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Lobbying over Exhaustible-Resource Extraction

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Abstract

In a dynamic model of natural-resource extraction, we characterize the extraction path that is chosen by a government which is lobbied by natural-resource suppliers. The lobby group pays the government in exchange for a favorable policy. We show how the development of payments relates to the development of a conflict of interest between profit maximization and welfare maximization. The agreed extraction reflects the resource owners' preference for supply restrictions that keep up the price and the government's preference for avoiding flow-pollution damages. Due to stock-pollution damages, the government prefers a lower level of total extraction than the lobby group. Resource extraction decreases monotonically. Lobby payments do not necessarily do so, but they decrease in the long run.

Keywords: Environmental Policy; Exhaustible Resources; Lobbying; Political Economy; Time Consistency

JEL Codes: D72; Q31; Q38; Q58

1 Introduction

It is common for environmental economists, policy-makers and NGOs to assume that the influence of natural-resource supplier interest groups distorts policy away from a "social planner's" ideal. For example, the Center for Responsive Politics, a watchdog NGO, suspects that the American coal-mining industry uses payments to politicians to lobby against environmental regulations (Rodriguez, 2015), World Bank representatives see "powerful lobbies" as an obstacle to "the carbon price that theory recommends" (Fay and Hallegatte, 2015), and a lignite lobby has been accused of exerting influence on the German government's coalition agreement (Delfs, 2013). If we believe that lobbyists can influence policy, we have to expect a distortion in favor of natural-resource suppliers almost by definition, at least if there are no sufficiently strong counterforces.

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The aim of this article is to analyze how the distortive influence of resource owners develops in the framework of a dynamic model of resource extraction.

The literature in the tradition of the Grossman and Helpman (1994) common-agency interest-group model assumes that interest groups offer conditional bribes to the government – interpreted as *contribution payments* to politicians – in order to shift policy into their preferred direction. This model has considerably enhanced our understanding of lobbies' political influence. The political economy of exhaustible resources, however, raises some specific questions, not least due to its inherently dynamic nature. How do the resource policy and its distortion develop over time? How does the resource owners' interest in influencing policy and, relatedly, how do contribution payments develop, as more and more of the resource has been extracted? How do the government's valuation of payments, the lobby's cost of paying them, and both parties' bargaining power affect policy and payments?

We focus on the relationship between the government and the resource-owner lobby; therefore, we assume that there are no other lobby groups. At the same time, realism is gained by allowing the government to have a more active role than it has in the Grossman and Helpman (1994) tradition (in which lobby groups are first movers who make offers to the government). To this end, we model policy and contribution payments as determined via (Nash) bargaining (cf. Goldberg and Maggi, 1999 and Grossman and Helpman, 2001, Section 7.5). The solution is time-consistent, such that both the lobby and the government always benefit from continued cooperation.

The lobbying-equilibrium resource extraction is a compromise between the government's aim of intertemporal welfare maximization and the lobby's aim of intertemporal profit maximization. The *first main contribution* of this article is to characterize how the conflict between these objectives develops if three important mechanisms on the resource market are taken into account: the increasing extraction costs due to resource depletion; environmental pollution; and the price elasticity of resource demand. The resource owners' preferred extraction is reduced by the motivation to keep up the price; at the same time, the government's preferred extraction is reduced by flow-pollution damages. If the market-power incentive is sufficiently strong compared to environmental damages, the lobby's preferred extraction may even be temporarily too low from the social planner's point of view. However, resource owners prefer higher *total* extraction than the government as they do not care about environmental damages, such that extraction continues for too long in the lobbying equilibrium. Finally, because extraction costs are increasing in cumulative past extraction and the marginal utility of resource consumption is finite, welfare-maximizing and profit-maximizing extraction both go to zero in the very long run.

We propose and analyze the model for relatively general functional forms. However, we enhance the analysis by solving a linear-quadratic specification in order to obtain clear-cut results. Our *second* contribution then is to relate the conflict of interest and its development to the underlying economic parameters. For instance, we show under which conditions this conflict weakens or intensifies over time. Note that the first two contributions do not depend on the specific political model; if policy were distorted in the resource owners' preferred direction for any other reason, understanding how market properties shape the conflict of interest would still be a relevant insight.

The *third* contribution directly relates to the lobbying model. We characterize the development of the time-consistent contribution payments. These payments may decrease or increase over time. In the very long run, however, they definitely go to zero as marginal extraction costs increase so much that even resource owners would prefer to end extraction. Moreover, there is a qualitative change when the cumulative past extraction exceeds the socially optimal level for the first time. The bargained extraction continues, but from that moment on, the government would stop resource extraction completely if the bargaining failed. The lobby then no more has to factor in that lobbying for higher *current* extraction deteriorates its *future* bargaining position. Therefore, its willingness to pay increases sharply. From a technical point of view, we thus show how a non-negativity constraint affects dynamic bargaining and leads to sharp points in the payments' development.

As a *fourth* contribution, we show how lobbying influences environmental damage costs. When lobbying implies unambiguously higher *and* faster resource extraction, environmental damages are higher. If lobbying slows down extraction, however, it either reduces the present value of environmental damages, or it reduces current extraction but increases intertemporal environmental damages. We discuss how this relates to the "green paradox" literature (Sinn, 2008; Gerlagh, 2011).

