Resource Market Power and Levels of Knowledge in General Equilibrium

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Abstract

We analyze monopoly power in a market for a complementary fossil resource like oil in a two country/two period model with international trade in general equilibrium. Focusing on the complex interplay of capital and resource market, we elaborate how these effects feed back into the resource monopolist's extraction decision. His level of knowledge about the economic structure thereby plays a key role. The accumulation of own capital assets over time, together with a recognized influence of extraction on the interest rate, can lead the monopolist to accelerate or postpone extraction. Considering the interaction of resource market and global capital accumulation poses an incentive for the monopolist to accelerate extraction and to exploit the importers' increased resource addiction in the future. The conservationist bias of resource market power can be increased, dampened or reversed through the general equilibrium effects.

JEL codes: D42; D58; D9; Q3

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1 Resource Monopoly in General Equilibrium

Over two centuries ago, the industrial revolution started when technical developments provided more and more ways to substitute human labor force and animals in production by fossil energy resources. And even after such a long period of unprecedented growth in economic wealth and technological knowledge the availability of fossil energy resources is still seen as a major driving force for economic growth and development in both the industrialized world, as well as in emerging market economies. From an economic perspective, the degree of complementarity between fossil energy resources and other production factors, in particular capital and labor, at the macro level, is still enormous. This is especially true for oil. The lively debates about peak oil, about the heavy dependency of the industrial countries on the supply of oil, and about the drastic consequences of a declining oil supply in the future can be considered as indications of its great influence and importance. The substitutability of oil in the transportation sector, especially with regard to freight and air transport, remains limited, in spite of technological advancements of electric and natural gas engines for passenger cars. Along the same lines, the macroeconomic development and growth paths of big economies and the oil market are naturally treated as strongly interrelated in the debates of market and policy analysts. For instance the oil price peak of 2008 is often explained by the extraordinary growth in emerging markets like China. Overall, reductions in oil supply or increases in the oil price affect the economy so strongly that it is hard to think of any other production input factor or any other market with similarly widespread effects on incomes, prices and expected returns.

To capture these broader effects of oil availability in a consistent model framework we extend the standard partial equilibrium models of resource extraction to a general equilibrium analysis where the overall equilibrium directly depends on the resource extraction path over time. In particular, we are interested in how the influence on the whole economy might feed back into the oil supply decision itself if it is not only implicitly present via equilibrium market prices but explicitly taken into account by oil suppliers. In contrast to a competitive market, this requires the single resource supplier to be able to manipulate and adapt the overall oil supply to his own advantage, so that we assume market power in the resource market. If we think of the geographical concentration of resource stocks and oil suppliers with high market shares such as OPEC, the assumption of resource market power does not seem unrealistic. For simplification – but of course in contrast to the real world oil market – we consider a resource monopolist instead of an oligopolistic (or competitive fringe) market structure.

Combining these two aspects, the broader economic relevance of the resource in question and market power in the resource market, raises the more general question of how a resource monopolist might act in general equilibrium. Like the usual textbook monopolist, a resource monopolist takes into account the price and demand changes he induces with his supply behaviour. But since the resource is exhaustible, the monopolist optimizes supply not only for one period, as in a static model, but simultaneously for all future periods up to exhaustion of his resource stock considering opportunity costs of restrictions in period supply and following the classical Hotelling rule (cf. Dasgupta and Heal (1979) or Stiglitz (1976)).

In general equilibrium, however, the investment returns, the capital accumulation dynamics, the future factor demand and future price reactions to changes in supply are not exogenously given, but generally dependent on the specific equilibrium outcome, which in turn is directly influenced by the monopolist's supply decision. When analyzing a resource monopolist's strategic behavior while at the same time extending the standard partial equilibrium framework, it is therefore of key importance to consider the monopolist's level of awareness of oil's prominent role and its overall effects on the world economy. In principle, this holds true for every monopolist in general equilibrium. However, given the widely recognized importance of oil, we believe that it is especially plausible for an oil supplier with market power to realize at least some of the widespread effects of his supply decision. With our paper we want to create a better and more realistic understanding of the behavior of an oil supplier with market power and far-reaching influence compared to the standard Hotelling rule in partial equilibrium, not least contributing to the design of more effective climate policy instruments.

We introduce a general equilibrium framework with a finite time horizon of two periods that mainly differs from the conventional partial equilibrium setting in resource economics by including a capital market with an endogenous accumulation of physical capital from the first to the second period, since the endogenous capital stock dynamics constitute the pivot of the various general equilibrium effects. Moreover, in a two country setting we reproduce the typical asymmetry in resource endowments and production technologies between resource exporting and importing countries where the resource-rich country does not have any consumption good to sell apart from the natural resource and where it "just" fuels the production and growth processes in the resource importing country. As a consequence, the resource exporter transforms his resource wealth into financial wealth to finance current consumption and to build up a capital asset stock for future consumption. Due to the lack of investment options at home, these funds are invested abroad. However, as we assume a perfect and competitive international capital market with globally uniform returns, we do not need to specify where the capital savings of resource-exporters are invested. Real exporting countries of fossil energy resources often dispose of considerable sovereign wealth funds following the same logic. The funds of the United Arab Emirates ($ 1,078.5 billion) and Saudi Arabia ($ 757 billion) being the two biggest such sovereign asset stocks among OPEC countries (Sovereign Wealth Fund Institute (2014)). Beyond official sovereign wealth funds, all other kinds of petrodollar bank deposits are invested in some manner in the capital market, very often in the industrialized countries.

From the linkage between resource supply and the capital market in general equilibrium in our model follows that the resource-exporting country will have a direct influence on the return of its accumulated capital funds. In contrast to Hillman and Long (1985), this influence runs only via resource market power and explicitly not by assuming that the resource monopolist has additionally capital market power. One of the most striking results of our general equilibrium approach is this inherent new role of capital assets in the resource monopolist's strategy once he realizes that his oil supply has an influence on the interest rate and the growth path (see sections 3.3 and 3.5.1).

On the one hand, this may be interpreted as an extension of conventional resource market power. On the other hand, the dependency of capital returns on the availability of resources constrains the resource exporter when he tries to exert market power in the resource market. The often discussed dependency of the oil importers on the "good-will" of key resource exporting countries therefore may not be as unilateral as expected at first, but in fact mutual. In any case, recognizing his influence on the return of petrodollar capital funds partly shifts the resource exporter's focus from the resource rents which he can receive from the resource-importing countries to their economic performance.

In the following, we start by comprehensively introducing and interpreting the general equilibrium framework. Since we aim to derive and interpret the optimal extraction policy depending on the monopolist's state of awareness of the overall economic structure, we first describe a conditional equilibrium, which solely depends on the extraction path the monopolist chooses. Next, we vary the monopolist's awareness of the transmission channels of resource supply into the capital market in four steps. In scenario N ('naive') the monopolist's knowledge is that of a partial equilibrium monopolist. In scenario NA ('naive + assets') awareness of his influence on the interest rate and the resulting capital asset motive is added to the monopolist's considerations. In scenario G ('general equilibrium knowledge') the monopolist knows about the capital stock dynamics and uses this knowledge in his strategic 'addiction motive', while the asset motive of scenario NA is excluded again. Finally, in scenario GA ('general equilibrium knowledge + assets') all previous aspects and levels of awareness are taken and analyzed together.

For each scenario, we derive a modified Hotelling rule or intertemporal non-arbitrage condition which characterizes optimal resource supply over time. We compare these different optimal extraction scenarios analytically, also with the standard monopoly case, to gain intuition on the impact of the general equilibrium feedback effects and on the impact of the specific level of awareness on optimal extraction. Since different supply policies will not only lead to different extraction paths, but also to different equilibrium outcomes, a full analytical comparison of all the scenarios is, however, not feasible. To resolve these analytical ambiguities we employ a numerical simulation of the model, which allows us to graphically illustrate the different scenarios and to derive quantitative results. Finally, we shortly discuss the role of changes in the elasticity of substitution between capital and the resource, which may be interpreted as a measure of input efficiency in production and thereby of technological development.

For our analysis we take into account and build upon previous steps in the literature from partial equilibrium to general equilibrium analysis of exhaustible resource extraction and supply. While Hoel (1981) introduced an influence of a resource monopolist's decision on the interest rate, this influence was still postulated in an otherwise partial equilibrium model and unspecified, disregarding the associated capital stock dynamics. Hassler et al. (2010) also incorporate an influence of the resource supplier on the capital returns, but lack the intertemporal optimization of supply. Hillman and Long (1985) bring forward a general equilibrium model, where the interest rate is freely chosen by a resource exporter with market power on both, the resource and the capital market. However, their model lacks the impact channel from resource extraction on the interest rate directly over the physical production function, as well as the corresponding effect of the capital stock dynamics on the interest rate over the production function and all resulting repercussions. Thus, they leave this aspect of complementarity between oil and physical capital in production out of the picture. Moreover, it's exactly their exporter's free choice of the interest rate as an additional independent variable that excludes the effects of resource supply behavior on the capital market (and the corresponding consequences), that naturally arise in our general equilibrium framework and that we are interested in, from their model. Moussavian and Samuelson (1984) incorporate an exhaustible resource monopolist's influence on the capital accumulation in their model. Our analysis of scenario G is consistent with this study and develops it further, drawing additional conclusions. Besides the studies mentioned above, however, a resource monopoly is usually, from Stiglitz (1976) to Fischer and Laxminarayan (2005), analyzed with an exogenous and constant interest rate, as far as we know.

Gaitan et al. (2006) also see the necessity for dynamic general equilibrium models and propose an own such contribution. But they focus on the case of isoelastic resource demand in a competitive resource market, not more general resource demand and monopoly power. Van der Meijden et al. (2014) propose a two-country general equilibrium setup, which is in many ways similar to ours, for the analysis of resource and capital taxation effects with a focus on the Green Paradox. Their model features perfect competition on the resouorce and capital markets, in contrast to our resource monopoly. Long and Stähler (2014) also establish a dynamic general equilibrium model in perfect competition: Their focus lies on the effects of technological change on the interest rate and the consequences for the Green Paradox, i.e. a different effect channel on the interest rate than the one we are looking at.

We start by introducing the model framework and by deriving equilibrium relationships conditional on the chosen resource supply path in section 2. In section 3, we analyze the optimal supply decision of a resource monopolist by distinguishing different scenarios according to the monopolist's level of awareness of the overall economic structure and the widespread effects of his supply decision. We present a visualization of the analytical results by use of an exemplary numerical simulation of the model in section 4 and briefly discuss the crucial importance of the elasticity of substitution in section 5. Section 6 concludes.

2 Model

Consider a two country setting consisting of a resource rich country E and the rest of the world represented by country I with a finite time horizon of two periods $t = 1, 2$. Country E owns the entire world stock of an exhaustible energy resource ("oil") $\bar{R}$ but has no production technologies to transform the resource into consumption goods and/or physical capital. Country E therefore has to export the resource to trade in final goods for household consumption. In contrast, country I produces final goods for consumption but its production technology and thereby its economic development (strongly) depend on the use of imported oil. We choose the consumption good as numeraire and assume perfect substitutability between consumption goods and physical capital.

In total, the model comprises three (international) markets, the final goods market, the resource market and the physical capital market. All agents can commit to their first period decisions and have perfect foresight but asymmetric knowledge of economic structures. Since we are interested in the importance of different levels of awareness of the model's economic structure for the monopolist's optimal supply behavior, we aim to describe the overall market equilibrium conditional on the resource supply path chosen. The ultimate goal in the following section therefore is to derive market equilibria, in particular market prices, as functions of resource supply only – just as in a partial equilibrium framework where a monopolist optimizes supply for a given demand curve. A monopolist knowing the complete economic structure of the model then will choose resource supply by taking into account the general equilibrium reaction of market prices, for example.

2.1 Country I

2.1.1 Consumption Goods Production: Firms in Country I

A large number of symmetric firms competitively produce consumption goods in country I by the use of three input factors, the imported (fossil) energy resource R_t, physical capital K_t and labour L. The firms merely observe market prices in each period and act as price-takers. The labour input is supplied by the households at home and assumed to be constant over time, so that we can suppress the time index t. Additionally we assume full employment in each period.

The production technology $F(K_t, R_t, L)$ is strictly concave with respect to each input factor, constant over time and of CES-type so that

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

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

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

With F_{tf}, F_{tff} denoting the first and second derivative with respect to input factor f

at period t, we therefore have

$$F_{tK}, F_{tR} > 0 \qquad \text{and} \qquad F_{tKK}, F_{tRR} < 0 \tag{2}$$

Additionally, and crucial for the channels that we want to model, we assume at least some complementarity between the input factors so that especially the cross derivative of capital and resource input is strictly positive

$$F_{tKR} = F_{tRK} > 0 \tag{3}$$

Note, that the given production technology is homogenous of degree 1 with respect to all three input factors to ensure compatibility with a (long-term) competitive market equilibrium for final goods. However, with respect to the only variable production inputs capital and oil, final good production exhibits decreasing returns to scale, so that (cf. Hillman and Long (1985))

$$\Gamma = F_{tRR}F_{tKK} - F_{tKR}^2 > 0 \tag{4}$$

In competitive equilibrium and with overall constant returns to scale firms earn zero profits. However, with respect to capital and oil only final good producers earn positive profits

$$\pi_{tI} = F(K_t, R_t, L) - p_t R_t - i_t K_t \tag{5}$$

which equal labour income (see e.g. van der Meijden et al. (2014)). For simplicity we omit the fixed input factor L in the following.

Since consumption goods are produced competitively, factor demand for the variable production factors K_t^d, R_t^d is derived from the first order conditions of profit maximization for given (world) market prices of oil p_t and capital i_t

$$F_{tR}(K_t, R_t^d) = p_t \tag{6}$$
$$F_{tK}(K_t^d, R_t) = i_t \tag{7}$$

Factor demands for oil and capital therefore are implicitly defined as functions of both market prices

$$R_t^d = R_t^d(p_t, i_t) \qquad \text{with} \qquad dR_t^d = \frac{F_{tKK}}{\Gamma} dp_t - \frac{F_{tKR}}{\Gamma} di_t \tag{8}$$

$$K_t^d = K_t^d(i_t, p_t) \qquad \text{with} \qquad dK_t^d = \frac{F_{tRR}}{\Gamma} di_t - \frac{F_{tKR}}{\Gamma} dp_t \tag{9}$$

Due to the concavity of the production function, the complementarity of capital and the resource, and $\Gamma > 0$ from (4) capital and resource demand negatively depend on both factor prices. For the first period the capital stock K_1 is given, so that the market interest rate i_1 represents the factor price for capital for a completely inelastic capital supply.

2.1.2 Households in Country I

Consider a representative household in country I with homothetic period utility from final goods consumption c_{tI}. With $\beta = \frac{1}{1+\rho}$ denoting the utility discount factor for time preference rate ρ, life-time welfare of the household is given by

$$U_I(c_{1I}, c_{2I}) = u(c_{1I}) + \beta u(c_{2I}) = \begin{cases} \dfrac{c_{1I}^{1-\eta}}{1-\eta} + \beta \dfrac{c_{2I}^{1-\eta}}{1-\eta} & \text{for} \quad \eta < 1 \\ \ln c_{1I} + \beta \ln c_{2I} & \text{for} \quad \eta = 1 \end{cases} \tag{10}$$

where $1/\eta$ represents the constant elasticity of intertemporal substitution.

Household income is derived from the fixed labour supply to final goods production π_{tI}. Additionally, for the first period, we assume that the household is endowed with exogenous savings from the previous period s_{0I}. Therefore, total period income, that the household takes as given for its savings decision, is for the first period

$$y_{1I} = \pi_{1I} + (1 + i_1) s_{0I} \tag{11}$$

and π_{2I} from (5) for the second period. Note, that the household is also assumed to correctly foresee (labour) income π_{2I} and the market interest rate i_2 in the second period.

The household maximizes life-time utility by optimally choosing savings in the first period s_{1I}, as to smooth first- and second-period consumption subject to the period constraints

$$c_{1I} + s_{1I} = y_{1I} \tag{12}$$

$$c_{2I} = \pi_{2I} + (1+i_2)s_{1I} \tag{13}$$

Utility maximization then yields the familiar Euler equation

$$\frac{u'(c_{1I})}{u'(c_{2I})} = \beta(1+i_2) \tag{14}$$

The Euler equation in combination with the period budget constraints (12) and (13) implicitly defines optimal first period capital savings

$$s_{1I} = s_{1I}(y_{1I}, \pi_{2I}, i_2) \tag{15}$$

as a function of period income streams and the second period interest rate, i.e. the return on savings. Totally differentiating the Euler equation and using households' budget constraints in (12) and (13) yields the partial influence of changes in period income streams and the interest rate on savings

$$\begin{aligned}
\frac{\partial s_{1I}}{\partial y_{1I}} &= \frac{u''(c_{1I})}{\Delta_I} = \frac{[\beta\,(1+i_2)]^{\frac{1}{\eta}}}{1+i_2+[\beta\,(1+i_2)]^{\frac{1}{\eta}}} > 0 \\
\frac{\partial s_{1I}}{\partial \pi_{2I}} &= -\frac{\beta(1+i_2)u''(c_{2I})}{\Delta_I} = -\frac{1}{1+i_2+[\beta\,(1+i_2)]^{\frac{1}{\eta}}} < 0 \\
\frac{\partial s_{1I}}{\partial i_2} &= -\beta\frac{u'(c_{2I})}{\Delta_I} + \frac{\partial s_{1I}}{\partial \pi_{2I}} s_{1I} = \frac{\pi_{2I} + (1+i_2)\,(1-\eta)\,s_{1I}}{\eta\,(1+i_2)\left[1+i_2+[\beta\,(1+i_2)]^{\frac{1}{\eta}}\right]} \gtrless 0
\end{aligned} \tag{16}$$

where $\Delta_I = u''(c_{1I}) + \beta(1+i_2)^2 u''(c_{2I}) < 0$. For homothetic prefences, the marginal propensities to save with respect to period income are constant for a given interest rate and do not depend on the income level of households.

The ambiguous influence of the interest rate i_2 on savings is due to counteracting income and substitution effects. On the one hand, a rising interest rate enlarges the consumption possibilities of the household in the second period for given savings. This income effect diminishes the incentive to save and is captured by the negative second term $\frac{\partial s_{1I}}{\partial \pi_{2I}} s_{1I}$ above. On the other hand, the (opportunity) costs of first period consumption (from foregone interest return) rise with an increase in the interest rate, creating an incentive to substitute first period consumption for consumption in the second period by increasing savings. This substitution effect is captured by the positive first term

$-\beta\frac{u'(c_{2I})}{\Delta_I}$ and counteracts the income effect in general. For homothetic preferences and $\eta \leq 1$ (including ln-utility), however, the generally ambiguous sign of the influence of the interest rate on savings turns positive. For $\eta = 1$ income and substitution effect of an increase in the interest rate exactly cancel out but the interest rate still has a positive influence on savings due to the positive labour income of households in period 2 apart from capital income.

2.2 Country E

2.2.1 Resource Extraction

Extraction of the world stock of the fossil energy resource is controlled by the government (or oil sheikh) in power in country E. We assume that the resource is scarce. This implies that after period t_2 reserves are exhausted and that aggregate resource supply R_t^s is limited by the available stock $\bar{R}$

$$R_1^s + R_2^s = \bar{R} \tag{17}$$

There are no further resources to explore and to turn into reserves at any point in time and oil extraction costs are assumed to be zero for simplicity.

2.2.2 Households in Country E

While countries differ with respect to their factor endowment and production capabilities, we assume symmetric consumption preferences in both countries. As in country I, the representative household in country E therefore maximizes life-time utility $U_E(c_{1E}, c_{2E})$ given by (10) by optimally adjusting period consumption c_{tE} via capital savings s_{1E} in period 1.

The household again has perfect foresight with regard to the market interest rate i_2 and the resource income in both periods but no control over resource extraction and supply decisions of the sheikh. In the end, the household simply reacts to the interest rate and the income streams it observes. Thus, the savings decision of the household in country E and the resource supply decision are in any case separated.

In contrast to country I, the household in country E does not derive income from labour supply but from resource revenues

$$\pi_{tE} = p_t R_t \tag{18}$$

which the sheikh earns in the resource market and (benevolently) distributes to the households of his country.

When maximizing lifetime-utility the household therefore has to obey the period budget constraints

$$c_{1E} + s_{1E} = y_{1E} \tag{19}$$
$$c_{2E} = \pi_{2E} + (1 + i_2)s_{1E} \tag{20}$$

where we define total first period income with given savings from the previous period s_{0E} as

$$y_{1E} = \pi_{1E} + (1 + i_1)s_{0E} \tag{21}$$

From the first-order condition, the Euler equation

$$\frac{u'(c_{1E})}{u'(c_{2E})} = \beta(1 + i_2) \tag{22}$$

together with budget constraints (19) and (20) implicitly define optimal savings as a function of income streams (exogenous to the savings decision) and the interest rate

$$s_{1E} = s_{1E}(y_{1E}, \pi_{2E}, i_2) \tag{23}$$

where the marginal effects of changes in period income streams and the interest rate are completely analogue to (16).

2.3 Capital Supply

Aggregate (world) capital supply K_t^s for final goods production in period t is derived from the savings of both countries s_{tm} $(m = I, E)$ from the previous period $t - 1$. We assume that both countries are "small" in the capital market so that neither country can exert market power in the capital market via its capital supply from household savings.

For period 1, savings or capital endowments, and therefore aggregate capital supply, are exogenously given

$$K_1^s = s_{0I} + s_{0E} \tag{24}$$

For period 2, aggregate capital supply is given by the savings from both countries. Given that savings are functions of period income streams and the interest rate i_2 according to (15) and (23) we derive aggregate capital supply from the first period for second period production as a function of the interest rate i_2, the resource supply path and aggregated endowments of capital and resources

$$K_2^s = K_2^s(i_2, R_2, \bar{R}, K_1) \tag{25}$$

On the one hand we show in appendix A.1.1 that period income streams y_{1m} and π_{2m} for country $m = I, E$, which influence the savings decision of households, are in the end functions of factor prices, capital endowments s_{0E}, s_{0I} and resource supply R_1, R_2. On the other hand, we also more extensively discuss in appendix A.1.2 that for symmetric homothetic preferences, the distribution of income between both countries has no influence on aggregated savings which is due to the constant marginal savings propensities with respect to income changes that are independent of the respective income level (see (16)). In particular, this implies that factor price changes for given factor inputs, i.e. for overall constant output and aggregated income, lead to a redistribution of aggregated income between production factors and thereby, in our asymmetric country setting, also between countries but do not influence savings. Using (16) we also derive in the appendix that for symmetric homothetic preferences

$$\begin{aligned} dK_2^s = & \left(\frac{\partial s_{1I}}{\partial i_2} + \frac{\partial s_{1E}}{\partial i_2} - \frac{\partial s_{1I}}{\partial \pi_{2I}} K_2 \right) di_2 + \left(\frac{\partial s_{1E}}{\partial \pi_{2E}} p_2 - \frac{\partial s_{1E}}{\partial y_{1E}} p_1 \right) dR_2 \\ & + \frac{\partial s_{1I}}{\partial y_{1I}} p_1 d\bar{R} + \frac{\partial s_{1I}}{\partial y_{1I}} i_1 dK_1 \end{aligned} \tag{26}$$

Note that we already use the resource constraint (17) to set $R_1 = \bar{R} - R_2$ and $dR_1 = -dR_2$ which has to hold in any case per assumption. The changes in aggregated capital and resource endowments are included for completeness.

The influence of the interest rate on aggregated capital supply is due to the pure (aggregated) substitution effect in the savings decisions. A rising interest rate in principle also leads to increases in second period capital income in both countries as we discussed in the previous sections. However, for given resource prices, these income effects represent just a redistribution from labour to capital income. The loss in labour income which is captured by the term $-\frac{\partial s_{1I}}{\partial \pi_{2I}} K_2$ completely offsets the capital income gains which therefore are completely neutral with respect to the savings decision for symmetric homothetic preferences. Using (16), the aggregated substitution effect in (26) can be stated as

$$\frac{\partial s_{1I}}{\partial i_2} + \frac{\partial s_{1E}}{\partial i_2} - \frac{\partial s_{1I}}{\partial \pi_{2I}} K_2 = \left. \frac{dK_2^s}{di_2} \right|_{R_2, K_1} > 0 \tag{27}$$

where the notation explicitly points out that the resource extraction path is assumed to be constant and unaffected by the increase in the interest rate here.

The second term in (26) captures the effect that an increase in aggregate future income has on capital supply when resources are reallocated to the future but capital stocks and market prices are held constant. Correspondingly, using the above notation we may summarize this aggregated income effect on total savings by writing

$$\frac{\partial s_{1E}}{\partial \pi_{2E}} p_2 - \frac{\partial s_{1E}}{\partial y_{1E}} p_1 = \left. \frac{dK_2^s}{dR_2} \right|_{i_2, K_1} < 0 \tag{28}$$

A marginal shift of resources to the second period increases aggregated income in period 2 by the marginal productivity of resources given by $p_2 = F_{2R}$ according to (6) and correspondingly reduces aggregated income in period 1 by p_1. Due to symmetric homothetic preferences, the aggregated impact savings only depends on the overall income redistribution and not on where period incomes change. However, with constant returns to scale country E is able to completely capture the production value of its resource supply so that the aggregated income effect is driven by the induced change in savings from country E.

2.4 Conditional Market Equilibrium

We now combine the different elements discussed in the previous sections to describe the market equilibrium of the world economy. We characterize the equilibrium conditional on the resource supply path. Of course, for the overall equilibrium the optimal supply policy of the resource monopolist is still missing. However, by deriving the equilibrium outcome conditional only on the resource supply chosen by the monopolist, the concept of the conditional market equilibrium will allow us to discuss the supply policy of the monopolist depending on his level of awareness of the more widespread effects of resource supply in general equilibrium and, in particular, of the interrelation of resource and capital market.

In the following, we first summarize the conditions which define the conditional equilibrium on the capital market, the resource market and the final good's market. Second, we provide a comparative static analysis of this conditional equilibrium with respect to changes of the resource supply path.

2.4.1 Capital Market Equilibrium

From (7), capital demand of producing firms is a function of factor prices. Whereas capital supply is exogenously given for the first period by capital endowment K_1, second period capital supply with symmetric homothetic preferences is a function of the interest rate, resource supply and capital endowment according to (25). In capital market equilibrium, we therefore must have

$$K_1^d(i_1, p_1) = K_1 \tag{29}$$

$$K_2^d(i_2, p_2) = K_2^s(i_2, R_2, \bar{R}, K_1) \tag{30}$$

Note that for the second period's capital supply we already take into account the resource constraint (17) here which is assumed to be binding in any case.

2.4.2 Resource Market Equilibrium

Resource demand is derived from the production of final goods in country I under competition as a function of factor prices according to (6). For the conditional market equilibrium, resource supply is not characterized by a specific supply policy but just taken as given. However, for any equilibrium resource supply path (R_1, R_2) the resource constraint has to hold by assumption. Resource market equilibrium, therefore, is characterized by the market clearing conditions

$$R_1^d(p_1, i_1) = R_1 \tag{31}$$

$$R_2^d(p_2, i_2) = R_2 \tag{32}$$

for each period. Additionally, equilibrium factor prices are such that

$$R_1 + R_2 = R_1^d(i_1, p_1) + R_2^d(i_2, p_2) = \bar{R}$$

holds intertemporally according to (17).

The actual market equilibrium of course also depends on the supply decision of the monopolist which we aim to derive later on. Note, however, that these market clearing conditions will be met in any case as long as the monopolist will optimize his supply over time for the given resource demand functions and for the resource stock available. This holds true independent of the level of awareness we assume the monopolist to have with respect to the economic structures.

2.4.3 Final Goods' Market Equilibrium

In equilibrium, aggregate consumption and savings of households in both countries must not exceed aggregate consumption possibilities given by the output F_t and the capital stock K_t in each period, i.e. the aggregate budget constraints for the world have to hold for given first-period capital stock K_1

$$c_{1I} + c_{1E} + K_2 = F_1 + K_1 \tag{33}$$

$$c_{2I} + c_{2E} = F_2 + K_2 \tag{34}$$

Note that since we assume symmetric consumption preferences the country specific Euler equations 14 and 22 have to hold for aggregate consumption, too. Thus

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

The Euler equation therefore also defines an intertemporal final goods market equilibrium (cf. van der Meijden et al. (2014)), i.e. we have

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

in equilibrium. From Walras' law we can, however, conclude, that the final goods' market will be in equilibrium whenever the capital and the resource market are in equilibrium.[1]

[1] Also note that capital supply is directly derived from the Euler equations (14) and (22).

2.4.4 Comparative Statics of the Conditional Market Equilibrium

We now conduct a comparative static analysis of the conditional market equilibrium defined by the market clearance conditions (30), (31), (32) and (33) with respect to the resource supply path in order to illustrate the overall influence of the monopolist's extraction decision on the equilibrium outcome. In particular, we aim to characterize how market prices for capital and the resource in both periods as well as the second period capital stock depend on second period resource supply in equilibrium taking into account that the resource constraint (17) must hold.

For the first period, the capital stock is exogenously given by capital endowments and therefore independent of changes in the resource supply path. Totally differentiating the capital and resource market equilibrium conditions (29) and (31) using (7) and (6) and taking into account $dR_1 = -dR_2$ by the resource constraint (17) yields

$$\frac{dp_1}{dR_2} = \frac{\partial p_1}{\partial R_1}\frac{dR_1}{dR_2} = -F_{1RR} > 0 \tag{35}$$

$$\frac{di_1}{dR_2} = \frac{\partial i_1}{\partial R_1}\frac{dR_1}{dR_2} = -F_{1KR} < 0 \tag{36}$$

Since there is no feedback effect from a change in the capital stock, there is obviously just a direct influence of resource supply on factor prices via the induced change in the marginal product of the respective production factor in final goods production.

