} dp_t \quad (7)$$

as functions of both, the consumer resource price  $p_t$  and the capital cost/return  $i_t$ .

From labour supply, the representative household earns labour income which derives from the residual profits

$$\pi_{tI} = F_t - p_t R_t - i_t K_t \quad (8)$$

given that we assume flexible wages (full employment).

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<sup>1</sup> Factor subscripts denote the first and second partial derivatives of the production function with respect to the respective factor(s).

## 2.3 Capital Supply

For the first period, there is an exogenously given capital endowment  $s_{0m}$  to households in both countries  $m = E, I$  which is used in final goods production. We therefore have

$$K_1^s = s_{0E} + s_{0I} \quad (9)$$

Second period capital supply derives from the aggregated but endogenous savings of households in both countries which do not add to the first period capital stock  $K_1$ . Instead, the existing capital stock is available for consumption (and savings) at the end of each period without depreciation. Positive capital accumulation therefore implies that  $s_{1E} + s_{1I} > K_1$ . The respective household has rational expectations and chooses savings as to maximize its life-time utility (1) subject to country-specific budget constraints.

In country  $I$ , the household takes current and future labour income, the market interest rates  $i_1$  and  $i_2$  as given, as well as tax revenue  $T_2$  which is collected from a value added (unit) resource tax  $\tau_2$  ( $\xi_2$ ) in the second period and lump-sum distributed to the household. Its budget constraints therefore are

$$c_{1I} = y_{1I} - s_{1I} \quad (10)$$

$$c_{2I} = \pi_{2I}^\tau + (1 + i_2)s_{1I} \quad (11)$$

where  $y_{1I} = \pi_{1I} + (1 + i_1)s_{0I}$  denotes the first period income stream and  $\pi_{2I}^\tau = \pi_{2I} + T_2$  the second period income stream which both are exogenous to the savings decision. In the text, we concentrate on the value added tax case and explicitly point out where a unit resource tax would have different implications. For the most part, the unit resource tax case is, however completely analogue.

In country  $E$ , the representative household earns income from capital endowment and from resource revenue so that the budget constraints for both periods are given by

$$c_{1E} = y_{1E} - s_{1E} \quad (12)$$

$$c_{2E} = \pi_{2E}^\tau + (1 + i_2)s_{1E} \quad (13)$$

where again  $y_{1E} = \pi_{1E} + (1 + i_1)s_{0E}$  denotes first period income exogenous to the savings decision and  $\pi_{2E}^\tau$  from (2) resource revenue net of taxes.

For given period income streams and a given interest rate  $i_2$ , optimal savings in both



countries are implicitly defined by the respective Euler equation

$$\frac{u'(c_{1m})}{\beta_m u'(c_{2m})} = 1 + i_2 \quad (14)$$

as a function

$$s_{1m} = s_{1m}(y_{1m}, \pi_{2m}^\tau, i_2) \quad (15)$$

From the total derivative of the Euler equation with respect to changes in period incomes and the interest rate, we derive the savings reactions

$$\begin{aligned} \frac{\partial s_{1m}}{\partial y_{1m}} &= \frac{[\beta_m(1+i_2)]^{\frac{1}{\eta}}}{1+i_2 + [\beta_m(1+i_2)]^{\frac{1}{\eta}}} > 0 \\ \frac{\partial s_{1m}}{\partial \pi_{2m}^\tau} &= \frac{\partial s_{1m}}{\partial \pi_{2m}} = -\frac{1}{1+i_2 + [\beta_m(1+i_2)]^{\frac{1}{\eta}}} < 0 \\ \frac{\partial s_{1m}}{\partial i_2} &= -\frac{\beta_m u'(c_{2m})}{u''(c_{1m}) + \beta_m(1+i_2)^2 u''(c_{2m})} + \frac{\partial s_{1m}}{\partial \pi_{2m}} s_{1m} \\ &= \frac{1}{\eta(1+i_2)} \frac{\pi_{2m}^\tau + (1-\eta)(1+i_2)s_{1m}}{1+i_2 + [\beta_m(1+i_2)]^{\frac{1}{\eta}}} \geq 0 \end{aligned} \quad (16)$$

Since we assume homothetic consumption preferences, the marginal savings propensities with respect to changes in period incomes are independent of the wealth of the household but are determined by the discount factor  $\beta_m$ , the intertemporal elasticity of substitution  $\frac{1}{\eta}$  and the market interest rate  $i_2$  only. As will be shown in the following section 2.4, the market interest is independent of the resource tax in the symmetric country case. Thus, in this case, the marginal savings propensities with respect to changes in period incomes are also independent of the resource tax and therefore completely equivalent to the no-tax case. The savings reaction to marginal changes in the interest rate generally is of ambiguous sign due to the counteracting income and substitution effect induced. Moreover, due to  $\pi_{2m}^\tau$  from (11) and (13) respectively it obviously depends on the resource tax and the distribution of resource remuneration between both countries.

In appendix A we show that, given that the resource constraint holds, second period capital supply from aggregated savings can be represented as a function of the resource supply path and the interest rate  $i_2$  only for *symmetric* ( $\beta_E = \beta_I$ ) and homothetic preferences, so that capital supply depends on the resource tax only via its influence

on the extraction decision. Thus,

$$K_2^s = K_2^s(R_2, i_2) \quad (17)$$

where just as in the no-tax case

$$dK_2^s = \left[ \frac{\partial s_{1E}}{\partial \pi_{2E}^\tau} p_2 - \frac{\partial s_{1E}}{\partial \tilde{y}_{1E}} p_1 \right] dR_2 + \left[ \frac{\partial s_{1E}}{\partial i_2} + \frac{\partial s_{1I}}{\partial i_2} - \frac{\partial s_{1I}}{\partial \pi_{2I}^\tau} K_2 \right] di_2 \quad (18)$$

A shift of resources to the future period decreases capital supply because it implies a transfer of final goods production and thereby aggregate (world) income from the first to the second period *ceteris paribus*. Given the savings propensities (16), this redistribution of income creates a disincentive to save. In contrast, aggregate savings unambiguously increase with a rise in the interest rate  $i_2$ . The ambiguity of the single household's savings reaction to an increase in the interest rate vanishes because the income effects which a higher interest rate induces for given savings in both countries are exactly compensated by the loss in labour income in country  $I$  from higher capital costs in final goods' production. In fact, we show in appendix A that

$$\frac{\partial s_{1E}}{\partial i_2} + \frac{\partial s_{1I}}{\partial i_2} - \frac{\partial s_{1I}}{\partial \pi_{2I}^\tau} K_2 = SE + ID_2 s_{1E}$$

where  $SE$  denotes the aggregated pure substitution effect from a change in the interest rate and  $ID_2 = \frac{\partial s_{1E}}{\partial \pi_{2E}^\tau} - \frac{\partial s_{1I}}{\partial \pi_{2I}^\tau}$  measures the net effect of a redistribution of second period's income from country  $I$  to country  $E$  on capital supply. A rising interest rate leads to a redistribution from labour to capital income which is obviously completely neutral within country  $I$  as households in  $I$  earn both, labour and capital income. However, since country  $E$  provides some part of the capital stock, a higher interest rate  $i_2$  in principle also leads to a redistribution from labour income in country  $I$  to capital income in country  $E$ . But as long as we assume symmetric homothetic preferences, all these distributive effects exactly offset each other ( $ID_2 = 0$ ) so that overall the reaction of aggregate capital supply to a change in the interest rate is solely driven by the pure substitution effect  $SE$ .

Similarly, aggregate capital supply does not depend on the future period's resource tax levied in country  $I$ . By raising the second period resource tax, country  $I$  is *ceteris paribus* able to capture a larger share of the resource rents from country  $E$ . With symmetric homothetic preferences, these income effects from the redistribution of the resource rents, however, exactly cancel out.

## 2.4 Conditional Market Equilibrium

In the following, we characterize the market equilibrium in all three markets, the resource market, the capital market and the market for final goods conditional on the resource supply path, i.e. given *any* allocation of resources to both periods that fulfills the binding resource constraint. The optimal resource supply for the sheikh controlling resource extraction in country  $E$  is derived later on. To this end, we also analyze the comparative statics of this conditional market equilibrium with respect to changes in the resource supply path. This gives us the actual (general equilibrium) market reaction to the supply decision which the resource monopolist takes into account if he has full level of information of the entire economic structure.<sup>2</sup>

**Resource Market:** The resource market equilibrium is characterized by the market clearing condition

$$R_t^d(p_t, i_t) = R_t^s \quad \text{for both periods } t = 1, 2 \quad (19)$$

for resource demand derived from competitive final goods production (6) and in conjunction with the binding resource constraint (3).

**Capital Market:** With fixed capital supply from aggregate endowments the capital market equilibrium condition in the first period therefore reads

$$K_1^d(i_1, p_1) = K_1 = s_{0E} + s_{0I} \quad (20)$$

with capital demand from (7).

In the second period, the capital market equilibrium is again characterized by the market clearing condition

$$K_2^d(i_2, p_2) = K_2^s(R_2, i_2) \quad (21)$$

where capital supply is a function of the resource supply path and the interest rate only in case of symmetric and homothetic consumption preferences according to (17).

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<sup>2</sup> We point to the role of information for the optimal resource supply decision in a general equilibrium framework in Marz and Pfeiffer (2015).

**Final Goods Market:** In equilibrium, aggregate consumption (and savings) of final goods has to equal aggregate consumption possibilities which are given from production and the capital stock in both periods:

$$\begin{aligned}c_{1E} + c_{1I} + K_2 &= F_1(K_1, R_1, L) + K_1 \\c_{2E} + c_{2I} &= F_2(K_2, R_2, L) + K_2\end{aligned}$$

If the resource and the capital market are in equilibrium, the market for final goods must be in equilibrium, too, due to Walras' law.

**Comparative Statics of the Conditional Market Equilibrium:** We now consider the dependency of the conditional market equilibrium laid out before on the resource supply path chosen. The conditional equilibrium is, in particular, characterized by equilibrium factor market prices in both periods and the equilibrium second period capital stock. Thus, we are interested in how the equilibrium market prices for the resource  $p_t$  and capital  $i_t$  as well as capital accumulation  $K_2$  depend on the resource supply path, i.e. on shifts of resources from one period to the other given that the resource constraint binds.

From the total derivative of (20) and (19) we observe that

$$\frac{dp_1}{dR_1} = \frac{\partial p_1}{\partial R_1} = F_{1RR} < 0 \quad (22)$$

due to the concavity of the production technology and

$$\frac{di_1}{dR_1} = \frac{\partial i_1}{\partial R_1} = F_{1KR} > 0 \quad (23)$$

by the complementarity of capital and resources in production.

For the second period, we get from totally differentiating (21) and (19), solving for the induced change in the equilibrium market prices and substituting in (18) the equilibrium

reaction of aggregated savings to a postponement of resource extraction<sup>3</sup>

$$\frac{dK_2}{dR_2} = \frac{\frac{\partial s_{1E}}{\partial \pi_{2E}} p_2 - \frac{\partial s_{1E}}{\partial y_{1E}} p_1 + F_{2KR} SE}{1 - F_{2KK} SE} \quad (24)$$

where  $SE$  again denotes the aggregated substitution effect from a change in the interest rate  $i_2$ .

The denominator captures the feedback effect of a change in the second period capital stock on savings incentives. A higher capital stock  $K_2$  decreases ceteris paribus the marginal productivity of capital due to the concavity of the production technology (4) and thus the interest rate  $i_2$  in capital market equilibrium, which induces households to substitute savings for present consumption.<sup>4</sup> Due to the concavity of the production technology and the positive substitution effect  $SE$ , the denominator is unambiguously positive.

The numerator in (24) measures the influence of a shift of resources to the future period on savings incentives. First, a reallocation of resources from the first to the second period shifts ceteris paribus production and thereby aggregate income to the future period. At the margin, these income changes are given by the marginal product of the resource in the respective period, i.e. by  $F_{1R}$  and  $F_{2R}$  which equal the resource (consumer) prices  $p_1$  and  $p_2$  in resource market equilibrium. From the marginal savings propensities in (16) it is obvious that such an intertemporal transfer of income works towards lower savings. Second, by the complementarity of resources and capital in production a higher future resource supply ceteris paribus boosts the marginal productivity of capital which translates into a higher capital return in market equilibrium ( $F_{2KR} = \frac{\partial i_2}{\partial R_2} > 0$ ). This again induces a substitution effect which unambiguously increases the savings incentives in both countries. Thus, the overall reaction of capital accumulation to a postponement of extraction is ambiguous, in general.<sup>5</sup>

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<sup>3</sup> We simplify notation by using

$$\frac{\partial s_{1E}}{\partial i_2} + \frac{\partial s_{1I}}{\partial i_2} - \frac{\partial s_{1I}}{\partial \pi_{2I}^*} K_2 = SE$$

in case of symmetric preferences as we showed above and in appendix A.

<sup>4</sup> Recall that the income effects induced in both countries by this decrease in the interest rate exactly offset each other in case of symmetric and homothetic consumption preferences.