We derive the cooperation between the government and the lobby as the outcome of bargaining in every period about that period's extraction quantity and payment; a time-consistent contract bargained at the beginning of time would have to fix the same values for extraction and payments. Similarly, the direct choice of quantities is analytically convenient, but not decisive. As a *fifth* contribution, we characterize the tax path that would implement the bargained extraction. Thus, the model can also be applied if the government can only indirectly influence extraction.[1]

Our model of the resource market is fairly general. The resource may be thought of as a fuel like coal or oil. The model allows for flow pollution, such as soot or dust,

[1]In the appendix, we address two additional variations of our model assumptions. Firstly, instead of assuming that a disagreement in one period makes a return to cooperation impossible as in the main body of the paper, we employ the *recursive Nash bargaining solution* of Sorger (2006) in Appendix D, in which disagreement ends cooperation for the current period only. The equilibrium policy is identical, and the contribution payments are identical if the government has no bargaining power. Secondly, in the main body of the paper, we assume that the government is in power forever; in Appendix E, we allow for the possibility that the government is ousted.

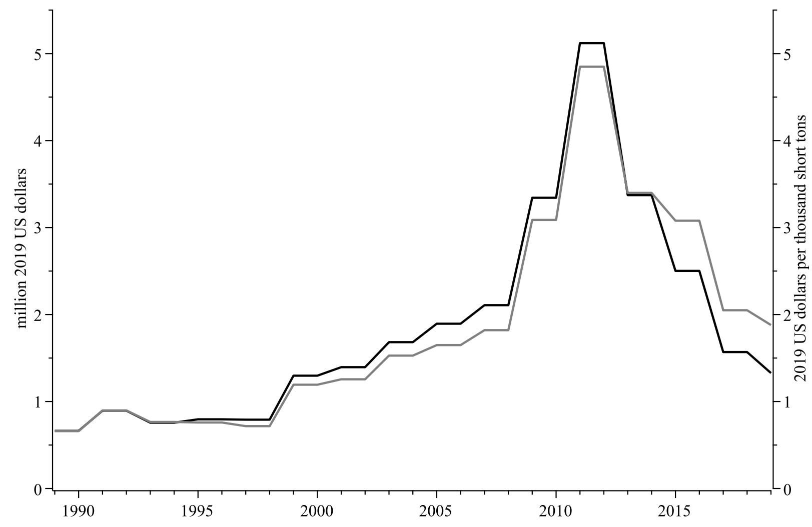


Figure 1: Campaign contributions (black curve, left axis) and campaign contributions per unit of production (gray curve, right axis) of the US coal mining industry.

and stock pollution, such as carbon dioxide or permanent landscape changes. It suggests implications for empirical analyses of lobby influence on natural-resource policy, and for welfare analyses of monopolistic extraction. *Firstly,* such analyses should take the amount of past extraction, the price elasticity of demand and potential flow- and stock-pollution damages into account. *Secondly,* the temporal dimension is important in understanding the conflict of interest between profit maximization and welfare maximization, and disregarding it may be misleading. Resource owners may seem to be the conservationists' friends (Solow, 1974) for a while; afterwards, the conflict of interest may be absent temporarily; but in the long run, profit-maximizing extraction will be too high. *Thirdly,* contribution payments do not always rise and shrink with the industry – a shrinking resource extraction does not imply shrinking payments. Instead, their development reflects how the conflict of interest between the bargaining parties changes over time. *Finally*, when payments from a shrinking industry begin to increase, it may imply that stopping extraction would be welfare-maximizing. Then, the lobby must compensate the government for the increasing welfare loss due to continuing extraction. However, in the long run extraction and the additional welfare loss cease, and so do the payments.

For an illustration of our approach, consider the US coal mining industry's lobby influence. Figure 1 shows the development of campaign contributions of the US coal mining industry from 1989 to 2019, both in absolute levels (black curve, left axis; Center for Responsive Politics, 2020) and per unit of production (gray curve, right axis; EIA, 2020*a*). We can see that campaign contributions grow strongly at first, peaking at 5.14 million US dollars per year in 2012; they then decline to 1.33 million US dollars per year in 2019. Campaign contributions are neither proportional to the amount of production, nor can we see a monotonic development.[2] Our model framework allows for two alternative explanations for a sudden increase in the payments. The first is that the government prefers to stop extraction, as further extraction would reduce welfare. The second is the shale gas boom that occurred in the United States between 2007 and 2012; we derive conditions under which such a negative demand shock increases the payments. The present article thus also contributes to the literature on the "losers' paradox", according to which declining industries lobby harder than emerging ones.[3]

Although we discuss the model as one of resource-owner lobbying, in reality such a lobby may represent firms along the entire supply chain; for example, the American Petroleum Institute (API), which is the largest special interest group of the American oil and gas industry (API, 2021), includes firms operating upstream, midstream and downstream. In 2020, the API lobbied the American government to expand the strategic oil reserve in order to stabilize the oil price (CNBC, 2020). In our model, costs increase in current production. If we reinterpret these costs as transportation or processing costs of resource products, we can apply the model to lobbying of the entire resource sector in this sense.