For the second period, we again totally differentiate the market equilibrium conditions (32) and (30) and solve for the equilibrium reaction of the factor prices to a shift of resources from the first to the second period. We show in appendix A.2.1 that the resource price still negatively reacts according to

$$\begin{aligned} \frac{dp_2}{dR_2} &= \frac{F_{2RR} - \Gamma \left.\frac{dK_2^s}{di_2}\right|_{R_2} + F_{2KR} \left.\frac{dK_2^s}{dR_2}\right|_{i_2}}{1 - F_{2KK} \left.\frac{dK_2^s}{di_2}\right|_{R_2}} \\ &= F_{2RR} + F_{2RK}\frac{dK_2}{dR_2} < 0 \end{aligned} \tag{37}$$

The negative sign can be observed from the first line and arises due to strict concavity of the production technology, which gives $\Gamma > 0$ according to (4), and the unambiguous signs of the induced substitution and income effects of aggregate savings according to (27) and (28). (37) measures the total resource price reaction to a change in the whole extraction path, i.e. including $dR_1 = -dR_2$, not only to an isolated increase in second period supply and separates the direct effect, given by the first term in the second line, from the indirect general equilibrium feedback effect of a change in the resource supply path. Correspondingly, (37) can be interpreted as the slope of the general equilibrium inverse resource demand curve which consists of the conventional/direct negative effect for a given inverse resource demand curve and of a shift of the overall inverse demand curve induced. Whereas the direct effect, as well as the overall effect, are negative, the feedback effect from capital accumulation may dampen or reinforce the standard partial equilibrium direct price effect depending on the general equilibrium effect of the second period resource supply on the capital stock.

Similarly, the interest rate still increases with a postponement of extraction:

$$\begin{aligned}\frac{di_2}{dR_2} &= \frac{F_{2KR} + F_{2KK}\left.\frac{dK_2}{dR_2}\right|_{i_2}}{1 - F_{2KK}\left.\frac{dK_2}{di_2}\right|_{R_2}} \\ &= F_{2KR} + F_{2KK}\frac{dK_2}{dR_2} > 0\end{aligned} \tag{38}$$

This is the case, even though we account for the endogenous saving reactions of households in both countries and while these savings reactions or, more specifically, the reaction of aggregate capital supply are not necessarily unambiguous due to counteracting income and substitution effects (cf. (27) and (28)).[2] In the second line of (38) we again separate the partial complementarity effect of resource supply from the general equilibrium feedback effect that results from the induced change in capital accumulation. As before, the general equilibrium feedback effect might increase or dampen the partial complementarity effect but cannot reverse its overall positive sign which again arises from the strict concavity of the production technology and the induced unambiguous income and substitution effects in aggregate savings.

The second line in (37) and (38) is derived by using the decomposition of the overall induced change in the second period capital stock into the aggregate substitution ((27)) and the aggregate income ((28)) effects that arise from a change in the extraction pattern and a thus change in the interest rate i_2

$$\frac{dK_2}{dR_2} = \frac{dK_2^s}{dR_2} = \left.\frac{dK_2^s}{dR_2}\right|_{i_2} + \left.\frac{dK_2^s}{di_2}\right|_{R_2}\frac{di_2}{dR_2} \tag{39}$$

This decomposition can be observed from (26) where we set $\frac{dK_1}{dR_2} = 0$ and $\frac{d\bar{R}}{dR_2} = 0$ for given (exogenous) capital and resource endowments. With the equilibrium change in

[2]Recall that the unambiguous positive sign of the substitution effect again is due to our assumption of symmetric homothetic preferences.

the interest rate from (38) and since the aggregated income effect from (28) was derived by accounting for the resource constraint (17), the induced change in aggregate capital supply gives the equilibrium change in the capital stock.

The main difference between the given general equilibrium framework and a partial equilibrium setting is therefore introduced by the feedback via the capital accumulation. Generally, the aggregate substitution and income effects from (28) and (27) are counteracting so that the sign of $\frac{dK_2}{dR_2}$ depends on the sign of $\frac{di_2}{dR_2}$ and is ambiguous as we have $\frac{di_2}{dR_2} > 0$ from (38).[3] However, the negative aggregated income effect from shifting resources from the present to the future period (cf. $\left.\frac{dK_2}{dR_2}\right|_{i_2}$ in (28)) dominates the positive aggregated substitution effect of an increase in the interest rate (cf. $\left.\frac{dK_2}{di_2}\right|_{R_2}$ in (27)) if[4]

$$\frac{1}{\sigma\eta} < \frac{(1+i_2)F_2}{i_2 F_2 + i_2 K_2}\left\{[\beta(1+i_2)]^{\frac{1}{\eta}}\frac{p_1}{p_2} + 1\right\} \tag{40}$$

Since the right side is larger than unity, a sufficient condition for a negative relationship between postponing extraction and the second period capital stock is

$$\sigma\eta \geq 1 \tag{41}$$

When resources are shifted to the second period, the production possibilities and thereby the world income will increase at the expense of the first period. Both, the decrease of first period income and the increase in the second period income, tend to reduce savings. With a high elasticity of substitution – and a low complementarity between capital and the resource (3) – a postponement of extraction boosts second period production and income even with a lower capital stock. For a high η, the elasticity of intertemporal substitution ($1/\eta$) is rather low and households' savings are rather insensitive to a change in the interest rate. This implies that the savings incentive from the increase in the interest rate, which a postponement of extraction induces according to (38), is rather weak and at the same time likely to be overcompensated by the effect on savings from the intertemporal redistrubtion of income.

For intuitive reasons, we assume the sufficient condition (41) to hold in the following.

[3]Recall that the overall capital stock is unaffected by the distribution of income (and resource rents) between both countries, for a given resource supply path, due to our assumption of symmetric homothetic preferences in both countries.

[4]See appendix A.2.2 for the derivation of this condition. In the appendix, we also include a figure taken from the numerical simulation of the model which shows the equilibrium sensitivity of second period capital stock and interest rate as a function of R_2.

Whenever resources are shifted from the first to the second period, a fall in the future capital stocks seems to be much more in line with economic history and the current world economy. For example, industrialized production and capital accumulation in the 19th century heavily relied on the use of fossil (energy) resources, i.e. by using fossil resources people were in a much better position to save and to build up capital stocks. Moreover, even at present an unexpected drop in fossil resource supply would most probably still lead to a decreasing world output and not to an increase in capital accumulation, especially not in physical capital accumulation, which we have in mind here.

Nevertheless, even if we assume that $\sigma\eta \geq 1$ holds and $\frac{dK_2}{dR_2} < 0$ according to (41) the equilibrium overall savings reaction with the partial effects given for the respective country by (16)

$$\frac{ds_{1m}}{dR_2} = \frac{\partial s_{1m}}{\partial y_{1m}}\frac{\partial y_{1m}}{\partial R_1}\frac{dR_1}{dR_2} + \frac{\partial s_{1m}}{\partial \pi_{2m}}\frac{\partial \pi_{2m}}{\partial R_2} + \frac{\partial s_{1m}}{\partial i_2}\frac{di_2}{dR_2} \quad \text{for country } m = I, E \qquad (42)$$

is of ambiguous sign, in general. In contrast to the overall capital accumulation, the signs of the savings reactions of each country depend on the distribution of wealth between both countries and thereby on the distribution of capital endowments as well as on the resource rents that country E can earn by exerting market power. We demonstrate this ambiguity in more detail in appendix A.2.3 where we also include a figure which illustrates the relationship between second period resource supply and savings in both countries as well as the capital stock in equilibrium in the numerical simulation we introduce and use for the discussion of the different supply scenarios in the following.

3 The Resource Monopolist's Optimal Extraction Path

In section 2 we characterized the general equilibrium of the model conditional on the monopolist's resource supply decision, in particular by deriving the resource price reaction (38) and the interest rate reaction (37) to changes in the resource extraction path. We now turn to the optimal resource supply decision of the monopolist, i.e. of country E, to characterize and interpret the overall (and no longer conditional) equilibrium of the model.

In a standard partial equilibrium setting, a monopolist exerts market power typically by choosing supply for a given (inverse) demand curve as to maximize his objective function. In contrast to competitive suppliers, a monopolist therefore directly accounts for market price reactions when he optimizes supply. Obviously, this requires the monopolist to know about the price-quantity relation that is defined by demand. In a general equilibrium setting, however, we know from the introduction of the model framework in section 2 that there are additional effects of the supply decision that can feed back into the resource market. Naturally, as far as these additional effects have implications for his objective function, the monopolist should account for them. However, this requires the monopolist to actually know about these additional effects which implies that the monopolist is aware of the underlying economic structures.

In a general equilibrium setting, the level of awareness of the economic structures therefore will determine what the monopolist considers optimal. For example, it depends on the monopolist's level of awareness whether he takes into account the overall general equilibrium resource price effect (37) of his supply decision or whether he neglects the feedback via the capital market and just accounts for the standard (partial) reaction of the resource price. Note that the additional general equilibrium transmission effects are still present and still influence the equilibrium outcome, even if the monopolist is not explicitly aware of them. In this case, the monopolist just cannot actively use them to his own advantage but observes equilibrium outcomes like a price taker in a competitive market.

In the following, to assess the importance of the various aspects of the monopolist's knowledge for optimal resource supply, we change his scope of information about the structure of the world economy, i.e. about various effects of resource supply that are introduced via the endogeneity of the capital market equilibrium and future resource demand. We start by deriving the characterization of optimal resource supply if the monopolist is indeed aware of the overall economic structure so that he realizes and internalizes all the widespread effects of his supply decision in general equilibrium. Given this overall equilibrium, we analyze how the equilibrium outcome will change as soon as we restrict the monopolist's awareness. Due to the additive structure of the first order condition that characterizes optimal resource supply, we can directly link assumptions about the monopolist's awareness of single effects to specific terms in the first order condition. Therefore, apart from the full knowledge scenario, we can distinguish three different scenarios by suppressing the corresponding terms in the first order condition for optimal resource supply.

First (scenario N), we consider a monopolist who only accounts for the resource market's

	Without Capital Assets	**With Capital Assets**
Partial Equilibrium Thinking	*Scenario N*: Naive Monopolist	*Scenario NA*: Naive Monopolist with Asset Motive
General Equilibrium Thinking	*Scenario G*: General Equilibrium Monopolist (Oil Addiction Motive)	*Scenario GA*: General Equilibrium Monopolist with Asset Motive (Omniscient Monopolist)

Table 1: Overview over the four scenarios

specific effects of his extraction decision, just as in a conventional partial equilibrium framework. Second (scenario NA), the monopolist is still assumed to base his overall supply decision on partial equilibrium information but now he knows about the production side/technology in the resource importing country. Hence, the monopolist is aware of the complementarity of fossil resources and capital in final goods production and thereby of the positive and instantaneous impact of resource supply on the return on capital assets. This enables the monopolist to pursue a so called asset motive as a second strategic motive of exerting market power in addition to the standard own price effect on infra-marginal resource units sold. In a third scenario (scenario G), the monopolist recognizes the influence of the resource extraction path on the accumulation of capital and the dependency of future resource demand on the capital stock from which the so called addiction motive may arise. At the same time and in contrast to the second case NA, we assume that the monopolist does not understand his influence on the interest rate. By isolating the different strategic motives of resource extraction – the asset motive and the addiction motive – this differentiation allows us to compare the equilibrium outcomes and thereby analyze the fully informed monopolist's extraction decision more intuitively. Scenario GA is then the full general equilibrium knowledge without any suspended terms. An overview over the scenarios is presented in table 1.

3.1 Optimal Resource Supply: Full General Equilibrium

Think of a sheikh[5], who controls resource extraction in country E and benevolently distributes resource revenues (18) back to his people. The sheikh as a benevolent planner knows about the households' consumption preferences (10) and savings behavior as characterized by (22) and is fully aware of the economic structure of the world economy.

Given these assumptions, the benevolent sheikh chooses the resource supply path (R_1, R_2) as to maximize life-time utility of the representative household in country E (10)

$$\max_{R_1,R_2} U(c_{1E}; c_{2E}) = u(c_{1E}) + \beta u(c_{2E}) = \frac{c_{1E}^{1-\eta}}{1-\eta} + \beta \frac{c_{2E}^{1-\eta}}{1-\eta}$$

Thereby, the sheikh has to obey the binding resource constraint (17) and knows about the budget constraints of the representative household in his country (19) and (20). Due to his level of awareness and information, the omniscient monopolist also explicitly takes into account that the conditional market equilibrium from section 2.4.1 holds. More specifically, the sheikh is aware of the total influence of his resource supply on the conditional market equilibrium. Following the concept of the familiar monopoly model, the sheikh therefore accounts not only for the partial resource price change but for the reactions of factor market prices in conditional equilibrium in both periods, i.e. for $\frac{dp_1}{dR_2}$ from (35) and $\frac{di_1}{dR_2}$ from (36) for the first period as well as $\frac{dp_2}{dR_2}$ from (37) and $\frac{di_2}{dR_2}$ from (38) for the second period.

The overall optimal extraction path from the sheikh's perspective, is then characterized by the first-order condition

$$u'(c_{1E}) \left[-\left(p_1 + \frac{\partial p_1}{\partial R_1} \right) - \frac{\partial i_1}{\partial R_1} s_{0E} - \frac{ds_{1E}}{dR_2} \right] + \beta u'(c_{2E}) \left[p_2 + \frac{dp_2}{dR_2} R_2 + s_{1E} \frac{di_2}{dR_2} + (1+i_2) \frac{ds_{1E}}{dR_2} \right] = 0$$

The sheikh only has an indirect influence on savings via his extraction policy as households in country E separately decide on savings given some distribution of period incomes y_{1E}, π_{2E} (exogenous to the savings decision) and the interest rate i_2. The latter implies, however, that the Euler equation (22) will hold for any distribution of period incomes and any interest rate in equilibrium and therefore for any resource extraction path. Thus, we can substitute for the marginal utilities from the Euler equation and

[5] or any other benevolent authority in country E.

finally characterize optimal resource supply as

$$(1 + i_2^{GA*})MR_1^{GA*} = MR_2^{GA*} \tag{43}$$

where we define the marginal resource value from the sheikh's perspective – the modified marginal resource revenue – if he is fully informed about the underlying economic structure as

$$MR_t^{GA} = MR_t^{GA}(K_t, R_t) = p_t + \frac{dp_t}{dR_t}R_t + \frac{di_t}{dR_t}s_{(t-1)E} \tag{44}$$

In the first period, the factor market price reactions to a change in resource supply are given by the partial effects $\frac{dp_1}{dR_1} = \frac{\partial p_1}{\partial R_1} = F_{1RR}$ and $\frac{di_1}{dR_1} = \frac{\partial i_1}{\partial R_1} = F_{1KR}$ as the capital stock K_1 is exogenously given. For the second period, the sheikh, due to his comprehensive level of awareness, takes into account the total change in factor prices in equilibrium as defined by (38) and (37).[6] Given that households always will save optimally, the resource extraction policy cannot increase life-time utility of households in country E via all the indirect effects on savings summarized in $\frac{ds_{1E}}{dR_2}$ from (42), in line with the Envelope theorem. Therefore, all these indirect effects cancel out. We may interpret condition (43) as a modified Hotelling rule for a omniscient monopolist in general equilibrium. The optimal equilibrium extraction path that is implicitly defined by (43) is denoted as (R_1^{GA*}, R_2^{GA*}) and correspondingly all equilibrium variable values for this scenario are labeled with " ^{GA*}".

Alternatively, we could consider the benevolent sheikh as an omnipotent social planner *for country E* if the sheikh is assumed to make the savings decision on his own instead of taking the households' decision as given. However, since households also have perfect foresight and in equilibrium always save optimally according to (22) for any extraction path, the social planner could not improve the outcome of the benevolent sheikh. Note that this holds true as long as the planner cannot exert market power in the capital market by his savings decision. However, to focus just on the effect of resource market power we explicitly excluded capital market power. For an analysis of a resource monopolist with additional capital market power in general equilibrium see Hillman and Long (1985).

We examine the existence of equilibria for the different scenarios, which are defined by the respective Hotelling-type condition, in the appendix B.4. In general, an equilibrium

[6]Note that these equilibrium reactions hold for changes in the overall extraction path, i.e. only for an intertemporal reallocation of the given resource stock, and cannot be interpreted for an isolated increase in second period resource supply.

is stable if we have $(1+i_2)MR_1^{GA} > MR_2^{GA}$ for a too high resource extraction in the future period and $(1+i_2)MR_1^{GA} < MR_2^{GA}$ for a too high resource extraction in the present. In each case, the sheikh then has an incentive to reallocate resource extraction towards the equilibrium. Considering both sides of (43) as functions of R_2, this stability criterion implies that the slope of the left side is steeper than the slope of the right side in the equilibrium.

In the following we will develop the interpretation of the modified Hotelling rule (43) and the corresponding extraction path from the discussion of different scenarios where the sheikh is constrained in his awareness of some or all of the more widespread effects of his supply decision in the general equilibrium framework at hand.

3.2 Scenario N: A 'Naive' Monopolist

We start with the most restrictive scenario. Assume that the sheikh does not realize the more widespread effects of his supply decision at all. The sheikh is "naive" (Moussavian and Samuelson (1984)) in the sense that he completely neglects the endogeneity of capital accumulation and second period resource demand and their dependency on the resource extraction path he directly chooses. Instead, the sheikh takes the second period capital stock K_2 and thereby resource demand as exogenously given for both periods and consequently also does not recognize the influence of resource supply on the interest rate i_t for periods $t = 1, 2$. With these assumptions the sheikh effectively has a conventional partial equilibrium thinking. Since from the naive sheikh's perspective $\frac{dK_2}{dR_2} = 0$ and $\frac{di_2}{dR_2} = 0$ in (43), the optimal resource supply is characterized by the condition

$$(1 + i_2^{N*})MR_1^{N*} = MR_2^{N*} \tag{45}$$

for given capital stocks K_1 and K_2, where we define

$$MR_t^N = MR_t^N(K_t, R_t) = p_t + \frac{\partial p_t}{\partial R_t} R_t = \frac{p_t}{\sigma}\left[\theta_{tR} - (1-\sigma)\right] \tag{46}$$

The last transformation holds for the CES production technology (1) in resource market equilibrium (cf. (6)) and $\theta_{tf} = \frac{F_{tf}f}{F_t}$ denotes the share of total output which factor f captures as remuneration.

Maximizing life-time utility of the representative household by choice of the resource extraction path is equivalent to maximizing the present-value of life-time income for the household, as the sheikh does not take into account the additional effects of resource supply on households' period income via the interest rate and on the capital stock. We could equivalently assume that the resource is extracted by a private firm in country E.[7]

Condition (45) requires an increase in the marginal value of the resource. The general equilibrium transmission channels influence the equilibrium outcome so that this increase may derive from the resource supply pattern over time as well as from the change in the capital stock, or a combination of both. Due to the concavity of the CES technology from (1), we have

$$\left.\frac{\partial MR_t^N}{\partial R_t}\right|_{K_t} = \frac{2-\sigma}{\sigma}\left[\theta_{tR} - \frac{1-\sigma}{2-\sigma}\right]\frac{\partial p_t}{\partial R_t} < 0 \quad \text{for all } \sigma > 0 \tag{47}$$

and

$$\left.\frac{\partial MR_t^N}{\partial K_t}\right|_{R_t} = \frac{F_{tRK}}{F_{tRR}}\left.\frac{\partial MR_t^N}{\partial R_t}\right|_{K_t} > 0 \quad \text{for all } \sigma > 0 \tag{48}$$

given that the monopolist has chosen supply such that $MR_t^N > 0$.[8]

3.2.1 Comparison with Perfect Competition

In the following, we analyze the naive monopolist's solution in more detail by comparison with the competitive outcome. Since an explicit solution for the optimal supply path defined by the modified Hotelling rule is generally not feasible, we first hold the capital stock fixed and focus on the effect of market power. In the next section, we consider the influence of capital accumulation on the optimal extraction path both for the monopolistic and the competitive case in more detail.

Without capital accumulation – the special case of a fixed capital stock $K_1 = K_2$ in our model framework –the inverse demand $p_t(K_t, R_t)$ is given by the same function for *both*

[7] In fact, from maximizing the present value of resource revenues π_{tE}

$$\max_{R_2} \pi_{1E} + \frac{\pi_{2E}}{1+i_2} \quad \text{s.t. } R_1 = \bar{R} - R_2$$

again condition (49) follows for *given* resource demand functions and a *given* second-period market interest rate i_2, i.e. for a naive private monopolist with perfect foresight. This equivalency also arises in Hillman and Long (1985) where in contrast to the model at hand the supply and savings decisions are not made separately by two distinct agents but by the authority controlling the resource supply.

[8] For $MR_t^N \leq 0$, the resource would not be scarce at least from the monopolist's perspective. In this case, the given resource stock would no longer constrain the monopolist in his supply decision over both periods and the dynamic setting effectively would be reduced to the static case where profit maximization without production costs always leads the monopolist to supply such that $MR_t^N = 0$.

periods. Moreover, for the comparison with the competitive outcome, it proves useful to rearrange the naive monopolist's solution (45) to

$$1 + i_2^{N*} = \frac{MR_2^N(K_2, R_2^*)}{MR_1^N(K_1, R_1^*)} \tag{49}$$

For constant capital stocks we know from (47) that condition (49) can only be met for a decreasing resource supply path. In fact, by holding the capital stock constant, we effectively replicate the well-known partial equilibrium analysis of monopolistic resource supply (see Stiglitz (1976)).

In the competitive market equilibrium, the overall market extraction path (R_1^{C*}, R_2^{C*}) is characterized by the Hotelling condition (see e.g. Dasgupta and Heal (1979))

$$1 + i_2^{C*} = \frac{p_2(K_2, R_2^{C*})}{p_1(K_1, R_1^{C*})} \tag{50}$$

Comparing both Hotelling conditions for constant capital stocks brings us to the following proposition which reproduces the results of Stiglitz (1976).

Proposition 1. *With a constant capital stock over time the monopolist will choose a more (less) conservationist extraction path compared to the competitive market outcome if $\sigma < 1$ ($\sigma > 1$). For iso-elastic demand or $\sigma = 1$, the monopolistic and competitive extraction path coincide.*

Even though both the monopolist and competitive resource suppliers will completely exhaust the resource stock and thereby choose the same total market supply if the resource is indeed scarce, the speed of extraction may differ due to the resource market power. In fact, the growth of the marginal resource revenue in the monopolistic equilibrium generally does not only derive from the growth of resource market prices over time as for the competitive case, but also from changes in the price elasticity of resource demand ϵ_{R_t,p_t}. This can be observed by rearranging marginal resource revenue MR_t^N to

$$MR_t^N = p_t \left(1 + \frac{\partial p_t}{\partial R_t} \frac{R_t}{p_t}\right) = p_t \left(1 + \frac{1}{\epsilon_{R_t,p_t}}\right)$$

where the price elasticity of demand ϵ_{R_t,p_t} is (negatively) defined for the CES-technology from (1)[9]

$$\epsilon_{R_t,p_t} = \frac{1}{F_{tRR}\frac{R_t}{F_{tR}}} = -\frac{\sigma}{1-\theta_{tR}} < 0 \tag{51}$$

In general, the change in the price elasticity of resource demand which is directly induced by resource supply for a fixed capital stock depends on the elasticity of substitution

$$\left.\frac{\partial \epsilon_{R_t,p_t}}{\partial R_t}\right|_{K_t} = \frac{\sigma-1}{\sigma}\frac{F_{tR}}{F_t}\epsilon_{R_t,p_t} \gtreqless 0 \quad \text{for } \sigma \lesseqgtr 1 \tag{52}$$

To assess the influence of market power on the extraction path, we evaluate the monopolistic Hotelling rule (49) for the optimal competitive extraction path (R_1^{C*}, R_2^{C*}). Since the Hotelling rule (50) for the competitive outcome holds per assumption, we have

$$\frac{1+\frac{1}{\epsilon_{R_2,p_2}}}{1+\frac{1}{\epsilon_{R_1,p_1}}} \gtreqless 1 \quad \text{or} \quad \epsilon_{R_2,p_2} \lesseqgtr \epsilon_{R_1,p_1} \tag{53}$$

so that any inequality in (49) derives from the induced change in the price elasticity of demand between both periods.[10] Since the optimal competitive extraction path (R_1^{C*}, R_2^{C*}) decreases for constant capital stocks we can conclude from (52) that

$$\epsilon_{R_2,p_2} \lesseqgtr \epsilon_{R_1,p_1} \quad \text{for} \quad \sigma \lesseqgtr 1$$

For $\sigma = 1$, i.e. for the special case of a Cobb-Douglas production technology, resource demand is iso-elastic. In this case, the marginal resource market revenue is directly proportional to the market prices so that the monopolistic and the competitive extraction paths clearly coincide completely (Stiglitz (1976)). If the absolute value of the price elasticity of demand falls in R or $\sigma < 1$,[11] (47) implies that the monopolist – starting from the competitive extraction path – has an incentive to shift resources to the second period to meet condition (49) and thereby to slow down extraction. This result motivates the famous suggestion of the monopolist being "the conservationist's best friend" (Solow (1974), referring to Hotelling (1931)). In contrast, if the absolute value of the price elasticity of demand increases in R for $\sigma > 1$,[12] the monopolistic

[9] The price elasticity of demand is always negative because the share of production factor f's remuneration in total output $\theta_{tf} = \frac{F_{tR}R_t}{F_t}$ cannot exceed unity by definition.

[10] Note that the price elasticity of demand is negatively defined according to (51).

[11] i.e. as the price elasticity is negatively defined here, if $\left.\frac{\partial \epsilon_{R_t,p_t}}{\partial R_t}\right|_{K_t} > 0$ and therefore $\sigma < 1$.

[12] i.e. if $\left.\frac{\partial \epsilon_{R_t,p_t}}{\partial R_t}\right|_{K_t} < 0$ and therefore $\sigma > 1$.

equilibrium is characterized by an even stronger decreasing supply path compared to the competitive case.

3.2.2 The Role of Capital Accumulation

To focus on the pure effect of market power on the optimal extraction path and the equilibrium outcome respectively we so far assumed constant capital stocks over time and thereby effectively removed one of the main differences between a partial equilibrium setting and the general equilibrium setting introduced before. However, the capital stock generally is very likely to change over time. We want to focus on positive capital accumulation over time, in the following, so that $K_2 > K_1$. Due to the complementarity of fossil resources and capital the resource will be more valuable with a higher capital stock so that there is an upward shift in the (inverse) resource demand.

Regarding resource extraction under competition, at least part of the resource market price increase from period 1 to period 2, which is necessary for the competitive Hotelling condition (50) to hold, results from the upward shift of resource demand. Compared to the standard case with a fixed demand curve (i.e. fixed capital stocks) over time, positive capital accumulation therefore tends to raise future resource extraction. If capital accumulation is sufficiently high, this extraction shift might even lead to an increasing competitive supply path over time. This holds also true for the naive monopolist as marginal revenue increases with capital ((48)).

Note that an increase in the second period capital stock will also lead to a lower equilibrium interest rate i_2 ceteris paribus, i.e. given the initially optimal competitive supply path for constant capital stocks, again due to the concavity of the CES production technology. This decrease in the interest rate additionally strengthens the incentives for competitive resource suppliers to postpone extraction (cf. van der Meijden et al. (2014)). In the general equilibrium framework, any shift of resources to the second period will also influence capital accumulation itself according to 4 and the equilibrium interest rate according to (38). However, even though these feedback effects dampen the impact of capital accumulation on the equilibrium extraction path, they cannot reverse the qualitative result that competitive and monopolistic extraction will be slowed down compared to a setting with constant capital stocks.

Nevertheless, given that both the monopolist and the competitive market tend to increase second period resource supply, we cannot exclude that capital accumulation may reverse the conclusions about the comparison between the naive monopolist and the competitive market outcome summarized in proposition 1. We know from the previous section that given (47) the monopolistic extraction bias is directly linked to the development of the price elasticity of demand over time for any given competitive extraction path (cf. (53)). With capital accumulation the price elasticity of demand changes due to the modified competitive extraction path, which we take as reference to characterize the monopolistic extraction bias, but also due to the influence of the higher capital stock. We summarize our results on the comparison between the naive monopolist and the competitive outcome with capital accumulation in the the following proposition 2.

Proposition 2. *With capital accumulation, naive monopoly power still leads to an extraction shift to the future compared to the competitive equilibrium ("conservationist's best friend") if* $R_1^{C*} > R_2^{C*}$ *and* $\sigma < 1$. *However, if capital accumulation leads to* $R_1^{C*} < R_2^{C*}$, *the monopolistic bias is ambiguous. A similar ambiguity arises for negative capital accumulation* $K_1 > K_2$.

The effect of capital accumulation on the price elasticity of demand is given by

$$\left.\frac{\partial \epsilon_{R_t,p_t}}{\partial K_t}\right|_{R_t} = (\sigma - 1)\frac{\theta_{tR}\frac{F_{tK}}{F_t}}{(1-\theta_{tR})^2} \lesseqgtr 0 \quad \text{for } \sigma \lesseqgtr 1. \tag{54}$$

and crucially depends on the elasticity of substitution σ. The overall positive influence of capital accumulation on marginal revenue MR_t^N according to (48) therefore derives from two distinct, and sometimes counteracting, effects as rearranging shows

$$\left.\frac{\partial MR_t^N}{\partial K_t}\right|_{R_t} = F_{tRK}\left(1 + \frac{1}{\epsilon_{R_t,p_t}}\right) - \frac{F_{tR}}{\epsilon_{R_t,p_t}^2}\left.\frac{\partial \epsilon_{R_t,p_t}}{\partial K_t}\right|_{R_t} > 0 \tag{55}$$

The first term on the right captures the induced upward shift in (inverse) resource demand in R_t-p_t-space that also drives the postponement of the extraction in the competitive case. For $\sigma < 1$, i.e. if capital and the resource are complementary in production, the second term on the right adds positively to the first. For $\sigma > 1$, the second term contributes negatively to the overall positive effect of capital accumulation on MR_t^N from (48).[13]

From comparing (52) and (54) we can conclude that the effect of capital accumulation on the (negatively defined) price elasticity of resource demand is exactly contrary to the effect of resource supply for any given elasticity of substitution $\sigma \neq 1$. If we have

[13]Note, that for $\sigma > 1$ resources and capital are substitutes in production. Capital accumulation then makes final goods producers less dependent on the resource and thereby lowers the market power the monopolist can exert in the second period.