<sup>5</sup> In our accompanying paper Marz and Pfeiffer (2015), we concentrate for intuitive reasons on the case where the savings disincentive from the intertemporal transfer of aggregate income to the second period dominates the induced substitution effect so that there is a negative relationship between the postponement of extraction and the second period capital accumulation. In appendix B, we show

Given (24) the equilibrium change in the resource consumer price is<sup>6</sup>

$$\frac{dp_2}{dR_2} = \frac{\partial p_2}{\partial R_2} + \frac{\partial p_2}{\partial K_2} \frac{dK_2}{dR_2} = F_{2RR} + F_{2RK} \frac{dK_2}{dR_2} < 0 \quad (25)$$

where the negative sign holds irrespective of the sign of  $\frac{dK_2}{dR_2}$ . This implies that the direct own price effect  $\frac{\partial p_2}{\partial R_2}$  always outweighs the indirect price effect from the endogeneity of capital accumulation. Analogously, the equilibrium change in the interest rate can be decomposed

$$\frac{di_2}{dR_2} = \frac{\partial i_2}{\partial R_2} + \frac{\partial i_2}{\partial K_2} \frac{dK_2}{dR_2} = F_{2KR} + F_{2KK} \frac{dK_2}{dR_2} > 0 \quad (26)$$

where again the direct complementarity driven effect always outweighs the indirect effect of the resource supply path change so that the positive relationship holds irrespective of the sign of  $\frac{dK_2}{dR_2}$ . This independence of the market price reactions of the sign of  $\frac{dK_2}{dR_2}$  is at least true as long as we assume symmetric (homothetic) preferences, i.e.  $\beta_E = \beta_I$ .

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that a sufficient condition for this to hold is

$$\sigma \geq \frac{1}{\eta}$$

i.e. the elasticity of substitution between capital and oil in final goods production must not be lower than the intertemporal elasticity of substitution. In fact, the elasticity of substitution measures how easily capital and oil can be substituted in production. Thereby, it also captures how strongly capital demand reacts to a change in resource input in the end. The intertemporal elasticity of substitution in turn indicates how sensitive households' savings and therefore capital supply are with respect to changes in the interest rate  $i_2$ . Thus, intuitively, if  $\sigma > \frac{1}{\eta}$ , shifting resources to the second period lowers the resource price and thereby capital demand so much that the strong reduction of capital demand outweighs the incentive to increase savings from the complementarity driven rise of the interest rate  $i_2$ .

<sup>6</sup> From total differentiating both market equilibrium conditions (21) and (19), we get

$$\frac{dp_2}{dR_2} = \frac{F_{2RR} - \Gamma_2 SE + F_{2KR} \left( \frac{\partial s_{1E}}{\partial \pi_{2E}} p_2 - \frac{\partial s_{1E}}{\partial y_{1E}} p_1 \right)}{1 - F_{2KK} SE} < 0$$

for the resource consumer price. The negative sign unambiguously holds as  $F_{2RR} < 0$ ,  $F_{2KK} < 0$  and  $\Gamma_2 > 0$  due to the concavity of the production technology (see (5)),  $F_{2KR} > 0$  due to the complementarity of production factors, and  $SE > 0$  as shown in appendix A as well as  $\frac{\partial s_{1E}}{\partial \pi_{2E}} < 0$  and  $\frac{\partial s_{1E}}{\partial y_{1E}} > 0$  according to (16). This also implies that the equilibrium change in the interest rate

$$\frac{di_2}{dR_2} = \frac{F_{2KR} + F_{2KK} \left( \frac{\partial s_{1E}}{\partial \pi_{2E}} p_2 - \frac{\partial s_{1E}}{\partial \pi_{2E}} p_1 \right)}{1 - F_{2KK} SE} > 0$$

is unambiguously positive.

### 3 Optimal Resource Extraction

We discuss the optimal extraction decision of the sheikh which crucially depends on his awareness of the general equilibrium structure in Marz and Pfeiffer (2015) in more detail. In the following, we briefly summarize our results and main conclusions from there.

Given the conditional market equilibrium and some second period resource tax  $\tau_2$  raised in country  $I$ , a benevolent and omniscient sheikh chooses resource extraction as to

$$\max_{R_1, R_2} u(c_{1E}) + \beta_E u(c_{2E}) \quad (27)$$

where he takes into account as optimization constraints that the budget constraints (13), and the conditional market equilibrium represented by conditions (19), (20), (21) and the corresponding equilibrium relationships between second period resource supply and factor market prices (25), (26) must hold. By the binding resource constraint (3) we actually have an one-dimensional optimization problem. Moreover, since the representative household in  $E$  has rational expectations and makes an optimal savings decision for any resource income streams and interest rates the household takes as given, the Euler equation (14) holds for any resource supply path the omniscient sheikh chooses.<sup>7</sup>

Thus, substituting the marginal rate of substitution from the Euler equation (14) into the first order condition and simplifying the first order condition for the optimal resource supply path gives the modified Hotelling rule

$$(1 + i_2) \left[ p_1 + \frac{\partial p_1}{\partial R_1} R_1 + \frac{\partial i_1}{\partial R_1} s_{0E} \right] = \tilde{p}_2 + \frac{d\tilde{p}_2}{dR_2} R_2 + \frac{di_2}{dR_2} s_{1E} \quad (28)$$

where  $\frac{d\tilde{p}_2}{dR_2} = (1 - \tau_2) \frac{dp_2}{dR_2}$  in case of a value added resource tax (and  $\frac{d\tilde{p}_2}{dR_2} = \frac{dp_2}{dR_2}$  for a unit resource tax). Interestingly, the market discount factor does not reflect the influence of resource supply on capital return even though the sheikh takes this influence explicitly into account. This is due to the lack of “direct” capital market power of country  $E$  (via the savings decision  $s_{1E}$ ) which also separates our framework from Hillman and Van Long (1985).

The overall marginal resource value to the sheikh consists of the marginal resource

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<sup>7</sup> See also appendix C for a more extensive presentation of the sheikh’s optimization problem.

revenue and the marginal capital income effect of resource supply. We have

$$MR_t^{GA,\tau} = \tilde{p}_t + \frac{d\tilde{p}_t}{dR_t} R_t + \frac{di_t}{dR_t} s_{(t-1)E} \quad (29)$$

with  $\frac{dp_1}{dR_1}$  from (22),  $\frac{di_1}{dR_1}$  from (23),  $\frac{d\tilde{p}_2}{dR_2} = (1 - \tau_2) \frac{dp_2}{dR_2}$  from (25), and  $\frac{di_2}{dR_2}$  from (26).<sup>8</sup> As in the standard resource extraction problem, the modified Hotelling rule requires that the present value of the *overall marginal resource value* (not marginal resource revenue) is equal in both periods. In Marz and Pfeiffer (2015) we discuss the additional elements of this modified Hotelling rule and their implications by comparison to the standard case of a, following Moussavian and Samuelson (1985), completely “naive” monopolist who, although deciding in a general equilibrium setting does not take into account all the more widespread effects of resource supply in more detail. The main conclusion is that being aware of the more widespread effects of resource supply and internalizing them into the supply decision introduces additional (strategic) considerations.

The direct and positive influence of resource supply on the capital return (interest rate) in the respective period driven by the complementarity of production factors gives rise to a so called asset motive. The omniscient sheikh takes into account that in each period a higher resource supply supports the marginal productivity of capital and thereby the return on capital assets held by his constituency abroad. The implication of this asset motive on the supply path is ambiguous in general if country  $E$  owns some share of the capital stock in both periods. If leaving resources underground yields a higher (lower) return in terms of the capital income effect than in terms of the pure resource revenue at the margin, then it is optimal from the sheik’s perspective to choose a more (less) conservationist extraction path in comparison to his naive counterpart. If the households in country  $E$  are not endowed with capital assets and only own capital assets in the second period, the asset motive in the second period unambiguously creates an incentive to postpone extraction.

Additionally, there are indirect effects of resource supply from the endogeneity of capital

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<sup>8</sup> In case of a value added resource tax, we have

$$MR_2^{GA,\tau} = (1 - \tau_2) \left[ p_2 + \frac{dp_2}{dR_2} R_2 \right] + \frac{di_2}{dR_2} s_{1E}$$

whereas for an unit resource tax

$$MR_2^{GA,\tau} = p_2 + \frac{dp_2}{dR_2} R_2 - \tau_2 + \frac{di_2}{dR_2} s_{1E}$$



accumulation in our framework. First, if  $\frac{dK_2}{dR_2} < 0$ , the negative own price effect of resource supply on the resource price is strengthened in the second period, i.e.  $\frac{dp_2}{dR_2} < \frac{\partial p_2}{\partial R_2}$ . Postponing extraction lowers the second period capital stock and thereby induces, via the complementarity of production factors, a downward shift in second period inverse resource demand. Accounting for the stronger resource price reaction leads the omniscient monopolist clearly to shift resources to the first period in order to boost production and savings in the current period and to take advantage of the, again by the complementarity, increased resource demand in the future period. The feedback effect by the endogeneity of capital accumulation on resource demand therefore introduces what we call the addiction motive. Second, however, the negative relationship between future resource supply (given that the resource constraint holds) and the second period capital stock also strengthens the reaction of the future capital return to an increase in the future period's resource supply. This is due to the concavity of the production technology by which a fall in the capital stock raises the marginal productivity and thereby the market price of capital (indirectly induced own-price effect of capital accumulation). The stronger reaction of the future capital return adds to the future period's asset motive which creates an incentive to shift resource extraction to the second period.

Overall and in contrast to the standard but completely naive monopolist, the omniscient sheikh's extraction decision is extended by the asset motive in the first and the second period which is of ambiguous influence, and two counteracting (but unambiguous) indirect effects of resource supply. Unsurprisingly, the omniscient monopolist therefore may choose a more or less conservationist extraction policy or even the same extraction policy as the standard but naive monopolist in the same setting. Nevertheless, we can conclude that iso-elastic resource demand, which corresponds to  $\sigma = 1$  in our framework, no longer is sufficient for monopolistic and competitive resource extraction to coincide when resource extraction comes at no costs. Moreover, the omniscient monopolist may extract even faster than the competitive market so that the conservationist bias which is introduced in the standard monopoly case for of a price elasticity decreasing in value with resource supply (or  $\sigma < 1$  in our setting) may be reversed. Given the unambiguous extraction incentive introduced by the addiction motive we also can conclude that if the omniscient monopolist chooses a more conservationist supply policy then this incentive to postpone extraction must be due to the influence of the second period's asset motive – either due to the complementarity driven component alone or in combination with the strengthening of the asset motive by the capital accumulation reaction.

## 4 Revisiting the Green Paradox

Given the modified supply decision as characterized in the previous section we discuss the effect of future climate policies on the extraction path chosen by the benevolent and omniscient sheikh. By use of a comparative statics analysis we first show that a marginal increase in the future resource tax may induce a postponement of resource extraction due to the asset motive. We extend the theoretical analysis by proofing the monotonicity of second period resource supply in the future resource tax which allows us to consider discrete increases in the resource tax rate such as the introduction of a future resource tax policy and to derive that the initial distribution of capital asset endowments between the resource exporting country and the resource-importing countries is without any effect for the arising or the reversal of the green paradox. We also discuss the more fundamental drivers for the effect of the future resource taxation in more detail, in particular by describing the crucial influence of the elasticity of substitution. In the next section, we further investigate how the more fundamental model structure defined by the production technology, the consumption preferences of households and the factor endowments influence the monopolist's response to the introduction of a future resource tax policy by undertaking numerical simulations and a sensitivity analysis of the corresponding model parameters.

### 4.1 Comparative Statics: The Effect of Raising Future Resource Taxes

The modified Hotelling rule (28) extends the optimal extraction decision with additional motives and market reactions which a omniscient and benevolent sheikh takes into account. We now analyze whether these additional components also affect the reaction of the sheikh to future climate policies.

To this end we evaluate the change in the extraction path by use of the comparative statics with respect to a marginal increase in the future period's resource tax. This gives us the following proposition.