Our paper proceeds as follows. In the next section, we relate the paper to the literature. In Section 3, we introduce the model economy and the political agents, namely the government and the resource-owner lobby group, for which we then introduce the dynamic lobbying equilibrium with general functional forms in Section 4. In Section 5, we apply a linear-quadratic specification in order to characterize specific cases of this equilibrium in which the lobbying distortion works in different directions or in which it develops in different ways. These cases are illustrated with specific parameter values in Section 6, and discussed with respect to fossil fuels, along with other implications of the lobby model, in Section 7. In Section 8, we demonstrate how the bargained extraction path can be implemented via taxes. Section 9 concludes.

2 Relation to the Literature

Our article contributes to different strands of literature, namely lobbying, resource extraction, and dynamic bargaining.

[2]Coal production and campaign contributions both increased through 2008. Coal production then started a fast decline, while contribution payments continued to increase until 2012. The figure shows campaign contributions from individuals and political action committees, expressed in 2019 US dollars using the US consumer price index (Federal Reserve Bank of St. Louis, 2020), and it spreads the campaign contributions of the two-year election cycles equally on the two respective years. For more details, see Center for Responsive Politics (2020).

[3]This phenomenon has been explained by low opportunity costs of lobbying when demand declines over time (Damania, 2002), by high rents from lobbying in sectors with low demand and, thus, little entry by competitors (Baldwin and Robert-Nicoud, 2007), or by loss aversion (Tovar, 2009).

The government in our model aims to maximize welfare, but it is willing to choose a different policy in exchange for lobby payments. This follows the tradition of the Grossman and Helpman (1994, 2001) common-agency model, with the deviations discussed above.[4] This framework has been applied to environmental policy in static settings by Fredriksson (1997*a*,*b*) and Aidt (1998). It has then been extended to repeated games by Damania and Fredriksson (2000), and to games with political instability by Fredriksson and Svensson (2003) and Fredriksson and Wollscheid (2008).

The first dynamic model of political influence on resource extraction that is similar to ours is Barbier, Damania and Léonard (2005). They provide an insightful model and empirical investigation of lobby pressure on governments in developing countries and demonstrate that lobbying accelerates the speed of deforestation. The private agent in their model sells the resource at the world-market price, so he would never have an incentive to limit supply. Another model related to ours is that of Boyce (2010). He analyzes the political influence of a fishery lobby. In his model, harvesters have a logarithmic utility function of their resource extraction, such that there is no motive to restrain supply in order to maximize profits. In contrast to these models, our framework includes the elasticity of demand and both stock and flow pollution; their relative strength determines the growth of the lobbying distortion. Additionally, we explicitly characterize the lobby payments and their development. In a model of intertemporally optimal deforestation, Andrés-Domenech, Martín-Herrán and Zaccour (2015) take demand reactions into account. However, they focus on parameter values that imply corner solutions to the effect that forest owners always prefer maximal deforestation and non-owners, who dislike environmental damages, prefer maximal conservation. For another recent lobbying analysis, see Harstad (2020). He focuses on the effect of voting-out probabilities, which relates his model to our analysis of short-lived governments in Appendix E (see footnote 1).

The most closely related contribution is Schopf and Voss (2019), whose model starts from a similar theoretical framework as the present one. There are two parties, lobbies, that repeatedly meet with a decision-maker, the government, and aim to influence the decisions by offering payments. As in the present article, the government's decision influences a stock, such that bargaining positions change over time. In an application, the lobbies are an environmental organization and a resource-extraction firm, and simple preferences are assumed for tractability. Both the government and the environmental organization prefer complete conservation of the resource; its price is exogenous. By contrast, in the present article we take the essential features of resource markets into account; both the government and the lobby (initially) prefer positive resource extraction, and we show how the development of payments changes when the government

[4]In this literature, lobbying is not clearly distinguishable from bribery, so that our analysis can be interpreted both ways; see Harstad and Svensson (2011) for a distinction.

later prefers to end extraction.

We model resources as economically, not physically, exhaustible; extraction costs increase with cumulative past extraction (cf. Livernois and Martin, 2001). Therefore, there are no Hotelling rents, but Ricardian rents due to increasing costs (Hartwick, 1982). Additionally, there may be monopoly rents. There is a large literature analyzing how the governments of resource-importing countries can capture the rents of foreign resource suppliers, either Hotelling rents (see, e.g., Bergstrom, 1982, Daubanes and Grimaud, 2010 and Keutiben, 2014) or monopoly rents or both (see, e.g., Wirl, 1994, 1995 and Rubio and Escriche, 2001). In our model, resource suppliers are part of the same country as consumers, so the government has no particular interest in distributing rents away from them. However, the government would like to avoid the monopolistic distortion of supply.

In our model, monopolistic resource extraction is slower than that of competitive, unregulated suppliers, which is a standard result in the literature (Solow, 1974; Krautkraemer, 1998).[5] A welfare-maximizing government might prefer even slower extraction, however, due to a second distortion, namely environmental damages. Accordingly, the insight that monopolistic supply restriction can be a second-best solution for environmental externalities (Buchanan, 1969; Barnett, 1980) also applies to exhaustible resources (Sweeney, 1977). Conversely, governmental welfare maximization does not always mean slowing down extraction, even if there are environmental externalities. Nevertheless, environmental externalities imply that welfare maximization requires curbing extraction in the long run (cf. Muzondo, 1993). This conflict of interest over extraction levels is central to our model.