$K_1 < K_2$ and $R_1^{C*} > R_2^{C*}$ in the competition case, then both, the capital accumulation and the falling resource extraction, contribute to an unambiguous decrease (rise) in ϵ_{R_t,p_t}[14] over time for $\sigma < 1$ (for $\sigma > 1$). This implies that the naive monopolist will choose a more (less) conservationist extraction path compared to the competitive market for $\sigma < 1$ (for $\sigma > 1$).[15] If either $K_1 < K_2$ while $R_1^{C*} < R_2^{C*}$ or $K_1 > K_2$ while $R_1^{C*} > R_2^{C*}$, then the effects of capital dynamics and supply pattern on the price elasticity of demand ϵ_{R_t,p_t} are counteracting each other. This implies that the incentive for the monopolist to deviate from the competitive outcome is ambiguous.[16]

For $\sigma = 1$ and Cobb-Douglas technology the price elasticity of demand is not affected by changes in the capital stock and naive monopolistic and competitive extraction coincide with and without capital dynamics.

3.2.3 General Equilibrium Feedback and Existence of Equilibrium

The role of capital accumulation was so far discussed with exogenous changes in the capital stock. In our model framework, however, the second period capital stock K_2 and the future interest rate i_2 are endogenous and lead to additional general equilibrium feedback effects while the monopolist deviates from the competitive extraction path. The interest rate even changes in the case with exogenously and constant capital stocks when switching from the competitive market to the naive monopoly in section 3.2.1. These feedback effects from the endogeneity of the capital market equilibrium have an impact on the naive monopolist's extraction path in equilibrium, even though the naive monopolist is not aware of them. For example, when the naive monopolist shifts resources to the future compared to the competitive outcome and thereby reproduces the conservationist bias the postponement of extraction goes along with an increase in i_2 according to (38) and a decrease in K_2 as (41) is assumed to hold throughout.

These feedback effects imply that in contrast to a partial equilibrium analysis, the left side of the Hotelling condition (45) effectively reacts to a shift of resources extraction from the first to the second period according to

$$\frac{d(1+i_2)MR_1^N}{dR_2} = \frac{d(1+i_2)MR_1^N}{dR_1}\frac{dR_1}{dR_2} = MR_1^N \frac{di_2}{dR_2} - \left.\frac{\partial MR_1^N}{\partial R_1}\right|_{K_1} > 0 \tag{56}$$

[14]A decrease in the negative ϵ means a rise in its absolute value.

[15]Nevertheless, we generally cannot conclude that the conservationist bias is stronger or weaker than in the partial equilibrium setting.

[16]Note that a scenario $K_1 > K_2$ and $R_1^{C*} < R_2^{C*}$ is logically inconsistent.

The effective total reaction of the right side of Hotelling condition (45) is given by

$$\frac{dMR_2^N}{dR_2} = \left.\frac{\partial MR_2^N}{\partial R_2}\right|_{K_2} + \left.\frac{\partial MR_2^N}{\partial K_2}\right|_{R_2} \frac{dK_2}{dR_2} = \frac{2-\sigma}{\sigma}\left(\theta_{2R} - \frac{1-\sigma}{2-\sigma}\right)\frac{dp_2}{dR_2} < 0 \qquad (57)$$

which is unambiguously negative at least for $MR_2^N \geq 0$ according to (47), (48) and $\frac{dK_2}{dR_2} < 0$.[17]

Since $MR_1^N \frac{di_2}{dR_2} \geq 0$ and $\left.\frac{\partial MR_2^N}{\partial K_2}\right|_{R_2} \frac{dK_2}{dR_2} < 0$, these feedback effects strengthen the partial equilibrium reaction of the marginal revenue in each period and thus dampen the reallocation of resources by the naive monopolist when starting from the competitive market equilibrium relative to a partial equilibrium analysis.

To prove the existence of an equilibrium solution, we consider the limits of the left and the right side of the Hotelling condition (45) for $R_2 \to 0$ ($R_1 \to \bar{R}$) and $R_2 \to \bar{R}$ ($R_1 \to 0$). We show in appendix B.4.2 that

$$\lim_{R_2 \to \bar{R}} (1+i_2)MR_1^N > \lim_{R_2 \to \bar{R}} MR_2^N$$

whereas

$$\lim_{R_2 \to 0} (1+i_2)MR_1^N < \lim_{R_2 \to 0} MR_2^N$$

This implies that there necessarily exists an inner equilibrium solution defined by the Hotelling condition (45) and given that the conditional market equilibrium holds. Moreover, since both sides of the Hotelling condition are falling in the respective resource supply, this equilibrium outcome is unique and stable.

3.3 Scenario NA: A 'Naive' Monopolist with a Capital Asset Motive

For the second scenario, we enlarge the monopolist's scope of information of the more widespread effects of resource supply. The monopolist is aware of the final goods' production technology in country I or, more specifically, of the complementarity of fossil resources and capital in production (see (3)). However, the monopolist still evaluates feasible resource supply paths based on partial equilibrium considerations and therefore

[17] Note that $MR_t^N \geq 0$ implies $\theta_{tR} \geq \frac{1}{2-\sigma}$.

is still considered "naive" with respect to the general equilibrium feedback effects from the endogeneity of the capital market equilibrium overall.

Without all the general equilibrium related terms in (43), the equilibrium and the corresponding optimal resource extraction path then is characterized by the modified Hotelling condition

$$\left(1 + i_2^{NA*}\right) MR_1^{NA*} = MR_2^{NA*} \tag{58}$$

where we define the modified marginal revenue

$$MR_t^{NA} = MR_t^{NA}(K_t, R_t) = MR_t^N + F_{tKR}(K_t, R_t) s_{(t-1)E}(y_{1E}, \pi_{2E}, i_2) \tag{59}$$

as the marginal value of the resource from the monopolist's perspective. We denote the optimal extraction policy by (R_1^{NA*}, R_2^{NA*}) and, correspondingly, the equilibrium outcomes of all the endogenous variables by the superscript "^{NA*}".

From the benevolent sheikh's perspective, there is now a positive and simultaneous influence of resource supply on the capital return on households' savings running via the complementarity of resources and capital in final goods' production.[18] This introduces an "asset motive" to the optimal resource supply decision, additional to the standard monopolistic strategic motive. The asset motive adds to the standard resource market revenue MR_t^N from (46) whenever country E's households have positive foreign capital holdings $s_{(t-1)E} > 0$, i.e. no debt positions (cf. Calvo and Findlay (1978)). It is interesting that there may be situations where the naive monopolist considers the resource only as scarce if he accounts for the asset motive (i.e. $MR_t^{NA} > 0$ while $MR_t^N < 0$). With a finite time horizon, the scarcity of the resource from the monopolistic supplier's perspective therefore not only depends on the resource stock available but also on the level of information that the supplier has.

An intuitive interpretation of the scenario at hand is again the notion of a benevolent sheikh. For a monopolistic profit maximizing oil firm there obviously would not be any reason to consider the returns on the households' capital savings. Moreover, due to the asset motive pure resource profit maximization does no longer lead to households' income or utility maximization. With households endogenously and optimally choosing

[18] Since the sheikh still takes capital stocks as given, but is aware of the complementarity of resources and capital in final goods production, the resource price p_t and the capital price i_t are just functions of resource supply from his perspective with

$$\frac{\partial p_t}{\partial R_t} = F_{tRR}(K_t, R_t) \qquad \text{and} \qquad \frac{\partial i_t}{\partial R_t} = F_{tKR}(K_t, R_t)$$

savings, utility maximization by planning resource extraction is, in the end, equivalent to maximizing households' life-time income. However, as soon as the sheikh accounts for the asset motive, maximizing just resource income by choice of the resource extraction path generally cannot be optimal in contrast to scenario N.

3.3.1 Effects of the Asset Motive

We now consider the effect of the asset motive on the optimal extraction choice of the benevolent sheikh. For a single period, the asset motive always raises the marginal value of the resource from the monopolist's perspective and thereby in principle creates an incentive to increase resource supply ceteris paribus whenever there are positive capital holdings $s_{(t-1)E} > 0$. Along the lines of section 3.2, we can rearrange the extended marginal revenue of resource supply to[19]

$$MR_t^{NA} = \frac{p_t}{\sigma} \left[\theta_{tR} + \theta_{tK} \frac{s_{(t-1)E}}{K_t} - (1 - \sigma) \right] \tag{60}$$

where $\theta_{tf} = \frac{F_f(t) f_t}{F_t}$ again denotes factor f's income share in total final goods output of period t. Thus, the weight of the asset motive relative to the standard monopoly considerations from scenario N in one period is determined by the share of total production (or income) that the monopolist's country E receives as capital income from abroad $\theta_{tK} \frac{s_{(t-1)E}}{K_t}$. The latter notably does not depend on the amount (value in terms of final goods) of capital assets held by country E but on the share of these assets in total capital stock.

However, for positive capital endowment and savings, there is an asset motive in both periods. Since we generally cannot solve for the optimal extraction path explicitly, we assess the effect of pursuing the asset motive on the extraction path by use of a thought experiment. We assume that the sheikh extracts according to the standard monopoly Hotelling rule (45) but then, for whatever reason, becomes aware of the (partial) complementarity of fossil resources and capital. The sheikh will update his decision rule for resource supply to (58) and assess the initially optimal extraction path (R_1^{N*}, R_2^{N*}) based on this updated optimality condition. In the following, we aim to characterize the direction of the adjustment in resource extraction that will be necessary to fulfill the new equilibrium condition (58).

As a benchmark, we derive the case when the asset motive is neutral relative to the

[19] A similar transformation can be found in Calvo and Findlay (1978).

standard monopoly outcome so that it does not induce any change in resource supply. Correspondingly, taking extraction path (R_1^{N*}, R_2^{N*}) from the naive monopolist's equilibrium as reference supply policy, neutrality of the asset motive implies that

$$\frac{MR_2^{NA}(K_2^{N*}, R_2^{N*})}{MR_1^{NA}(K_1, R_1^{N*})} = 1 + i_2^{N*} = \frac{MR_2^{N}(K_2^{N*}, R_2^{N*})}{MR_1^{N}(K_1, R_1^{N*})}$$

holds when we combine the equilibrium resource supply conditions (45) and (58). Rearranging and using $\frac{\partial i_2}{\partial R_2} = F_{2KR}$, yields

$$\frac{F_{2KR}(K_2^{N*}, R_2^{N*}) \cdot s_{1E}(y_{1E}^{N*}, \pi_{2E}^{N*}, i_2^{N*})}{F_{1KR}(K_1, R_1^{N*}) \cdot s_{0E}} = \frac{MR_2^{N*}}{MR_1^{N*}} = 1 + i_2^{N*} \tag{61}$$

Thus, the asset motive is exactly neutral if the returns for conserving one resource unit underground are the same in terms of capital income and resource income.[20]

We summarize our results on the effect of the asset motive in the following proposition.

Proposition 3. *The effect of the asset motive on the monopolist's extraction decision in comparison to the equilibrium outcome of scenario N* (R_1^{N*}, R_2^{N*}) *depends on country E's asset accumulation. The asset motive is exactly neutral if*

$$\frac{s_{1E}^{N*}}{s_{0E}} = \frac{\frac{MR_2^{N*}}{F_{2KR}(K_2^{N*}, R_2^{N*})}}{\frac{MR_1^{N*}}{F_{1KR}(K_1, R_1^{N*})}} \equiv \Phi(R_1^{N*}, R_2^{N*}) \tag{62}$$

If $\frac{s_{1E}}{s_{0E}} < \Phi$, *the asset motive leads to a shift of resources to the first period. In contrast, for* $\frac{s_{1E}}{s_{0E}} > \Phi$ *or* $s_{0E} = 0$ *and* $s_{1E} > 0$ *the asset motive induces a postponement of extraction.*

Taking the extraction path (R_1^{N*}, R_2^{N*}) as reference effectively fixes all the endogenous variables from the conditional market equilibrium but country E's capital savings s_{1E}.

[20] In this case the difference in the second and the first period share of total production which is captured by country E and taken into account by the sheikh when choosing resource supply is the same as when the sheikh does not pursue the asset motive and just considers resource income as in scenario N, i.e. we have

$$\theta_{2R}^{N*} + \theta_{2K}^{N*}\frac{s_{1E}}{K_2^{N*}} - \left(\theta_{1R}^{N*} + \theta_{1K}^{N*}\frac{s_{0E}}{K_1}\right) = \theta_{2R}^{N*} - \theta_{1R}^{N*}$$

When shifting resources to period t, the sheikh knows that he can capture from the marginal production increase F_{tR} the share $\theta_{tR} + \theta_{tK}\frac{s_{(t-1)E}}{K_t}$ if he pursues the asset motive. In contrast, from the purely naive monopolist's perspective this share is reduced to θ_{tR}.

Since the aggregated capital stock K_2 is a function of the resource supply path only.[21] the reference equilibrium from scenario N does not depend on the distribution of capital endowment between both countries. In contrast, the savings decision of households in country E is a function of the overall first period household income y_{1E} according to (23).[22] Therefore, not only MR_1^{NA} but also capital holdings of households in the second period s_{1E} directly depend on the (exogenous) distribution of the given capital stock K_1 between both countries. To isolate the role of capital endowment s_{0E}, we solve neutrality condition (61) for the ratio of asset holdings which gives the threshold Φ in (62). The threshold Φ may be lower or greater than unity, in general.[23] For $\sigma = 1$, the factor shares θ_{tf} for $f = K_t, R_t$ are constant over time[24] so that $\Phi = \frac{K_2^{N*}}{K_1}$.[25]

If $\frac{s_{1E}}{s_{0E}} > \Phi$, we can refer to (61) and conclude that conserving a marginal resource unit for future supply yields a higher return from capital income than from resource income due to the increase in capital holdings. This implies that the sheikh is confronted with the inequality

$$MR_2^{NA}(K_2^{N*}, R_2^{N*}) > (1 + i_2^{N*})MR_1^{NA}(K_1, R_1^{N*})$$

when he suddenly becomes aware of the asset motive and evaluates the modified Hotelling rule with assets (58) for the extraction path (R_1^{N*}, R_2^{N*}) which is optimal according to (49). For $\frac{s_{1E}}{s_{0E}} < \Phi$, the contrary holds true.

In either case, the sheikh has an incentive to adjust his extraction path and will shift resources to the period where the marginal resource value from his perspective is higher. For $\frac{s_{1E}}{s_{0E}} > \Phi$, the asset motive leads to a postponement of extraction compared to the standard monopoly equilibrium of scenario N. This is also the case for $s_{0E} = 0$ when the asset motive only adds to the second period marginal resource value.[26] In contrast, for $\frac{s_{1E}}{s_{0E}} < \Phi$, the asset motive induces the sheikh to accelerate extraction compared to the standard monopoly equilibrium, because the positive effect of resource supply

[21]Recall that this is due to our assumption of symmetric homothetic preferences in both countries and the exogeneity of the aggregated capital endowment K_1.

[22]Recall that $y_{1E} = \pi_{1E} + (1 + i_1)s_{0E}$ by (21).

[23]Recall that $\theta_{tR} > 1 - \sigma$ for $MR_t^N > 0$.

[24]For $\sigma = 1$ or $\alpha = 0$, the CES-technology in (1) is equivalent to a Cobb-Douglas production function $F_t = K_t^{\gamma} R_t^{\lambda} L^{1-\gamma-\lambda}$ so that the income share of the respective production factor is given by the respective constant exponent.

[25]By use of (46), we may rewrite $\Phi = \frac{K_2^{N*}}{K_1} \frac{\frac{\theta_{2R}^{N*} - (1-\sigma)}{\theta_{1R}^{N*} - (1-\sigma)}}{\frac{\theta_{2K}^{N*}}{\theta_{1K}^{N*}}}$.

[26]Note that the elasticity of substitution determines whether and how neutrality condition (62) is violated for a given capital endowment s_{0E} as it influences the right side and via the savings decision also the left side. We discuss the role of the elasticity of substitution in more detail in section 5.

on capital income in the first period dominates the capital income effect in the second period.

The impact of a redistribution of capital endowments is summarized in proposition 4.

Proposition 4. *A redistribution of capital endowments towards country E always leads to an acceleration of extraction.*

A redistribution of capital endowments between both countries does not influence the threshold Φ because the equilibrium outcome in scenario N does not depend on the distribution of capital endowments. From (16), the marginal savings propensities then are insensitive to changes in the capital endowment distribution, too. We show in appendix B.1.1 that savings s_{1E} therefore are ceteris paribus linearly increasing in capital endowment s_{0E} when capital endowments are redistributed to country E whereas we have[27]

$$\left.\frac{\partial \frac{s_{1E}}{s_{0E}}}{\partial s_{0E}}\right|_{K_1, R_1^{N*}, R_2^{N*}} = \frac{1}{s_{0E}} \left[\frac{\partial s_{1E}}{\partial y_{1E}}(1 + i_1^{N*}) - \frac{s_{1E}}{s_{0E}}\right] = -\frac{s_{1E}(0)}{s_{0E}^2} < 0 \tag{63}$$

so that the ratio of asset holding will fall with any redistribution of capital endowment to country E. This implies that the monopolist's incentive to postpone extraction is more and more reduced and is even reversed if the ratio of second to first period capital holdings falls below Φ. By increasing first period capital holdings, the redistribution of endowments disproportionally strengthens the capital income component in the first period over the one of the second period and thereby lowers the return via capital income which the sheikh can get from conserving resources underground.

The capital endowment redistribution to country E is, however, limited by the given first period capital stock K_1 so that there is a lower bound on the ratio of asset holdings. Therefore, the neutrality condition (62) cannot be met even for any $s_{0E} > 0$ (cf. appendix B.1.1) if

$$\Phi \leq \frac{\partial s_{1E}}{\partial y_{1E}}(1 + i_1^{N*}) = \lim_{s_{0E}\to\infty} \left.\frac{s_{1E}}{s_{0E}}\right|_{K_1, R_1^{N*}, R_2^{N*}}$$

where $\frac{\partial s_{1E}}{\partial y_{1E}}(1 + i_1^{N*})$ measures the marginal increase in savings from a marginal increase in capital endowment upon redistribution. In this case, we always have $\frac{s_{1E}}{s_{0E}} > \Phi$ and a postponement of extraction compared to the outcome of scenario N for all $s_{0E} > 0$.

[27] $s_{1E}(0)$ denotes savings for the case of no capital endowment $s_{0E} = 0$.

3.3.2 Asset Motive and Competitive Resource Extraction

We showed that the asset motive may induce the monopolist both to speed up or to slow down extraction depending on the capital endowment s_{0E}. In general, the asset motive, therefore, may strengthen, dampen or even reverse the conservationist bias in the extraction pattern which is introduced by market power in comparison with a competitive resource sector for $\sigma < 1$ (see section 3.2.1).

To analyze the extraction decision of the naive monopolist pursuing the asset motive in comparison with the competitive outcome we again rely on a comparative static analysis. We assume that the optimal competitive extraction path (R_1^{C*}, R_2^{C*}) falls over time even though we have capital accumulation and evaluate Hotelling condition (58) for the optimal competitive extraction. The asset motive will exactly overturn the conservationist bias of the naive monopolist without asset motive in scenario N if

$$(1 + i_2^{C*})MR_1^{NA}(K_1, R_1^{C*}) = MR_2^{NA}(K_2^{C*}, R_2^{C*}) \tag{64}$$

The following proposition summarizes our results.

Proposition 5. *The asset motive counterbalances the conservationist bias from (naive) monopoly power for $\sigma < 1$ and a decreasing competitive supply path if*

$$\Delta \equiv \theta_{2R} + \theta_{2K}\frac{s_{1E}}{K_2} - \left(\theta_{1R} + \theta_{1K}\frac{s_{0E}}{K_1}\right) = 0 \quad \textit{for } (R_1^{C*}, R_2^{C*}). \tag{65}$$

If $\Delta < 0$, the asset motive reverses the conservationist bias whereas for $\Delta > 0$, the naive monopolist with asset motive still extracts more conservationist than the competitive market. For iso-elastic demand, the equivalency of competitive and monopolistic extraction may fall apart. A reversal of the conservationist bias is more likely with higher asset endowments in country E.

Since along the optimal competitive extraction path the Hotelling rule (50) holds, we can rearrange and simplify the equality condition (64) using (60) to get (65). The parameter Δ indicates whether the share of final goods' production which the sheik consciously can capture as factor remuneration for his constituency increases or falls over time for the competitive equilibrium extraction path.[28]

[28] The reasoning is, therefore, similar to the previous assessment of the effect of the asset motive in comparison with the purely naive monopolist from scenario N. However, whereas the latter only accounts for resource income and thereby considers the development of the resource income share over time when choosing the extraction path, a competitive resource supplier does not account for his

The monopolist will shift resources to the period where the share of the marginal increase in total output which he captures as factor income is greater. Therefore, if $\Delta < 0$ for (R_1^{C*}, R_2^{C*}), the monopolist has an incentive to shift resources to the first period and thereby to reverse the conservationist bias. In contrast, if $\Delta > 0$, the monopolist will choose a more conservationist extraction policy relative to the competitive extraction path. In this case, the conservationist bias may be dampened or strengthened, in general.[29]

Even though iso-elastic resource demand for $\sigma = 1$ implies constant resource and capital factor shares θ_{tR} and θ_{tK} (see above), resource market power no longer needs to be neutral compared to the competitive outcome when the monopolist pursues the asset motive. The reason is that at least the share of country E's assets in the capital stock is very likely to change over time. Moreover, since the naive monopoly outcome coincides with the competitive case for $\sigma = 1$, the effect of the asset motive on the supply choice of the monopolist can equivalently be identified from Δ from (65) and the threshold Φ from (62).

With a redistribution of endowment to country E, Δ falls as the ratio of asset holdings $\frac{s_{1E}}{s_{0E}}$ decreases (cf. (88)) whereas competitive extraction and thereby the factor shares θ_{tR}, θ_{tK} do not change due to the assumption of symmetric homothetic consumption preferences. Thus, the asset motive therefore is more likely to reverse the conservationist bias the higher the asset endowment of country E. This is also in line with our previous conclusion that an increase in asset endowment s_{0E} generally creates an incentive to speed up extraction relative to the standard monopoly case.

3.3.3 General Equilibrium Feedbacks and Existence of Equilibrium

As in section (3.2), even though the naive monopolist with asset motive is not aware of the general equilibrium feedback effects from the endogenous adjustment of the overall

influence on aggregated supply, production and market prices at all.

Moreover, note that the conservationist bias for $\sigma < 1$ and a falling competitive extraction path $(R_1^{C*} > R_2^{C*})$ (see section 3.2) arises because we then have $\theta_{1R} < \theta_{2R}$. Similarly, the monopolist speeds up extraction for $\sigma > 1$ when $\theta_{1R} > \theta_{2R}$, and does not deviate from the competitive extraction path for $\sigma = 1$ which implies $\theta_{1R} = \theta_{2R}$.

Therefore, with and without asset motive, the extraction decision of the monopolist in comparison to the competitive market is directly linked to the development of the share of total production which the monopolist can capture for "his" households and which the monopolist, depending on his level of information, is consciously influencing by his extraction decision.

[29]Note that for $\Delta < 0$ we must have $\theta_{1K}\frac{s_{0E}}{K_1} > \theta_{2K}\frac{s_{1E}}{K_2}$ as the conservationist bias in the standard naive monopoly case follows from $|\epsilon_{R_1,p_1}| < |\epsilon_{R_2,p_2}|$ which implies $\theta_{1R} < \theta_{2R}$ by (51). In contrast, for $\Delta > 0$ the capital income share of country E may rise or fall over time.

capital market equilibrium, these feedback effects influence the overall equilibrium outcome. Moreover, with the asset motive both sides of the modified Hotelling condition (58) may no longer fall monotonously in the resource supply of the respective period.

We show in appendix B.1.2 that the left side in (58) unambiguously decreases in R_1 taking into account the resource constraint (17) and therefore unambiguously increases in R_2,[30] i.e. we have

$$\frac{d(1+i_2)MR_1^{NA}}{dR_2} = -(1+i_2)\left.\frac{\partial MR_1^{NA}}{\partial R_1}\right|_{s_{0E},K_1} + MR_1^{NA}\frac{di_2}{dR_2} > 0 \tag{66}$$

at least as long as $MR_1^{NA} \geq 0$. The first term measures the partial (ceteris paribus) change in the modified marginal revenue from a marginal shift of resource supply from the first to the second period. The second term captures the feedback effect in general equilibrium via the induced change in the market discount rate i_2 and is positive according to $\frac{di_2}{dR_2} > 0$ from (38). As already pointed out before, this endogenous reaction of the interest rate in the general equilibrium setting generally attenuates any incentive to reallocate resource extraction compared to a partial equilibrium analysis but cannot reverse the incentive to accelerate or postpone extraction itself.

For the left side of (58), the discussion in appendix B.1.2 demonstrates that

$$\frac{dMR_2^{NA}}{dR_2} = \left.\frac{\partial MR_2^{NA}}{\partial R_2}\right|_{s_{1E},K_2} + \left.\frac{\partial MR_2^{NA}}{\partial K_2}\right|_{s_{1E},R_2}\frac{dK_2}{dR_2} + \left.\frac{\partial MR_2^{NA}}{\partial s_{1E}}\right|_{R_2,K_2}\frac{ds_{1E}}{dR_2} \tag{67}$$

is generally of ambiguous sign. The ambiguity arises due to the second and third terms which capture the feedback effects from the endogeneity of overall capital accumulation and of the households' asset holdings in general equilibrium and their influence on MR_2^{NA}. The second term measures the effect of the induced decrease in the second period capital stock ($\frac{dK_2}{dR_2} < 0$ from (41)) on the modified marginal revenue MR_2^{NA} which generally may be positive or negative. The third term in (67) represents the feedback from the induced change in asset holdings in the second period where we have $\left.\frac{\partial MR_2^{NA}}{\partial s_{1E}}\right|_{R_2,K_2} = F_{2KR} > 0$. Since a change in the extraction path leads to changes in the interest rate and the period incomes, the savings reaction of households in country E is generally of ambiguous sign due to counteracting substitution and income effects (see also appendix A.2.3) although overall capital accumulation falls with any postponement

[30] Note again that the resource monopolist always chooses the extraction path such that $MR_t^{NA} > 0$ in both periods. Otherwise, the resource would not be scarce so that the resource constraint no longer binds and the functional relationships in the conditional market equilibrium derived in section 2.4 no longer hold.

of extraction.

In contrast to MR_2^N, which monotonously falls in R_2 according to (67), we therefore cannot exclude that MR_2^{NA} may increase in R_2 due to the influence of the endogeneity of capital accumulation and savings on the second period asset motive. In appendix B.1.2, we show that MR_2^{NA} may increase only for rather high R_2 on the one hand and is ceteris paribus more likely to increase in R_2 if country E owns higher capital endowment s_{0E} on the other.

The potential upward slope of MR_2^{NA} may in principle be problematic for proving the existence of an equilibrium outcome defined by Hotelling condition (58) by following the reasoning of section 3.2.3 and considering the limits of the left and the right side of the Hotelling condition for $R_2 \to 0$ and $R_2 \to \bar{R}$. However, we show in appendix B.4.3 that still

$$\lim_{R_2 \to \bar{R}} (1 + i_2) MR_1^{NA} > \lim_{R_2 \to \bar{R}} MR_2^{NA}$$

whereas

$$\lim_{R_2 \to 0} (1 + i_2) MR_1^{NA} < \lim_{R_2 \to 0} MR_2^{NA}$$

so that there again must exist at least one interior solution for which Hotelling condition (58) holds in the conditional market equilibrium. In contrast to scenario N, if MR_2^{NA} is indeed upward sloping for some R_2, the equilibrium in scenario NA may not be uniquely defined but there may be multiple (interior) solutions. Still, our previous conclusions about the effect of the asset motive on the extraction decision of the monopolist hold as long as we consider only stable equilibrium outcomes. As generally pointed out in section 3.1, stability requires that

$$\frac{d(1 + i_2) MR_1^{NA}}{dR_2} > \frac{dMR_2^{NA}}{dR_2} \quad \text{for } (R_1^{NA*}, R_2^{NA*})$$

which implies that if the monopolist is confronted with any inequality in the Hotelling condition, he is induced to restore the equilibrium outcome by comparing the marginal resource value in both periods (in terms of period 2 values).

3.4 Scenario G: General Equilibrium Information without Asset Motive

We now assume that the monopolist realizes the endogeneity of second period resource demand $p_2(K_2, R_2)$ in general equilibrium, but does not consider his influence on the return on capital. The monopolist therefore accounts for the total price reaction $\frac{dp_2}{dR_2}$ from (37), which notably also includes the feedback from capital accumulation. At the same time, however, he does not recognize (or does not care for[31]) any influence on the interest rate, neither from the complementarity effect of resource supply (F_{tKR}) nor from the induced change in capital accumulation ($F_{2KK}\frac{dK_2}{dR_2}$).