**Proposition 1.** *Due to pursuing the asset motive and endogenous savings the sheikh may no longer accelerate but postpone extraction upon an increase in the future period's resource tax. Such a reversal of the green paradox will arise if the strengthening of the future asset motive via larger asset holdings dominates the devaluation of future resource supply from the larger tax deduction.*

By totally differentiating (28) and thereby taking into account that (consumer) factor prices are functions of the resource supply path only according to (22), (23), (25), (26) the induced change in the optimal second period resource supply from a marginal increase in the future (value added) resource tax is

$$\frac{dR_2^{GA*}}{d\tau_2} = \frac{-\left(p_2 + \frac{dp_2}{dR_2} R_2\right) + \frac{di_2}{dR_2} \frac{\partial s_{1E}}{\partial \pi_{2E}} \frac{\partial \pi_{2E}^\tau}{\partial \tau_2}}{\frac{d[(1+i_2)MR_1^{GA}]}{dR_2} - \frac{dMR_2^{GA,\tau}}{dR_2}} \quad (30)$$

The denominator measures how the left and the right side of Hotelling condition (28) change with a marginal adjustment of the extraction path, i.e. a marginal shift of resources from the first to the second period. We have

$$\frac{d[(1+i_2)MR_1^{GA}]}{dR_2} - \frac{dMR_2^{GA,\tau}}{dR_2} = \frac{di_2}{dR_2} MR_1^{GA} - (1+i_2) \frac{dMR_1^{GA}}{dR_1} - \frac{dMR_2^{GA,\tau}}{dR_2} > 0$$

In appendix (C) we demonstrate that the positive sign has to hold due to the second order condition of the sheikh's maximization problem (27) as we (locally) evaluate the effect of the tax increase for a given welfare maximizing supply path  $(R_1^{GA*}, R_2^{GA*})$ .<sup>9</sup>

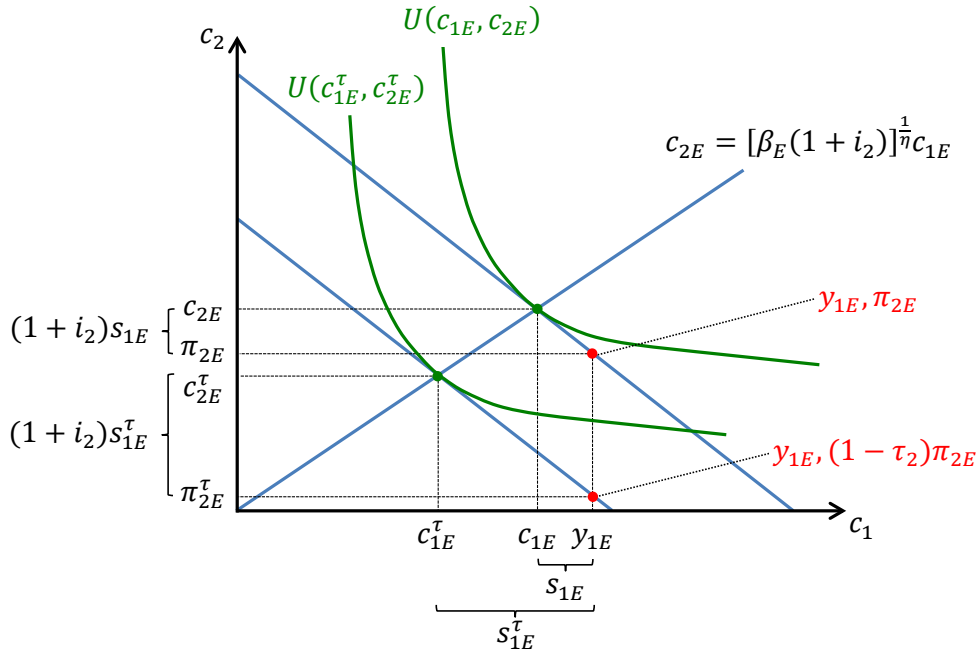
The numerator, in contrast, is generally of ambiguous sign and captures the direct effect of a marginal increase in the second period's resource tax on the Hotelling condition (28) for the initially, i.e. before the tax increase, optimal resource supply path. If the numerator is positive, we get a reversal of the green paradox in the sense that the sheikh will shift resources to the second period even though the resource is more heavily taxed in the future period. Since the introduction or change of the resource tax does not have any influence on the capital market equilibrium for symmetric homothetic consumption preferences, the direct effect of the resource tax is limited to the right side of Hotelling condition (28), i.e. to the future overall marginal resource value from the sheikh's perspective  $MR_2^{GA,\tau}$ . We know from (29) that the latter consists of two elements, the resource income component given by the general equilibrium version of the marginal resource revenue, as  $\frac{dp_2}{dR_2}$  from (25) includes the feedback from capital accumulation, and the capital income component introduced by the asset motive.

We start by considering the direct effect of the resource tax increase on the capital income component which is captured by the last term in the numerator of (30) and arises for the value added as well as for the unit resource tax case. Raising the resource

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<sup>9</sup> More generally, the positive sign also implies that the familiar Hotelling arbitrage consideration will lead the sheikh to the equilibrium outcome (at least locally).

tax for a given consumer resource price  $p_2$ <sup>10</sup> leads to a pure redistribution of income, or resource rents, from country  $E$  to country  $I$  which is measured by  $\frac{\partial \pi_{2E}^\tau}{\partial \tau_2} < 0$ . This income redistribution is completely neutral with respect to aggregated capital accumulation for symmetric homothetic consumption preferences as we have already discussed, but not with respect to the savings in both countries. The representative household in country  $E$  – having rational expectations – correctly foresees the loss in its future period’s resource income. Since  $\frac{\partial s_{1E}}{\partial \pi_{2E}} < 0$  from (16), the household reacts to this anticipated income loss by *increasing* its savings as to smooth consumption over time given its constant first period income.<sup>11</sup> Figure 1 graphically illustrates the effect of an introduction of a value added resource tax in the future period and demonstrates that the household will unambiguously increase its savings upon a rise in the resource tax rate even though the increase/introduction of the resource tax reduces the present value of its total life-time income or wealth  $w_E = y_{1E} + \frac{\pi_{2E}^\tau}{1+i_2}$ .<sup>12</sup> The reason is that for homothetic preferences



**Figure 1:** Savings reaction of the household in country  $E$  to an increase/introduction of the future period’s resource tax

<sup>10</sup> Recall that the numerator measures the effect of the tax rate increase for a given extraction path.  
<sup>11</sup> In turn, the households in country  $I$  will decrease their savings due to the higher resource tax revenue and thereby will exactly compensate for the larger capital supply from country  $E$  so that overall capital accumulation is constant.  
<sup>12</sup> The fall in the present value of life-time income can be observed from the point of interception of the budget line and the  $c_1$ -axis.

the household spends a specific share of the present value of total life-time income on first period consumption  $c_{1E}$ . This share only depends on the interest rate  $i_2$  which is independent of the resource tax for symmetric preferences according to (26), the utility discount factor  $\beta_E$  and the intertemporal elasticity of substitution  $\frac{1}{\eta}$  but not on the wealth  $w_E$  of the household. By the budget constraint (12) we have<sup>13</sup>

$$s_{1E} = y_{1E} - c_{1E} = y_{1E} - \frac{1 + i_2}{1 + i_2 + [\beta_E(1 + i_2)]^{\frac{1}{\eta}}} w_E = \frac{[\beta_E(1 + i_2)]^{\frac{1}{\eta}} y_{1E} - \pi_{2E}^T}{1 + i_2 + [\beta_E(1 + i_2)]^{\frac{1}{\eta}}}$$

Thus, first period consumption decreases with a fall in life-time income  $w_E$  for a given interest rate  $i_2$  but savings increase as the first period income  $y_{1E}$  is not affected by the tax induced income redistribution in the second period *ceteris paribus*.

Regarding the extraction incentives of the sheikh, the larger savings directly strengthen the asset motive in the second period because the marginal return on resource supply in the second period in terms of the capital income gain is larger. The value of future period's resource supply to the sheikh therefore raises which creates an incentive for the sheikh to shift resources to the second period. Thus, the resource tax induced adjustment of the future asset holdings unambiguously works towards a reversal of the green paradox if the sheikh pursues the asset motive.

The bracketed term in the numerator of (30) represents the marginal resource revenue before taxes and captures the effect of a marginal increase in the resource tax on the resource income component of the marginal resource value  $MR_2^{GA,\tau}$  from (29). Note that (30) gives the comparative statics for the effect of a value added resource tax. In case of a unit resource tax, the marginal effect of a tax increase on the marginal resource revenue, i.e. on the resource income component, would just be given by  $-1$ . If the marginal resource revenue is positive, the interpretation of both tax policies does not differ. An increase in the resource tax reduces the resource market related marginal value of future resource supply, i.e. the marginal resource revenue, and thereby obviously creates an incentive for the sheikh to shift resources from the second to the first period. It is exactly this devaluation of future resource supply that drives the acceleration of extraction upon the introduction or strengthening of future climate

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<sup>13</sup> Note that the present value of life-time consumption must not exceed  $w_E$ , i.e.

$$c_{1E} + \frac{c_{2E}}{1 + i_2} = w_E$$

By substituting  $c_{2E}$  from the Euler equation (14), we get the share of life-time income spent on first period consumption given in the text.

policies and thereby the arising of the green paradox in a standard partial equilibrium framework. The same holds true if we consider a naive resource monopolist instead of the omniscient monopolist in our general equilibrium setting.<sup>14</sup>

Overall, if the marginal resource revenue is positive, there are two counteracting effects so that the marginal tax effect is generally of ambiguous sign. If the strengthening of the asset motive via the endogenous savings reaction dominates the reduction in the marginal resource revenue in the resource market, the future marginal resource value to the sheikh will increase and the sheikh will be induced to shift resources to the period in which the resource is taxed more heavily. This supply reaction is exactly opposite to the one in a comparable partial equilibrium framework, i.e. monopolistic resource extraction without extraction costs, or opposite to the naive monopolist who does not pursue the asset motive. It crucially depends on the one hand on the sheikh's awareness of his influence on the return on household savings and thereby on the asset motive and on the other hand on the endogeneity of savings, or, more specifically, on the endogeneity of savings with respect to future resource income ( $\pi_{2E}^T$ ). If savings did not depend on second period income, for example by assuming that a constant share of first period income is saved (a constant savings rate), the reversal of the green paradox would be excluded as the second term in the numerator of (30) would vanish.

However, when considering the effect a *value added resource tax*, we additionally have to account for a special case. Due to the asset motive positively adding to the marginal resource revenue, the resource income component of  $MR_2^{GA,\tau}$ , i.e. the marginal resource revenue before taxes, may be negative even though  $MR_2^{GA,\tau}$  must be positive as long as we are interested in scenarios with resource scarcity. This leads to the following proposition.

**Proposition 2.** *The marginal resource revenue may be negative due to the asset motive. In this case, for a value added resource tax, the green paradox will always be reversed.*

Obviously, this special case can only arise for a value added resource tax which lowers the resource income component at the margin by the marginal resource revenue before taxes. Since the induced savings reaction already creates an incentive to postpone extraction, such a negative marginal resource revenue is a sufficient condition for the reversal of the green paradox. For this sufficient condition to hold the resource must

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<sup>14</sup>Note, however, that in contrast to these more standard, or more familiar, scenarios the marginal resource revenue from the omniscient sheikh's perspective in our general equilibrium framework does not only include the direct own price effect of resource supply but also the indirect price effect via the endogeneity of capital accumulation as we have  $\frac{dp_2}{dR_2}$  from (25) instead of  $\frac{\partial p_2}{\partial R_2}$ .

be so valuable in terms of capital market income that the sheikh is willing to accept an suboptimal low resource revenue. An increase in the value added resource tax then decreases the *negative* contribution of the resource income component and therefore *raises* the overall marginal resource value. The reason is that a higher value added resource tax lowers the negative own price effect of resource supply on the infra-marginal resource quantities sold so that the (negative) marginal resource revenue increases.<sup>15</sup> Finally, and in contrast to the unit tax case, we can also conclude that an endogenous savings reaction is no longer necessary for a reversal of the green paradox in this special case if we consider the effect of an increase of a value added resource tax.

## 4.2 Neutrality of Future Resource Taxation

The ambiguity of the numerator in (30) suggests that resource taxation may be completely neutral so that the (discrete) introduction of the resource tax policy would not alter the extraction path. The comparative statics in (30), however, characterizes the local effect of a marginal increase in the resource tax. Based on the (marginal or local) comparative statics analysis we therefore only can draw a conclusion about such a non-marginal tax policy change if the sign of the marginal tax effect at least prevails. But for the symmetric country case, even the following holds true.

**Proposition 3.** *The effect of the resource tax on second period resource supply is monotonous for symmetric homothetic consumption preferences.*

To show that the marginal tax effect given by (30) is of the same sign (but not necessarily of the same value which would imply linearity) irrespective of the initially given tax rate and irrespective of the magnitude of the tax increase, we first argue that the sign of (30) does not change with the tax rate. Since the denominator must be positive for any tax rate as long as we restrict the analysis to utility maximizing resource extraction policies, we just consider the numerator. The numerator depends on the tax rate not directly (or explicitly) but only indirectly via the resource supply path because the second period capital stock  $K_2$  and market prices  $i_2$  and  $p_2$  are functions of the resource supply path only (see (24), (25), (26)). However, this implies that even for different resource taxes the numerator must have the same sign if the sheikh happens to choose the same

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<sup>15</sup> Resource demand after taxes becomes more price elastic from the sheikh's perspective which increases the marginal resource revenue, i.e. inverse resource demand pivots inwards around the point of intersection with the horizontal ( $R_t$ -) axis. Note also that in case of value added resource tax, increasing resource supply at the margin lowers not only the price on infra-marginal resource quantities sold but also the absolute tax revenue collected from these quantities.

extraction policy. Thus, as we show in the following by contradiction, we can at least infer the sign of the discrete tax effect from the sign of the marginal tax effect, i.e. given any initial tax rate we must have a (reversal of the) green paradox for a marginal increase as well as for a discrete increase in the tax. Otherwise, if we had for example a reversal of the green paradox indicated by the marginal tax effect – a positive sign of the numerator in (30) – but a green paradox outcome for a non-marginal (discrete) increase in the tax rate, there must be at least one tax rate in between for which the sheikh would not adjust the supply policy at all given that the numerator is continuous in second period resource supply. In particular, for such a change from a reversal of the green paradox to a green paradox there must be at least one neutral tax rate for which the marginal tax effect is negative so that second period resource supply falls for any further increase in the resource tax  $\tau_2$ . But since differing signs of the marginal tax effect for the same extraction policy are excluded as long as the influence of the resource tax on the numerator in (30) runs via the resource supply path only, we can conclude that the sign of the marginal tax effect must prevail for any discrete tax policy changes. Second, since the same line of reasoning applies to any initial tax rate and extraction policy, second period resource supply must be monotonous in the tax rate.