The last relevant strand of literature is that of dynamic cooperative games. Modeling the bargaining between the lobby and the government in an intertemporal context requires assumptions about the bargaining parties' outside options and commitment abilities. We assume that there is no commitment, such that the bargaining solution has to be time-consistent. If no agreement can be reached, the bargaining parties choose uncooperative strategies forever, such that no further payments are made and the government enforces the welfare-maximizing amount of extraction. This modeling assumption follows Petrosyan (1997) and is used, for example, by Kaitala and Pohjola (1990), Jørgensen, Martín-Herrán and Zaccour (2005) and Fanokoa, Telahigue and Zaccour (2011). It may represent situations in which a bargaining failure destroys trust, and it allows analytical solutions. For alternative approaches, see Boyce (2010), who applies the truthful Markov perfect equilibrium of Bergemann and Välimäki (2003), and Appendix D, in which we consider an application of the recursive Nash bargaining solution of Sorger (2006); see footnote 1.

[5]Situations where a monopolist chooses faster extraction are possible, but less common; see the list in Fischer and Laxminarayan (2005) for an overview of the literature on monopolistic resource supply.

3 Model

We develop a partial-equilibrium model of resource extraction under the influence of a resource-owner lobby group. In this model, $q_t \geq 0$ denotes resource extraction in period $t = 0, 1, 2, ...$, and $z_t \geq 0$ denotes cumulative extraction of all previous periods. Then the equation of motion of z is

$$z_{t+1} = z_t + q_t. \tag{1}$$

We only consider feasible (pairs of) sequences, such that a sequence $(z_{t+s})_{s=0}^{\infty}$ always implies a corresponding sequence $(q_{t+s})_{s=0}^{\infty}$. In the following, we drop the time index where no ambiguities arise.

The agents in our model are a government and a lobby group representing all resource owners from the same (closed) economy. The government's utility in any period is

$$g(q, m, z) = w(q, z) + \phi \cdot m, \tag{2}$$

where $\phi \geq 0$. In line with the lobbying literature, the lobby payments m may be interpreted as campaign contributions or any kind of bribe that goes directly to the politicians' instead of the state coffers. The marginal-utility parameter ϕ reflects the preference for lobby payments relative to (utilitarian) welfare

$$w(q, z) = u(q) - c(q, z) - x(q, z), \tag{3}$$

which is gross consumer surplus from resource consumption $u(q)$ minus extraction costs $c(q, z)$ and environmental damage costs $x(q, z)$. We assume all functions to be at least twice continuously differentiable, and the functions and their first and second derivatives to take finite values for all finite q. Marginal utility is strictly positive for $q = 0$ and strictly decreasing in resource consumption: $u'(0) > 0$ and $u''(q) < 0$. For extraction, we assume the following cost function:

Assumption 1 *The cost function is of the form $c(q, z) = c(q) + \kappa_{qz} \cdot q \cdot z$ with $c(0) = 0$, $c'(q) > 0$, $c''(q) \geq 0$ and $\kappa_{qz} > 0$.*

Thus, costs are zero for $q = 0$ and strictly positive for $q > 0$. Over time, extraction is limited not by a physical stock but because cumulative extraction increases extraction costs and marginal extraction costs. Finally, environmental damages are caused by current and cumulative resource consumption and are therefore referred to as flow-pollution damages and stock-pollution damages, respectively. Stock pollution does not depreciate over time and is thus identical to cumulative extraction. We assume $x(q, z)$ to be additively separable, convex, and strictly increasing in each argument.

The resource owners' profit in any period is

$$\pi(q, z) = p(q) \cdot q - c(q, z), \tag{4}$$

where p is the market price of the resource. We assume the consumers to take this price as given and to choose their consumption so as to maximize their net surplus $u(q) - p \cdot q$, implying $p(q) = u'(q)$. In the following analysis, we use p both for the price and for this stationary inverse demand function. The resource owners are represented by a lobby group and collectively pay m to the government, such that their net profit is

$$l(q, m, z) = \pi(q, z) - \lambda \cdot m, \tag{5}$$

where $\lambda \geq 1$. The marginal-cost parameter λ may, for example, reflect the coordination problems within the group.[6] Alternatively, the resource could be owned by a (lobbying) monopolist. Then, λ should be equal to one.

The form of the utility functions (2) and (5) is standard in the interest-group literature (cf. Grossman and Helpman, 2001). The quasi-linearity of preferences allows the derivation of the lobbying equilibrium in the following analysis.[7] Finally, to simplify the characterization of this equilibrium, we use a technical assumption from Salant, Eswaran and Lewis (1983):

Assumption 2 *For all* q, z *it holds that* $\frac{\partial^2 w(q,z)}{\partial q^2} < \frac{\partial^2 w(q,z)}{\partial q \partial z}$ *and* $\frac{\partial^2 \pi(q,z)}{\partial q^2} < \frac{\partial^2 \pi(q,z)}{\partial q \partial z}$.