By suppressing the asset related terms in (43), optimal extraction and the overall equilibrium in this third scenario G is therefore defined by condition

$$(1 + i_2^{G*})MR_1^{G*} = MR_2^{G*} \tag{68}$$

where the marginal resource value from the sheikh's perspective is given by

$$MR_2^G = MR_2^G(K_2, R_2) = p_2 + \frac{dp_2}{dR_2}R_2 = MR_2^N + \frac{\partial p_2}{\partial K_2}R_2\frac{dK_2}{dR_2} \tag{69}$$

The optimal extraction path, which is again implicitly defined by (68), is denoted by (R_1^{G*}, R_2^{G*}) and correspondingly the equilibrium outcome of the endogenous variables by the superscript "^{G*}". We may interpret scenario G as the general equilibrium counterpart to scenario N of a naive monopolist in section 3.2. With the scenario at hand we introduce a distinction between cases with and without an asset motive in general equilibrium, which is in line with the distinction of scenarios N and NA for the naive monopolist.

3.4.1 Addiction Motive

To analyze the influence of the general equilibrium feedback effects we compare condition (68) with (49), the respective Hotelling rule from scenario N. Since the first period's marginal revenues formally coincide without pursuing any asset motive and with given capital endowments K_1, we can first restrict the analysis to the second period. In particular, we do not need to derive an intertemporal neutrality condition as

[31]Maybe the intuitive interpretation as an oil ministry as more appropriate than a comprehensively benevolent sheikh in this scenario.

in scenario NA in section 3.3.

For the comparison of the optimal extraction paths, that are implicitly defined by (68) and (49), we again assume that the sheikh initially supplies the resource according to (49), but then notices the dependency of second period demand on his extraction policy via capital accumulation, so that he updates his supply policy to (68). Proposition 6 summarizes the results on the comparison with the naive monopolist's outcome.

Proposition 6. *Letting the monopolist become aware of the endogeneity of second-period resource demand, the so-called addiction motive of resource supply arises in general equilibrium if capital and resources are complementary in production and* $\frac{dK_2}{dR_2} < 0$. *The addiction motive always induces the monopolist to speed up extraction compared the naive monopolist's equilibrium solution from scenario* N. *The strength of the addiction motive depends on the relationship between first period resource supply and second period resource demand but not on the distribution of capital endowments.*

From (37) we know that

$$\frac{dp_2}{dR_2} < \frac{\partial p_2}{\partial R_2} < 0$$

for $\frac{dK_2}{dR_2} < 0$, and correspondingly

$$MR_2^G = p_2 + \frac{\partial p_2}{\partial R_2} + \frac{\partial p_2}{\partial K_2}\frac{dK_2}{dR_2} < MR_2^N = p_2 + \frac{\partial p_2}{\partial R_2}$$

for any extraction path (R_1, R_2). This implies on the one hand that there is no point of intersection between MR_2^G and MR_2^N (for the same extraction path) as long as $\frac{dK_2}{dR_2} \neq 0$. Moreover, as before, the Hotelling rule (68) only constitutes an equilibrium condition if $MR_1^N, MR_2^G > 0$ for extraction path (R_1^{G*}, R_2^{G*}) and complete exhaustion of the resource stock $\bar{R}$. Changing the monopolist's level of knowledge from scenario N to scenario G thus could turn a scarce resource into an abundant one for some extraction paths from his perspective. Assuming, as we do, that the resource constraint indeed binds, we can also conclude from these observations that for the optimal extraction path in scenario G (R_1^{G*}, R_2^{G*}) the marginal revenue in scenario N $MR_2^N(R_1^{G*}, R_2^{G*})$ from (46) has to be strictly positive, too.

For extraction policy (R_1^{N*}, R_2^{N*}), which is initially optimal in our thought experiment, we therefore always have $MR_2^G < MR_2^N$. The first period marginal revenues and the interest rate i_2 completely coincide for the given extraction path (R_1^{N*}, R_2^{N*}). Thus, the sheikh will unambiguously speed up extraction as soon as he becomes aware of his negative influence on capital accumulation, future resource demand and the value of future extraction.

By shifting resources from the second to the first period, the monopolist aims to boost capital accumulation and to increase – given the complementarity of capital and resources in production – the dependency of the importing economy on the input factor "oil" or, equivalently, future resource demand. The monopolist therefore may be seen as an "oil-drug" dealer who is not only exploiting but even manipulating country I's addiction to fossil resources. We refer to this strategic component of resource supply in general equilibrium as "addiction motive" which inherently arises from the introduced general equilibrium framework for $\frac{dK_2}{dR_2} < 0$ as soon as we let the monopolist become aware of the endogeneity of second period resource demand.

The effect of the addiction motive may also be described with the aid of a total general equilibrium price elasticity of demand, which incorporates the general equilibrium feedback effects (cf. appendix B.2.1). The according reformulation of the Hotelling condition shows that the higher the sensitivity of the capital stock $\frac{dK_2}{dR_2}\frac{K_2}{R_2}$, the less price elastic will be second period demand and the less attractive will be second period resource supply from the monopolist's perspective. Moreover, with symmetric homothetic preferences the relationship between aggregated capital accumulation and the extraction path does not depend on the distribution of asset endowments between both countries. In contrast to the asset motive, any redistribution of endowments is completely neutral with respect to the addiction motive.

As in general equilibrium the interest rate reacts with shifting resources according to (38) and depending on the elasticity of substitution between resource and capital, the addiction motive is dampened and the difference between the equilibrium extraction paths defined by (68) and by (45) is reduced. The acceleration of extraction cannot be reversed though.

3.4.2 Addiction Motive and Competitive Extraction

Proposition 6 does not depend on the elasticity of substitution being lower or greater than unity. Extraction is always accelerated relative to the naive monopoly in scenario N. The occurrence of the addiction motive thus modifies the comparison monopoly vs. competition in section 3.2.1 as summarized by the following proposition.

Proposition 7. *The addiction motive induces the monopolist to additionally accelerate extraction. For $\sigma > 1$, the monopolist accelerates extraction even further compared to the competitive outcome than the naive monopolist. He also speeds up extraction for $\sigma = 1$ (iso-elastic demand) so that the equivalency of monopolistic and competitive extraction no longer holds. For $\sigma < 1$ and a sufficiently high $\frac{dK_2}{dR_2}$, the addiction motive may even reverse the conservationist bias of the standard naive monopoly case.*

The condition for a reversal of the conservationist bias is explained in the appendix (cf. B.2.3).

3.4.3 General Equilibrium Feedbacks and Existence of Equilibrium

Due to the general equilibrium feedback effects, the total reaction of the future marginal revenue MR_2^G to changes in R_2 is of ambiguous sign. All additive terms in $\frac{dMR_2^G}{dR_2}$ are negative (cf. appendix B.2.2) apart from $F_{2KR}R_2\frac{d^2K_2}{(dR_2)^2}$, which can be positive, at least according to our numerical example in figure 4 (cf. appendix). Therefore, we can not exclude one or more areas with a positive slope and the incidence of multiple (interior) equilibria, although we did not observe any in our numerical examples. In the appendix (B.4.4) we show that at least one interior equilibrium exists, that it must be a stable one according to the stability criterion in section 3.1 and that multiple equilibria (in case they exist) must also be interior solutions. Even if multiple equilibria occured, $MR_2^G < MR_2^N$ holds and the conclusion that the addiction motive always leads to an acceleration of extraction remains unaffected.

3.5 Scenario GA: General Equilibrium Information with Asset Motive

Finally, if we let the sheikh be aware of the endogeneity of the second period capital stock as well as of the dependency of the capital income on resource supply, we return to equilibrium condition (43) and consider a truly omniscient and benevolent resource monopolist. In general equilibrium, a full level of awareness of the economic structure naturally leads the benevolent monopolist to pursue both strategic motives at the same time, the asset motive and the addiction motive. In the following, we first will show that the asset motive is modified by the general equilibrium feedback effect from the capital market. Moreover, we will discuss the interaction between both strategic motives which characterizes the supply policy in this final scenario by comparison with the naive standard monopoly case and with the competitive extraction path.

3.5.1 The Asset Motive in General Equilibrium and the Interrelationship Between the Resource and the Capital Market

We start by considering the modified marginal revenues MR_t^{GA} in (43) in more detail. The left side of (43) is identical to the left side in (58) so that we have

$$(1+i_2)MR_1^{GA} = (1+i_2)MR_1^{NA} \quad \text{for any extraction path } (R_1, R_2).$$

Expanding the monopolist's awareness does not change his marginal revenue in the first period in comparison to scenario NA, since the present capital stock K_1 is fixed and does not cause any general equilibrium feedback effects.

Since the omniscient monopolist explicitly recognizes the endogeneity of the second period capital stock, the marginal revenues in the second period of scenarios NA and GA are not identical, i.e. the right side of (43) significantly differs from the right side in (58) as decomposing MR_2^{GA} by use of (37) and (38) demonstrates

$$MR_2^{GA} = p_2 + \left(\frac{\partial p_2}{\partial R_2} + \frac{\partial p_2}{\partial K_2}\frac{dK_2}{dR_2}\right) R_2 + \left(\frac{\partial i_2}{\partial R_2} + \frac{\partial i_2}{\partial K_2}\frac{dK_2}{dR_2}\right) s_{1E} \tag{70}$$

Proposition 8. *Letting the naive monopolist with a partial or naive asset motive become aware of the overall economic structure strengthens the asset motive in period 2 by adding a feedback effect from capital accumulation, which unambiguously contributes to an extraction shift to the future.*

With full general equilibrium knowledge, the monopolist pursuing the asset motive not only considers the positive influence of resource supply on capital returns from the complementarity of fossil resources and capital but also the effect of changes in capital accumulation that are induced by any shift in the extraction path. The asset motive in the "true" marginal revenue in period 2 (from the omniscient monopolist's point of view), therefore, encompasses an additional component relative to scenario NA which supports the complementarity effect on the capital return

$$\frac{di_2}{dR_2}s_{1E} = \frac{\partial i_2}{\partial R_2}s_{1E} + \frac{\partial i_2}{\partial K_2}\frac{dK_2}{dR_2}s_{1E}$$

according to (38). This feedback effect from capital accumulation is positive because we have a strictly concave production technology ($F_{2KK} < 0$) and assume $\sigma\eta > 1$ and therefore $\frac{dK_2}{dR_2} < 0$ (see (41)) throughout the analysis. Shifting resources to the second period, on the one hand, increases future capital returns since additional resources foster the productivity of the given capital stock. On the other hand, the future capital stock will be lower, which also raises the marginal productivity of capital, i.e. (in equilibrium) the interest rate i_2. Thus, the second period asset motive is generally strengthened by the additional term $\frac{\partial i_2}{\partial K_2}\frac{dK_2}{dR_2}s_{1E}$ for given savings and capital endowment which in principle establishes an incentive for the omniscient monopolist to slow down extraction relative to scenario NA.

The decomposition of MR_2^{GA} in (70), however, also demonstrates that becoming aware of the overall economic structure and the interrelation between capital and resource market also introduces the addiction motive of scenario G. In total, therefore, two additional but counteracting considerations influence the monopolist's supply strategy. The addiction motive creates an unambiguous incentive to speed up extraction. Thereby, it obviously counteracts the strengthening of the second period's asset motive. The overall implication of being aware of the interrelation between the capital and resource markets for the monopolist's supply decision therefore depends on the weighting of these counteracting effects and motives. To this end, we may define

$$\Psi \equiv \frac{\partial p_2}{\partial K_2}R_2 + \frac{\partial i_2}{\partial K_2}s_{1E} \tag{71}$$

which is a nonlinear function of R_2 and generally of ambiguous sign, discussed in more detail in appendix B.3.1. Wherever $\Psi > 0$, we have $\frac{\partial p_2}{\partial K_2}R_2 > -\frac{\partial i_2}{\partial K_2}s_{1E}$ and the addiction motive dominates the strengthening of the second period's asset motive. In this case, internalizing the feedback effect from capital accumulation creates an incentive for the omniscient monopolist to accelerate extraction at the given extraction path for which we evaluate Ψ. In contrast, for $\Psi < 0$, the strengthening of second period's asset motive outweighs the addiction motive so that the feedback effect from capital accumulation overall works towards a more conservationist extraction policy relative to the given extraction path. By (44) and (59), Ψ also indicates whether the marginal resource value from the omniscient monopolist's perspective exceeds the marginal revenue from the perspective of the naive monopolist with asset motive or not.

3.5.2 Scenario GA vs. Scenario G

The general equilibrium counterpart to our analysis of the asset motive in section 3.3 is a comparison between the omniscient monopolist's outcome and scenario G from section 3.4. Proceeding along the lines of section 3.3 we characterize the effect of the full general equilibrium asset motive on the extraction path relative to a monopolist who already pursues the addiction motive only. We summarize our results by the following proposition.

Proposition 9. *Taking the addiction scenario G as reference, the asset motive may induce the omniscient monopolist to both postpone or speed up extraction in general equilibrium. It is exactly neutral if*

$$\frac{s_{1E}}{s_{0E}} = \frac{MR_2^{G*}}{MR_1^{G*}} \frac{\frac{\partial i_1}{\partial R_1}}{\frac{di_2}{dR_2}} \equiv \hat{\Phi} \tag{72}$$

The monopolist accelerates extraction for $\frac{s_{1E}}{s_{0E}} < \hat{\Phi}$ *but slows down extraction for* $\frac{s_{1E}}{s_{0E}} > \hat{\Phi}$ *(for* $\frac{dK_2}{dR_2} < 0$*). A redistribution of capital endowments to country E makes the monopolist shift the resource extraction to the present.*

The overall asset motive in general equilibrium (i.e. including the partial complementarity effect F_{tKR} as well as the general equilibrium feedback via capital accumulation for the second period $F_{2KK}\frac{dK_2}{dR_2}$) will be neutral compared to the pure addiction scenario G so that it does not induce any change in the optimal extraction path if

$$\frac{MR_2^{GA*}}{MR_1^{GA*}} = \frac{MR_2^{G*}}{MR_1^{G*}} = 1 + i_2^{G*}$$

holds for extraction path (R_1^{G*}, R_2^{G*}) that is implicitly defined by (68). Following the reasoning from section 3.3.1, we isolate the effect of capital endowment s_{0E} by solving for the ratio of asset holdings which yields the modified neutrality threshold in (72). For extraction path (R_1^{G*}, R_2^{G*}) we may additionally substitute for $\frac{MR_2^{G*}}{MR_1^{G*}}$ from (68). The modified threshold $\hat{\Phi}$ thus is the general equilibrium counterpart of threshold Φ from (62). Since $MR_1^G = MR_1^N$ and $MR_2^G < MR_2^N$ according to (46), (69) and (37) as well as $F_{2KR} < \frac{di_2}{dR_2}$ according to (38), we have $\Phi > \hat{\Phi}$ for any extraction path.[32] Note, however, that we evaluate the neutrality conditions (62) and (72) for different reference extraction paths.

The interpretation of the modified neutrality condition (72) is completely analog to our previous discussion of threshold Φ in section 3.3.1. If $\frac{s_{1E}}{s_{0E}} < \hat{\Phi}$, conserving resources

[32] From the definition of $\hat{\Phi}$ and Φ in (62) also follows that $\hat{\Phi} = \Phi \frac{F_{2KR}}{\frac{di_2}{dR_2}} \frac{MR_2^G}{MR_2^N}$ which shows that $\hat{\Phi} < \Phi$ as $\frac{F_{2KR}}{\frac{di_2}{dR_2}} < 1$ and $\frac{MR_2^G}{MR_2^N} < 1$.

underground yields a lower return in terms of capital income from the now omniscient monopolist's perspective than in terms of pure resource market income. Therefore, the monopolist will speed up extraction even further (compared to the already non-conservationist extraction path of the addiction scenario) as soon as he updates his extraction strategy from (68) to (43). As the general equilibrium component of the asset motive contributes to a postponement of extraction, this incentive to speed up extraction even more than in the addiction case G for $\frac{s_{1E}}{s_{0E}} < \hat{\Phi}$ must be established by the naive or partial equilibrium component of the asset motive.[33]

For $\frac{s_{1E}}{s_{0E}} > \hat{\Phi}$, the second period asset motive overall gives the monopolist an incentive to conserve more resources for future supply compared to the reference extraction path (R_1^{G*}, R_2^{G*}). However, in this case, we cannot attribute the incentive to slow down extraction to a specific component of the second period's asset motive because the complementarity component of the asset motives may or may not establish an incentive to speed up extraction at the same time. This also demonstrates that we generally cannot conclude from the threshold condition (72) on the sign of the weighting parameter Ψ from (71).

Since the addiction motive and the according extraction decision in scenario G are completely independent of the distribution of capital endowments (symmetric homothetic preferences), taking extraction path (R_1^{G*}, R_2^{G*}) as reference, therefore, fixes all the endogenous variables which are functions of the extraction path. The only exception is that for the omniscient monopolist savings s_{1E} depend on the initial distribution of capital endowments between both countries, as in section 3.3.1. Thus, $\hat{\Phi}$, just as Φ, is independent of the distribution of capital endowments whereas we know (cf. (88) in the appendix) that the ratio of asset holdings is a decreasing function of capital endowments for a given extraction path. Just as for the naive monopolist with asset motive, we therefore can conclude the following:

Proposition 10. *A redistribution of the capital endowment to country E ceteris paribus will accelerate extraction in absolute terms (and thus also relative to the addiction scenario which remains unaffected by the endowment redistribution) by strengthening the capital income motive of resource supply in the first period relative to the one in the second period.*

[33] I.e. we must have $\frac{s_{1E}}{s_{0E}} < \hat{\Phi} < \Phi$.

3.5.3 Omniscient vs. Purely Naive Monopoly

As in sections 3.3 and 3.4 the natural benchmark for the omniscient monopolist's extraction decision (defined by (43)) is the naive monopoly scenario N. In the following, we characterize the additional extraction incentives of the omniscient monopolist and their implications for the optimal extraction path by investigating the incentive of the omniscient monopolist to deviate from reference path (R_1^{N*}, R_2^{N*}) which fulfills the naive monopolist's Hotelling rule (49). We summarize our results in the next proposition.

Proposition 11. *The omniscient monopolist exactly follows the extraction policy of the naive monopolist if*

$$\frac{s_{1E} + \frac{\Psi}{F_{2KR}} \frac{dK_2}{dR_2}}{s_{0E}} = \Phi \quad \textit{for extraction path } (R_1^{N*}, R_2^{N*}). \tag{73}$$

If $\frac{s_{1E} + \frac{\Psi}{F_{2KR}} \frac{dK_2}{dR_2}}{s_{0E}} > \Phi$*, the omniscient monopolist chooses a more conservationist extraction path and for* $\frac{s_{1E} + \frac{\Psi}{F_{2KR}} \frac{dK_2}{dR_2}}{s_{0E}} < \Phi$ *a less conservationist extraction path than the naive monopolist.*

Since full general equilibrium information affects both, the first period and the second period marginal resource value from the monopolist's perspective, we start by analyzing analogue to section 3.3 when the additional information is completely neutral relative to the standard naive monopoly case. In this sense, neutrality implies that by combining Hotelling conditions (49) and (43)

$$\frac{MR_2^{GA*}}{MR_1^{GA*}} = \frac{MR_2^{N*}}{MR_1^{N*}} = 1 + i_2^{N*}$$

holds for extraction path (R_1^{N*}, R_2^{N*}). Using (44), (46) and (71) we can rearrange this neutrality condition along the lines of (62) to get (73). The threshold Φ is known from (62) and our discussion of the asset motive which derives solely from the complementarity effect of resource supply on capital return F_{tKR} in section 3.3.1 where we notably based our analysis on exactly the same reference extraction path (R_1^{N*}, R_2^{N*}) according to (45) as in the scenario comparison at hand. Since the omniscient monopolist explicitly internalizes the feedback effect from capital accumulation (cf. section 3.5.1), the neutrality condition relative to the purely naive monopolist is modified for the omniscient monopolist by including the parameter Ψ.

The interpretation of neutrality condition (73) and the conclusion about the extraction incentives of the omniscient monopolist in comparison with the purely naive monopolist is completely analogue to section 3.3.1. Still, neutrality condition (73) illustrates that the extraction decision of the omniscient monopolist is characterized by the interaction of the asset motive (with its partial and general equilibrium components) and the addiction motive. Due to the ambiguity of Ψ and the ambiguity of the partial equilibrium asset motive which we observed in section 3.3.1 we may in principle get any ordering of the supply scenarios of the purely naive monopolist, the naive monopolist with asset motive and the omniscient monopolist, depending on the relative weights of the different motives. Our previous results, however, allow us to draw the following conclusions about the ordering and the relationship of scenarios N, NA and GA in equilibrium:

- When we evaluate neutrality condition (73) and the sign of Ψ for the optimal extraction path (R_1^{N*}, R_2^{N*}) in scenario N, we still generally cannot draw any conclusion whether the omniscient monopolist extracts more or less conservationist than the naive monopolist with assets. The only exception is the special case when scenarios N and NA coincide ($\frac{s_{1E}}{s_{0E}} = \Phi$).
- If $\Psi = 0$ and $\frac{s_{1E}}{s_{0E}} = \Phi$, all three scenarios, N, NA and GA, coincide, despite very different levels of knowledge.

Similar conclusions are possible regarding scenarios N, G and GA in equilibrium, because the purely addiction motivated monopolist always chooses a less conservationist extraction policy than the naive monopolist from scenario N:

- The extraction paths in scenarios N, G and GA can never coincide at the same time.[34]
- For scenarios N and GA to coincide or GA to be more conservationist than N (according to (73)), the omniscient monopolist must choose a more conservationist extraction path than the purely addiction motivated monopolist from scenario G and pursuing the general equilibrium asset motive must induce a postponement of extraction (cf. (72)).

In line with section 3.3.1 and the discussion of neutrality condition (62), the right side of (73) will not change with a redistribution of capital endowments, as the threshold Φ remains unaffected. Redistributing capital endowments to country E, however, will alter the left side and thus the extraction policy of the omniscient monopolist as the

[34]The same holds true for scenario NA. If $\frac{s_{1E}}{s_{0E}} = \Phi$ and the naive monopolists with and without asset motive choose exactly the same extraction path, the monopolist of scenario G pursuing only the addiction motive will always extract less conservationist.

following proposition summarizes.

Proposition 12. *Redistributing capital endowment to country E will overall increase the speed of extraction by the omniscient monopolist relative to the standard naive monopolist's outcome.*

Following the previous section 3.5.2 we already know that redistributing capital endowment to country E always gives the omniscient monopolist an incentive to speed up extraction compared to the monopolist pursuing only the addiction motive whose extraction decision does not depend on the distribution of capital endowment. However, since the naive monopolist does not react to any redistribution of the capital endowment either, the omniscient monopolist must accelerate extraction also in comparison with the naive monopolist's outcome and the proposition holds.[35]

3.5.4 Comparison with Competitive Extraction

In the following, we again extend the characterization of the omniscient monopolist's supply decision by comparing it with the competitive supply path and examining whether the omniscient monopolist may reverse the standard textbook conservationist bias of a resource monopolist for $\sigma < 1$.

Proposition 13. *The omniscient monopolist generally may choose a more or less conservationist extraction path than the competitive market due to the interplay of addiction and asset motive. Iso-elastic resource demand or $\sigma = 1$ is no longer a sufficient condition for the neutrality of market power with a full level of information.*

Following the reasoning in section 3.3.2 the omniscient monopolist's extraction path will correspond to the competitive outcome if

$$(1 + i_2^{C*})MR_1^{GA} = MR_2^{GA} \quad \text{for the competitive extraction path } (R_1^{C*}, R_2^{C*})$$

[35] Proposition 3 showed that increasing first period's asset holdings establishes – except for the special case $(\Phi < (1 + i_1^{N*})\frac{\partial s_{1E}}{\partial y_{1E}})$ where the endowment distribution does not influence the effect of the asset motives on the extraction path at all – an incentive for the naive monopolist pursuing an asset motive to speed up extraction, too. Since both extraction policies change, we generally cannot derive any conclusion about the influence of the endowment distribution on the comparison between scenarios GA and NA in equilibrium.

or by using (70), (65), (71) and (60) if

$$\hat{\Delta} \equiv \frac{p_2^{C*}}{\sigma}\Delta + \Psi\frac{dK_2}{dR_2} = 0 \quad \text{for the competitive extraction path } (R_1^{C*}, R_2^{C*}). \tag{74}$$

We define the parameter $\hat{\Delta}$ as the general equilibrium counterpart to Δ from (65). In analogy to scenario NA, $\hat{\Delta}$ measures the incentive of the omniscient monopolist to deviate from the competitive outcome. The omniscient monopolist chooses a more conservationist extraction path for $\hat{\Delta} > 0$ but speeds up extraction relative to the competitive outcome for $\hat{\Delta} < 0$.

Obviously, whether the omniscient monopolist deviates from the competitive outcome or not depends on the respective incentive of the naive monopolist with asset motive (Δ from (65)) and the influence of the additional considerations which the omniscient monopolist takes into account due to his awareness of the endogeneity of capital accumulation (Ψ from (71)). If, for example, the share of final goods' production which country E can capture as factor remuneration increases over time ($\Delta > 0$) and the naive monopolist with asset motive extracts more conservationist than the competitive market according to (65), the omniscient monopolist will only offset the conservationist extraction bias for $\Psi > 0$ due to $\frac{dK_2}{dR_2} < 0$ according to (41). Intuitively, the addiction motive must dominate sufficiently the strengthening of the second period's asset motive to establish a sufficient incentive for the omniscient monopolist to speed up extraction compared to the naive monopolist with asset motive.

In general, however, we may have any combination of Δ and Ψ so that the omniscient monopolist can have an incentive to extract faster than the competitive market ($\hat{\Delta} < 0$) even if the scenario NA monopolist chooses a more conservationist extraction path ($\Delta > 0$), or vice versa.

For iso-elastic resource demand, i.e. for the case $\sigma = 1$, the factor shares θ_{tR} and θ_{tK} are constant.[36] Nevertheless, since the share of country E's asset holdings in total capital stock $\frac{s_{1E}}{K_2}$ is likely to change over time so that $\Delta \neq 0$ and, similarly, since $\sigma = 1$ does not necessarily imply $\Psi = 0$, iso-elastic resource demand no longer is a sufficient condition for the monopolistic outcome to coincide with the competitive outcome.

[36]Indeed, we have $\theta_{tR} = \frac{F_{tR}R_t}{F_t} = \lambda\frac{R_t}{F_t}\left(\frac{F_t}{R_t}\right)^{1-\alpha} = \lambda$ and $\theta_{tK} = \frac{F_{tK}K_t}{F_t} = \gamma\frac{K_t}{F_t}\left(\frac{F_t}{K_t}\right)^{1-\alpha} = \gamma$ according to (1) because $\sigma = \frac{1}{1-\alpha} = 1$ implies $\alpha = 0$.

3.5.5 General Equilibrium Feedbacks and Existence

To prove the existence of an equilibrium outcome as defined by the Hotelling condition (43) given that the conditional market equilibrium holds, we again have to consider how the left and the right side of (43) react to a change in the extraction pattern. However, in contrast to scenarios N and NA, the omniscient monopolist is explicitly aware of the feedback effect in general equilibrium from the endogeneity of the capital market equilibrium.

For the left side of condition (43), we can refer to (66) and conclude that it unambiguously will fall in R_1 or, correspondingly, increase in R_2, because we have $MR_1^{GA} = MR_1^{NA}$ and the functional relationship $i(R_2)$ in the conditional equilibrium is independent of the respective supply scenario.

Totally differentiating the right side of condition (43) gives

$$\frac{dMR_2^{GA}}{dR_2} = \frac{dMR_2^{NA}}{dR_2} + \frac{d\Psi}{dR_2}\frac{dK_2}{dR_2} + \Psi\frac{d^2K_2}{(dR_2)^2} \tag{75}$$

by using (71) and the decomposition in (70). The first term is already known from (67) and generally of ambiguous sing. The second and third terms arise due to the monopolist's awareness of the general equilibrium feedback effects and measure how this general equilibrium effects change in response to a change in the extraction path. Both are of ambiguous sign, in general. We discuss $\frac{d\Psi}{dR_2}$ in more detail in appendix B.3.1. In the last term, Ψ from (71) is generally ambiguous, as well as $\frac{d^2K_2}{(dR_2)^2}$ which was already pointed out before in section 3.4.3. As in scenario NA (s. section 3.3.3), the ambiguity of the total derivative implies that the marginal resource value in the second period from the omniscient monopolist's perspective may increase in R_2. However, in the scenario at hand such an upward slope may not only arise from the influence of the general equilibrium feedback effect on the partial equilibrium asset motive (as captured by the first term in (75)) but also from the induced change in the general equilibrium feedback effects which the omniscient monopolist explicitly takes into account.

We discuss the total derivative and the potential upward sloping of MR_2^{GA} in particular in more detail in appendix B.3.2. This analysis suggests that an upward sloping of MR_2^{GA} is more likely to arise the more capital endowments are distributed to country E ceteris paribus, just as in scenario NA. Moreover, MR_2^{GA} tends to increase stronger than MR_2^{NA} if both are indeed increasing in R_2.