The monotonicity of second period resource supply allows us to explain an intertemporal neutral tax policy by just considering the marginal tax effect. By the monotonicity we also may interpret (30) for an initially time constant value added resource taxation in *both* periods or the case where there is no resource taxation at all initially. This gives us the following proposition. An analogue proposition holds for the unit tax case.

**Proposition 4.** *In contrast to the standard case of a naive monopolist without extraction costs, even an over time increasing value added resource tax or the introduction of a value added resource tax in the future may be completely neutral due the asset motive and the endogeneity of savings.*

Both, an over time increasing value added resource tax or the introduction of a value added resource tax in the second period will not induce any adjustment of the extraction path if the numerator in (30) is exactly zero, i.e. both elements in the numerator of (30) must be counteracting, which holds true as long as the marginal resource revenue is positive, and exactly compensating each other. By the monotonicity of future resource supply we know that if a marginal change in the future resource tax does not induce any adjustment of the extraction path this must also be true for a discrete increase in the resource tax or, similarly, for an introduction of a resource tax in the second period. In fact, irrespective to the tax rate, resource taxation will always be neutral with respect



to the extraction path in this case. Note that this neutrality result crucially depends on our assumption of symmetric consumption preferences by which this transfer of resource rents does not influence aggregate capital accumulation.

Generally, the fact that an increase in the value added resource tax rate, or the introduction of a resource tax policy in the future period can be completely neutral with respect to the extraction decision is in contrast to the resource economics literature from which we know that with costless resource extraction only a time constant value added resource tax rate, i.e. a tax policy with a constant tax burden on resource rents in present value terms, does not create any incentive to reallocate resources between both periods for a competitive resource sector as well as for a resource monopolist (see, for example, Dasgupta and Heal (1979)).

### 4.3 The Role of the Asset Endowments Distribution

The monotonicity of second period resource supply allows us not only to infer discrete from marginal resource tax changes but also to analyze the influence of the distribution of the capital endowment  $K_1$  between both countries. This gives us the following proposition.

**Proposition 5.** *The arising or reversal of the green paradox does not depend on the distribution of the capital endowment between the resource exporting country and the resource-importing countries for symmetric preferences.*

To proof this we can rely on a very similar reasoning as for the monotonicity of second period resource supply. The asset endowments distribution, i.e.  $s_{0E}$ , does not have any direct influence on the numerator of (30) apart from its influence on the extraction path, just as the resource tax. Redistributing capital endowments to country  $E$  (i.e. without increasing  $K_1$ ) is purely distributive and therefore does not alter neither aggregate capital accumulation nor the relationship between resource supply and capital accumulation in the symmetric country case as we already have seen before when discussing (24)). However, since the households save a constant share of their first period income  $y_{1E}$  for a given interest rate  $i_2$  by (16), it disproportionally increases the asset holdings of country  $E$  in the first period compared to the second period and therefore strengthens the first period's over the second period's asset motive which induces the sheikh to speed up extraction for any given resource tax (see the analysis of the asset motive in our accompanying paper Marz and Pfeiffer (2015)). This implies that the sheikh chooses a less conservationist extraction policy for any tax rate than before

the asset endowment redistribution. Nevertheless, we may restore the initially chosen supply path by changing the tax rate. But since neither the tax rate nor the asset endowment of country  $E$  do have a direct or separate influence on the numerator in (30), we can conclude that the sign of the numerator – and given the unambiguously positive sign of the denominator also of the overall comparative statics (30) – cannot differ for the same extraction path irrespective of the redistribution of the capital endowment. From the monotonicity of second period resource supply with respect to the future tax rate then also follows that the arising or reversal of the green paradox does not depend on the redistribution of capital endowment between both countries.

#### 4.4 What Drives the Reversal of the Green Paradox? The Role of the Elasticity of Substitution

The discussion so far and the monotonicity of second period resource supply in particular indicate that whether we will observe a reversal of the green paradox or not neither depends on the specific tax rate nor on its growth over time nor on the initial extraction path chosen by the sheikh. Instead, the arising or the reversal of the green paradox must depend on more fundamental market structures in the end, i.e. on the resource demand side, on capital demand and supply, and on the interaction of these markets which is in particular represented by the capital accumulation process from (24). To gain further insight into the more fundamental drivers for the effect of the future resource tax policy on the optimal resource extraction path, we rearrange the numerator of (30)<sup>16</sup>

$$-\left(p_2 + \frac{dp_2}{dR_2}R_2\right) + \frac{di_2}{dR_2} \frac{\partial s_{1E}}{\partial \pi_{2E}} \frac{\partial \pi_{2E}^\tau}{\partial \tau_2} = -\frac{p_2}{\sigma} \left[1 - \frac{1}{e_{R_2,p_2}} + \frac{1}{e_{K_2,p_2}} \frac{\partial s_{1E}}{\partial \pi_{2E}} i_2\right]$$

where we define

$$e_{R_2,p_2} = -\frac{1}{\frac{dp_2}{dR_2} \frac{R_2}{p_2}} = \frac{\sigma}{1 - \theta_{2R} - \theta_{2K} \frac{dK_2}{dR_2} \frac{R_2}{K_2}} \quad (31)$$

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<sup>16</sup> In the unit resource tax case, we have similarly

$$-1 - \frac{di_2}{dR_2} \frac{\partial s_{1E}}{\partial \pi_{2E}} R_2 = -\left[1 + \frac{1}{e_{K_2,p_2}} i_2 \frac{\partial s_{1E}}{\partial \pi_{2E}}\right] = 0$$

as the own price elasticity of resource demand which in contrast to its partial equilibrium counterpart  $\epsilon_{R_2,p_2}$  includes the feedback effect from the endogeneity of capital accumulation and is unambiguously positive due to  $\frac{dp_2}{dR_2} < 0$  by (25).  $\theta_{tf} = \frac{p_t f_t}{F_t} < 1$  denotes the share of the remuneration (before taxes) of production factor  $f_t$  in total output  $F_t$ .<sup>17</sup> Correspondingly, we define by

$$e_{K_2,p_2} = \frac{1}{\frac{di_2}{dR_2} \frac{R_2}{i_2}} = \frac{\sigma}{\theta_{2R} - (1 - \theta_{2K}) \frac{dK_2}{dR_2} \frac{R_2}{K_2}} \quad (32)$$

the cross price elasticity of capital demand which again differs from the partial equilibrium cross price elasticity  $\epsilon_{K_2,p_2}$  in including the capital accumulation feedback and which is unambiguously positive due to  $\frac{di_2}{dR_2} > 0$  by (26) irrespective of the sign of  $\frac{dK_2}{dR_2}$  (see (24)).

Obviously, since apart from the limiting case of a Leontieff production technology  $\sigma > 0$  and  $p_2 > 0$  due to the concavity of the production technology, we have

$$\frac{dR_2^{GA,\tau}}{d\tau_2} \begin{matrix} \leq \\ \geq \end{matrix} 0 \quad \Leftrightarrow \quad 1 - \frac{1}{e_{R_2,p_2}} + \frac{1}{e_{K_2,p_2}} \frac{\partial s_{1E}}{\partial \pi_{2E}} i_2 \begin{matrix} \geq \\ \leq \end{matrix} 0 \quad (33)$$

Thus, the green paradox is reversed (arises) if (33) is negative (positive). Moreover, since  $\frac{\partial s_{1E}}{\partial \pi_{2E}} < 0$  and  $|i_2 \frac{\partial s_{1E}}{\partial \pi_{2E}}| < 1$  by (16), a *sufficient* condition for a green paradox outcome is

$$1 - \frac{1}{e_{R_2,p_2}} \geq \frac{1}{e_{K_2,p_2}}$$

or, by using the definitions of the price elasticities in (31) and (32)

$$\sigma \geq 1 - \frac{dK_2}{dR_2} \frac{R_2}{K_2} \quad (34)$$

$\frac{dK_2}{dR_2} \frac{R_2}{K_2}$  represents the elasticity of the second period's capital stock with respect to future resource supply and is generally of ambiguous sign (see (24)).

From (34) we can conclude that the possibility that we observe a reversal of the green paradox crucially depends on the interplay of the elasticity of substitution and the relationship between capital accumulation and the resource supply path. Starting with the role of the endogeneity of capital accumulation brings us to our next proposition.

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<sup>17</sup> Due to the constant returns to scale CES technology, the Euler theorem holds and  $\theta_{tR} + \theta_{tK} + \theta_{tL} = 1$ .

**Proposition 6.** *The feedback effect from the endogeneity of the second period capital stock in general equilibrium works towards a reversal of the green paradox if an acceleration of extraction increases the second period capital stock ( $\frac{dK_2}{dR_2} < 0$ ).*

If the capital stock  $K_2$  negatively depends on second period's resource supply, the right side of (34) is obviously greater than unity. This implies that we may get a reversal of the green paradox even for a rather high elasticity of substitution  $\sigma \geq 1$ . Of course, if the future capital stock positively reacts to a postponement of extraction, the opposite holds true and the green paradox may only be reversed for an elasticity of substitution  $\sigma$  below unity. The reason for this significant influence of the relationship between capital accumulation and the supply path is that by internalizing a negatively (positively) dependent second period capital stock resource demand becomes less (more) price-elastic from the sheikh's perspective<sup>18</sup> according to (31)

$$e_{R_2, p_2} = -\frac{1}{\frac{dp_2}{dR_2} \frac{R_2}{p_2}} = \frac{\sigma}{1 - \theta_{2R} - \theta_{2K} \frac{dK_2}{dR_2} \frac{R_2}{K_2}} \leq \frac{\sigma}{1 - \theta_{2R}} = -\frac{1}{\frac{\partial p_2}{\partial R_2} \frac{R_2}{p_2}} = \epsilon_{R_2, p_2} \quad \text{if } \frac{dK_2}{dR_2} \leq 0$$

At the same time, the cross price elasticity of capital demand is reduced (increased) from the sheikh's perspective as we have

$$e_{K_2, p_2} = \frac{1}{\frac{di_2}{dR_2} \frac{R_2}{i_2}} = \frac{\sigma}{\theta_{2R} + (\theta_{2K} - 1) \frac{dK_2}{dR_2} \frac{R_2}{K_2}} \leq \frac{\sigma}{\theta_{2R}} = \frac{1}{\frac{\partial i_2}{\partial R_2} \frac{R_2}{i_2}} = \epsilon_{K_2, p_2} \quad \text{if } \frac{dK_2}{dR_2} \leq 0$$

according to (26). Both implications of the internalization of the capital accumulation feedback work against (towards) the arising of the green paradox from the tax induced reduction in the marginal resource revenue. A lower (higher) price elasticity of demand decreases (increases) the tax induced loss in the marginal resource value by reducing (increasing) the marginal resource revenue whereas a stronger (weaker) interest rate reaction amplifies (alleviates) the effect of the tax induced savings reaction on the future asset motive.

The discussion so far also points out the crucial role of the elasticity of substitution  $\sigma$  which determines the mutual dependency of resource and capital demand via the substitutability of capital and fossil resources in final goods' production ("substitutability effect") but also the overall production possibilities given the capital and resource endowments ("scale effect"). In particular, we will show next that the following proposition holds.

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<sup>18</sup> This gives also rise to the addiction motive previously discussed in section 3 if  $\frac{dK_2}{dR_2} < 0$ .