The government and the resource owners have an infinite planning horizon and an identical discount rate $r > 0$, implying a discount factor $\delta = 1/(1 + r) \in (0, 1)$. In our partial-equilibrium setting, r is exogenous and reflects pure time preference. Thus, the intertemporal utility of the government and of the lobby group are the discounted sums of the respective utility stream,

$$\sum_{s=0}^{\infty} \delta^s \cdot g(q_{t+s}, m_{t+s}, z_{t+s}) = \sum_{s=0}^{\infty} \delta^s \cdot w(q_{t+s}, z_{t+s}) + \phi \cdot \sum_{s=0}^{\infty} \delta^s \cdot m_{t+s}, \tag{6a}$$

$$\sum_{s=0}^{\infty} \delta^s \cdot l(q_{t+s}, m_{t+s}, z_{t+s}) = \sum_{s=0}^{\infty} \delta^s \cdot \pi(q_{t+s}, z_{t+s}) - \lambda \cdot \sum_{s=0}^{\infty} \delta^s \cdot m_{t+s}, \tag{6b}$$

where $\sum_{s=0}^{\infty} \delta^s \cdot w(q_{t+s}, z_{t+s})$ and $\sum_{s=0}^{\infty} \delta^s \cdot \pi(q_{t+s}, z_{t+s})$ are intertemporal welfare and profit, and $\sum_{s=0}^{\infty} \delta^s \cdot m_{t+s}$ are the intertemporal payments.

The profit from resource sales accrues to the resource owners, but the government can ultimately determine the extraction quantity. For most of our analysis, we assume

[6] Such (organizational) coordination costs have been introduced into the Grossman and Helpman (1994, 2001) common-agency model by Fredriksson, Vollebergh and Dijkgraaf (2004).

[7] See Klein, Krusell and Ríos-Rull (2008) for the complications that can arise when current choices affect future marginal utility from the control variables.

that it does so by direct prescription; we therefore model a direct choice of q.[8] In Section 8, we extend the analysis to resource taxes. To take influence on the extraction quantity, the lobby group bargains with the government about q and the payment m. In order to concentrate on the development of the conflict of interest over resource extraction, we assume that the government stays in power forever (see footnote 1 for a generalization).

In our dynamic setting, we have to assume how often bargaining takes place and what happens in case of disagreement. Concerning the consequences of disagreement, we assume that if no agreement is reached, cooperation breaks down forever (following Petrosyan, 1997). Though this assumption could be interpreted as a commitment to permanent non-cooperative behavior (Sorger, 2006; see footnote 1), an alternative interpretation would be that the parties no longer trust each other. Given that contribution payments in exchange for a favor are hardly enforceable in court, it is plausible that trust is crucial for such a cooperation (on the importance of trust in lobbying, see, e.g., Godwin, Ainsworth and Godwin, 2012, p. 223).

Concerning the bargaining frequency, we assume the government and the lobby group to bargain in each period about a payment and an extraction quantity for that period. Because bargaining itself is not costly, it is always possible to reach an agreement that is better for both parties than the government's unilateral extraction choice. By the bargaining-frequency assumption, the solution will be time-consistent and does not require a commitment on the cooperative behavior (cf. Jørgensen and Zaccour, 2001). Note that the assumption of a negotiation in each period does not have to be understood literally; a contract that is agreed on at the beginning of time is time-consistent if and only if it yields the same policy and contribution payments as such a periodwise negotiation.

Instead of explicitly modeling the bargaining process, we use the asymmetric Nash bargaining solution. Thus, the government plays an active role in the bargaining process, and its strength is represented by the respective parameter in the Nash product.[9] A take-it-or-leave-it offer by the lobby group, which is more typical in the literature, is a special case of this solution.[10]

[8]If the preferred quantity of the resource owners is above that of the government, the prescription could equivalently be understood as auctioning extraction quotas. We would then assume all auction revenues to be redistributed among the resource owners in a lump-sum fashion, such that we disregard these revenues.

[9]This bargaining-power parameter may represent influences on the bargaining outcome like different bargaining tactics, negotiation procedures and information structure (cf. Muthoo, 1999, Section 7.5). While the parameter often also represents time-preference differences, we assume the bargaining parties to have identical discount factors.

[10]The take-it-or-leave-it offers – or *contribution schedules* – are compared with Nash bargaining in Voss and Schopf (2018). Given quasi-linear utility functions, the resulting policies will be identical, but if there is only one organized sector as in the present article, payments and utility will only be identical

4 Nash Bargaining Solution

In this section, we define and characterize the Nash bargaining solution for our dynamic setting. To do so, we need to know the bargaining parties' outside options. In case of disagreement, the government unilaterally decides on the quantity in the current and all future periods. Thus, it chooses $(z_{t+s})_{s=0}^{\infty}$ so as to maximize $\sum_{s=0}^{\infty} \delta^s \cdot w(q_{t+s}, z_{t+s})$. By stationarity of the optimization problem, this implies a state-dependent resource-extraction function $q^w(z)$, where the superscript w denotes the welfare-maximizing solution. We can then define the maximized intertemporal welfare recursively by[11]

$$W^w(z) = w(q^w(z), z) + \delta \cdot W^w(z + q^w(z)). \tag{7}$$

Since the lobby gets nothing in case of disagreement, it pays nothing and its intertemporal utility equals the intertemporal profit along the welfare-maximizing extraction path. We can define it recursively by[12]

$$\Pi^w(z) = \pi(q^w(z), z) + \delta \cdot \Pi^w(z + q^w(z)). \tag{8}$$

Next, let the superscript a denote the values of the variables q and m on which the bargaining parties agree. Suppose for the moment that they depend on cumulative extraction, thus, $q = q^a(z)$ and $m = m^a(z)$. We can then define the intertemporal utility of the government and of the lobby group in case of continued cooperation recursively by