In contrast to scenario NA, the upward sloping of MR_2^{GA} might not only give rise to multiple equilibria but also to corner solutions in scenario GA. We show in appendix B.4.5 that we have

$$\lim_{R_2 \to 0} (1 + i_2) MR_1^{GA} < \lim_{R_2 \to 0} MR_2^{GA}$$

but we cannot exclude in general that

$$\lim_{R_2 \to \bar{R}} (1 + i_2) MR_1^{GA} < \lim_{R_2 \to \bar{R}} MR_2^{GA}$$

Thus, there need not be an equilibrium outcome for which Hotelling condition (43) is met given that the conditional market equilibrium holds. However, the assessment of the limits of the left and the right side of the Hotelling condition at least demonstrates that there might be a corner solution for $R_2 \to \bar{R}$ but not for $R_2 \to 0$, i.e. there might only be such a corner solution that the monopolist chooses to extract the whole resource stock just in the second period. Given that the addiction motive always works towards an acceleration of extraction, this is only possible for a very strong second period asset motive.[37] Note that the occurrence of such a corner solution is, in general, independent of whether we assume $\sigma \leq 1$ or $\sigma > 1$ even though the latter ensures that final goods production in the first period does not break down for $R_1 = 0$.[38]

If there is no corner solution, the upward sloping of MR_2^{GA} may lead to multiple equilibria, just as in scenarios NA and G. Due to the left side of Hotelling condition (43) monotonously falling in R_1, however, there will be at least one stable equilibrium outcome, i.e. we will have

$$\frac{d(1 + i_2) MR_1^{NA}}{dR_2} > \frac{dMR_2^{GA}}{dR_2}$$

for some extraction path (R_1^{GA*}, R_2^{GA*}) for which Hotelling condition (43) is met. Note that for any stable equilibrium outcome the interpretation and intuition laid out in the previous sections and scenario comparisons hold irrespective of whether MR_2^{GA} is upward or downward sloping for the respective equilibrium extraction path.

[37] In particular, since such a corner solution is excluded in scenario NA, it must be due to the strengthening of the second period asset motive via the feedback effect from capital accumulation.

[38] If $\sigma \leq 1$ and $R_2 = \bar{R}$, consumption needs of the first period are satisfied out of capital endowments only.

4 Numerical Simulation and Graphical Illustration

To illustrate our results, figure 1 shows the respective paths of the perceived marginal revenue of all four scenarios from a numerical simulation. The curves show the resulting manifestations of the effects that the respective monopolist considers in the model for the exemplary parameters $\sigma \approx 0.91$ (high but below 1), $\eta = 2$, $\beta = 0.3$, $\lambda = 0.1$, $\gamma = 0.4$, $A = 300$ and the exemplar endowments $K_1 = 200$, $s_{0E} = 20$, $s_{0I} = 180$, $\bar{R} = 10$. I.e. we construct figure 1 by exogenously varying the extraction path within the limits of the given resource stock and by calculating the extended marginal resource revenues MR_t and the corresponding endogenous variables. The conditional market equilibrium holds along these marginal revenue curves which implies that the capital stock and the interest rate i_2 change along the curves. In particular, there is a unique and specific second period capital stock for the extraction paths feasible within the given resource constraint. The width of the diagram is defined by the resource stock available so that we can include both sides of the respective Hotelling condition into one figure. The overall equilibrium and optimal extraction path is obviously defined by the point of intersection of the first and the second period marginal revenue curves.

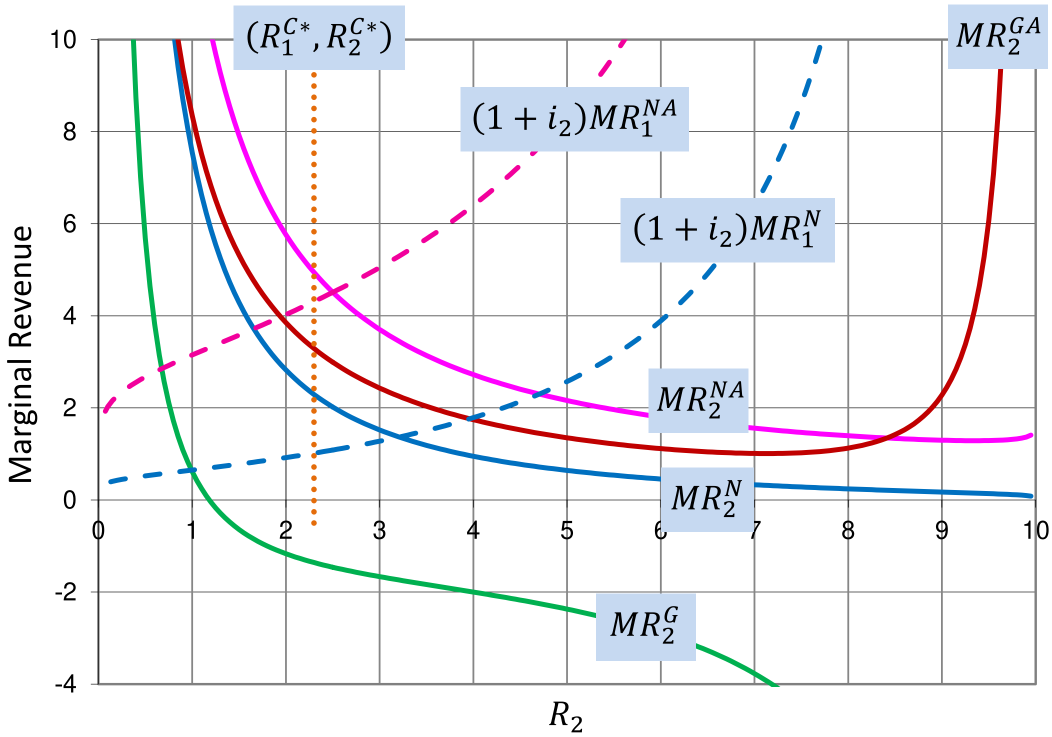

Figure 1: Marginal revenues for all four analyzed scenarios in comparison

Compared to scenario N, the asset motive of scenario NA induces the monopolist to speed up extraction. The vertical difference between the revenue curves exactly measures the influence of the asset motive. In scenario NA, the second-period marginal revenue curve with assets does indeed not fall monotonously in R_2 but exhibits a slightly upward sloping part for high values of R_2, which illustrates the analytical ambiguity of (67), that results from the asset motive in general equilibrium. An even stronger upward sloping part due to an enhanced asset motive is visible for scenario GA. Such an upward sloping part is more likely with higher capital endowments to country E, which also tends to accelerate extraction ceteris paribus.

In scenario G the monopolist speeds up extraction compared to the standard monopoly case due to the addiction motive. If we compare the shape of both marginal revenue curves MR_2^N and MR_2^G, the figure also demonstrates the influence of the capital accumulation feedback on the marginal revenue MR_2^G. While MR_2^G strongly declines for high R_2 due to the internalization of the increasingly strong feedback effects from capital accumulation, these effects are overcompensated in scenario GA by the asset motive related general equilibrium effects.

The conservationist extraction bias from naive monopoly power relative to the competition case is dampened by the asset motive in scenario NA ($\Delta > 0$) and even reversed for the omniscient monopolist ($\hat{\Delta} < 0$) and the monopolist in the addiction scenario G.

5 The Role of the Elasticity of Substitution σ

As the interplay of the resource market and the capital market is the central field of analysis in our paper, a change in the substitution parameter is of direct importance for the considered effects. In the following we use the numerical simulation to vary the elasticity of factor substitution, discuss the impact on the equilibrium outcomes of the different scenarios and thus to elaborate on the role of the substitution elasticity in our model.

5.1 Influence of σ on the Equilibrium Extraction Path

The influence of the elasticity of substitution on the equilibrium extraction paths in all four treated monopoly cases and in the competition case is visible in figure 2. Evidently, it varies substantially.

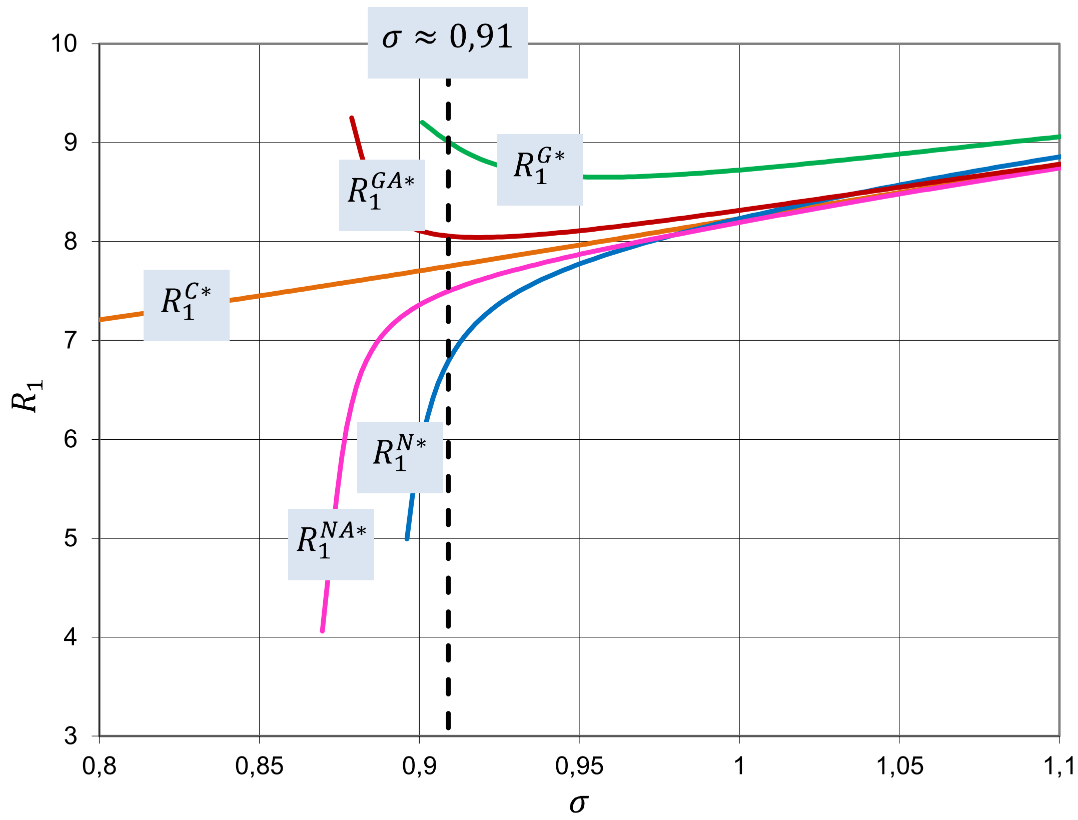

Figure 2: Dependence of the equilibrium present extraction rates on the elasticity of substitution σ between R and K

The dashed vertical line marks the value of approximately $\sigma = 0.091$, which was used in the numerical simulation of the scenarios above. The order of scenarios is mostly constant over the range of σ, but we see two intersection points for $\sigma \leq 1$: As mentioned in section 3.2, the equilibrium extraction path of the naive monopoly case N coincides with the one of the competition case for $\sigma = 1$ (isoelastic resource demand). And the second intersection is between cases N and NA (at roughly $\sigma = 0.98$). This is the point where the asset motive as described in section 3.3.1 is exactly neutral and does not lead to any extraction shift at all, compared to scenario N.[39]

The curves of the monopoly cases in figure 2 all end between $\sigma = 0.87$ and $\sigma = 0.91$. While σ is falling, the marginal revenues of all cases are going down, finally reaching zero at the end of the respective curve. For lower values of σ the marginal revenue would become negative and the optimization problem changes in the way that it becomes favorable for the monopolist to leave some resource in the ground. This regime change is

[39]Keep in mind here, that the neutrality threshold Φ and the level of savings s_{1E} depend on σ themselves.

beyond the scope of this paper. The marginal revenue in the competitive case goes down as well, but it can never hit zero, since the marginal products with a CES production function are always positive.

5.2 Present Extraction Falling with a Decrease in σ

A reduction in the substitution elasticity obviously causes a decrease in the present extraction rate R_1 in the competitive case. And since this effect is transmitted over the marginal product of the resource in each period, which plays a prominent role in every modification of the Hotelling rule, it affects the four monopoly cases as well. For higher values of σ all scenarios exhibit mostly the same extraction shift to the future as σ goes down. But for lower values of σ mechanisms, which cause the divergence of the scenario outcomes (discussed in the next section), more and more dominate the pure extraction shift to the future. First of all, with a decrease in σ, all marginal products are reduced. But in the competitive case the first period's marginal revenue in current terms $(1 + i_2)p_1$ experiences a stronger reduction through the movement in both, i_2 and p_1, than the second period's marginal revenue p_2, although p_1 alone goes down less than p_2. As a result, the extraction path shifts towards the higher marginal revenue in the future.

5.3 Divergence of Scenarios with a Reduction in σ

Another striking feature of the plot is the increasing divergence of the scenario outcomes with sinking values for σ. While the difference between the cases for $\sigma > 1$ is almost negligible (except for scenario G, whose addiction motive (see section 3.4.1) is persistent), it grows substantially for lower σ. This divergence is explained by two factors: An accelerated extraction shift to the future in the 'naive' scenario N and an increasing shift to the present in scenario G. The scenarios NA and GA exhibit additional deviations from their 'base cases' N and G due to the asset motive, but do not change the divergence finding dramatically.

As we have already seen in section 3.2, the naive monopoly scenario N generally features a more conservationist extraction path compared to the competition case. But this difference increases with a falling substitution elasticity σ. When monopoly power is 'switched on' in the competitive equilibrium, then the resulting imbalance in the monopolist's Hotelling rule must be sorted out through an extraction shift to the future and the according adjustment of both periods' marginal revenues. However, the adjustment reaction of the marginal revenue depends itself on σ (cf. (47) and (57)).

While $\frac{dp_2}{dR_2}$ is the reaction function of the marginal revenue of the competitive case to a shift in R_2, the factor in front of it falls almost linearly with a reduction in σ until it reaches zero shortly below $\sigma = 0.9$. As a result, the extraction shift, that is necessary to achieve a certain movement of the marginal revenue in the monopoly case, rises approximately in a hyperbolic manner, as we see in figure 2 for the curve of scenario N. [40]

On the other hand, the curves of scenario G and of the full general equilibrium case GA are convex and a reduction in σ prompts a smaller postponement of extraction than we see in the competitive case and, finally, even an increase in present extraction, when further reducing the elasticity of substitution. The addiction motive, as it is described in section 3.4.1, is reinforced through the reduction in σ. The corresponding negative term $\frac{\partial p_2}{\partial R_2}\frac{dK_2}{dR_2}R_2$ in this scenario's marginal revenue is increased in absolute terms. This fast growth in the addiction motive obviously overcompensates the extraction postponement of the scenarios N and NA, that follows from the reduction in σ, in this simulation example and leads to ever higher extraction rates in the present, the further the elasticity of substitution is reduced. As we have seen in 3.4.2, while the outcome of scenario G always exhibits a higher present extraction than the naive monopoly of scenario N, it does not necessarily have to feature even a higher present extraction than the competition case, but can rather also lie between the outcomes of scenario N and competition.

6 Conclusion

We provide an analysis of monopoly power on the market for a crucial resource like oil in general equilibrium with elastic demand. The formal analysis is enhanced with a numerical simulation of the model. Our model framework takes the impact of oil extraction on the endogenous interest rate, output and capital accumulation into account, as well as the resulting complex effects on resource demand and again on the

[40] The σ-depending factor in (47) and (57), that dampens the necessary adjustment reaction of the monopolist's marginal revenue, is overlain by the increasing demand elasticity $\frac{\partial \epsilon}{\partial R_2} > 0$ in equation (51) during the extraction shift, that increases the effect of a shift in R_2 on MR_2^N and thus alleviates the adjustment of the monopolist's Hotelling rule. However, this alleviation melts down itself with a reduction in σ, so that a low $\frac{dMR_2^N}{dR_2}$ remains.

interest rate. As a central contribution of the paper, we find that the monopolist's level of knowledge about the different effect channels, feedback effects and economic structures in the general equilibrium setup is crucial for his choice of the optimal extraction path from his respective view. We change his level of awareness in steps to define and analyze four scenarios and to make the influence of different parts of the monopolist's knowledge on his resource extraction decision more transparent. Finally, the scenario GA incorporates complete knowledge about the whole economic structure on the side of the monopolist and constitutes a case of comprehensive general equilibrium resource monopoly.

In the naive monopoly case (scenario N), as in a partial equilibrium model, where the monopolist only knows the resource demand behavior, monopoly power leads to a postponement of extraction if the according competitive extraction path is falling over time and capital accumulation is positive. This classical conservationist bias of the monopoly, however, is put in question as the extraction shift of the monopolist relative to the competitive outcome becomes ambiguous if capital accumulation is negative, or if the competitive extraction path is upward sloping (due to high enough positive capital accumulation).

Knowledge about the impact of resource extraction on the capital accumulation dynamics and the resulting changes in resource demand in scenario G lead to the emergence of an unambiguous 'addiction motive': Taking into account this aspect of interconnectedness of the capital market and the resource market, the monopolist is less conservationist than the naive monopolist of scenario N and shifts the extraction path to the present (for $\frac{dK_2}{dR_2} < 0$). The higher resource supply in the present leads to more output and capital accumulation in the present and a higher dependence on the resource in the future, that can be exploited strategically by the exporter. The strength of the addiction motive in the monopolist's considerations depends on the relationship between changes in resource extraction in period 1 and the resulting changes in resource demand (via capital accumulation) in period 2. This acceleration of extraction due to general equilibrium knowledge can even lead to faster extraction under monopoly than in the perfect competition case, so that Robert Solow's (1974) dictum of the monopolist being 'the conservationist's friend' can be reversed. Also, it is possible that the monopolist chooses the social optimum extraction path of the competition case. Moreover, even for an isoelastic resource demand (i.e. elasticity of substitution between capital and resource $\sigma = 1$) the extraction shift to the present persists and the resulting extraction paths of monopoly and competitive case cease to be identical, in contrast to the usual partial equilibrium setup.

Another striking result of our analysis of resource market power in general equilibrium is the emergence of what we call the 'capital asset motive'. The investment of a part of the resource revenues from period 1 leads to the build up of a capital asset stock by the resource exporting country, akin to the recycling of petrodollars and the creation of sovereign wealth funds and other capital deposits, that we have seen in the last decades by many OPEC countries. As a result, returns on capital investments are added as a second income source and the role of the classical resource monopolist, as he is known from the literature, changes to that of a simultaneous resource extractor and capital investor. In scenario NA the monopolist first knows about his direct power over the future interest rate and then, in scenario GA, even about the whole capital market dynamics, which affect his capital income. Taking this asset motive into account can shift the monopolist's optimal extraction path to the future or to the present. The direction of the shift depends on the initial capital endowments and on the rate of growth of the resource exporting country's share in the world capital asset stock. Put differently, the relative 'strength' of the asset motive in both periods determines the direction of the extraction shift. In scenario GA with its full general equilibrium dynamics being considered by the monopolist, the future period's asset motive is stronger than in scenario NA with its lower level of the monopolist's awareness. Thresholds for the change in direction of the extraction shift when switching from one scenario to another are provided. Another interesting phenomenon, for both scenarios NA and GA, is that the monopolist's marginal resource revenue in period 2 can develop an area with a positive slope in resource extraction R_2, in contrast to the normal falling marginal revenue in a case without an asset motive. The conclusions that we draw in the different sections, however, refer to constellations where the marginal revenue curves in both periods fall in a conventional manner.

The analysis of the strategic capital asset motive makes dynamic changes in the role of a resource exporter with market power visible. Starting as a pure resource exporter, the monopolist over time turns into a capital investor with influence on the capital market via his resource market power. The pure resource revenues may become secondary during this process. A change of strategic incentives and political priorities of OPEC countries over the decades in their competition with industrialized countries in the political arena can be made plausible in this way.

Both, the asset motive and the addiction motive constitute different aspects of the mutual dependency of oil exporters and importers. The industrialized countries are not simply at the exporter's mercy, but the monopolist's interest in the importing countries' prosperity is at the least twofold: On the one hand, the exporter wants to maintain and increase the importers' 'oil addiction' for the future. On the other hand, he does not want to jeopardize his capital asset returns. The general equilibrium perspective has proven very useful for gaining insights, not only into the strategic relation of resource exporters and importers, but also into the complex interlocking of capital and resource markets (especially for oil). Our analysis thus contributes to a better understanding of the supply motives and strategies of suppliers of fossil energy resources and of the conditions of successful climate policy.

A Appendix: Model

A.1 Capital Supply

A.1.1 General Characterization

Without assuming symmetric and homothetic consumption preferences for both countries, aggregated capital supply is given by

$$K_2^s = K_2^s(y_{1I}, y_{1E}, \pi_{2I}, \pi_{2E}, i_2) = s_{1I}(y_{1I}, \pi_{2I}, i_2) + s_{1E}(y_{1E}, \pi_{2E}, i_2) \tag{76}$$

Totally differentiating aggregate capital supply yields

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

However, in both countries, period income streams are functions of factor prices and quantities as well as capital endowment. For describing the fundamental functional form of aggregate capital supply we therefore have to further decompose the changes in period income streams in both countries. To this end, we totally differentiate y_{1E} from (21) and π_{2E} from (18) which gives

$$\begin{aligned} dy_{1E} &= p_1 dR_1 + R_1 dp_1 + s_{0E} di_1 + (1 + i_1) ds_{0E} \\ d\pi_{2E} &= p_2 dR_2 + R_2 dp_2 \end{aligned} \tag{77}$$

Similarly, for country I, totally differentiating period income streams y_{1I} from (11) and π_{2I} from (5) yields

$$\begin{aligned} dy_{1I} &= F_{1R} dR_1 + F_{1K} dK_1 - p_1 dR_1 - R_1 dp_1 - i_1 dK_1 - K_1 di_1 + s_{0I} di_1 + (1 + i_1) ds_{0I} = \\ &= -R_1 dp_1 - K_1 di_1 + s_{0I} di_1 + (1 + i_1) ds_{0I} \\ d\pi_{2I} &= F_{2R} dR_2 + F_{2K} dK_2 - p_2 dR_2 - R_2 dp_2 - i_2 dK_2 - K_2 di_2 = \\ &= -R_2 dp_2 - K_2 di_2 \end{aligned} \tag{78}$$

where we set $F_{tR} = p_t$ and $F_{tK} = i_t$ according to (7) and (6) which both hold due to the Envelope theorem. However, note, that since households in both countries derive their period incomes from supplying production factors and the production technology exhibits constant returns to scale (cf. (5)), aggregate period income that is available for consumption and savings in period 1 is made up of total output and capital endowments for period 1

$$Y_1 = y_{1I} + y_{1E} = \pi_{1I} + (1+i_1)s_{0I} + \pi_{1E} + (1+i_1)s_{0E} = F_1 + K_1$$

and just of total output for period 2

$$\Pi_2 = \pi_{2I} + \pi_{2E} = F_2$$

Thus, changes in factor prices do not (directly) influence aggregate period incomes, unless they induce changes in factor inputs.

Given (77) and (78) we can conclude that aggregate capital supply is, in the end, a function factor prices, resource input and asset endowments:

$$K_2^s = K_2^s(p_1, p_2, i_1, i_2, R_1, R_2, s_{0I}, s_{0E}) \tag{79}$$

Correspondingly, by use of (77) and (78), we may rearrange the total derivative of (76) to get

$$\begin{aligned} dK_2^s =& \left(\frac{\partial s_{1E}}{\partial y_{1E}} - \frac{\partial s_{1I}}{\partial y_{1I}}\right) R_1 dp_1 + \left(\frac{\partial s_{1E}}{\partial \pi_{2E}} - \frac{\partial s_{1I}}{\partial \pi_{2I}}\right) R_2 dp_2 \\ &+ \left(\frac{\partial s_{1E}}{\partial y_{1E}} s_{0E} + \frac{\partial s_{1I}}{\partial y_{1I}} s_{0I} - \frac{\partial s_{1I}}{\partial y_{1I}} K_1\right) di_1 + \left(\frac{\partial s_{1E}}{\partial i_2} + \frac{\partial s_{1I}}{\partial i_2} - \frac{\partial s_{1I}}{\partial \pi_{2I}} K_2\right) di_2 \\ &+ \frac{\partial s_{1E}}{\partial y_{1E}} p_1 dR_1 + \frac{\partial s_{1E}}{\partial \pi_{2E}} p_2 dR_2 + \frac{\partial s_{1I}}{\partial y_{1I}} (1+i_1) ds_{0I} + \frac{\partial s_{1E}}{\partial y_{1E}} (1+i_1) ds_{0E} \end{aligned} \tag{80}$$

where exogenous changes in first-period capital endowments s_{0m} are taken into account for completeness. Obviously, with an higher capital endowment households have an incentive to save more and to enlarge capital supply.

Given the constant return to scale technology, factor prices determine the distribution of the value added from production between all production factors. However, since households from country E and I supply different factors and labour income is defined as residual profits according to (5), factor prices also determine the distribution of aggregate income between both countries. Therefore, as far as countries differ in their propensity to save with respect to income changes, factor prices do influence capital supply, even though they do not directly change aggregate (world) income. With fixed factor inputs, an increase in the resource price (for whatever reason) reduces labour income (cf. (5)) and therefore shifts income from country I to country E in both periods. If households in country E react stronger to the income gain with respect to savings than households in I to their income loss, then an increase in the first period resource price will boost capital supply as the first term on the right in (80) shows. Correspondingly, with an increase in the second period resource price capital supply will be reduced.

For the influence of the interest rate – the factor price of capital – note, that an increase in the interest rate raises the return from capital holdings (endowments or savings) of households in both countries and in both periods. However, higher capital income is directly at the expense of labour income according to (5). Thus, whenever country E owns part of the capital stock, a higher interest rate also involves a redistributive effect between countries, because households in country I will earn only a part of the increased capital costs as capital income if everything else is held constant. In fact, with fixed capital endowments, the first period interest rate has an influence on capital supply (for the second period) only via its redistributive effect as the aggregate change in exogenous capital endowment equals a change in the first period capital stock $ds_{0I} + ds_{0E} = dK_1$ so that

$$\frac{\partial s_{1E}}{\partial y_{1E}} s_{0E} + \frac{\partial s_{1I}}{\partial y_{1I}} s_{0I} - \frac{\partial s_{1I}}{\partial y_{1I}} K_1 = \left(\frac{\partial s_{1E}}{\partial y_{1E}} - \frac{\partial s_{1I}}{\partial y_{1I}} \right) s_{0E}$$

The redistributive effect from labour income in country I to capital income in country E also holds for the effect the second period interest rate has on aggregate savings which can be observed by substituting for the partial derivatives with respect to the interest rate from (16)

$$\begin{aligned}\frac{\partial s_{1E}}{\partial i_2} + \frac{\partial s_{1I}}{\partial i_2} - \frac{\partial s_{1I}}{\partial \pi_{2I}} K_2 &= -\beta \frac{u'(c_{2E})}{\Delta_E} + \frac{\partial s_{1E}}{\partial \pi_{2E}} s_{1E} - \beta \frac{u'(c_{2I})}{\Delta_I} + \frac{\partial s_{1I}}{\partial \pi_{1I}} s_{1I} - \frac{\partial s_{1I}}{\partial \pi_{2I}} K_2 \\ &= -\beta \frac{u'(c_{2E})}{\Delta_E} - \beta \frac{u'(c_{2I})}{\Delta_I} + \left(\frac{\partial s_{1E}}{\partial \pi_{2E}} - \frac{\partial s_{1I}}{\partial \pi_{2I}} \right) s_{1E}\end{aligned}$$

However, the second period interest rate applies to capital holdings the households actively decide on. The redistributive effect derives from the standard (negative) income effect, that a rising interest rate has for given savings. Again, since households in country I earn labour and capital income, the overall standard income effect is at least attenuated as some parts of the gains in capital income are compensated by the loss in labour income. In addition, the first two positive terms capture the counteracting substitution effects on savings in both countries. Hence, the overall effect of the second-period interest rate on capital supply is generally ambiguous.

Increasing first period resource supply (dR_1) raises first period production marginally by $p_1 = F_{1R}$. The same holds true for second period resource supply (dR_2). Since country E completely captures the production value of its resources due to the constant returns to scale technology, these resource supply induced changes of total output in the respective period only affect savings of households of country E by the corresponding income effects as the third line in (80) demonstrates. In contrast to an increase in first period income any increase in second period income π_{2E} lowers savings from country E according to (16).

However, since we assume that the resource constraint (17) is binding in any case, we have $R_1 = \bar{R} - R_2$ and shifting resources to the second period always is associated with a decreasing resource use in the first period, i.e. $dR_1 = -dR_2$. This implies that capital supply, in its most general specification, is a function of factor prices, the resource supply *path*, as well as the resource and capital endowments

$$K_2^s = K_2^s(p_1, p_2, i_1, i_2, R_2, \bar{R}, s_{0I}, s_{0E}) \tag{81}$$

and the third the third line in (80) is overall modified by having

$$\left(\frac{\partial s_{1E}}{\partial \pi_{2E}} p_2 - \frac{\partial s_{1E}}{\partial y_{1E}} p_1\right) dR_2 + \frac{\partial s_{1E}}{\partial y_{1E}} p_1 d\bar{R}$$

For given factor prices, resource income of country E rises in the second period while it shrinks in the first period according to (77) when shifting resources to the second period. This unambiguously lowers savings from country E given the partial effects in (16). For a given production technology (and given capital stocks) the resource constraint implies that reallocating resources to the future shifts total production output and thereby aggregate income from the present to the future. However, since country E completely captures the production value of its resources, the induced redistribution of aggregate income directly corresponds to changes in period incomes of country E so that the reallocation of resources between both periods only affects savings from country E ceteris paribus.[41] The effect of an increase in the resource stock $d\bar{R}$ which is directly comparable to an increase in capital endowments.

A.1.2 Capital Supply for Homothetic Preferences

To simplify this so far very general characterization of capital supply in (80) we assume symmetric and homothetic consumption preferences for households in both countries

[41] i.e. not taking into changes of the interest rate.