**Proposition 7.** *A reversal of the green paradox is less likely the higher the elasticity of substitution. The green paradox will always arise for an elasticity of substitution sufficiently exceeding unity.*

To disentangle the role of the elasticity of substitution we consider a special case first. If the sheikh does not internalize the endogeneity of capital accumulation or if, although somewhat inconsistently in our framework with endogenous savings of the household in country  $E$ , the second period capital stock  $K_2$  does not react to a change in the extraction path, (34) will simplify to

$$1 - \frac{1}{\epsilon_{R_2, p_2}} = 1 - \frac{1 - \theta_{2R}}{\sigma} \geq \frac{\theta_{2R}}{\sigma} = \frac{1}{\epsilon_{K_2, p_2}} \quad \text{and therefore} \quad \sigma \geq 1$$

Thus, in this case a reversal of the green paradox is excluded for  $\sigma \geq 1$ .<sup>19</sup> Irrespective of  $\theta_{2R} (< 1)$ , the (partial) own price elasticity of resource demand and the (partial) cross price elasticity of capital demand with respect to the resource price

$$\epsilon_{R_2, p_2} = -\frac{1}{\frac{\partial p_2}{\partial R_2} \frac{R_2}{p_2}} = \frac{\sigma}{1 - \theta_{2R}} \quad \epsilon_{K_2, p_2} = \frac{1}{\frac{\partial i_2}{\partial R_2} \frac{R_2}{i_2}} = \frac{\sigma}{\theta_{2R}}$$

ceteris paribus increase in  $\sigma$  and necessarily exceed unity for  $\sigma \geq 1$ , so that resource and capital demand become price elastic with respect to the resource price. This on the one hand comes along with a high and always positive marginal resource revenue and therefore a high (marginal) tax induced loss in the future resource value from the sheikh's perspective. On the other hand, it implies that the effect of the induced savings adjustment is weak due to a low elasticity of capital return with respect to resource supply. In fact, for  $\sigma \geq 1$  the (partial) cross price elasticity of capital demand  $\epsilon_{K_2, p_2}$  is so high – and therefore the elasticity of the capital return with respect to resource supply so low – that the tax induced loss in the marginal resource revenue can never be overcompensated by the strengthening of the asset motive from the savings reaction and that a reversal of the green paradox is excluded. Thus, the green paradox necessarily arises for a sufficiently high elasticity of substitution  $\sigma$ , at least in this special case where we abstract from the endogeneity of capital accumulation, due to the influence of the elasticity of substitution on the sensitivity of both, (inverse) resource and capital

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<sup>19</sup> Note that this restriction also arises whenever the sheikh is unable to internalize the endogeneity of capital accumulation due to a limited level of awareness/information of the economic structure. This again illustrates the crucial role of information/awareness for the resource owner's behavior as already pointed out in our accompanying paper Marz and Pfeiffer (2015).

demand to changes in resource supply.<sup>20</sup>

For the more general case, in which the omniscient sheikh internalizes the endogeneity of capital accumulation according to (24) into his supply decision, we also have to take into account that the elasticity of substitution  $\sigma$  has an influence on the relationship between capital accumulation and the resource supply path and therefore on the right side of (34), too. First, we derive in appendix B that a sufficient condition for  $\frac{dK_2}{dR_2} < 0$  is  $\sigma \geq \frac{1}{\eta}$ . Intuitively, the production increase in the second period from a shift of resources from the first to the second period is the larger the better the substitutability of capital and resources, or, equivalently, with a higher elasticity of substitution  $\sigma$  capital can be substituted for resources in production more easily, i.e. at lower losses in aggregate output and income, so that the savings disincentive from the transfer of aggregate income to the future period is more likely to outweigh the substitution effect from the higher capital return<sup>21</sup> (see (24)). Thus, by increasing  $\sigma$  for a given intertemporal elasticity of substitution  $\frac{1}{\eta}$  (cf. (1)) we are more likely to have  $\frac{dK_2}{dR_2} < 0$  so that the right side of condition (34) exceeds unity and therefore increases with  $\sigma$ , in principle, too. Second, however, in the limiting case  $\sigma \rightarrow \infty$  the CES production technology (4) becomes linear<sup>22</sup> which implies

$$\lim_{\sigma \rightarrow \infty} \frac{\partial i_2}{\partial R_2} = \lim_{\sigma \rightarrow \infty} \frac{\partial F_{2K}}{\partial R_2} = 0 \quad \text{and} \quad \lim_{\sigma \rightarrow \infty} \frac{\partial i_2}{\partial K_2} = \lim_{\sigma \rightarrow \infty} \frac{\partial F_{2K}}{\partial K_2} = 0$$

Thus, resource supply no longer influences capital *demand*. However, there still is an influence of the resource supply path on the capital market equilibrium via capital *supply* because, as already argued before, a shift in the resource supply path *ceteris paribus* transfers aggregate income from one period to the other to which households adapt their savings, i.e. aggregate capital supply. Since in the limiting case  $\sigma \rightarrow \infty$  the extraction profile no longer has a direct influence on the interest rate and therefore cannot induce a substitution effect anymore, the capital accumulation process (24) is

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<sup>20</sup> Note that  $|i_2 \frac{\partial s_{1E}}{\partial \pi_{2E}}| < 1$  in (33) for any  $\sigma$  according to (16).

<sup>21</sup> Recall that according to (26) the interest rate  $i_2$  always increases with a shift of resources to the second period.

<sup>22</sup> We then have  $F(R_t, K_t, L) = \lambda R_t + \gamma K_t + (1 - \lambda - \gamma)L$

entirely driven by this income transfer from the first to second period and therefore<sup>23</sup>

$$\lim_{\sigma \rightarrow \infty} \frac{dK_2}{dR_2} = \lim_{\sigma \rightarrow \infty} \frac{\frac{\partial s_{1E}}{\partial \pi_{2E}} p_2 - \frac{\partial s_{1E}}{\partial y_{1E}} p_1 + F_{2KR} SE}{1 - F_{2KK} SE} = \frac{\partial s_{1E}}{\partial \pi_{2E}} p_2 - \frac{\partial s_{1E}}{\partial y_{1E}} p_1$$

But, since  $p_t = F_{tR} = \lambda$  and  $i_t = F_{tK} = \gamma$  for the linear production technology in the limiting case  $\sigma \rightarrow \infty$  and since the savings reactions are just functions of the interest rate  $i_2$  and preference parameters by (16), we can conclude that  $|\frac{dK_2}{dR_2}|$  is bounded from above for  $\sigma \rightarrow \infty$ . This reasoning implies that when increasing  $\sigma$  we will necessarily meet the sufficiency condition for the arising of the green paradox (34) at some point as the left side approaches infinity whereas the right side is bounded from above. The basic intuition from the case without endogenous capital accumulation (or without explicit internalization of the endogeneity of capital accumulation into the resource supply decision) laid out before therefore still applies. The switch from a regime for which a reversal of the green paradox is possible to a regime where the green paradox must arise for a rising elasticity of substitution  $\sigma$  is obviously influenced by the internalization of the endogeneity of capital accumulation as a reversal of the green paradox may even be possible for  $\sigma \geq 1$ . But in the end the change in the production structure from the rising elasticity of substitution, which is reflected in the price elasticities of resource and the cross price elasticity of capital demand, prevents a reversal of the green paradox for sufficiently high  $\sigma$ .

If we consider the opposite case where  $\sigma \rightarrow 0$ , we can state the following.

**Proposition 8.** *For a sufficiently low elasticity of substitution the green paradox always gets reversed.*

To proof this we start by analyzing whether the marginal resource revenue (before taxes), i.e. the first element of the numerator in (30), turns negative for the limiting case  $\sigma \rightarrow 0$ . The sign of the marginal resource revenue in the limiting case is determined by

$$\lim_{\sigma \rightarrow 0} 1 - \frac{1}{e_{R_2, p_2}} = \lim_{\sigma \rightarrow 0} \sigma - 1 + \theta_{2R} + \theta_{2K} \frac{dK_2}{dR_2} \frac{R_2}{K_2} = -1 + \theta_{2R} + \theta_{2K} \frac{dK_2}{dR_2} \frac{R_2}{K_2} < 0$$

where we again use the definition of the price elasticity of resource demand (31). The

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<sup>23</sup> Regarding the denominator note that  $F_{2KK} = 0$  for a linear production technology. Moreover, from appendix A we know that  $SE = \frac{\partial s_{1E}}{\partial y_{1E}} \frac{c_{1E} + c_{1I}}{\eta(1+i_2)}$  which is bounded for  $\sigma \rightarrow \infty$  due to the limited capital and resource endowments,  $c_{1E} + c_{1I} = F_1 + K_1 - K_2 = \lambda R_1 + (1 + \gamma)K_1 + (1 - \lambda - \gamma)L - K_2$  by the budget constraints (10) and (12) and  $i_2 = F_{2K} = \gamma$ . This implies that  $\lim_{\sigma \rightarrow \infty} F_{2KK} SE = 0$ .

negative sign holds as the factor remuneration shares are lower than unity by definition and we know that even though the elasticity of the second period capital stock with respect to future resource supply may be positive, it is bounded from above as we have by the unambiguous signs of (31) and (32)

$$\frac{dK_2}{dR_2} \frac{R_2}{K_2} < \min \left\{ \frac{1 - \theta_{2R}}{\theta_{2K}}; \frac{\theta_{2R}}{1 - \theta_{2K}} \right\} = \frac{\theta_{2R}}{1 - \theta_{2K}} < 1$$

The last (in-)equality follows from the Euler theorem by which  $\theta_{2R} + \theta_{2K} + \theta_{2L} = 1$ . This implies that the marginal resource revenue will turn negative for a sufficiently low elasticity of substitution  $\sigma$ . To complete the proof we now can refer to proposition 2 in which a negative marginal resource revenue was already identified as a sufficient condition for the reversal of the green paradox. Intuitively, the reason is that lowering  $\sigma$  reduces the overall production possibilities of the economy in both periods for the given production factor endowments (“scale effect” of the elasticity of substitution), i.e. by more and more approaching a Leontieff technology total output over both periods decreases.<sup>24</sup> With shrinking production possibilities exhausting the resource stock implies a higher resource supply in both periods as compared to the final goods production and therefore a lower marginal productivity of the resource due to the concavity of the production technology. But this also implies that resource demand which is directly derived from the marginal productivity for competitive final goods producers becomes less and less price elastic and finally inelastic for a decreasing elasticity of substitution  $\sigma$  so that the marginal resource revenue gets negative (see also the definition of the partial price elasticity  $\epsilon_{R_2, p_2}$  above). We will further investigate the role of the elasticity of substitution in the following section by numerically simulating the model and conducting a sensitivity analysis.

## 5 Numerical Simulation and Sensitivity Analysis

We employ a numerical simulation of the model and the reaction of the equilibrium extraction path to a future tax increase to determine the parameter settings which lead to the green paradox or its reversal. To observe the sign of the tax reaction for a certain parameter setting in the simulation, we compare the future extraction rates with and

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<sup>24</sup>Note that as long as  $\sigma > 0$  the resource is always valuable for final goods production due to the concavity of the production technology.



without a future resource tax.<sup>25</sup> A negative sign of  $\frac{dR_2^{GA*}}{d\tau_2}$  indicates a green paradox, while a positive sign indicates its reversal.

We find that first of all the parameters characterizing the production technology play a prominent role for the direction of the tax reaction: the elasticity of substitution  $\sigma$  and the productivity parameter of oil in the CES production function  $\lambda$ . The factor endowments  $K_1$  and  $\bar{R}$  and the parameters of the households' utility function  $\beta$  and  $\eta$  also affect the direction of the reaction to a future tax increase. As the following analysis shows, the influence of these latter four parameters is especially significant at higher values of the productivity parameter of oil  $\lambda$  beyond approx. 10%. With values of  $\lambda$  below 10% their influence is less pronounced. The sensitivity analysis with regard to these parameters will be discussed in the following subsections. If we assumed that our model is a satisfactory representation of the real oil and capital markets and that the productivity parameter of oil  $\lambda$  is below 10%, while the substitution elasticity  $\sigma$  is realistically below 1, then the reversal of the green paradox could be expected as a robust outcome of an announced future carbon tax increase, according to the simulation.

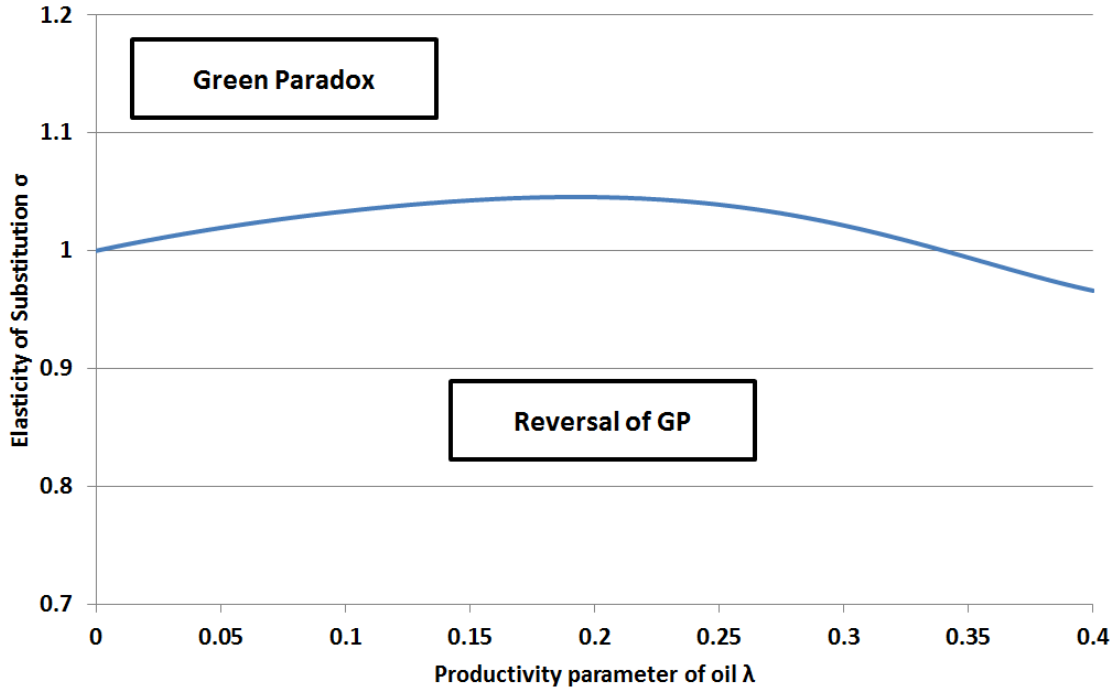
## 5.1 Elasticity of Substitution $\sigma$

We vary the two key features of the production technology, the elasticity of factor substitution  $\sigma$  and the productivity parameter of oil  $\lambda$  to map the according tax reaction. Given that the monopolist is internalizing all the effects of his extraction decision on the interest rate and the capital stock and the resulting feedbacks, the result is shown in figure 2 .