$$W^a(z) + \phi \cdot M^a(z) = G^a(z) = g(q^a(z), m^a(z), z) + \delta \cdot G^a(z + q^a(z)), \tag{9a}$$
$$\Pi^a(z) - \lambda \cdot M^a(z) = L^a(z) = l(q^a(z), m^a(z), z) + \delta \cdot L^a(z + q^a(z)), \tag{9b}$$

where $W^a(z) = w(q^a(z), z) + \delta \cdot W^a(z + q^a(z))$ and $\Pi^a(z) = \pi(q^a(z), z) + \delta \cdot \Pi^a(z + q^a(z))$ are intertemporal welfare and profit along the bargained extraction path, and $M^a(z) = m^a(z) + \delta \cdot M^a(z + q^a(z))$ are the intertemporal payments. Finally, we define the Nash product under the assumption that all future periods' extraction and payment values are also chosen cooperatively, and understand these cooperatively chosen values of q and m as those that maximize this Nash product:

$$N(q, m, z) \equiv [g(q, m, z) + \delta \cdot G^a(z + q) - W^w(z)]^{\eta} \cdot$$
$$[l(q, m, z) + \delta \cdot L^a(z + q) - \Pi^w(z)]^{1-\eta}, \tag{10a}$$

if the government's bargaining-power parameter in the asymmetric Nash-bargaining function is zero.

[11] $W(z)$ is bounded and $W^w(z)$ is a maximum; see Lemma A.1 in Appendix A.

[12] $\Pi^w(z)$ is bounded; see Lemma A.1 in Appendix A.

$$(q^a(z), m^a(z)) \in \underset{q,m}{\operatorname{argmax}} \left[N(q,m,z) | q \geq 0 \right], \tag{10b}$$

where $\eta \in [0,1]$ measures the bargaining power of the government relative to that of the lobby group. Define $\mu \equiv \phi/\lambda \geq 0$. We can then characterize the solution of the Nash bargaining as follows:[13]

Proposition 1 (Nash Bargaining Solution) *The extraction function maximizes a weighted sum of intertemporal welfare and intertemporal profit:*

$$q^a(z) = \underset{q}{\operatorname{argmax}} \left[\frac{1}{1+\mu} \cdot [w(q,z) + \delta \cdot W^a(z+q)] + \frac{\mu}{1+\mu} \cdot [\pi(q,z) + \delta \cdot \Pi^a(z+q)] \right]. \tag{11}$$

The intertemporal payments and the payments within the periods are:

$$M^a(z) = \frac{1-\eta}{\phi} \cdot [W^w(z) - W^a(z)] + \frac{\eta}{\lambda} \cdot [\Pi^a(z) - \Pi^w(z)] \geq 0, \tag{12a}$$

$$m^a(z) = M^a(z) - \delta \cdot M^a(z + q^a(z)). \tag{12b}$$

The intertemporal utilities are:

$$G^a(z) = W^a(z) + \phi \cdot M^a(z) = W^w(z) + \eta \cdot [W^a(z) - W^w(z) + \mu \cdot [\Pi^a(z) - \Pi^w(z)]], \tag{13a}$$

$$L^a(z) = \Pi^a(z) - \lambda \cdot M^a(z) = \Pi^w(z) + \frac{1-\eta}{\mu} \cdot [W^a(z) - W^w(z) + \mu \cdot [\Pi^a(z) - \Pi^w(z)]]. \tag{13b}$$

Since the intertemporal utilities exceed their outside options, the solution of the Nash bargaining is an equilibrium.

Proof. See Appendix A. □

Thus, q is chosen so as to maximize a weighted sum of intertemporal welfare and intertemporal profit, the *joint product*. The policy weight μ depends on the government's marginal utility ϕ of receiving money relative to the lobby's marginal cost λ of paying it. The bargaining power η then determines how the gains from cooperation are shared. Since these gains are always positive, both bargaining parties anticipate the cooperation to continue, and this continuation will indeed always be in both parties' interest. Furthermore, since the extraction and payments in case of agreement are independent of

[13] Along the lines of the proof of Proposition 1, the Nash bargaining for different discount factors of the government (δ_w) and the resource owners (δ_π) maximizes $\frac{1}{1+\mu} \cdot [w(q,z) + \delta_w \cdot W(z+q)] + \frac{\mu}{1+\mu} \cdot [\pi(q,z) + \delta_\pi \cdot \Pi(z+q)]$, and the payments within the periods are implicitly defined by $\sum_{s=0}^{\infty} [\eta \cdot \delta_\pi^s + (1-\eta) \cdot \delta_w^s] \cdot m_{t+s}^a = \frac{1-\eta}{\phi} \cdot [W^w(z) - W^a(z)] + \frac{\eta}{\lambda} \cdot [\Pi^a(z) - \Pi^w(z)] \equiv X^a(z)$. For $\eta = 0$ or $\eta = 1$, we obtain $m^a(z) = X^a(z) - [\eta \cdot \delta_\pi + (1-\eta) \cdot \delta_w] \cdot X^a(z + q^a(z))$.

the market structure, and the extraction in case of disagreement is always the welfare-maximizing one, the lobbying equilibrium is the same whether we consider the lobby to represent many competitive resource owners, or to be a lobbying monopolist.