$m \in \{E, I\}$ in the model (see (10)). From the Euler equations (14) and (22) then follows

$$\frac{c_{1m}}{c_{2m}} = [\beta (1 + i_2)]^{-\frac{1}{\eta}} \tag{82}$$

i.e. along the optimal intertemporal consumption path, the relation of first and second-period consumption only depends on the time preference and the interest rate but not on the income level. Moreover, this implies that for a given present-value of life-time income

$$w_m = y_{1m} + \frac{\pi_{2m}}{1 + i_2} = c_{1m} + \frac{c_{2m}}{1 + i_2} \tag{83}$$

only the prevailing interest rate and the time preference rate determine the expenditures that the household dedicates to first and second period consumption[42]

$$c_{1m} = \frac{1 + i_2}{1 + i_2 + [\beta(1 + i_2)]^{\frac{1}{\eta}}} w_m$$
$$c_{2m} = \frac{\beta^{\frac{1}{\eta}} (1 + i_2)^{\frac{1}{\eta}}}{1 + i_2 + [\beta(1 + i_2)]^{\frac{1}{\eta}}} w_m$$

For $\eta = 1$ (ln-utility), the income and substitution effect of a changing interest rate exactly offset each other and the expenditure share for first-period consumption no longer depends on the interest rate.

From (16) we already observed that the marginal propensities to save with respect to income changes are constant in both countries for a given interest rate and do not depend on the absolute income levels. Since the preferences of the two countries are not only homothetic, but also symmetric, the distribution of income between the countries has no effect on the saving propensities, nor on the total amount of savings. For any distribution of wealth between country E and country I we therefore have

$$\frac{\partial s_{1I}}{\partial y_{1I}} = \frac{\partial s_{1E}}{\partial y_{1E}} \quad \text{and} \quad \frac{\partial s_{1I}}{\partial \pi_{1I}} = \frac{\partial s_{1E}}{\partial \pi_{1E}} \quad \text{but not necessarily} \quad \frac{\partial s_{1I}}{\partial i_2} = \frac{\partial s_{1E}}{\partial i_2}.$$

This implies that all terms representing pure redistribution of income between countries I and E cancel out. Moreover, the distribution of capital endowments between both countries no longer has any influence on capital supply as well as any exertion of market power. Thus, based on (81) capital supply with symmetric homothetic preferences in

[42] The expenditure shares can be derived by substituting for the second-period consumption in (83) from the Euler equation.

both countries is just a function of the second period interest rate, the resource supply path, as well as resource and capital endowments as stated in (25). An overview over the different components of the aggregate savings reaction for the case of symmetric homothetic utility is given in figure 3.

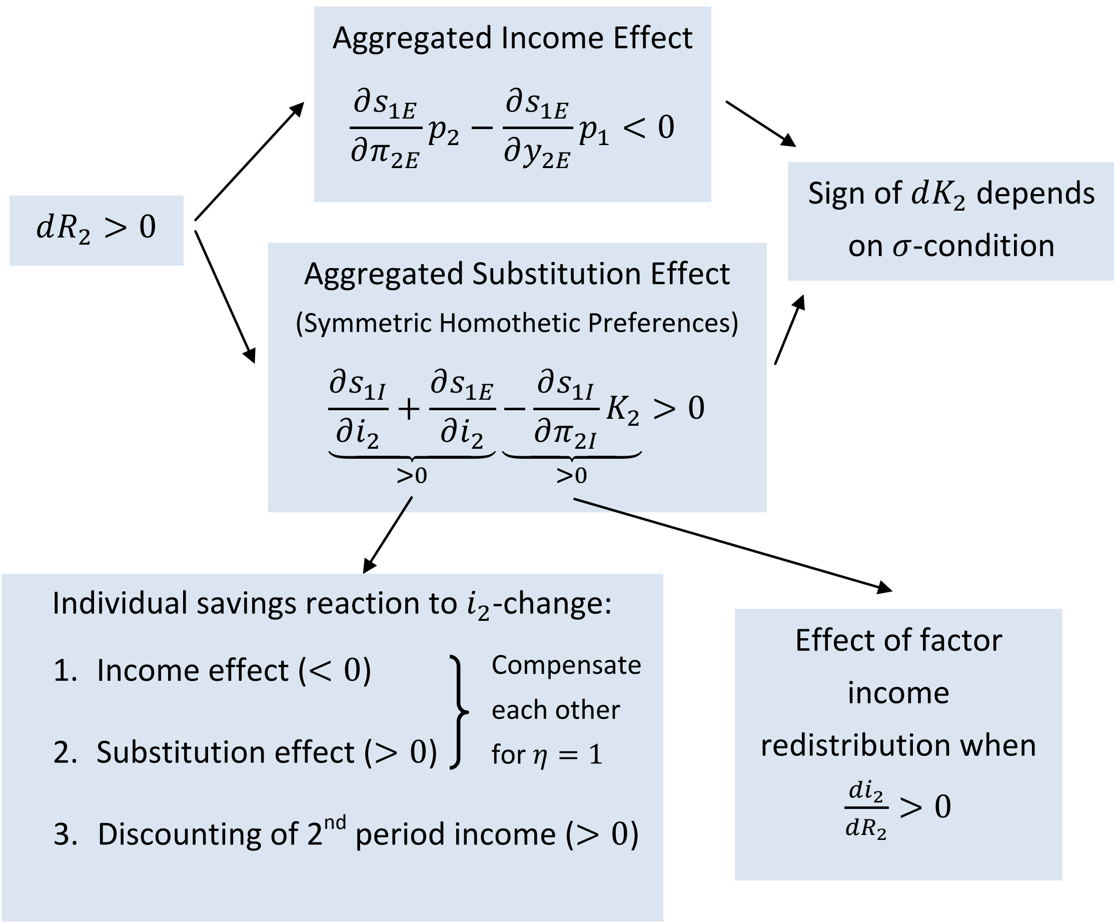

Figure 3: Overview over the reaction of aggregate savings for homothetic utility to a shift in resource supply dR_2

A.2 Conditional Market Equilibrium

A.2.1 Comparative Statics

In the conditional market equilibrium, all three markets, the resource market, the capital market and the final goods' market, clear given some resource supply path (R_1, R_2).

To derive (35) and (36) we totally differentiate (31) and substitute dR_1^d from (6) which gives

$$\frac{F_{1KK}}{\Gamma}dp_1 - \frac{F_{1KR}}{\Gamma}di_1 = -dR_2$$

where Γ is positive according to (4) and where we use $dR_1 = -dR_2$ by the binding resource constraint (17). Setting

$$di_1 = \frac{F_{1KR}}{F_{1RR}}dp_1$$

by totally differentiating (29) we get (35) and finally (36).

For the second period, we start by totally differentiating (32) which yields

$$\frac{dp_2}{dR_2} = \frac{\Gamma}{F_{2KK}} + \frac{F_{2KR}}{F_{2KK}}\frac{di_2}{dR_2} \tag{84}$$

In equilibrium, this has to coincide with

$$\frac{dp_2}{dR_2} = -\frac{\Gamma}{F_{2KR}}\left.\frac{dK_2^s}{dR_2}\right|_{i_2} + \frac{1}{F_{2KR}}\left[F_{2RR} - \Gamma\left.\frac{dK_2^s}{di_2}\right|_{R_2}\right]\frac{di_2}{dR_2}$$

from totally differentiating (30) by use of (6) and (26). Due to the exogeneity of capital and resource endowments, we have $dK_1 = d\bar{R} = 0$. Note that we have $\left.\frac{dK_2^s}{dR_2}\right|_{i_2} = \left(\frac{\partial s_{1E}}{\partial \pi_{2E}}p_2 - \frac{\partial s_{1E}}{\partial y_{1E}}p_1\right)$ from (28) and $\left.\frac{dK_2^s}{di_2}\right|_{R_2} = \left(\frac{\partial s_{1E}}{\partial i_2} + \frac{\partial s_{1I}}{\partial i_2} - \frac{\partial s_{1I}}{\partial \pi_{2I}}K_2\right)$ from (27).

By equating and rearranging we get for the induced change in the equilibrium interest rate

$$\frac{di_2}{dR_2} = \frac{F_{2KR} + F_{2KK}\left.\frac{dK_2}{dR_2}\right|_{i_2}}{1 - F_{2KK}\left.\frac{dK_2}{di_2}\right|_{R_2}} \tag{85}$$

and by substituting for $\frac{di_2}{dR_2}$ in (84)

$$\frac{dp_2}{dR_2} = \frac{F_{2RR} - \Gamma\left.\frac{dK_2^s}{di_2}\right|_{R_2} + F_{2KR}\left.\frac{dK_2^s}{dR_2}\right|_{i_2}}{1 - F_{2KK}\left.\frac{dK_2^s}{di_2}\right|_{R_2}} \tag{86}$$

Thus, the interest rate unambiguously reacts positively to a shift of resources from the first to the second period whereas the resource price unambiguously falls at the same time, even though we account for the influence of resource supply on capital accumulation, which is generally ambiguous due to counteracting income and substitution effects, and for the complementarity of capital and resources in production. This is due to the strict concavity of the production technology which ensures that $\Gamma > 0$ holds.

A.2.2 Sign of $\frac{dK_2}{dR_2}$

First, given that the conditional market equilibrium and in particular final goods market equilibrium from section 2.4.3 holds, we can rewrite the aggregate substitution effect in (27)

$$\left.\frac{dK_2^s}{di_2}\right|_{R_2,K_1} = \frac{\partial s_{1I}}{\partial i_2} + \frac{\partial s_{1E}}{\partial i_2} - \frac{\partial s_{1I}}{\partial \pi_{2I}} K_2$$
$$= \frac{1}{\eta(1+i_2)} \cdot \frac{c_{2I} + c_{2E}}{1 + i_2 + [\beta(1+i_2)]^{\frac{1}{\eta}}}$$
$$= \frac{1}{1 + i_2 + [\beta(1+i_2)]^{\frac{1}{\eta}}} \frac{F_2 + K_2}{\eta(1+i_2)}$$

and the aggregate income effect in (28)

$$\left.\frac{dK_2^s}{dR_2}\right|_{i_2,K_1} = \frac{\partial s_{1E}}{\partial \pi_{2E}} p_2 - \frac{\partial s_{1E}}{\partial y_{1E}} p_1 = -\frac{[\beta(1+i_2)]^{\frac{1}{\eta}} p_1 + p_2}{1 + i_2 + [\beta(1+i_2)]^{\frac{1}{\eta}}}$$

Given (39) and (38) we know that

$$\frac{dK_2}{dR_2} = \left.\frac{dK_2^s}{dR_2}\right|_{i_2,K_1} + \left.\frac{dK_2^s}{di_2}\right|_{R_2,K_1} \left[F_{2KR} + F_{2KK}\frac{dK_2}{dR_2}\right]$$

Rearranging and defining $\Omega = 1 - F_{2KK} \left.\frac{dK_2^s}{di_2}\right|_{R_2,K_1}$, we then have

$$\frac{dK_2}{dR_2} = \frac{\left.\frac{dK_2^s}{dR_2}\right|_{i_2,K_1} + F_{2KR} \left.\frac{dK_2^s}{di_2}\right|_{R_2,K_1}}{\Omega}$$
$$= \frac{1}{\Omega}\frac{1}{1 + i_2 + [\beta(1+i_2)]^{\frac{1}{\eta}}} \left[F_{2KR}\frac{F_2 + K_2}{\eta(1+i_2)} - \left([\beta(1+i_2)]^{\frac{1}{\eta}} p_1 + p_2\right)\right]$$
$$= \frac{1}{\Omega}\frac{1}{1 + i_2 + [\beta(1+i_2)]^{\frac{1}{\eta}}} \left\{p_2\left[\frac{i_2}{1+i_2}\frac{F_2+K_2}{\sigma\eta F_2} - 1\right] - (\beta(1+i_2))^{\frac{1}{\eta}} p_1\right\}$$
$$= \frac{1}{1 + i_2 + (\beta(1+i_2))^{\frac{1}{\eta}} - F_{2KK}\frac{F_2+K_2}{\eta(1+i_2)}} \left\{p_2\left[\frac{i_2}{1+i_2}\frac{F_2+K_2}{\sigma\eta F_2} - 1\right] - (\beta(1+i_2))^{\frac{1}{\eta}} p_1\right\}$$

Since the denominator is unambiguously positive, a necessary condition for $\frac{dK_2}{dR_2} < 0$ is

$$\frac{1}{\sigma\eta} < \frac{(1+i_2)F_2}{i_2F_2 + i_2K_2}\left\{[\beta(1+i_2)]^{\frac{1}{\eta}}\frac{p_1}{p_2} + 1\right\}$$

Note that the right side is greater than unity because $i_2K_2 < F_2$ and $[\beta(1+i_2)]^{\frac{1}{\eta}} > 0$. Therefore, a sufficient condition for $\frac{dK_2}{dR_2} < 0$ is

$$\sigma\eta \geq 1$$

In the intertemporal final goods market equilibrium (see section 2.4.3) we may substitute for

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

in the necessary condition to get

$$\frac{1}{\sigma\eta} < \frac{1+i_2}{i_2}\frac{F_2}{p_2}\left[\frac{p_1}{F_1 + K_1 - K_2} + \frac{p_2}{F_2 + K_2}\right]$$

Figure 4 shows the reactions of the period 2 interest rate and capital stock for an increase in future extraction R_2.

A.2.3 The savings reactions of country E and I to a change in the resource supply path

Households in country E react to a change in the resource supply path, i.e. when observing an intertemporal redistribution of the given resource stock, according to

$$\begin{aligned}
\frac{ds_{1E}}{dR_2} &= \frac{\partial s_{1E}}{\partial y_{1E}}\frac{\partial y_{1E}}{\partial R_1}\frac{dR_1}{dR_2} + \frac{\partial s_{1E}}{\partial \pi_{2E}}\frac{d\pi_{2E}}{dR_2} + \frac{\partial s_{1E}}{\partial i_2}\frac{di_2}{dR_2} \\
&= -\frac{\partial s_{1E}}{\partial y_{1E}}\left(MR_1^N + F_{1KR}s_{0E}\right) + \frac{\partial s_{1E}}{\partial \pi_{2E}}\left(p_2 + \frac{dp_2}{dR_2}R_2\right) \\
&\quad + \frac{\partial s_{1E}}{\partial \pi_{2E}}s_{1E}\frac{di_2}{dR_2} - \beta\frac{u'(c_{2E})}{\Delta_E}\frac{di_2}{dR_2} \\
&= \frac{\partial s_{1E}}{\partial \pi_{2E}}\left\{[\beta(1+i_2)]^{\frac{1}{\eta}}MR_1^{NA} + \left(p_2 + \frac{dp_2}{dR_2}R_2\right) + \left[s_{1E} - \frac{\pi_{2E} + (1+i_2)s_{1E}}{\eta(1+i_2)}\right]\frac{di_2}{dR_2}\right\} \\
&= \frac{\partial s_{1E}}{\partial \pi_{2E}}\left\{[\beta(1+i_2)]^{\frac{1}{\eta}}MR_1^{NA} + MR_2^{GA} - \frac{\pi_{2E} + (1+i_2)s_{1E}}{\eta(1+i_2)}\frac{di_2}{dR_2}\right\}
\end{aligned}$$

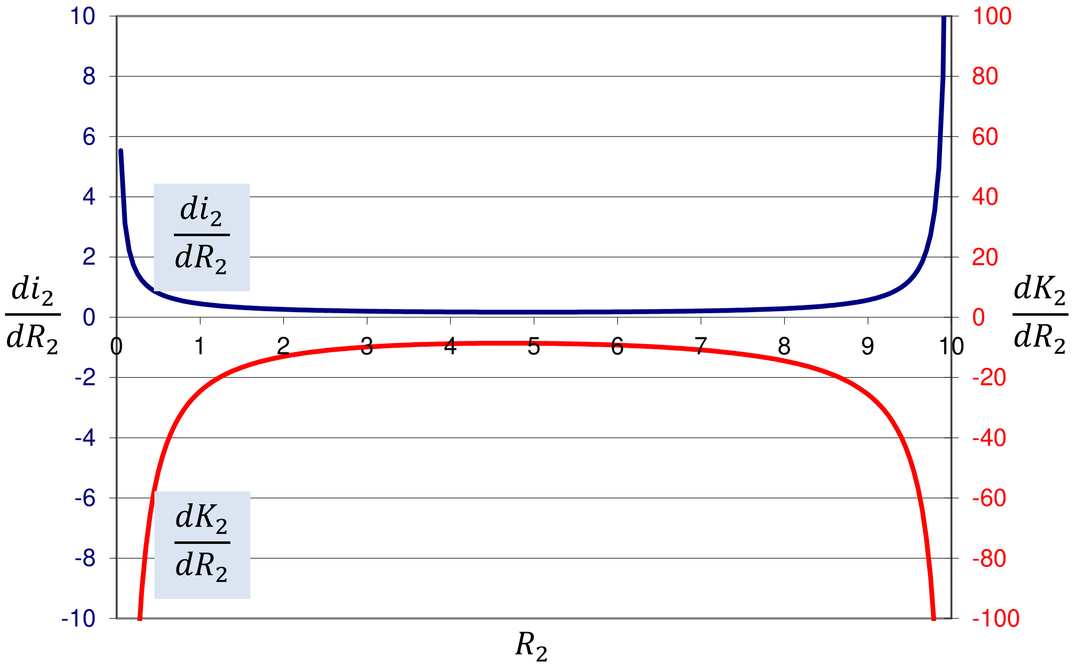

Figure 4: Reaction of the capital stock and the interest rate to a change in R_2 over the extraction rate R_2 for parameter values $\sigma \approx 0.9$, $\eta = 2$, $\beta = 0.3$, $\lambda = 0.1$, $\phi = 0.4$, $K_1 = 200$, $\bar{R} = 10$.

Note that we substituted for $\frac{\partial s_{1E}}{\partial i_2}$ as we know from the implicit definition of the savings function in (16) for homothetic preferences that

$$\frac{\partial s_{1E}}{\partial i_2} = \frac{\partial s_{1E}}{\partial \pi_{2E}} \left[s_{1E} - \frac{\pi_{2E} + (1 + i_2)s_{1E}}{\eta(1 + i_2)} \right]$$

The savings reaction is generally of ambiguous sign and depends on the level of resource income streams in both periods and the capital endowments s_{0E}.

Correspondingly, the savings reaction of households in country I is given by

$$
\begin{aligned}
\frac{ds_{1I}}{dR_2} &= \frac{\partial s_{1I}}{\partial y_{1I}}\frac{\partial y_{1I}}{\partial R_1}\frac{dR_1}{dR_2} + \frac{\partial s_{1I}}{\partial \pi_{2I}}\frac{d\pi_{2I}}{dR_2} + \frac{\partial s_{1I}}{\partial i_2}\frac{di_2}{dR_2} \\
&= -\frac{\partial s_{1I}}{\partial y_{1I}}\left[F_{1R} - p_1 - \frac{\partial p_1}{\partial R_1}R_1 - \frac{\partial i_1}{\partial R_1}K_1 + \frac{\partial i_1}{\partial R_1}s_{0I}\right] \\
&\qquad + \frac{\partial s_{1I}}{\partial \pi_{2I}}\left[\frac{dF_2}{dR_2} - p_2 - \frac{dp_2}{dR_2}R_2 - \frac{di_2}{dR_2}K_2 - i_2\frac{dK_2}{dR_2}\right] + \frac{\partial s_{1I}}{\partial i_2}\frac{di_2}{dR_2} \\
&= \frac{\partial s_{1I}}{\partial y_{1I}}\left[\frac{\partial p_1}{\partial R_1}R_1 + \frac{\partial i_1}{\partial R_1}s_{1E}\right] + \frac{\partial s_{1I}}{\partial \pi_{2I}}\left[s_{1I}\frac{di_2}{dR_2} - \frac{\pi_{1I} + (1+i_2)s_{1I}}{\eta(1+i_2)}\frac{di_2}{dR_2}\right] \\
&\qquad + \frac{\partial s_{1I}}{\partial \pi_{2I}}\left[F_{2R} + F_{2K}\frac{dK_2}{dR_2} - p_2 - \frac{dp_2}{dR_2}R_2 - \frac{di_2}{dR_2}K_2 - i_2\frac{dK_2}{dR_2}\right] \\
&= \frac{\partial s_{1I}}{\partial \pi_{2I}}\left\{-\left[\beta(1+i_2)\right]^{\frac{1}{\eta}}\left[F_{1RR}R_1 + F_{1KR}s_{0E}\right] - \left[\frac{dp_2}{dR_2}R_2 + \frac{di_2}{dR_2}s_{1E}\right]\right\} \\
&\qquad - \frac{\partial s_{1I}}{\partial \pi_{2I}}\left\{\frac{\pi_{2I} + (1+i_2)s_{1I}}{\eta(1+i_2)}\frac{di_2}{dR_2}\right\} \\
&= \frac{\partial s_{1I}}{\partial \pi_{2I}}\left\{-\left[\beta(1+i_2)\right]^{\frac{1}{\eta}}\left[MR_1^{NA} - p_1\right] - \left[MR_2^{GA} - p_2\right] - \frac{\pi_{2I} + (1+i_2)s_{1I}}{\eta(1+i_2)}\frac{di_2}{dR_2}\right\}
\end{aligned}
$$

where we again set $\frac{\partial s_{1I}}{\partial i_2} = \frac{\partial s_{1I}}{\partial \pi_{2I}}\left[s_{1I} - \frac{\pi_{2I}+(1+i_2)s_{1I}}{\eta(1+i_2)}\right]$ due to the symmetry of preferences. Furthermore, we use $s_{1I} = K_2 - s_{1E}$ and $\frac{dF_2}{dR_2} = F_{2R} + F_{2K}\frac{dK_2}{dR_2}$.

Figure 5 shows these savings functions for the numerical simulation which is used in the scenario analysis.

B Appendix: Scenario Analysis

B.1 Scenario NA

B.1.1 Relationship of capital endowment s_{0E} and savings s_{1E} in country E

We show in the following, that savings s_{1E} are linearly increasing in capital endowment if capital endowments are redistributed from country I to country E for a given extraction path and a given overall first period capital stock K_1.

Due to our assumption of symmetric homothetic preferences, overall capital accumulation is just a function of the extraction path and the first period capital stock K_1 ((26) and (39)). This implies that for any given extraction path the interest rates in both

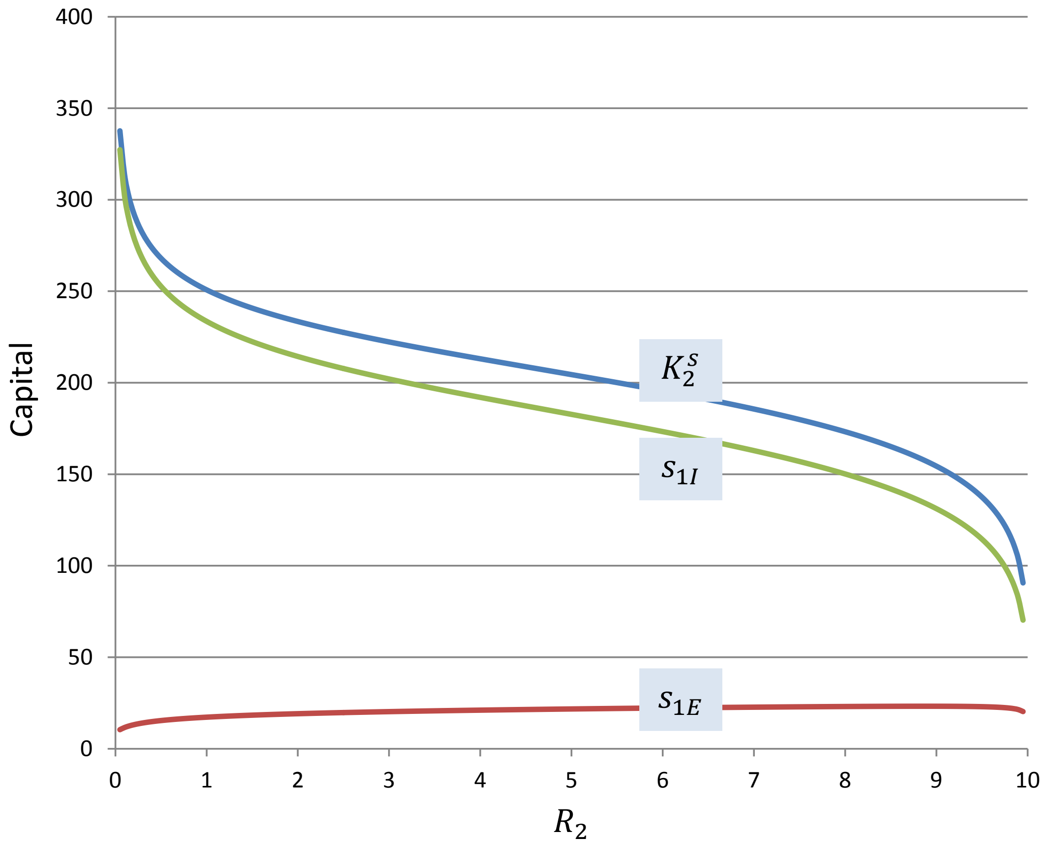

Figure 5: Country E's s_{1E}, country I's savings s_{1I} and the resulting capital stock K_2 over the extraction rate R_2 for parameter values $\sigma \approx 0.9$, $\eta = 2$, $\beta = 0.3$, $\lambda = 0.1$, $\phi = 0.4$, $K_1 = 200$, $\bar{R} = 10$.

periods i_1, i_2 and the period resource income streams π_{1E}, π_{2E} from (18) are determined and independent of any redistribution of capital endowment. In contrast, overall first period household income y_{1E} from (21) still depends on the capital endowment s_{0E}.

For a given extraction path and given K_1, we therefore can decompose savings as a function of endowments

$$s_{1E}(s_{0E}) = s_{1E}(0) + \frac{\partial s_{1E}}{\partial s_{0E}} s_{0E} = s_{1E}(0) + \frac{\partial s_{1E}}{\partial y_{1E}} \frac{\partial y_{1E}}{\partial s_{0E}} s_{0E} = s_{1E}(0) + \frac{\partial s_{1E}}{\partial y_{1E}} (1 + i_1^{N*}) s_{0E} \tag{87}$$

where the marginal savings propensity with respect to increases in first period household income, $\frac{\partial s_{1E}}{\partial y_{1E}}$ from (16), is a positive constant (again greater or lower than unity).

Using this functional relationship, we observe from

$$\left.\frac{\partial \frac{s_{1E}}{s_{0E}}}{\partial s_{0E}}\right|_{K_1,R_1,R_2} = \frac{1}{s_{0E}}\left[\frac{\partial s_{1E}}{\partial y_{1E}}(1+i_1^{N*}) - \frac{s_{1E}}{s_{0E}}\right] = -\frac{s_{1E}(0)}{s_{0E}^2} < 0$$

that the ration of asset holdings falls upon redistributing capital endowment to country E. Moreover, we can characterize the influence of an (ceteris paribus) increase in endowment s_{0E} on the ratio of second to first period capital holdings by considering the limits

$$\begin{aligned}
\lim_{s_{0E}\to 0} \left.\frac{s_{1E}}{s_{0E}}\right|_{K_1,R_1,R_2} &= \lim_{s_{0E}\to 0}\left[\frac{s_{1E}(0)}{s_{0E}} + \frac{\partial s_{1E}}{\partial y_{1E}}(1+i_1^{N*})\right] = +\infty \\
\lim_{s_{0E}\to \infty} \left.\frac{s_{1E}}{s_{0E}}\right|_{K_1,R_1,R_2} &= \lim_{s_{0E}\to \infty}\left[\frac{s_{1E}(0)}{s_{0E}} + \frac{\partial s_{1E}}{\partial y_{1E}}(1+i_1^{N*})\right] = \frac{\partial s_{1E}}{\partial y_{1E}}(1+i_1^{N*}) \\
\lim_{s_{0E}\to K_1} \left.\frac{s_{1E}}{s_{0E}}\right|_{K_1,R_1,R_2} &= \frac{s_{1E}(K_1)}{K_1} = \frac{s_{1E}(0)}{K_1} + \frac{\partial s_{1E}}{\partial y_{1E}}(1+i_1^{N*}) > \frac{\partial s_{1E}}{\partial y_{1E}}(1+i_1^{N*})
\end{aligned} \tag{88}$$

B.1.2 Reaction of the Hotelling Condition to Changes in R_2

In this section, we discuss the effective change of the left and the right side of the modified Hotelling condition (45) in general equilibrium. The left side given by (66) monotonously falls R_1 taking into account the resource constraint (17), or, equivalently, increases in R_2 for a given capital endowment s_{0E} and given capital stock K_1. The first term is unambiguously of negative sign for $MR_t^{NA} \geq 0$ because we have[43]

$$\left.\frac{\partial MR_t^{NA}}{\partial R_t}\right|_{s_{(t-1)E},K_t} = \frac{1}{\sigma}\frac{1}{R_t}\left[(\theta_{tR}-1)\, MR_t^{NA} + (1-\sigma)\theta_{tR}\left(MR_t^{NA} - F_{tR}\right)\right] < 0 \tag{89}$$

as $\theta_{tR} < 1$ and $MR_t^{NA} < F_{tR}$ due to the Euler theorem.[44]

For the right side of the modified Hotelling condition (58), the effective total reaction of the second period marginal revenue MR_2^{NA} in general equilibrium to a shift of resources to the second period is given by (67) and of ambiguous sign. This ambiguity arises due to the second and the third term, whereas the first term represents the ceteris paribus

[43] From (60) we get for given asset holdings and given capital stock

$$\left.\frac{\partial MR_t^{NA}}{\partial R_t}\right|_{s_{(t-1)E},K_t} = \frac{F_{tRR}}{\sigma}\left[\theta_{tR} + \theta_{tK}\frac{s_{(t-1)E}}{K_t} - (1-\sigma)\right] + \frac{F_{tR}}{\sigma}\left[\frac{\partial\theta_{tR}}{\partial R_t} + \frac{\partial\theta_{tK}}{\partial R_t}\frac{s_{(t-1)E}}{K_t}\right]$$

Using $\frac{\partial\theta_{tR}}{\partial R_t} = \frac{\sigma-1}{\sigma}\frac{F_{tR}}{F_t}(1-\theta_{tR})$ and $\frac{\partial\theta_{tK}}{\partial R_t} = \frac{1-\sigma}{\sigma}\frac{F_{tR}}{F_t}\theta_{tK}$ and rearranging by use of (60) yields (89).