For high levels of  $\sigma$  the green paradox effect prevails. It is always attenuated and, finally, reversed through a proceeding reduction of the substitution elasticity. This is a robust result for all observed parameter settings and confirms the analytical arguments of section 4.4. With the elasticity of substitution falling, the marginal resource revenue (i.e. without the capital asset income) goes down as well due to falling productivity of all factors. Also, the elasticity of resource demand decreases with  $\sigma$  falling. As the simulations show, the capital asset term, which is driving a reversal of the green paradox, in the numerator of (30) is hardly affected by a falling  $\sigma$ . When the marginal

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<sup>25</sup> As we have seen above in section 4.2, the extraction reaction to a tax increase in the second period is monotonous over the tax rate. A non-marginal discrete tax increase thus has the same sign as a marginal tax increase (independent of its magnitude). This sign is determined by the numerator in (30). In the numerical simulation we use an exemplary tax rate of 10%.



**Figure 2:** Zones of green paradox and its reversal over the elasticity of substitution  $\sigma$  and the productivity parameter of oil  $\lambda$ . ( $\beta = 0.3$ ,  $\eta = 2$ ,  $s_{0E} = 20$  and  $s_{0I} = 180$  yielding  $K_1 = s_{0E} + s_{0I} = 200$ ,  $\bar{R} = 10$ )

resource revenue falls low enough and finally even below zero<sup>26</sup>, then the numerator of (30) must finally turn positive and the green paradox outcome turns into a reversed green paradox.

## 5.2 Productivity Parameter of Oil $\lambda$

The second highly influential variable is the productivity parameter of oil in the CES production function  $\lambda$ . In the case with iso-elastic demand ( $\sigma = 1$ )  $\lambda$  is the income share of oil. When shifting the weights between oil and capital in the production structure we assumed that these two factors together receive 50% of output in the Cobb-Douglas case and that the output share of capital is at least 10%, while labor receives the other half. Increasing the weight of oil thus always implies reducing the weight of capital.

An increase of oil's productivity parameter  $\lambda$  directly raises the marginal resource rev-

<sup>26</sup> Recall that the monopolist's overall marginal resource value consists of the marginal resource revenue and the marginal increase of country E's capital asset income. Thus, the overall marginal resource value can still be positive even when the marginal resource revenue has fallen below zero due to the contribution of the capital asset motive.

enue (without capital asset income) and the monopolist's losses through the tax increase. This contributes to the green paradox. But at the same time, the reversal driver (second term in the numerator of (30)) rises with  $\lambda$  too, because our simulations show that the monopolist's influence on the interest rate  $\frac{di_2}{dR_2}$  grows with  $\lambda$  and the higher income loss due to the tax triggers a stronger response in savings contributing to the reversal. The resulting effect of the increase in  $\lambda$  depends on the relative strength of these two counteracting effects. Again, the substitution elasticity is important here.

**Proposition 9.** *If the elasticity of substitution  $\sigma$  is high, then the marginal resource revenue rises stronger with  $\lambda$  than the reversal impulse, resulting in a green paradox. With a low  $\sigma$  the reversal impulse rises stronger with  $\lambda$ , yielding a reversal. In the intermediate range the predominance of the two counteracting factors can change over  $\lambda$ .*

In the case  $\sigma < 1$  the marginal resource revenue becomes negative with  $\lambda$  approaching zero. Therefore, for low  $\lambda$  the numerator in (30) becomes positive and the green paradox is always reversed. For  $\sigma > 1$  and  $\lambda \rightarrow 0$  the green paradox always arises, while higher  $\lambda$  can yield an area of reversal.

### 5.3 Initial Factor Endowments $K_1$ and $\bar{R}$

The simulations show that the initial endowments of capital and oil can affect the position of the boundary between the green paradox zone and the reversal zone in figure 2.

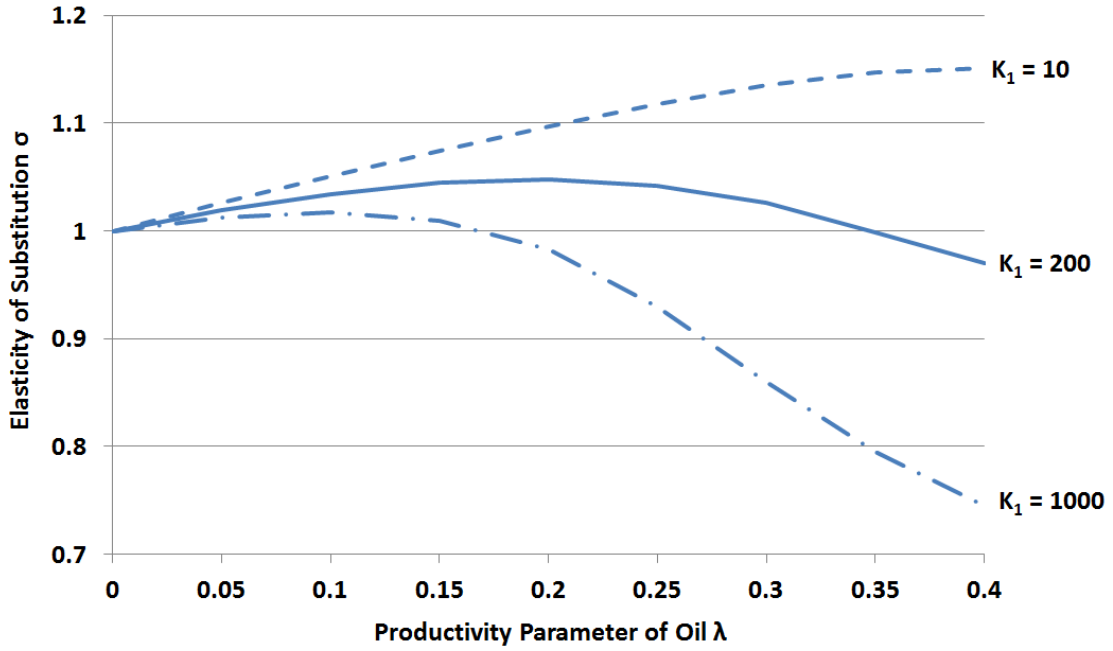
**Proposition 10.** *A higher initial capital endowment  $K_1$  of the economy increases the resource's value and productivity and, thus, makes the green paradox more likely. This effect is more pronounced at higher values of the productivity parameter of oil  $\lambda$ .*

We see the influence of the capital endowment  $K_1$  in figure 3. With a higher capital endowment the marginal product of the resource and the monopolist's marginal revenue (cf. numerator of (30)) are higher.<sup>27</sup> The monopolist's higher tax-induced losses in resource rents reinforce his incentive to accelerate extraction. As a result, lower levels of  $\sigma$  are necessary to weaken the driver of the green paradox sufficiently to yield a

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<sup>27</sup> Due to the decreasing returns to scale in final goods production, higher capital endowments can lead to scenarios in which there is no longer positive capital accumulation as households more and more tend to consume and save out of the given stock which rises linearly in capital endowments (cf.  $c_{1E} + c_{1I} + K_2 = F_1 + K_1$ ).

reversal of the green paradox.



**Figure 3:** Influence of the initial capital endowment  $K_1$  on the borderline between the green paradox and the reversal area. ( $\beta = 0.3$ ,  $\eta = 2$ ,  $\frac{s_{0e}}{s_{0E}+s_{0I}} = 0.1$ ,  $\bar{R} = 10$ )

Moreover, with a higher capital endowment  $K_1$  the marginal resource revenue reacts much stronger and steeper to a rise in  $\lambda$  and dominates the reversal term of (30) already at lower levels of  $\lambda$ .

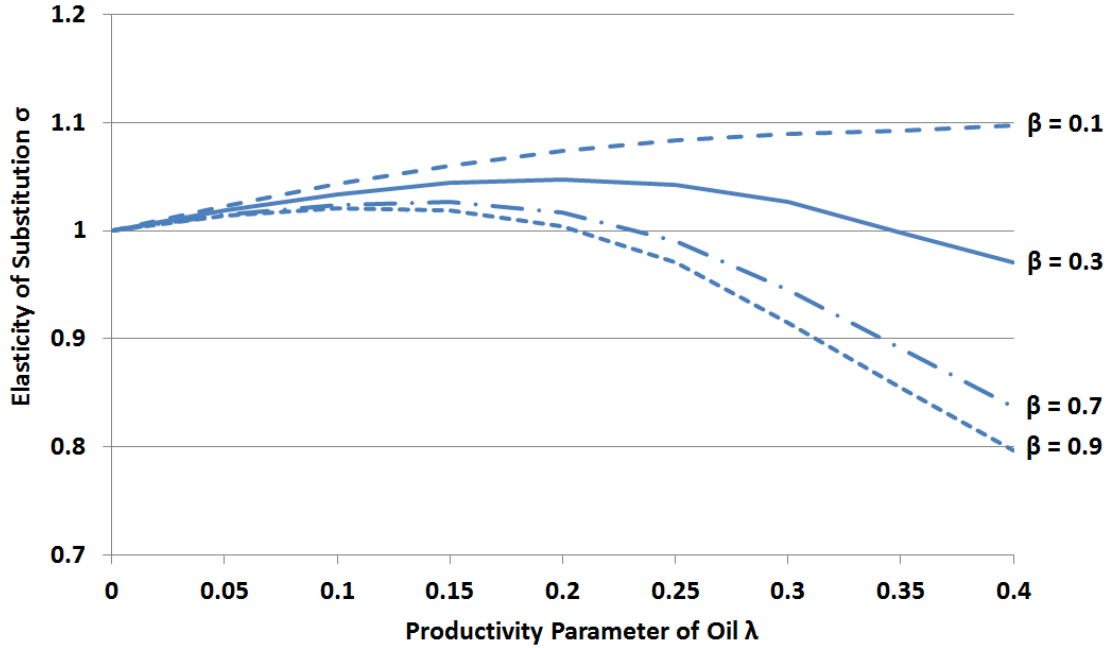
The same line of reasoning applies to changes in the resource endowment  $\bar{R}$ . A smaller resource endowment also leads to a higher marginal product and a higher marginal resource revenue. Again, the green paradox arises already at lower levels of  $\lambda$  and  $\sigma$  (cf. figure 6 in the appendix section D).

## 5.4 Household Preferences

The households' preference parameters  $\beta$  and  $\eta$  can additionally affect the direction of the extraction reaction to a future tax increase. Figure 4 illustrates the role of the utility discount factor  $\beta$ .

**Proposition 11.** *A lower utility discount factor  $\beta$ , indicating a higher impatience, reinforces the savings reaction to the tax increase and makes the reversal of the green paradox more likely. This effect is more pronounced at higher values of the productivity parameter of oil  $\lambda$ .*

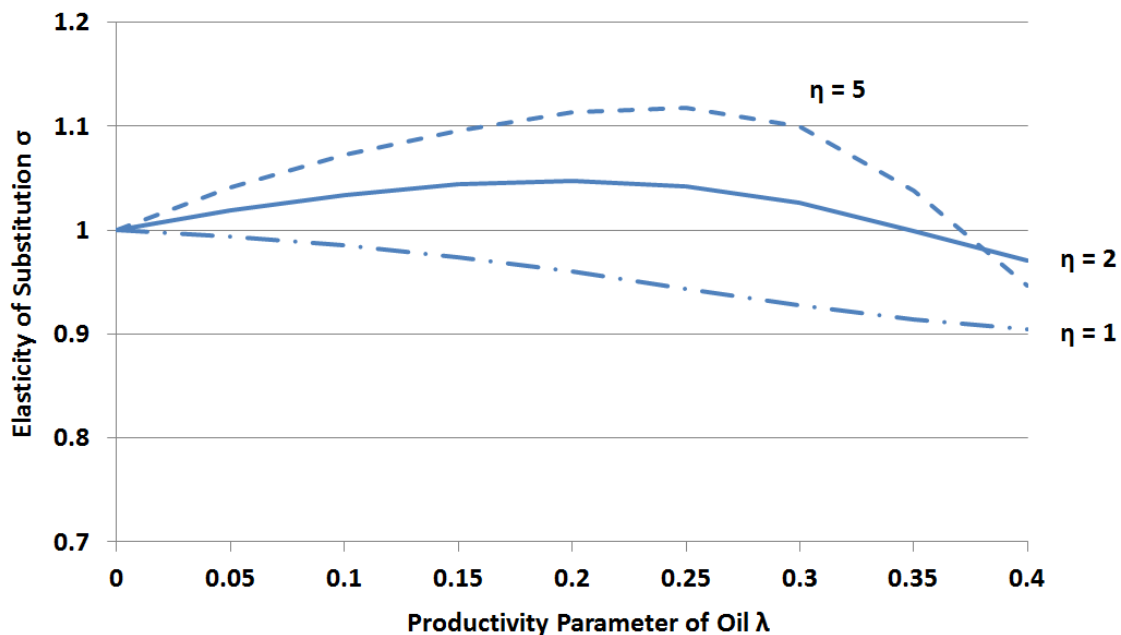
The change of savings as a reaction to the tax increase and the according income loss in the second period  $\frac{\partial s_{1m}}{\partial \pi_{2m}^r}$  is higher with a lower discount factor  $\beta$  and higher impatience (cf. (16)). This strengthens the reversal channel, as the capital asset motive applies to a higher capital asset stock in the future, and therefore makes the reversal more likely. The tax induced income loss and the according savings adjustment are higher when a higher productivity parameter of oil  $\lambda$  leads to a higher marginal product and a higher income share of oil.