The optimization problem (11) is stationary, such that the result is a state-dependent extraction function $q^a(z)$. It implies the following Euler equation (see Lemma A.2 in Appendix A), which is a weighted Hotelling rule, modified for the effects of cumulative extraction:

$$\begin{aligned} &p(q_t^a) - \frac{\partial c(q_t^a, z_t)}{\partial q} - \frac{1}{1+\mu} \cdot \frac{\partial x(q_t^a, z_t)}{\partial q} + \frac{\mu}{1+\mu} \cdot p'(q_t^a) \cdot q_t^a \\ &= \delta \cdot \Bigg\{ p(q_{t+1}^a) - \frac{\partial c(q_{t+1}^a, z_{t+1}^a)}{\partial q} + \frac{\partial c(q_{t+1}^a, z_{t+1}^a)}{\partial z} \\ &\qquad - \frac{1}{1+\mu} \cdot \left[\frac{\partial x(q_{t+1}^a, z_{t+1}^a)}{\partial q} - \frac{\partial x(q_{t+1}^a, z_{t+1}^a)}{\partial z} \right] + \frac{\mu}{1+\mu} \cdot p'(q_{t+1}^a) \cdot q_{t+1}^a \Bigg\}, \end{aligned} \tag{14}$$

where $q_t^a = q^a(z_t)$ and $z_{t+1}^a = z_t + q_t^a$. The lower the policy weight μ, the less does the lobby determine the extraction path. For $\mu = 0$, we have the Hotelling rule of a welfare-maximizing social planner. Then the current welfare created by marginal resource extraction, which is its consumer benefit net of extraction costs and flow-pollution damages, must equal the discounted welfare that could be gained from the resource if it were extracted a period later, plus the additional extraction costs and environmental damages due to the higher cumulative extraction. This is also the extraction path that determines the bargaining parties' outside options, $q^w(z)$. Conversely, for $\mu \to \infty$, we have the Hotelling rule of a profit-maximizing monopolist. A monopolist would not care about environmental damages, but about the effect of supply on the price. We let the superscript π denote the profit-maximizing extraction policy, $q^\pi(z)$.

To analyze the impact of lobbying on total resource extraction, consider $\frac{1}{1+\mu} \cdot \left[\frac{\partial w(0,z)}{\partial q} - \frac{\partial x(0,z)}{\partial z}/r\right] + \frac{\mu}{1+\mu} \cdot \frac{\partial \pi(0,z)}{\partial q}$. This is the joint product of the first marginal extracted unit in the current period, net of the present value of its future stock-pollution costs that accrue even if extraction ceases in the current period. If cumulative extraction z exceeds $\bar{z}^a$, where $\bar{z}^a$ fulfills

$$\begin{aligned} &\frac{1}{1+\mu} \cdot \left[\frac{\partial w(0, \bar{z}^a)}{\partial q} - \frac{1}{r} \cdot \frac{\partial x(0, \bar{z}^a)}{\partial z} \right] + \frac{\mu}{1+\mu} \cdot \frac{\partial \pi(0, \bar{z}^a)}{\partial q} \\ &= p(0) - \frac{\partial c(0, \bar{z}^a)}{\partial q} - \frac{1}{1+\mu} \cdot \left[\frac{\partial x(0, \bar{z}^a)}{\partial q} + \frac{1}{r} \cdot \frac{\partial x(0, \bar{z}^a)}{\partial z} \right] = 0, \end{aligned} \tag{15}$$

then the first-unit joint product cannot be positive, and the non-negativity constraint is binding for the bargained extraction, $q^a(z) = 0$ (see Lemma A.3 in Appendix A). The effects on future extraction costs do not appear in (15) because $\frac{\partial c(0,z)}{\partial z} = 0$. Because the lobby does not care about the flow-pollution costs and the future stock-pollution costs, and because the influence of q on p is irrelevant for $q = 0$, the lobby would like to continue extracting even when cumulative extraction has exceeded the level at which the government would prefer to stop. This level, $\bar{z}^w$, is defined by $\frac{\partial w(0,\bar{z}^w)}{\partial q} - \frac{\partial x(0,\bar{z}^w)}{\partial z}/r = 0$, whereas a monopolist would stop when $p(0) - \frac{\partial c(0,\bar{z}^\pi)}{\partial q} = 0$, with $\bar{z}^\pi > \bar{z}^a > \bar{z}^w$. More generally, using Assumptions 1 and 2, we characterize the resource extraction paths as follows:

Proposition 2 (Extraction Paths) *For $z \geq \bar{z}^i$, we have $q^i(z) = 0$ for $i = w, \pi, a$. Furthermore, $\frac{\partial q^i(\bar{z}^i)}{\partial z} \leq 0$. For $z < \bar{z}^i$, we have $q^i(z) > 0$, $\frac{\partial q^i(z)}{\partial z} \in (-1, 0)$, and $\bar{z}^i$ is reached asymptotically.*