[44] We have $MR_t^{NA} - F_{tR} = \frac{p_2}{\sigma}\left[\theta_{tR} + \theta_{tK}\frac{s_{(t-1)E}}{K_t} - 1\right] < 0$.

influence of resource supply and is unambiguously negative for MR_2^{NA} according to (89). The second term captures the feedback effect from capital accumulation. Given $\frac{dK_2}{dR_2} < 0$ according to (41), the sign of the second term depends on the ceteris paribus influence of capital on the modified marginal resource value[45]

$$\begin{aligned}\left.\frac{\partial MR_2^{NA}}{\partial K_2}\right|_{s_{1E},R_2} &= \left.\frac{\partial MR_2^{N}}{\partial K_2}\right|_{R_2} + \frac{\partial F_{2KR}}{\partial K_2}s_{1E} \\ &= \frac{F_{2KR}}{\sigma}\left[(1-\sigma)\left(\theta_{2R}+\theta_{2K}\frac{s_{1E}}{K_2}-1\right)+\theta_{2R}+\theta_{2K}\frac{s_{1E}}{K_2}-\frac{s_{1E}}{K_2}\right]\end{aligned} \tag{90}$$

which is generally ambiguous. The first term in the first line is positive for $MR_2^N > 0$ according to (48) which on the one hand no longer needs to be the case for the naive monopolist with asset motive as $MR_2^{NA} > MR_2^N$. On the other hand, $MR_2^N > 0$ also implies that the second term is negative and thereby counteracting the first.[46]

From the second line, we can conclude that a sufficient condition for (90) to be negative is

$$\theta_{2R}+\theta_{2K}\frac{s_{1E}}{K_2}-\frac{s_{1E}}{K_2} \leq 0 \tag{91}$$

where $\theta_{2R}+\theta_{2K}\frac{s_{1E}}{K_2}-\frac{s_{1E}}{K_2}$ may be positive or negative, in general.[47] A necessary condition is

$$\theta_{2R}+\theta_{2K}\frac{s_{1E}}{K_2}-\frac{s_{1E}}{K_2} < \frac{1-\sigma}{2-\sigma}\left(1-\frac{s_{1E}}{K_2}\right)$$

where the right side is non-negative for $\sigma < 1$.

The third term in (67) captures the feedback from the induced change in asset holdings in the second period where we have $\left.\frac{\partial MR_2^{NA}}{\partial s_{1E}}\right|_{R_2,K_2} = F_{2KR} > 0$. Since a change in the extraction path leads to changes in the interest rate and the period incomes of households, this savings reaction is generally of ambiguous sign, due to counteracting substitution and income effects (see also appendix A.2.3).

In the following, we discuss the influence of capital endowment s_{0E} on the total reaction

[45] The second line is derived from $\left.\frac{\partial MR_2^N}{\partial K_2}\right|_{R_2}$ from (48) and $\frac{\partial F_{2KR}}{\partial K_2} = \frac{2-\sigma}{\sigma}\frac{F_{2RK}}{K_2}\left(\theta_{2K}-\frac{1}{2-\sigma}\right)\frac{dK_2}{dR_2}$.

[46] For $MR_2^N > 0$ we have $\theta_{2R} > 1-\sigma$. By the Euler theorem, we then must have $\theta_{2K} < \frac{1}{2-\sigma}$ and therefore $\frac{\partial F_{2KR}}{\partial K_2} = \frac{2-\sigma}{\sigma}\frac{F_{2KR}}{K_2}\left[\theta_{2K}-\frac{1}{2-\sigma}\right] < 0$.

[47] Note that $\theta_{2R}+\theta_{2K}\frac{s_{1E}}{K_2}-\frac{s_{1E}}{K_2} \leq 0$ also implies that the marginal revenue curve plotted for scenario NA lies below the marginal revenue curve of scenario GA for a given extraction path (R_1, R_2).

(67). By analyzing the limits, we can show, that MR_2^{NA} approaches MR_2^N for $R_2 \to 0$.[48] Given that MR_2^N falls in R_2 according to (57), this implies that MR_2^{NA} may only increase in R_2 for rather high R_2. If we assume that $MR_2^{NA} \geq 0$ for all feasible extraction paths within the resource constraint $\bar{R}$, the first term in (67) is always negative so that the right side in (58) may only increase if the second and/or the third term positively contribute to the slope in (67). However, since the savings reaction of households in country E is entirely ambiguous in general, we focus on the second term, the influence of the capital dynamics, where we assume throughout that condition (41) holds and therefore that $\frac{dK_2}{dR_2} < 0$.

Given (67) and $\frac{dK_2}{dR_2} < 0$ for $\sigma\eta \geq 1$, the capital dynamics positively contribute to the slope of the marginal revenue curve if the partial or ceteris paribus effect of capital accumulation on the modified marginal revenue $\left.\frac{\partial MR_2^{NA}}{\partial K_2}\right|_{R_2, s_{1E}}$ from (90) is negative, at least for high R_2. From the discussion of the ambiguity of (90) we know that the sign of this partial influence of capital on MR_t^{NA} strongly depends on the ambiguous term $\theta_{2R} + \theta_{2K}\frac{s_{1E}}{K_2} - \frac{s_{1E}}{K_2}$. For any given extraction path (R_1, R_2), this term is, however, a function of capital endowment. Whereas overall capital accumulation and thereby the factor shares θ_{2R}, θ_{2K} do not directly depend on the distribution of capital endowments for symmetric homothetic preferences, savings are ceteris paribus – for a given extraction path and a given aggregated capital endowment K_1 – a positive and linear function of households capital endowment s_{0E} (see (87)). Since $\theta_{2K} < 1$ by the Euler theorem, redistributing capital endowments to country E, therefore, ceteris paribus tends to lower the term $\theta_{2R} + \theta_{2K}\frac{s_{1E}}{K_2} - \frac{s_{1E}}{K_2}$. Thus, the partial influence of capital on the marginal revenue from (90) is more likely of negative sign for high asset endowments s_{0E}.[49]

B.2 Scenario G

B.2.1 General Equilibrium Price Elasticity of Demand

When accounting for the endogeneity of second-period resource demand, the monopolist effectively no longer considers just the standard price elasticity ϵ_{R_t,p_t} from (51) which measures the reaction of resource demand to changes in the resource price for a *given*

[48] See section B.4.3 for a more extensive discussion of the limits of MR_2^{NA}.

[49] From (90) we know that $\theta_{2R} + \theta_{2K}\frac{s_{1E}}{K_2} - \frac{s_{1E}}{K_2} < 0$ is a sufficient (but not a necessary) condition for $\left.\frac{\partial MR_2^{NA}}{\partial K_2}\right|_{R_2, s_{1E}} < 0$. However, the analysis in section 3.5 will show that for $\theta_{2R} + \theta_{2K}\frac{s_{1E}}{K_2} - \frac{s_{1E}}{K_2} < 0$ we also have $MR_2^{NA} < MR_2^{GA}$. Therefore, we can also conclude that MR_2^{NA} will unambiguously rise for high R_2 if $MR_2^{NA} < MR_2^{GA}$.

capital stock. Instead, we can think of the monopolist now taking into account a "total" price elasticity based on the total price reaction from (37) and defined as

$$e_{R_2,p_2} = \frac{1}{\frac{dp_2}{dR_2}\frac{R_2}{p_2}} = \frac{\epsilon_{R_2,p_2}}{1+\epsilon_{R_2,p_2}\frac{\partial p_2}{\partial K_2}\frac{dK_2}{dR_2}\frac{R_2}{p_2}} = -\frac{\sigma}{1-\theta_{2R}-\theta_{2K}\frac{dK_2}{dR_2}\frac{R_2}{K_2}} \tag{92}$$

which includes the simultaneously induced change in capital accumulation on resource demand. Since in general equilibrium any postponement of extraction induces a downward shift in (inverse) resource demand in addition to the standard own-price effect as long as $\frac{dK_2}{dR_2} < 0$, the price elasticity of second period resource demand decreases in value ceteris paribus when we let the monopolist become aware of the total price reaction.[50] Just as in a static/one-period analysis of monopolistic supply, second period resource supply thereby becomes less attractive from the monopolist's perspective and the monopolist starts to shift resources to the first period.

Correspondingly, we may restate Hotelling rule (68) in terms of price elasticities as

$$(1+i_2^{G*})p_1^{G*}\left[1+\frac{1}{\epsilon_{R_1,p_1}(R_1^{G*},R_2^{G*})}\right] = p_2^{G*}\left[1+\frac{1}{e_{R_2,p_2}(R_1^{G*},R_2^{G*})}\right]$$

By the comparison with the standard Hotelling rule (49) it is obvious that the addiction motive is introduced by the term $\theta_{2K}\frac{dK_2}{dR_2}\frac{R_2}{K_2}$ in the total price elasticity. The strength of the addiction motive's effect on the extraction path, crucially depends on the sensitivity of the second period capital stock to changes in the extraction pattern which is measured by the elasticity of the capital stock with respect to a postponement of extraction $\frac{dK_2}{dR_2}\frac{K_2}{R_2}$ in (92).

[50] Note that the denominator in (92) is greater than in (51) so that e_{R_2,p_2} is lower *in value* than ϵ_{R_2,p_2} for any extraction path (R_1, R_2).

B.2.2 Slope of Marginal Revenue Curve

While the marginal revenue curve of period 1 does not differ from scenario N and is falling monotonously, the slope of the marginal revenue curve in period 2 is ambiguous:

$$\begin{aligned}\frac{dMR_2^G}{dR_2} &= \left.\frac{\partial MR_2^N}{\partial R_2}\right|_{K_2} + \left.\frac{\partial MR_2^N}{\partial K_2}\right|_{R_2}\frac{dK_2}{dR_2} + \frac{\partial p_2}{\partial K_2}\frac{dK_2}{dR_2} + \frac{\partial^2 p_2}{\partial K_2 \partial R_2}R_2\frac{dK_2}{dR_2} \\ &\quad + \frac{\partial^2 p_2}{(\partial K_2)^2}R_2\left(\frac{dK_2}{dR_2}\right)^2 + \frac{\partial p_2}{\partial K_2}R_2\frac{d^2K_2}{(dR_2)^2} \\ &= \frac{dMR_2^N}{dR_2} + \frac{2-\sigma}{\sigma}F_{2KR}\left[\left(\theta_{2R} - \frac{1-\sigma}{2-\sigma}\right) + \left(\theta_{2K} - \frac{1}{2-\sigma}\right)\frac{R_2}{K_2}\frac{dK_2}{dR_2}\right]\frac{dK_2}{dR_2} \\ &\quad + F_{2RK}R_2\frac{d^2K_2}{(dR_2)^2}\end{aligned} \tag{93}$$

with $\frac{dMR_2^N}{dR_2}$ from (57) and $\frac{dp_2}{dR_2}$ from (37) reveals that the ambiguity arises only from the term $\frac{d^2K_2}{(dR_2)^2}$ whereas all the other terms are analytically of negative sign for $\frac{dK_2}{dR_2} < 0$ and $MR_2^N > 0$.[51]

B.2.3 Scenario G vs. Competition - Reversal of Conservationist Bias

The addiction motive may even reverse the naive conservationist bias (for $\sigma < 1$), if it is sufficiently strong. To show this assume that the optimal competitive extraction path (R_1^{C*}, R_2^{C*}) – even with capital accumulation – falls over time so that $R_1^{C*} > R_2^{C*}$ and the standard monopolist chooses a more conservationist extraction policy due to the more price elastic demand in the second period.[52] The addiction motive will induce the monopolist to speed up extraction compared to the competitive outcome if the evaluation of the Hotelling rule (68) for the competitive extraction path yields

$$(1 + i_2^{C*})MR_1^N(R_1^{C*}, R_2^{C*}) > MR_2^G(R_1^{C*}, R_2^{C*})$$

By using the definition of the respective marginal revenue from (46) and (69) as well as the definition of the (standard partial) price elasticity of demand in (51), this inequality

[51] $MR_2^N > 0$ ensures that $\frac{\partial MR_2^N}{\partial R_2} < 0$ (cf. (47)), $\frac{\partial MR_2^N}{\partial K_2} > 0$ (cf. (48)) and $\left(\theta_{2R} - \frac{1-\sigma}{2-\sigma}\right) + \left(\theta_{2K} - \frac{1}{2-\sigma}\right)\frac{R_2}{K_2}\frac{dK_2}{dR_2} > 0$ because by combining $\theta_{2R} > 1 - \sigma$ from $MR_2^N > 0$ and $\theta_{2R} + \theta_{2K} < 1$ by the Euler theorem we have $\theta_{2R} > \frac{1+\sigma}{2-\sigma} > \frac{1}{2-\sigma}$ and $\theta_{2K} < \frac{1}{2-\sigma}$ at least for $\sigma < 2$.

[52] i.e. we have $|\epsilon_{R_2,p_2}| > |\epsilon_{R_1,p_1}|$ for the falling competitive extraction path due to $\sigma < 1$ and (52) and (54).

will only arise if

$$-\frac{dK_2}{dR_2}\frac{R_2^{C*}}{K_2(R_1^{C*}, R_2^{C*})} > \frac{\theta_{2R}(R_1^{C*}, R_2^{C*}) - \theta_{1R}(R_1^{C*}, R_2^{C*})}{\theta_{2K}(R_1^{C*}, R_2^{C*})} \tag{94}$$

Note that the right side is positive because $\theta_{2R}(R_1^{C*}, R_2^{C*}) > \theta_{1R}(R_1^{C*}, R_2^{C*})$ directly follows from the definition of the price elasticity of demand (51) and $|\epsilon_2| > |\epsilon_1|$ which ensures that the naive monopolist indeed postpones extraction compared to the competitive outcome. For $\sigma\eta > 1$, we know that the left side is also positive according to (41). Obviously, the addiction motive will induce the monopolist to speed up extraction compared to competitive extraction only for a sufficiently high sensitivity of second period capital stock to changes in the resource extraction path which is measured in (94) by the elasiticity of the second-period capital stock with respect to a postponement of extraction[53] if demand is not iso-elastic and $\sigma < 1$. Note that the sensitivity of second period capital stock does in the end depend on the consumption preferences in both countries and the production structure given by the CES-technology (1).

From the definitions of the standard partial price elasticity (51) and of the total price elasticity (92) it readily can be seen that such a sufficiently high sensitivity of the second period capital stock as defined by (94) in turn implies that second period demand is less price elastic in terms of the total price elasticity e_{R_2,p_2} than first period demand for the competitive supply path (R_1^{C*}, R_2^{C*}), i.e. that

$$\left|e_{R_2,p_2}(R_1^{C*}, R_2^{C*})\right| < \left|\epsilon_{R_1,p_1}(R_1^{C*}, R_2^{C*})\right|$$

At the same time, we still have $|\epsilon_{R_2,p_2}| > |\epsilon_{R_1,p_1}|$ for (R_1^{C*}, R_2^{C*}) due to our assumption that the naive monopolist postpones extraction compared to the competitive market solution (thereby introducing the conservationist bias).

[53]i.e. a change in the resource extraction path by shifting resources from the first to the second period.

B.3 Scenario GA

B.3.1 Sign and Slope of the General Equilibrium Feedback Effect Ψ

The total general equilibrium feedback effect Ψ from (71) changes with the extraction path ambiguously. This can be observed from the total derivative

$$\frac{d\Psi}{dR_2} = \left.\frac{\partial\Psi}{\partial R_2}\right|_{K_2,s_{1E}} + \left.\frac{\partial\Psi}{\partial K_2}\right|_{R_2,s_{1E}} \frac{dK_2}{dR_2} + \left.\frac{\partial\Psi}{\partial s_{1E}}\right|_{R_2,K_2} \frac{ds_{1E}}{dR_2} \tag{95}$$

where we use for abbreviation

$$\left.\frac{\partial\Psi}{\partial R_2}\right|_{K_2,s_{1E}} = \frac{2-\sigma}{\sigma} F_{2KR}\left[\theta_{2R} + \theta_{2K}\frac{s_{1E}}{K_2} - \frac{s_{1E}}{K_2} - \frac{1-\sigma}{2-\sigma}\left(1-\frac{s_{1E}}{K_2}\right)\right] = \left.\frac{\partial MR_2^{NA}}{\partial K_2}\right|_{R_2,s_{1E}} \tag{96}$$

according to (90),

$$\left.\frac{\partial\Psi}{\partial K_2}\right|_{R_2,s_{1E}} = \frac{1}{\sigma}\frac{F_{2K}}{K_2}\left[\frac{2-\sigma}{\sigma}\left(\theta_{2K} - \frac{1}{2-\sigma}\right)\left(\theta_{2R} + \theta_{2K}\frac{s_{1E}}{K_2} - \frac{s_{1E}}{K_2}\right) + (1-\theta_{2K})\frac{s_{1E}}{K_2}\right] \tag{97}$$

which implies that if either $\sigma \geq 2$ or $\sigma < 2$ and $\theta_{2K} < \frac{1}{2-\sigma}$, then $\left.\frac{\partial\Psi}{\partial K_2}\right|_{R_2,s_{1E}} > 0$ whenever $\left.\frac{\partial\Psi}{\partial R_2}\right|_{K_2,s_{1E}} < 0$. Note that $\theta_{2K} < \frac{1}{2-\sigma}$ holds due to the Euler theorem at least as long as $MR_2^N > 0$.

Finally we have

$$\left.\frac{\partial\Psi}{\partial s_{1E}}\right|_{R_2,K_2} = F_{2KK} \tag{98}$$

The first two terms in (95) are ambiguous because $\theta_{2R} + \theta_{2K}\frac{s_{1E}}{K_2} - \frac{s_{1E}}{K_2}$ or, equivalently, Ψ is of ambiguous sign, in general.[54] The last term is ambiguous due to the generally ambiguous savings reaction (see section A.2.3). In general, therefore, Ψ may change sign

[54] Ψ may also be stated as

$$\Psi = \frac{F_{2K}}{\sigma}\left[\theta_{2R} + \theta_{2K}\frac{s_{1E}}{K_2} - \frac{s_{1E}}{K_2}\right]$$

by use of the CES-technology (1) and the resource and capital market equilibrium conditions $p_t = F_{tR}$ and $i_t = F_{tK}$. $\Psi > 0$ therefore also implies that the share of total output which country E can capture as factor remuneration exceeds its share in the second period capital stock, and the other way round. Moreover, note that $\theta_{2K} - \frac{1}{2-\sigma} < 0$ for $\sigma < 2$ and $MR_2 > 0$ from (59).

when redistributing resources from one period to another so that MR_2^{GA} and MR_2^{NA} intersect.

B.3.2 Slope of MR_2^{GA}

Recall that by (44), (59) and (71) we have

$$MR_2^{GA} = MR_2^{NA} + \Psi \frac{dK_2}{dR_2}$$

By using (67) and (95) we get (75) which we decompose by noting the $\frac{di_2}{dR_2} = F_{2KR} + F_{2KK}\frac{dK_2}{dR_2}$ according to (38). Using our previous results in sections B.3.1 and B.1.2 we then can state the following:

$$\begin{aligned} \frac{dMR_2^{GA}}{dR_2} &= \frac{dMR_2^{NA}}{dR_2} + \frac{d\Psi}{dR_2}\frac{dK_2}{dR_2} + \Psi\frac{d^2K_2}{(dR_2)^2} \\ &= \underbrace{\left.\frac{\partial MR_2^{NA}}{\partial R_2}\right|_{K_2,s_{1E}}}_{<0 \text{ for } MR_2^{NA}>0 \text{ ((89))}} + \underbrace{\left.\frac{\partial MR_2^{NA}}{\partial K_2}\right|_{R_2,s_{1E}}}_{1 \text{ from (90)}} \underbrace{\frac{dK_2}{dR_2}}_{<0} + \underbrace{\left.\frac{\partial \Psi}{\partial R_2}\right|_{K_2,s_{1E}}}_{2 \text{ from (96)}} \underbrace{\frac{dK_2}{dR_2}}_{<0} \\ &\quad + \underbrace{\left.\frac{\partial \Psi}{\partial K_2}\right|_{R_2,s_{1E}}}_{3 \text{ from (97)}} \underbrace{\left(\frac{dK_2}{dR_2}\right)^2}_{>0} + \underbrace{\frac{di_2}{dR_2}}_{>0 \text{ from (38)}} \underbrace{\frac{ds_{1E}}{dR_2}}_{\gtreqless 0} + \underbrace{\Psi}_{\gtreqless 0 \text{ from (71)}} \underbrace{\frac{d^2K_2}{(dR_2)^2}}_{\gtreqless 0} \end{aligned} \tag{99}$$

Overall, the total derivative is of ambiguous sign. In addition to the terms where we already indicated the ambiguity note that, even though the omniscient monopolist will never choose a supply path for which $MR_t^{GA} < 0$, $MR_2^{NA} > 0$ does not necessarily hold if $\Psi < 0$ (see (70) and (71)). Moreover, the terms 1, 2 and 3 are generally of ambiguous sign due to (90) in appendix B.1.2 and (96) and (97) from appendix B.3.1. Finally, the overall ambiguity of the total derivative above is also due to the ambiguous savings reaction $\frac{ds_{1E}}{dR_2}$ from (42), which also complicated the analysis in scenario NA (see (67)), and due to the ambiguity of $\frac{d^2K_2}{(dR_2)^2}$, which is already pointed out in section 3.4 when we analyze the slope of the addiction-motivated monopolist's marginal revenue curve of the second period (see (93) in section B.2.2).

Upward Sloping of MR_2^{GA} The ambiguity of (75) is also illustrated by the numerical simulation example in section 4 as MR_2^{GA} is obviously not downward sloping for all feasible extraction paths but sharply increasing at the right end of the diagram when the resource stock is quite unevenly allocated to the second period. A similar but much attenuated upward sloping is observed for MR_2^{NA}, too. We argue in appendix B.1.2 that such an increase of MR_2^{NA} crucially depends on the effect which the capital accumulation dynamics has on the total derivative (67) and on the partial equilibrium asset motive, in particular. In principle, the same reasoning also applies for the omniscient monopolist's scenario at hand. Nevertheless, as the comparison of (75) with (67) shows there are some additional elements to account for which obviously must give rise to the much more pronounced increase of MR_2^{GA} in figure 1.

From (90) and (96) we know that the terms 1 and 2 are identical and therefore always have the same sign. Moreover, if either $\sigma \geq 2$ or $\sigma < 2$ and $\theta_{2K} < \frac{1}{2-\sigma}$ we know from (97) that 3 will be positive whenever 1 and 2 are negative. Note that in this case, all three terms 1, 2, 3 positively contribute to the overall total derivative of MR_2^{GA} as we assume $\frac{dK2}{dR_2} < 0$ (see section 2.4.4). In appendix B.1.2 we identify (91)

$$\theta_{2R} + \theta_{2K}\frac{s_{1E}}{K_2} - \frac{s_{1E}}{K_2} \leq 0 \leftrightarrow \Psi \leq 0$$

as a sufficient (and independent of σ) condition for 1 (and 2) being negative which is also of crucial importance for an upward sloping of MR_2^{NA}. Thus, as soon as $MR_2^{GA} \geq MR_2^{NA}$ which implies $\Psi \leq 0$ according to (70) and (71), the terms 1 and 2 are negative, 3 is positive and MR_2^{GA} is likely to increase in R_2.

Since savings s_{1E} are a linear increasing function of capital endowment s_{0E} ceteris paribus (see appendix B.1.1) whereas overall capital accumulation does not depend on the endowment distribution, this condition is more likely to hold if we redistribute capital endowment to country E, i.e. for higher capital endowment s_{0E}, because $\theta_{2K} - 1 < 0$ due to the Euler theorem and the left side of condition (91) decreases with s_{0E} ceteris paribus. Moreover, if the sufficient condition (91) holds, note that the terms 2 and 3 positively add to the derivative of MR_2^{NA} in (67). Therefore, if MR_2^{NA} indeed increases which is according to appendix B.1.2 mainly due to the capital feedback effect dominating, MR_2^{GA} tends to increase more strongly.

Nevertheless, the analytical assessment of the total derivative of MR_2^{GA} is rather restricted due to the ambiguous savings reaction $\frac{ds_{1E}}{dR_2}$ (see appendix A.2.3) and the entirely ambiguous second derivative of the relationship between capital accumulation and the extraction path, as we pointed out in section 3.4.3. Note that the influence of the savings reaction is strengthened in (99) compared to the total derivative MR_2^{NA}, because we have $\frac{di_2}{dR_2}$ instead of F_{2KR} in (67) and $\frac{di_2}{dR_2} > F_{2KR}$ according to (38). Thus, if households in country E react to a postponement of extraction with an increase in savings, the savings reaction works towards an upward sloping of MR_2^{GA} as well as of MR_2^{NA}, but the effect is again stronger for MR_2^{GA}. If capital accumulation increasingly falls with R_2 and $\frac{d^2K_2}{(dR_2)^2}$, the last term in (99) contributes to an overall positive sign as soon as $\Psi < 0$ or condition (91) holds so that the upward sloping tendency for MR_2^{GA} arising from the terms 1, 2 and 3 is further strengthened.

Given the decomposition in (99) and the analytical assessment, we can discuss the sharp increase of MR_2^{GA} in our numerical example at right end of figure 1. First, note MR_2^{NA} increases, too, and that $MR_2^{GA} > MR_2^{NA}$ for $R_2 \to \bar{R}$. Since therefore $\Psi < 0$, condition (91) holds and the terms 1, 2 and 3 all positively contribute to the total derivative for high R_2. Moreover, whereas the savings reaction is mostly positive but rather weak according to figure 5, the interest rate reaction now directly mirrors the increasingly negative sensitivity of capital accumulation and therefore sharply increases for high R_2 as can be observed from figure 4. Finally, figure 4 also illustrates that we have $\frac{d^2K_2}{(dR_2)^2} < 0$ for high R_2 which in turn implies that the last term in (99) also positively contributes to the total derivative because $\Psi < 0$ due to (91). In the numerical example, all the additional effects in (99) compared to (67) therefore work towards an upward sloping of MR_2^{GA} which correspondingly increases stronger than MR_2^{NA}.

B.4 Existence of Equilibrium

To proof the existence of an overall equilibrium outcome in the respective scenario, we evaluate the left and the right side of the respective Hotelling condition for the limiting cases $R_2 \to 0$ and $R_2 \to \bar{R}$ thereby taking into account that the conditional market equilibrium holds. The latter implies that on the one hand the resource constraint (17) binds and, on the other hand, that in every scenario the capital market equilibrium represented by (K_2, i_2) is a function of the resource extraction path only.

B.4.1 Limiting Behavior of Capital Market Equilibrium

Due to the assumption of symmetric homothetic preferences, the functional relationship between capital accumulation or the interest rate and the resource supply path is the same across all scenarios and the competitive case. Since aggregate savings cannot exceed aggregate income in period 1, we have

$$\lim_{R_2 \to 0} K_2(R_2) = K_2^{max} < F(\bar{R}, K_1) + K_1 \tag{100}$$

and

$$\lim_{R_2 \to \bar{R}} K_2(R_2) = K_2^{min} < K_1 \tag{101}$$

where the inequality signs are due to the strict concavity of the period utility functions $u(c_t)$. Note that for $\sigma \leq 1$ we also can conclude that $K_2^{min} > 0$ as there would be no production in period 2 otherwise. For $\sigma > 1$, when the a positive capital input no longer is necessary for final goods' production, the lower bound on capital accumulation is, however, $K_2^{min} \geq 0$.

As $i_2 = F_{2K}(R_2, K_2)$ according to (7) in the conditional market equilibrium, the CES technology (1) and (100) imply that[55]

$$\begin{aligned}
\lim_{R_2 \to 0} i_2(R_2, K_2) &= \lim_{R_2 \to 0} \gamma A \left[\gamma + \lambda \left(\frac{R_2}{K_2}\right)^{\alpha} + (1-\gamma-\lambda)\left(\frac{L}{K_2}\right)^{\alpha}\right]^{\frac{1-\alpha}{\alpha}} \\
&= \begin{cases} 0 & \text{for } \sigma \leq 1 \\ \gamma A \left[\gamma + (1-\gamma-\lambda)\left(\frac{L}{K_2^{max}}\right)^{\alpha}\right]^{\frac{1-\alpha}{\alpha}} = i_2(0, K_2^{max}) & \text{for } \sigma > 1 \end{cases}
\end{aligned} \tag{102}$$

due to the finite upper and lower bounds of K_2 according to (100) and (101) and because we have for a given and exogenous capital stock

$$\begin{aligned}
\lim_{R_t \to 0} F_{tK}\Big|_{K_t} &= \lim_{R_t \to 0} \gamma A \left[\gamma + \lambda \left(\frac{R_t}{K_t}\right)^{\alpha} + (1-\gamma-\lambda)\left(\frac{L}{K_t}\right)^{\alpha}\right]^{\frac{1-\alpha}{\alpha}}\Bigg|_{K_t} \\
&= \begin{cases} 0 & \text{for } \sigma \leq 1 \\ \gamma A \left[\gamma + (1-\gamma-\lambda)\left(\frac{L}{K_t}\right)^{\alpha}\right]^{\frac{1-\alpha}{\alpha}} & \text{for } \sigma > 1 \end{cases}
\end{aligned}$$

This also implies, that for $R_2 \to \bar{R}$, i_2 approaches some positive upper bound for both $\sigma \leq 1$ as well as for $\sigma > 1$:

$$\begin{aligned}
\lim_{R_2 \to \bar{R}} i_2(R_2, K_2) &= \gamma A \left[\gamma + \lambda \left(\frac{\bar{R}}{K_2^{min}}\right)^{\alpha} + (1-\gamma-\lambda)\left(\frac{L}{K_2^{min}}\right)^{\alpha}\right]^{\frac{1-\alpha}{\alpha}} \\
&= i_2(\bar{R}, K_2^{min}) < +\infty
\end{aligned} \tag{103}$$

[55]Note that $\alpha < 0$ implies $\sigma < 1$ and vice versa.