**Figure 4:** Influence of the utility discount factor  $\beta$  on the boundary between the green paradox area and the reversal area. ( $\eta = 2$ ,  $K_1 = 200$ ,  $\bar{R} = 10$ )

**Proposition 12.** *A higher curvature of the utility function  $\eta$  reinforces the savings reaction to the tax increase and makes the reversal of the green paradox more likely.*

The second preference parameter  $\eta$ , which indicates the curvature of the utility function and whose inverse  $\frac{1}{\eta}$  is the rate of intertemporal substitution, also affects the strength of the savings reaction to the tax induced income loss in the future (cf. figure 5). According to (16) the absolute value of the savings reaction to an income loss  $\frac{\partial s_{1m}}{\partial \pi_{2m}^r}$  is higher for higher values of  $\eta$ .



**Figure 5:** Influence of the curvature of the utility function  $\eta$  on the boundary between the green paradox area and the reversal area. ( $\beta = 0.3$ ,  $K_1 = 200$ ,  $\bar{R} = 10$ )

## 6 Conclusion

It is well known that the introduction, or announcement, of future carbon taxes may lead to supply reactions of fossil fuel owners which are adverse to the climate mitigation targets and the intentions of policy makers. Building upon our previous analysis of monopolistic resource extraction in a general equilibrium framework which we use as we are particularly interested in the interrelation of the international markets for fossil energy and physical capital we show, however, that such a green paradox may not arise if the monopolistic resource exporter pursues the asset motive and future capital asset holdings of the resource rich country endogenously react to the redistribution of resource rents that is induced by carbon taxes. With the omniscient and benevolent resource owner taking into account the positive influence of resource supply on the return on savings, larger capital asset holdings, which result from the consumption smoothing motives of households and the tax induced loss in future resource rents, create an incentive to shift resource extraction to that period in which the carbon tax is introduced or increased. If this capital income related incentive to postpone extraction is stronger than the familiar incentive to accelerate extraction due to the devaluation of future resource supply in terms of pure resource income from taxing resource use in the future period (more heavily), the green paradox will be reversed.

To focus on the effect of the in the previous paper identified extended supply motives of a resource monopolist in general equilibrium, and the asset motive in particular, we abstract from extensions such as stock-dependent extraction costs or asymmetric preferences. In this framework, we demonstrate that the whether the green paradox arises or not does neither depend on the level nor on the change of the future resource tax nor on the initial distribution of capital endowments between the resource rich country and the resource-importing countries. Instead, we identify the sensitivity of inverse resource demand compared the sensitivity of the capital return to changes in resource supply and therefore the substitutability between the fossil resource and capital in final goods production measured by the elasticity of substitution as crucial for the weighting of the different and mostly counteracting extraction incentives that are created by future carbon taxes. Since the relationship of capital accumulation and resource supply also has some influence on these sensitivities of the market resource price and capital return, we can also show that the reversal of the green paradox is more likely if an acceleration of extraction comes along with higher capital accumulation.

We further assess the influence of model parameters in a numerical simulation and sensitivity analysis which also confirms that the arising or reversal of the green paradox depends strongly on parameters which define the production structure and the equilibrium capital accumulation. On the production side, these parameters and assumptions are apart from the elasticity of substitution the productivity (share) parameter of the fossil resource in the CES production technology and the relation of aggregate capital endowment to the resource stock, which, from an intuitive point of view, both more or less specify the importance and scarcity of fossil resources in production compared to capital especially in scenarios with rather limited substitutability (low elasticity of substitution). The utility discount factor and the intertemporal elasticity of substitution on the one hand fundamentally influence the (sign of the) equilibrium relationship between capital accumulation and the extraction path but on the other hand also determine how strongly the capital asset holdings of the resource rich country react to the future resource income loss incurred by the resource tax. Generally, a reversal of the green paradox is more likely for a lower elasticity of substitution, a higher capital endowment (and a lower resource endowment), a lower discount factor and a lower elasticity of intertemporal substitution. Moreover, in our simulations we observe the reversal of the green paradox for a wide, and also not implausible or completely unrealistic, value range of these parameter.

Without stock dependent extraction costs we concentrate on scenarios where the resource stock is binding and consequently always completely exhausted. Thus, we so

far analyze the effect of the resource tax only with respect to the timing of extraction and thereby emissions whereas total emissions are constant. From a macroeconomic perspective, a reversal of the green paradox implies in our framework that the current output is always reduced. Future output may unambiguously increase if the induced shift of resources to the future comes along with a higher capital accumulation, but may fall if the postponement of extraction lowers capital accumulation. In either case, due to the redistribution of resource rents between the resource rich and the resource-importing country and the induced savings reactions, the future share of the resource rich country in the global capital stock in such a scenario increases which may give rise to a discussion of the capital market influence of “petro dollars”. We leave these issues for future research as well as the introduction of stock dependent extraction costs and of asymmetric consumption preferences. The latter, for example, would imply that the capturing of resource rents by the resource-importing country is no longer neutral with respect to aggregate capital accumulation and therefore that the change or introduction of a future resource tax induces additional effects via the endogeneity of capital accumulation.



# Appendix

## A Capital Supply with Homothetic Preferences

We show in the following that capital supply is a function of the resource extraction path only as long as we assume symmetric (and homothetic) consumption preferences. In case of an unit resource tax, the derivation is completely analogue.

Totally differentiating  $K_2^s = s_{1E} + s_{1I}$  and taking into account changes in the resource taxes gives

$$dK_2^s = \frac{\partial s_{1E}}{\partial y_{1E}} dy_{1E} + \frac{\partial s_{1E}}{\partial d\pi_{2E}^\tau} d\pi_{2E}^\tau + \frac{\partial s_{1E}}{\partial i_2} di_2 + \frac{\partial s_{1I}}{\partial y_{1I}} dy_{1I} + \frac{\partial s_{1I}}{\partial \pi_{2I}^\tau} d\pi_{2I}^\tau + \frac{\partial s_{1I}}{\partial i_2} di_2$$

as  $s_{1m} = s_{1m}(y_{1m}, \pi_{2m}, i_2)$  by the Euler equation of the respective country  $m = E, I$ .

The changes in the period income streams in both countries can be further decomposed. For simplicity, we ignore changes in asset endowments  $s_{0E}$  and  $s_{0I}$ :

$$\begin{aligned} dy_{1E} &= \frac{\partial y_{1E}}{\partial R_1} dR_1 + \frac{\partial y_{1E}}{\partial p_1} dp_1 + \frac{\partial y_{1E}}{\partial i_1} di_1 = p_1 dR_1 + R_1 dp_1 + s_{0E} di_1 \\ d\pi_{2E}^\tau &= \frac{\partial \pi_{2E}^\tau}{\partial R_2} dR_2 + \frac{\partial \pi_{2E}^\tau}{\partial p_2} dp_2 + \frac{\partial \pi_{2E}^\tau}{\partial \tau_2} d\tau_2 = (1 - \tau_2)p_2 dR_2 + (1 - \tau_2)R_2 dp_2 - p_2 R_2 d\tau_2 \end{aligned}$$

for country  $E$  and for country  $I$

$$\begin{aligned} dy_{1I} &= \frac{\partial y_{1I}}{\partial R_1} dR_1 + \frac{\partial y_{1I}}{\partial p_1} dp_1 + \frac{\partial y_{1I}}{\partial i_1} di_1 \\ &= [F_{1R} - p_1] dR_1 - R_1 dp_1 + (-K_1 + s_{0I}) di_1 = -R_1 dp_1 - s_{0E} di_1 \\ d\pi_{2I}^\tau &= \frac{\partial \pi_{2I}^\tau}{\partial R_2} dR_2 + \frac{\partial \pi_{2I}^\tau}{\partial K_2} dK_2 + \frac{\partial \pi_{2I}^\tau}{\partial p_2} dp_2 + \frac{\partial \pi_{2I}^\tau}{\partial \tau_2} d\tau_2 + \frac{\partial \pi_{2I}^\tau}{\partial i_2} di_2 \\ &= (F_{2R} - p_2 + \tau_2 p_2) dR_2 + (-R_2 + \tau_2 R_2) dp_2 + p_2 R_2 d\tau_2 + (F_{2K} - i_2) dK_2 - K_2 di_2 \\ &= \tau_2 p_2 dR_2 + (1 - \tau_2) R_2 dp_2 + p_2 R_2 d\tau_2 - K_2 di_2 \end{aligned}$$

as  $\frac{\partial F_2}{\partial R_2} = F_{2R} = p_2$  and  $F_{2K} = i_2$  due to competitive factor demand from final goods' producers.

Substituting, setting  $dR_1 = -dR_2$  due to the binding resource constraint (3), and

rearranging then yields

$$dK_2^s = \left[ \frac{\partial s_{1E}}{\partial \pi_{2E}} p_2 - \frac{\partial s_{1E}}{\partial y_{1E}} p_1 - ID_2 \tau_2 p_2 \right] dR_2 + ID_1 R_1 dp_1 + ID_1 s_{0E} di_1 \\ + ID_2 (1 - \tau_2) R_2 dp_2 - ID_2 p_2 R_2 d\tau_2 + [SE + ID_2 s_{1E}] di_2$$

where we define

$$ID_1 = \frac{\partial s_{1E}}{\partial y_{1E}} - \frac{\partial s_{1I}}{\partial y_{1I}} \\ ID_2 = \frac{\partial s_{1E}}{\partial \pi_{2E}^\tau} - \frac{\partial s_{1I}}{\partial \pi_{2I}^\tau}$$

Additionally, we denote by  $SE$  the aggregated substitution effect from an increase in the interest rate  $i_2$ . To derive  $SE$ , we use the decomposition

$$\frac{\partial s_{1m}}{\partial i_2} = -\beta_m \frac{u'(c_{2m})}{u''(c_{1m}) + \beta_m (1 + i_2)^2 u''(c_{2m})} + \frac{\partial s_{1m}}{\partial \pi_{2m}} s_{1m}$$

from (16) to separate the substitution and the income effect. Thus, the aggregated substitution effect is given by<sup>28</sup>

$$SE = - \left[ \frac{\beta_E u'(c_{2E})}{u''(c_{1E}) + \beta_E (1 + i_2)^2 u''(c_{2E})} + \frac{\beta_I u'(c_{2I})}{u''(c_{1I}) + \beta_I (1 + i_2)^2 u''(c_{2I})} \right] > 0$$

which is positive due to the concavity of the utility function  $u(c_{1m})$  as intuitively expected. This decomposition also implies that

$$\frac{\partial s_{1E}}{\partial i_2} + \frac{\partial s_{1I}}{\partial i_2} - \frac{\partial s_{1I}}{\partial \pi_{2I}} K_2 = SE + ID_2 s_{1E}$$

For symmetric and homothetic preferences we have  $\frac{\partial s_{1E}}{\partial y_{1E}} = \frac{\partial s_{1I}}{\partial y_{1I}}$  and  $\frac{\partial s_{1E}}{\partial \pi_{2E}^\tau} = \frac{\partial s_{1I}}{\partial \pi_{2I}^\tau}$  and therefore

$$dK_2^s = \left[ \frac{\partial s_{1E}}{\partial \pi_{2E}} p_2 - \frac{\partial s_{1E}}{\partial y_{1E}} p_1 \right] dR_2 + SE di_2$$

---

<sup>28</sup> For the life-time utility from (1), the aggregated pure substitution effect is given by

$$SE = \frac{1}{\eta(1 + i_2)} \left[ c_{1E} \frac{\partial s_{1E}}{\partial y_{1E}} + c_{1I} \frac{\partial s_{1I}}{\partial y_{1I}} \right] > 0$$