Furthermore, we know that

$$\frac{di_2}{dR_2} = \frac{F_{2KR} + F_{2KK} \left.\frac{dK_2}{dR_2}\right|_{i_2}}{1 - F_{2KK} \left.\frac{dK_2}{di_2}\right|_{R_2}} > 0$$

with $\left.\frac{dK_2}{dR_2}\right|_{i_2}$ from (28) and $\left.\frac{dK_2}{di_2}\right|_{R_2}$ from (27) in the conditional market equilibrium (i.e. $K_2^s = K_2^d$). We first consider the limits of the components of $\frac{di_2}{dR_2}$ for $R_2 \to 0$, separately, thereby again taking into account that $K_2 \to K_2^{max} < \infty$ from (100):

- for F_{2KR}:

$$\begin{aligned} \lim_{R_2 \to 0} F_{2KR} &= \lim_{R_2 \to 0} \frac{1}{\sigma} \frac{F_{2R}}{K_2} \frac{\gamma}{\gamma + \lambda \left(\frac{R_2}{K_2}\right)^{\alpha} + (1-\gamma-\lambda)\left(\frac{L}{K_2}\right)^{\alpha}} \\ &= \begin{cases} 0 & \text{for } \sigma < 1 \\ \infty & \text{for } \sigma \geq 1 \end{cases} \end{aligned} \tag{104}$$

- for F_{2KK}:

$$\begin{aligned} \lim_{R_2 \to 0} F_{2KK} &= \lim_{R_2 \to 0} \frac{1}{\sigma} \frac{F_{2K}}{K_2} \left[\frac{\gamma}{\gamma + \lambda \left(\frac{R_2}{K_2}\right)^{\alpha} + (1-\gamma-\lambda)\left(\frac{L}{K_2}\right)^{\alpha}} - 1 \right] \\ &= \begin{cases} 0 & \text{for } \sigma \leq 1 \\ \frac{1}{\sigma} \frac{\gamma A \left[\gamma + (1-\gamma-\lambda)\left(\frac{L}{K_2^{max}}\right)^{\alpha}\right]^{\frac{1-\alpha}{\alpha}}}{K_2^{max}} \left[\frac{\gamma}{\gamma + (1-\gamma-\lambda)\left(\frac{L}{K_2^{max}}\right)^{\alpha}} - 1 \right] & \text{for } \sigma > 1 \end{cases} \end{aligned} \tag{105}$$

- for $\left.\frac{dK_2}{dR_2}\right|_{i_2}$:

$$\begin{aligned} \lim_{R_2 \to 0} \left.\frac{dK_2}{dR_2}\right|_{i_2} &= \lim_{R_2 \to 0} -\frac{[\beta(1+i_2)]^{-\frac{1}{\eta}} p_2 + p_1}{1 + (1+i_2)\,[\beta(1+i_2)]^{-\frac{1}{\eta}}} \\ &= \begin{cases} -\frac{\beta^{-\frac{1}{\eta}} A \lambda^{\frac{1}{\alpha}} + F_{1R}(\bar{R}, K_1)}{1 + \beta^{-\frac{1}{\eta}}} > -\infty & \text{for } \sigma < 1 \\ -\infty & \text{for } \sigma \geq 1 \end{cases} \end{aligned} \tag{106}$$

- for $\left.\frac{dK_2}{di_2}\right|_{R_2}$:

$$\lim_{R_2\to 0}\left.\frac{dK_2}{di_2}\right|_{R_2} = \lim_{R_2\to 0}\frac{1}{\eta(1+i_2)}\frac{F_2+K_2}{1+i_2+[\beta(1+i_2)]^{\frac{1}{\eta}}}$$
$$= \begin{cases} \frac{1}{\eta}\frac{K_2^{max}}{1+\beta^{\frac{1}{\eta}}} < +\infty & \text{for } \sigma \leq 1 \\ \frac{1}{\eta(1+i_2(0,K_2^{max}))}\frac{F_2(0,K_2^{max})+K_2^{max}}{1+i_2(0,K_2^{max})+\left[\beta(1+i_2(0,K_2^{max}))\right]^{\frac{1}{\eta}}} < +\infty & \text{for } \sigma > 1 \end{cases} \quad (107)$$

From the behavior of these components of $\frac{di_2}{dR_2}$ we can conclude that

$$\lim_{R_2\to 0}\frac{di_2}{dR_2} = \begin{cases} 0 & \text{for } \sigma \leq 1 \\ \infty & \text{for } \sigma > 1 \end{cases} \quad (108)$$

Moreover, from (39) we have $\frac{dK_2}{dR_2} = \left.\frac{dK_2}{dR_2}\right|_{i_2} + \left.\frac{dK_2}{di_2}\right|_{R_2}\frac{di_2}{dR_2}$ so that

$$\lim_{R_2\to 0}\frac{dK_2}{dR_2} = \begin{cases} \lim_{R_2\to 0}\left.\frac{dK_2}{dR_2}\right|_{i_2} = -\frac{\beta^{-\frac{1}{\eta}}A\lambda^{\frac{1}{\alpha}}+F_{1R}(\bar{R},K_1)}{1+\beta^{-\frac{1}{\eta}}} > -\infty & \text{for } \sigma < 1 \\ \lim_{R_2\to 0}\left.\frac{dK_2}{dR_2}\right|_{i_2} = -\infty & \text{for } \sigma = 1 \\ \in \left[\lim_{R_2\to 0}\left.\frac{dK_2}{dR_2}\right|_{i_2};0\right] & \text{for } \sigma > 1 \end{cases} \quad (109)$$

as long as $\sigma\eta \geq 1$ and $\frac{dK_2}{dR_2} < 0$ for all R_2. Recall that $\lim_{R_2\to 0}\frac{di_2}{dR_2} = 0$ for $\sigma \leq 1$ according to (108). The interval for $\sigma > 1$ is due to the fact that $\lim_{R_2\to 0}\left.\frac{dK_2}{dR_2}\right|_{i_2} = -\infty$ according to (106) but $\lim_{R_2\to 0}\left.\frac{dK_2}{di_2}\right|_{R_2}\frac{di_2}{dR_2} = +\infty$ according to (107) and (108).

B.4.2 Scenario N: Existence of Equilibrium

For the limiting behavior of the marginal revenue from (46) for $R_t \to 0$, we have

$$\lim_{R_t\to 0} MR_t^N = \lim_{R_t\to 0}\frac{p_t}{\sigma}\left[\theta_{tR}-(1-\sigma)\right] = \lim_{R_t\to 0}F_{tR}(R_t,K_t)$$
$$= \begin{cases} A\lambda^{\frac{1}{\alpha}} & \text{for } \sigma < 1 \\ \infty & \text{for } \sigma \geq 1 \end{cases} \quad (110)$$

because $\theta_{tR} = \frac{p_t R_t}{F_t}$, $p_t = F_{tR}$ according to (6) in the conditional market equilibrium and

$$F_{tR} = \frac{\partial F_t}{\partial R_t} = \lambda A^{\alpha} \left(\frac{F_t}{R_t}\right)^{1-\alpha}$$

Note that the limits for $R_t \to 0$ do not depend on the capital stock K_t for $\sigma < 1$ as well as for $\sigma \geq 1$. Since K_2 is bounded from above according to (100), the limits of MR_t^N or F_{tR} derived in (110) therefore also hold for the second period in the conditional market equilibrium where the capital stock increases for $R_2 \to 0$ (cf. (41)).

Evaluating the left side of Hotelling condition (45) for $R_2 \to \bar{R}$ and correspondingly $R_1 \to 0$ therefore yields

$$\lim_{R_2 \to \bar{R}} (1 + i_2) MR_1^N = \begin{cases} (1 + i_2(\bar{R}, K_2^{min})) A\lambda^{\frac{1}{\alpha}} & \text{for } \sigma < 1 \\ \infty & \text{for } \sigma \geq 1 \end{cases}$$

For the right side, we get

$$\lim_{R_2 \to \bar{R}} MR_2^N = MR_2^N(\bar{R}, K_2^{min}) < A\lambda^{\frac{1}{\alpha}}$$

where the inequality follows from $\frac{dMR_2^N}{dR_2} < 0$ in (57).

In contrast, for $R_2 \to 0$ and $R_1 \to \bar{R}$ we get for the left side

$$\lim_{R_2 \to 0} (1 + i_2) MR_1^N = \begin{cases} MR_1^N(\bar{R}, K_1) & \text{for } \sigma \leq 1 \\ (1 + i_2(0, K_2^{max}))\, MR_1^N(\bar{R}, K_1) & \text{for } \sigma > 1 \end{cases}$$

and for the right side

$$\lim_{R_2 \to 0} MR_2^N = \begin{cases} A\lambda^{\frac{1}{\alpha}} & \text{for } \sigma < 1 \\ \infty & \text{for } \sigma \geq 1 \end{cases}$$

This implies that for $R_2 \to 0$ and $R_1 \to \bar{R}$ the right side of Hotelling condition always exceeds the left side whereas the opposite holds true for $R_2 \to \bar{R}$ and $R_1 \to 0$. Thus, there necessarily exists an interior solution for which the equilibrium resource extraction fulfills Hotelling condition (45). Moreover, since both sides of the Hotelling condition are monotonously falling in the resource supply of the respective period according to (56) and (57), this equilibrium solution is unique.

B.4.3 Scenario NA: Existence of Equilibrium

With the monopolist pursuing the asset motive in scenario NA, we first have to derive the limits for the second period asset holdings. Although the influence of shifting resources to or from the second period is generally of ambiguous sign due to counteracting income and substitution effects, savings s_{1E} approach some finite limits for $R_2 \to 0$

$$\begin{aligned}\lim_{R_2 \to 0} s_{1E}(y_{1E}, \pi_{2E}, i_2) &= s_{1E}\left(y_{1E}(\bar{R}, K_1, s_{0E}), \pi_{2E}(0, K_2^{max}), i_2(0, K_2^{max})\right) \\ &< y_{1E}(\bar{R}, K_1, s_{0E}) < F_1(\bar{R}, K_1) + K_1\end{aligned} \tag{111}$$

Note that for $\sigma \leq 1$, we have $\pi_{2E}(0, K_2^{max}) = 0$ and $i_2(0, K_2^{max}) = 0$. Similarly, for $R_2 \to \bar{R}$ we get

$$\begin{aligned}\lim_{R_2 \to \bar{R}} s_{1E}(y_{1E}, \pi_{2E}, i_2) &= s_{1E}\left(y_{1E}(0, K_1, s_{0E}), \pi(\bar{R}, K_2^{min}), i_2(\bar{R}, K_2^{min})\right) \\ &< F_1(0, K_1) + K_1\end{aligned} \tag{112}$$

where $y_{1E}(0, K_1, s_{0E}) = s_{0E}$ and $F_1(0, K_1) = 0$ for $\sigma \leq 1$.

From (59) we know that $MR_t^{NA} = MR_t^N + F_{tKR}s_{(t-1)E}$. Since s_{1E} and K_2 according to (101) are bounded for $R_2 \to 0$, we can conclude that

$$\begin{aligned}\lim_{R_t \to 0} MR_t^{NA} &= \lim_{R_t \to 0} MR_t^N + \lim_{R_t \to 0} F_{tKR}s_{(t-1)E} \\ &= \lim_{R_t \to 0} MR_t^N + \lim_{R_t \to 0} \frac{1}{\sigma} F_{tR} \frac{s_{(t-1)E}}{K_t} \frac{\gamma}{\gamma + \lambda\left(\frac{R_t}{K_t}\right)^{\alpha} + (1-\gamma-\lambda)\left(\frac{L}{K_t}\right)^{\alpha}} \\ &= \begin{cases} A\lambda^{\frac{1}{\alpha}} & \text{for } \sigma < 1 \\ \infty & \text{for } \sigma \geq 1 \end{cases}\end{aligned} \tag{113}$$

holds for both periods according to (110) because the limits are independent of K_2 and s_{1E}.

Evaluating the left side of Hotelling condition (58) therefore gives for $R_2 \to \bar{R}$

$$\lim_{R_2 \to \bar{R}} (1 + i_2) MR_1^{NA} = \begin{cases} \left(1 + i_2(\bar{R}, K_2^{min})\right) A\lambda^{\frac{1}{\alpha}} & \text{for } \sigma < 1 \\ \infty & \text{for } \sigma \geq 1 \end{cases}$$

and for $R_2 \to 0$

$$\lim_{R_2\to 0}(1+i_2)MR_1^{NA} = \begin{cases} MR_1^{NA}(\bar{R}, K_1, s_{0E}) & \text{for } \sigma \leq 1 \\ (1+i_2(0, K_2^{max}))\, MR_1^{NA}(\bar{R}, K_1, s_{0E}) & \text{for } \sigma > 1 \end{cases}$$

where $MR_1^{NA}(\bar{R}, K_1, s_{0E})$ is some finite value which may be positive or negative and $i_2(0, K_2^{max}) = 0$ for $\sigma \leq 1$ according to (102). Since the right side of (58) unambiguously falls in R_1 according to (66), we also can conclude that

$$\lim_{R_2\to 0}(1+i_2)MR_1^{NA} = (1+i_2(0, K_2^{max}))MR_1^{NA}(\bar{R}, K_1, s_{0E}) < \lim_{R_2\to \bar{R}}(1+i_2)MR_1^{NA}$$

for all $\sigma > 0$.

Combining this observation and with the limit of the right side of the Hotelling condition (58) for $R_2 \to 0$ from (113) we have

$$A\lambda^{\frac{1}{\alpha}} = \lim_{R_2\to 0} MR_2^{NA} > MR_1^{NA}(\bar{R}, K_1) = \lim_{R_2\to 0}(1+i_2)MR_1^{NA} \qquad \text{for } \sigma \leq 1$$

and

$$\infty = \lim_{R_2\to 0} MR_2^{NA} > (1+i_2(0, K_2^{max}))MR_1^{NA}(\bar{R}, K_1) = \lim_{R_2\to 0}(1+i_2)MR_1^{NA} \quad \text{for } \sigma > 1$$

This implies that right side always exceeds the left side for $R_2 \to 0$.

For $R_2 \to \bar{R}$, the right side approaches some, again positive or negative, finite value

$$\lim_{R_2\to \bar{R}} MR_2^{NA}(K_2, R_2, s_{1E}) = MR_2^{NA}(K_2^{min}, \bar{R}, s_{1E}) \quad \text{for all } \sigma > 0$$

with K_2^{min} from (101).

In contrast to the left side, MR_2^{NA} does not necessarily fall in R_2 due to the influence of the feedback effect from capital accumulation on the asset motive in the second period as (67) demonstrates. Nevertheless, we can show by contradiction that

$$MR_2^{NA} < p_2(R_2, K_2)$$

holds for all feasible extraction paths $R_2 \leq \bar{R}$, because due to the Euler theorem $\theta_{2R} + \theta_{2K}\frac{s_{1E}}{K_2} < 1$. However, since $\frac{dp_2}{dR_2} < 0$ from (37), this implies that even though MR_2^{NA} might increase in R_2 given that the conditional market equilibrium holds we necessarily have for all $\sigma > 0$

$$\lim_{R_2 \to \bar{R}} MR_2^{NA} < p_2(\bar{R}, K_2^{min}) < A\lambda^{\frac{1}{\alpha}} \leq \lim_{R_2 \to 0} MR_2^{NA} \leq \lim_{R_2 \to \bar{R}} (1 + i_2) MR_1^{NA}$$

Thus, the right side of Hotelling condition (58) is necessarily lower for $R_2 \to \bar{R}$ than the left side whereas for $R_2 \to 0$ the right side always exceeds the left side. This implies that there must be at least one feasible extraction path within the given resource constraint for which the equilibrium condition (58) holds. Since the right side of Hotelling condition (58) monotonously falls in R_1, this proves the existence of an interior equilibrium solution in scenario NA for which the Hotelling condition and the conditional market equilibrium hold. In contrast to scenario N, this equilibrium solution does not have to be unique due to the eventually upward sloping of the MR_2^{NA}. Referring to the stability criterion laid out in section 3.1, however, we can also conclude that there necessarily must be at least one stable equilibrium outcome.

B.4.4 Scenario G: Existence of Equilibrium

The first period's marginal revenues in the scenarios G and N are identical ($MR_1^G = MR_1^N$) (cf. (68) and (49)) and are strictly monotonic decreasing in R_1. The existence of an equilibrium in scenario N is given (cf. B.4.2 above), and in period 2 $MR_2^G < MR_2^N$ necessarily holds. Therefore, in scenario G an interior equilibrium exists, too, if we can show that $MR_2^G(R_2 = 0) > MR_1^G(R_2 = 0)$. We again look at the limits of the components of $MR_2^G = MR_2^N + F_{2KR}R_2\frac{dK_2}{dR_2}$.

For $F_{2KR}R_2$:

$$\lim_{R_2 \to 0} F_{2KR}R_2 = \lim_{R_2 \to 0} \left[\frac{1}{\sigma} \lambda A^{\alpha} \left[\frac{F_2}{R_2} \right]^{-\alpha} F_{2K} \right] = 0$$

for all σ with

$$\lim_{R_2 \to 0} \left[\frac{F_2}{R_2} \right]^{-\alpha} = \begin{cases} \frac{1}{A^{\alpha}\lambda} & \text{for } \sigma < 1 \\ 1 & \text{for } \sigma = 1 \\ 0 & \text{for } \sigma > 1 \end{cases}$$

Case 1) $\sigma < 1$**:** As $\lim_{R_2 \to 0} \frac{dK_2}{dR_2}$ is a constant, we get

$$\lim_{R_2 \to 0} \left[F_{2KR} R_2 \frac{dK_2}{dR_2} \right] = 0 \cdot const. = 0$$

And as a result

$$\lim_{R_2 \to 0} MR_2^G = \lim_{R_2 \to 0} MR_2^N = A\lambda^{\frac{1}{\alpha}}$$

Case 2) $\sigma = 1$**:** In the Cobb-Douglas case we have

$$\begin{aligned}
&\lim_{R_2 \to 0} \left[F_{2KR} R_2 \frac{dK_2}{dR_2} \right] \\
&= \lim_{R_2 \to 0} \left[\frac{\lambda \gamma A^{2\alpha}}{\sigma K_2} F_2 \frac{dK_2}{dR_2} \right] \\
&= \lim_{R_2 \to 0} \left[\frac{\lambda \gamma A^{2\alpha}}{\sigma K_2} F_2 (-C_0 F_{2R} + C_1) \right] \\
&= \lim_{R_2 \to 0} [-C_2 R_2^{2\lambda - 1}] = \begin{cases} 0 & \text{for } \lambda > 0.5 \\ -C_2 & \text{for } \lambda = 0.5 \\ -\infty & \text{for } \lambda < 0.5 \end{cases}
\end{aligned}$$

with C_0, C_1, C_2 being positive constants in the limit. For the other part of MR_2^G we have from (110)

$$\begin{aligned}
&\lim_{R_2 \to 0} [p_2 + F_{2RR} R_2] \\
&= +\infty
\end{aligned}$$

For the sum of both parts, i.e. for the limit of MR_2^G for $R_2 \to 0$ we get

$$\begin{aligned}
&\lim_{R_2 \to 0} MR_2^G \\
&= \lim_{R_2 \to 0} \left[p_2 + F_{2RR} R_2 + F_{2KR} R_2 \frac{dK_2}{dR_2} \right] \\
&= \lim_{R_2 \to 0} \left[\lambda^2 A K_2^{\gamma} R_2^{\lambda - 1} \right] + \lim_{R_2 \to 0} [-C_2 R_2^{2\lambda - 1}] \\
&= \lim_{R_2 \to 0} MR_2^N \\
&= +\infty
\end{aligned}$$

For $\lambda \geq 0.5$, $F_{2KR}R_2\frac{dK_2}{dR_2}$ approaches a constant or zero, so that $\lim_{R_2\to 0} MR_2^N = +\infty$ dominates. For $\lambda < 0.5$ the term $p_2 + F_{2RR}R_2$ dominates in the limit too, because its exponent has a higher absolute value:

$$|\lambda - 1| > |2\lambda - 1|$$

Case 3) $\sigma > 1$**:** In the Cobb-Douglas case above we had (cf. (101))

$$\begin{aligned}
\lim_{R_2\to 0} \frac{dK_2}{dR_2} &= \lim_{R_2\to 0} \left.\frac{dK_2}{dR_2}\right|_{i_2} + \left.\frac{dK_2}{di_2}\right|_{R_2} \frac{di_2}{dR_2} \\
&= \lim_{R_2\to 0} \left.\frac{dK_2}{dR_2}\right|_{i_2} \\
&= -\infty
\end{aligned}$$

But this negative force was too weak to dominate $\lim_{R_2\to 0} MR_2^N = +\infty$. In the following we first show, that the same holds true for $\sigma > 1$: With $\lim_{R_2\to 0} \frac{F_2}{R_2} = +\infty$ we have for the addition motive in the limit

$$\begin{aligned}
&\lim_{R_2\to 0} F_{2KR}R_2 \left.\frac{dK_2}{dR_2}\right|_{i_2} \\
&= \lim_{R_2\to 0} F_{2KR}R_2\,(-C_3 p_2) \\
&= \lim_{R_2\to 0} -C_3 \frac{1}{\sigma}\frac{F_{2K}F_{2R}}{F_2} R_2 F_{2R} \\
&= \lim_{R_2\to 0} -C_3 \frac{1}{\sigma} F_{2K}\lambda^2 A^{2\alpha} \left[\frac{F_2}{R_2}\right]^{1-2\alpha} \\
&= \lim_{R_2\to 0} -C_4 \left[\frac{F_2}{R_2}\right]^{1-2\alpha} = \begin{cases} -\infty & \text{for } 0 < \alpha < 0.5 \\ -\text{const.} & \text{for } \alpha = 0.5 \\ 0 & \text{for } 0.5 < \alpha < 1 \end{cases}
\end{aligned}$$

with C_3, C_4 being further constants in the limit. The limit of the marginal revenue according to (110) is

$$\begin{aligned}
&\lim_{R_2\to 0} p_2 + F_{2RR}R_2 \\
&= +\infty
\end{aligned}$$

Putting both components together we get

$$\begin{aligned}
&\lim_{R_2\to 0}\left[p_2 + F_{2RR}R_2 + F_{2KR}R_2 \left.\frac{dK_2}{dR_2}\right|_{i_2}\right] \\
&= \lim_{R_2\to 0}\left[MR_2^N - C_4\left[\frac{F_2}{R_2}\right]^{1-2\alpha}\right] \\
&= \lim_{R_2\to 0} MR_2^N \\
&= +\infty
\end{aligned}$$

for all α and $\lim_{R_2\to 0} MR_2^N$ indeed dominates the rest, because its exponent is again higher:

$$1-\alpha > 1-2\alpha$$

Now the additional positive term $\left.\frac{dK_2}{di_2}\right|_{R_2}\frac{di_2}{dR_2}$ further attenuates the force towards $-\infty$. Moreover, this additional positive force grows infinitely itself for $R_2 \to 0$

$$\lim_{R_2\to 0}\left[\left.\frac{dK_2}{di_2}\right|_{R_2}\frac{di_2}{dR_2}\right] = +\infty$$

Therefore, $\lim_{R_2\to 0} MR_2^N = +\infty$ will continue to dominate and we finally get also for $\sigma > 1$

$$\begin{aligned}
&\lim_{R_2\to 0} MR_2^G \\
&= \lim_{R_2\to 0}\left[MR_2^N + F_{2KR}R_2 \left.\frac{dK_2}{dR_2}\right|_{i_2}\right] \\
&= \lim_{R_2\to 0} MR_2^N \\
&= +\infty
\end{aligned}$$

Thus, $MR_2^G(R_2 = 0) > MR_1^G(R_2 = 0)$ always holds and we necessarily have at least one stable (cf. stability criterion in section 3.1) interior equilibrium. In case, that an upward sloping part of MR_2^G indeed arises and gives way to multiple equilibria (which we cannot totally exclude, although we did not observe any), all of these must be interior solutions.

B.4.5 Scenario GA: Existence of Equilibrium

According to (44), we have $MR_1^{GA} = MR_1^{NA}$ and $MR_2^{GA} = MR_2^{NA} + \Psi\frac{dK_2}{dR_2}$ with Ψ from (71). Thus, according to (113) we have for the first period

$$\lim_{R_1\to 0} MR_1^{GA} = \lim_{R_1\to 0} MR_1^{NA} = \begin{cases} A\lambda^{\frac{1}{\alpha}} & \text{for } \sigma \leq 1 \\ \infty & \text{for } \sigma > 1 \end{cases}$$

In contrast, for the second period we get

$$\lim_{R_2\to 0} MR_2^{GA} = \lim_{R_2\to 0} MR_2^{NA} + \lim_{R_2\to 0} \Psi\frac{dK_2}{dR_2} \tag{114}$$

where the second limit is given by

$$\lim_{R_2\to 0} \Psi\frac{dK_2}{dR_2} = \lim_{R_2\to 0} \frac{\partial p_2}{\partial K_2} R_2 \frac{dK_2}{dR_2} + \lim_{R_2\to 0} \frac{\partial i_2}{\partial K_2} s_{1E} \frac{dK_2}{dR_2}$$

Regarding the first limit, we can refer to the discussion of the existence of an equilibrium solution for scenario G in section B.4.4 and conclude given (113) that

$$\begin{aligned} \lim_{R_2\to 0} MR_2^{G} &= \lim_{R_2\to 0} MR_2^{N} + \lim_{R_2\to 0} \frac{\partial p_2}{\partial K_2} R_2 \frac{dK_2}{dR_2} \\ &= \lim_{R_2\to 0} MR_2^{NA} + \lim_{R_2\to 0} \frac{\partial p_2}{\partial K_2} R_2 \frac{dK_2}{dR_2} \end{aligned}$$

Regarding the second component of Ψ, we have

$$\begin{aligned} \lim_{R_2\to 0} \frac{\partial i_2}{\partial K_2} s_{1E} &= \lim_{R_2\to 0} F_{2KK} s_{1E} \\ &= \begin{cases} 0 & \text{for } \sigma < 1 \\ F_{2KK}(0, K_2^{max}) s_{1E}\left(y_{1E}(\bar{R}), \pi_{2E}(0, K_2^{max}), i_2(0, K_2^{max})\right) & \text{for } \sigma \geq 1 \end{cases} \end{aligned}$$

according to (105) and due to s_{1E} being bounded according to (111). Note that the limit for $\sigma \geq 1$ is some negative but finite value.

However, given that $\frac{dK_2}{dR_2} < 0$ for all feasible R_2, we can combine these results and conclude that the right side of (43) for $R_2 \to 0$ goes to

$$\lim_{R_2\to 0} MR_2^{GA} = \lim_{R_2\to 0} MR_2^{NA} + \lim_{R_2\to 0} \frac{\partial p_2}{\partial K_2} R_2 \frac{dK_2}{dR_2} + \lim_{R_2\to 0} F_{2KK} s_{1E} \frac{dK_2}{dR_2}$$
$$= \begin{cases} A\lambda^{\frac{1}{\alpha}} & \text{for } \sigma < 1 \\ +\infty & \text{for } \sigma \geq 1 \end{cases}$$

Following the same reasoning as in section B.4.3, this implies that the right side of Hotelling condition (43) necessarily exceeds the left side for $R_2 \to 0$ and $R_1 \to \bar{R}$, i.e. we have

$$\lim_{R_2\to 0} (1+i_2) MR_1^{GA} = (1 + i_2(0, K_2^{max}))\, MR_1^{NA}(\bar{R}, K_1) < \lim_{R_2\to 0} MR_2^{GA}$$

with $i_2(0, K_2^{max})$ from (102).

For $R_2 \to \bar{R}$, the left side of Hotelling condition (43) approaches

$$\lim_{R_2\to \bar{R}} (1+i_2) MR_1^{NA} = \begin{cases} (1 + i_2(\bar{R}, K_2^{min}))A\lambda^{\frac{1}{\alpha}} & \text{for } \sigma < 1 \\ +\infty & \text{for } \sigma \geq 1 \end{cases}$$

according to (103) and (113). However, we know from the discussion of (75) that the right side may increase with shifting resources to the second period. Moreover, in contrast to scenario NA, for which we could show in section B.4.3 that the eventually increasing right side of Hotelling condition (58) is bounded above by F_{2R}, MR_2^{GA} might even exceed F_{2R}. Thus, we generally cannot exclude

$$\lim_{R_2\to \bar{R}} MR_2^{GA} > \lim_{R_2\to \bar{R}} (1+i_2) MR_1^{GA}$$

Since in this case we may have $MR_2^{GA} > (1+i_2)MR_1^{GA}$ for all feasible extraction paths, a corner solution may arise where the monopolist extracts the resource just in period 2 and the Hotelling condition (43) does not hold. If, however,

$$\lim_{R_2\to \bar{R}} MR_2^{GA} < \lim_{R_2\to \bar{R}} (1+i_2) MR_1^{GA}$$

there must be at least one stable and interior equilibrium solution defined by the Hotelling condition (43) as the right side necessarily exceeds the left side for $R_2 \to 0$ and as we know from (66) that the left side of the Hotelling condition unambiguously falls in R_1 even when taking into account the resource constraint.

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