## B Equilibrium Capital Accumulation with Symmetric Preferences

From (24) we know that

$$\frac{dK_2}{dR_2} = \frac{\frac{\partial s_{1E}}{\partial \pi_{2E}} p_2 - \frac{\partial s_{1E}}{\partial y_{1E}} p_1 + F_{2KR} SE}{1 - F_{2KK} SE}$$

where  $SE = \frac{\partial s_{1E}}{\partial y_{1E}} \frac{c_{1E} + c_{1I}}{\eta(1+i_2)}$  as derived in the previous section A. Since the denominator is unambiguously positive, the sign of the capital reaction depends just on the numerator. From the final goods market equilibrium and the symmetric Euler equations (14) follows that

$$c_{1E} + c_{1I} = F_1 + K_1 - K_2 = \frac{c_{2E} + c_{2I}}{[\beta(1+i_2)]^{\frac{1}{\eta}}} = \frac{F_2 + K_2}{[\beta(1+i_2)]^{\frac{1}{\eta}}}$$

Moreover, since  $\frac{\partial s_{1E}}{\partial y_{1E}} = -\frac{\partial s_{1E}}{\partial \pi_{2E}} [\beta_E(1+i_2)]^{\frac{1}{\eta}}$  from (16), we can rearrange the numerator and conclude that capital accumulation will negatively react to a shift of resources to the future period if

$$\frac{\partial s_{1E}}{\partial \pi_{2E}} p_2 \left\{ 1 + [\beta_E(1+i_2)]^{\frac{1}{\eta}} \frac{p_1}{p_2} - \frac{1}{\eta\sigma} \frac{i_2(F_2 + K_2)}{F_2(1+i_2)} \right\} < 0$$

and therefore if

$$\frac{1+i_2}{\theta_{2K} + i_2} \left\{ 1 + [\beta_E(1+i_2)]^{\frac{1}{\eta}} \frac{p_1}{p_2} \right\} > \frac{1}{\sigma\eta}$$

Since the left side is greater than unity ( $\theta_{2K} < 1$ ), this implies that  $\sigma\eta \geq 1$  is a sufficient condition for  $\frac{dK_2}{dR_2} < 0$ .

## C Second Order Condition: Scenario GA

Consider the maximization problem of the omniscient benevolent monopolist (27).

$$\begin{aligned} \max U(c_{1E}, c_{2E}) &= u(c_{1E}) + \beta u(c_{2E}) \\ &= u[p_1 R_1 + (1+i_1)s_{0E} - s_{1E}] + \beta u[p_2 R_2 + (1+i_2)s_{1E}] \end{aligned}$$

The omniscient monopolist is aware that

$$p_t = F_{tR}(K_t, R_t) \quad \text{with} \quad \frac{dp_2}{dR_2} = \frac{\partial p_2}{\partial R_2} + \frac{\partial p_2}{\partial K_2} \frac{dK_2}{dR_2} \quad \text{from (25)}$$

$$i_t = F_{tK}(K_t, R_t) \quad \text{with} \quad \frac{di_2}{dR_2} = \frac{\partial i_2}{\partial R_2} + \frac{\partial i_2}{\partial K_2} \frac{dK_2}{dR_2} \quad \text{from (26)}$$

$K_1$  given

$$K_2 = K_2(R_2) \quad \text{from (24)}$$

$$s_{1E} = s_{1E}(y_{1E}, \pi_{2E}, i_2) \quad \text{with} \quad \frac{ds_{1E}}{dR_2} = -\frac{\partial s_{1E}}{\partial y_{1E}} \frac{\partial y_{1E}}{\partial R_1} + \frac{\partial s_{1E}}{\partial \pi_{2E}} \frac{d\pi_{2E}}{dR_2} + \frac{\partial s_{1E}}{\partial i_2} \frac{di_2}{dR_2}$$

Additionally taking into account the budget constraints (12), (13) and the resource constraint (3) reduces (27) to an one-dimensional optimization problem. Thus, we get for the necessary first-order-condition

$$\begin{aligned} \frac{dU}{dR_2} = u'(c_{1E}) \left[ \underbrace{\left( p_1 + \frac{\partial p_1}{\partial R_1} R_1 + \frac{\partial i_1}{\partial R_1} s_{0E} \right)}_{MR_1^{GA}} \frac{dR_1}{dR_2} - \frac{ds_{1E}}{dR_2} \right] \\ + \beta u'(c_{2E}) \left[ \underbrace{p_2 + \frac{dp_2}{dR_2} R_2 + \frac{di_2}{dR_2} s_{1E}}_{MR_2^{GA}} + (1 + i_2) \frac{ds_{1E}}{dR_2} \right] \stackrel{!}{=} 0 \quad (35) \end{aligned}$$

where  $u'(c_{tE}) = \frac{\partial u}{\partial c_{tE}}$ . The second-order condition for a (local) welfare maximum then reads

$$\begin{aligned} \frac{d^2U}{(dR_2)^2} = u''(c_{1E}) \left[ MR_1^{GA} \frac{dR_1}{dR_2} - \frac{ds_{1E}}{dR_2} \right]^2 + u'(c_{1E}) \left[ \frac{\partial MR_1^{GA}}{\partial R_1} \left( \frac{dR_1}{dR_2} \right)^2 - \frac{d^2 s_{1E}}{(dR_2)^2} \right] \\ + \beta u''(c_{2E}) \left[ MR_2^{GA} + (1 + i_2) \frac{ds_{1E}}{dR_2} \right]^2 \\ + \beta u'(c_{2E}) \left[ \frac{dMR_2^{GA}}{dR_2} + \frac{di_2}{dR_2} \frac{ds_{1E}}{dR_2} + (1 + i_2) \frac{d^2 s_{1E}}{(dR_2)^2} \right] \quad (36) \end{aligned}$$

where

$$\begin{aligned} \frac{\partial MR_1^{GA}}{\partial R_1} &= 2 \frac{\partial p_1}{\partial R_1} + \frac{\partial^2 p_1}{(\partial R_1)^2} R_1 + \frac{\partial^2 i_1}{(\partial R_1)^2} s_{0E} \\ \frac{dMR_2^{GA}}{dR_2} &= 2 \frac{dp_2}{dR_2} + \frac{d^2 p_2}{(dR_2)^2} R_2 + \frac{d^2 i_2}{(dR_2)^2} s_{1E} + \frac{di_2}{dR_2} \frac{ds_{1E}}{dR_2} \end{aligned}$$

From the savings decision of the representative household, we know that the Euler equation

$$\frac{u'(c_{1E})}{\beta u'(c_{2E})} = 1 + i_2$$

holds in the optimal equilibrium outcome. This implies on the one hand, that the necessary first-order condition of the sheikh's utility maximization problem (27)

$$-u'(c_{1E}) \left[ p_1 + \frac{\partial p_1}{\partial R_1} R_1 + \frac{\partial i_1}{\partial R_1} s_{0E} \right] + u'(c_{2E}) \left[ p_2 + \frac{dp_2}{dR_2} R_2 + \frac{di_2}{dR_2} s_{1E} \right] = 0$$

can be reduced to the modified Hotelling rule (28), i.e.

$$(1 + i_2)MR_1^{GA} = MR_2^{GA}$$

On the other hand, we can also conclude that for any extraction path in the conditional market equilibrium the Euler equation has to hold. Thus, from the total derivative of the Euler Equation with respect to  $R_2$  we get

$$u''(c_{1E}) \left[ MR_1^{GA} \frac{dR_1}{dR_2} - \frac{ds_{1E}}{dR_2} \right] = \beta u'(c_{2E}) \frac{di_2}{dR_2} + \beta(1 + i_2)u''(c_{2E}) \left[ MR_2^{GA} + (1 + i_2) \frac{ds_{1E}}{dR_2} \right]$$

This allows us to substitute the first term in (36) and upon rearranging to arrive at

$$\begin{aligned} \frac{d^2U}{(\partial R_2)^2} &= \left[ MR_1^{GA} \frac{dR_1}{dR_2} - \frac{ds_{1E}}{dR_2} \right] \left[ \beta u'(c_{2E}) \frac{di_2}{dR_2} + \beta(1 + i_2)u''(c_{2E}) \left( MR_2^{GA} + (1 + i_2) \frac{ds_{1E}}{dR_2} \right) \right] \\ &\quad + \beta u'(c_{2E}) \left[ (1 + i_2) \frac{\partial MR_1^{GA}}{\partial R_1} \left( \frac{dR_1}{dR_2} \right)^2 + \frac{dMR_2^{GA}}{dR_2} \right] + \beta u'(c_{2E}) \frac{di_2}{dR_2} \frac{ds_{1E}}{dR_2} \\ &\quad + \beta u''(c_{2E}) \left[ MR_2^{GA} + (1 + i_2) \frac{ds_{1E}}{dR_2} \right]^2 \\ &= \beta u'(c_{2E}) \left[ (1 + i_2) \frac{\partial MR_1^{GA}}{\partial R_1} + MR_1^{GA} \frac{dR_1}{dR_2} \frac{di_2}{dR_2} + \frac{dMR_2^{GA}}{dR_2} \right] \end{aligned}$$

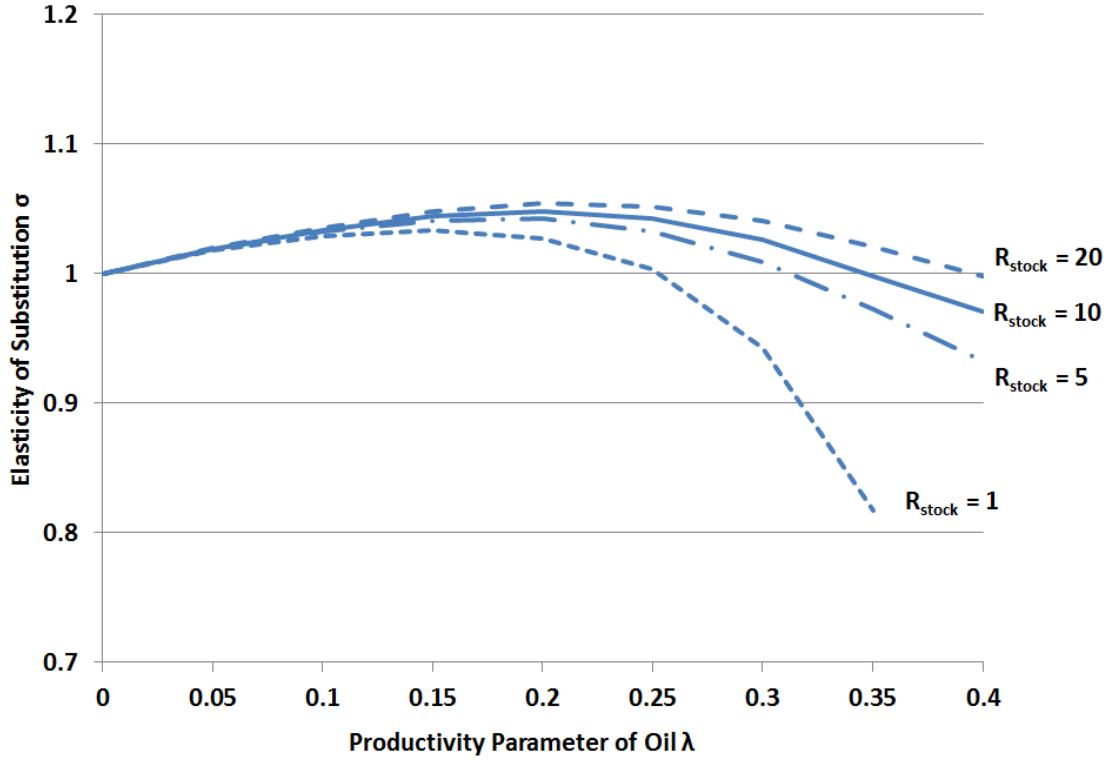
For a welfare maximum we must have  $\frac{d^2U}{(dR_2)^2} < 0$  and therefore, since  $\beta u'(c_{2E}) > 0$ ,

$$(1 + i_2) \frac{\partial MR_1^{GA}}{\partial R_1} + MR_1^{GA} \frac{dR_1}{dR_2} \frac{di_2}{dR_2} + \frac{dMR_2^{GA}}{dR_2} < 0$$

Given that  $\frac{dR_1}{dR_2} = -1$  by the resource constraint, this also implies that

$$\frac{d[(1 + i_2)MR_1^{GA}]}{dR_2} - \frac{dMR_2^{GA}}{dR_2} = (1 + i_2)\frac{\partial MR_1^{GA}}{\partial R_1}\frac{dR_1}{dR_2} + \frac{di_2}{dR_2}MR_1^{GA} - \frac{dMR_2^{GA}}{dR_2} > 0$$

## D Numerical Sensitivity Analysis



**Figure 6:** Influence of the initial resource endowment  $\bar{R}$  on the boundary between the green paradox and the reversal area. ( $\beta = 0.3$ ,  $\eta = 2$ ,  $K_1 = 200$ )

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