Proof. See Appendix A. □

Therefore, as long as cumulative extraction is small enough for the welfare-maximizing extraction, the profit-maximizing extraction or the bargained extraction to be positive, the respective extraction declines monotonically in z and, thus, over time. Since they are reached asymptotically, we refer to $\bar{z}^w$, $\bar{z}^\pi$ and $\bar{z}^a$ as *convergence levels*. For a given level of cumulative extraction, we can understand the difference between the government's choice under lobby influence and the welfare-maximizing extraction as the *lobbying distortion* $\Delta_{a,w}(z)$:

$$\Delta_{a,w}(z) \equiv q^a(z) - q^w(z). \tag{16}$$

For $z \in [\bar{z}^w, \bar{z}^a)$, the welfare-maximizing extraction is zero, whereas the bargained extraction is still positive and declines monotonically in z, implying $\Delta_{a,w}(z) > 0$ and $\Delta'_{a,w}(z) < 0$. Before $\bar{z}^w$ is reached, the sign and magnitude of the lobbying distortion and its development depend on the relative impact of resource extraction on the revenues and on the marginal pollution costs. The government and the lobby are more inclined to stretch resource extraction over time if its negative effect on current marginal welfare or profit is stronger. Thus, if resource extraction reduces marginal revenues, by reducing the price, more than it increases marginal pollution costs, then the bargained extraction path is flatter than the welfare-maximizing one, and vice versa. We then say that the *market-power effect* of resource extraction exceeds the *marginal-pollution effect*. Suppose for the moment that cumulative extraction does not influence the extraction costs or the environmental damages, $c(q, z) = c(q)$ and $x(q, z) = x(q)$. Then, the setting becomes static, the left-hand side of (14) is zero, and the bargained extraction q^a is constant.[14] In this case, $q^a \lesseqgtr q^w$ just depends on whether $-p'(q^a) \cdot q^a \gtreqless \frac{\partial x(q^a)}{\partial q}$, that is, on whether a marginal increase of extraction reduces revenues, by reducing the price,

[14]By contrast, the lobbying equilibrium remains fully dynamic if $c(q, z) = c(q)$ while $x(q, z)$ depends on z. The lobby's preferred quantity then is constant, but that of the government declines over time.

more or less than it increases flow-pollution costs. However, in our dynamic setting the direction of the lobbying distortion can change over time because the z accumulation affects the welfare-maximizing extraction and the profit-maximizing extraction differently. To investigate the development of the lobbying distortion for $z \in [0, \bar{z}^w)$ in more detail, we will turn to specific functional forms in Section 5.

While the bargaining power of the government, η, does not influence the extraction, it does influence the payments. Their present value as defined in Proposition 1 takes away all of the resource owners' additional profit if the government has all the bargaining power ($\eta = 1$), and only compensates the government for not maximizing welfare in the opposite case ($\eta = 0$). The present value of payments $M^a(z)$ is always positive.

In a full-commitment situation, the lobby could pay $M^a(z_0)$ at the beginning of time. Without the possibility to commit, the present value of payments has to be $M^a(z_t)$ in each period. Substituting (12a) into (12b) and simplifying, the payments within the periods can be determined as:

$$\begin{aligned} m^a(z_t) = {} & \frac{1-\eta}{\phi} \cdot [w(q_t^w, z_t) - w(q_t^a, z_t)] + \frac{\eta}{\lambda} \cdot [\pi(q_t^a, z_t) - \pi(q_t^w, z_t)] \\ & + \delta \cdot \left\{ \frac{1-\eta}{\phi} \cdot \left[W^w(z_{t+1}^w) - W^w(z_{t+1}^a) \right] + \frac{\eta}{\lambda} \cdot \left[\Pi^w(z_{t+1}^a) - \Pi^w(z_{t+1}^w) \right] \right\}. \end{aligned} \tag{17}$$

The first line reflects how current cooperation changes contemporaneous profit and welfare. If, for example, $q^a < q^w \Leftrightarrow \Delta_{a,w} < 0$, then cooperation reduces current welfare, which requires a compensation for the government. In the static setting discussed above ($c(q), x(q)$), only this line matters, so that the (constant) payments are then positive and increasing in η. In the second line, we see the effects of current cooperation on the next-period outside options. These outside options are intertemporal welfare and profit along the welfare-maximizing extraction path. Since they are declining in z, current cooperation impairs the next-period outside options if $\Delta_{a,w} > 0$, and improves them if $\Delta_{a,w} < 0$. Depending on whether the lobby's part or the government's part in the second line dominates, and depending on whether $\Delta_{a,w} \gtreqless 0$, this change in future intertemporal welfare and profit increases or decreases the payments. The government's part of (17) is always positive because it reflects the welfare loss from deviating from the welfare-maximizing extraction path for one period. The lobby's part, however, could be temporarily negative; a one-period deviation from the government's preferred extraction path to the bargained one does not necessarily increase intertemporal profit.

There are thus several (partly opposing) influences on the payments, and their relative importance depends on the parties' bargaining power. In order to develop an understanding of the payments' development, first note that we can consider three different phases. First, cumulative extraction could be so low that both parties would like extraction to be positive ($z < \bar{z}^w < \bar{z}^a$). Second, it could be so high that it exceeds the welfare-maximizing convergence level ($\bar{z}^w \leq z < \bar{z}^a$), such that the government would prefer extraction to stop. Third, it could exceed the joint convergence level ($\bar{z}^w < \bar{z}^a \leq z$), such that both parties would agree not to extract. In the last case, payments would be zero. Thus, we start by considering the relatively simple second case.

For $z \geq \bar{z}^w$ and thus $q^w = 0$, (17) simplifies to

$$m^a(z_t) = \frac{1-\eta}{\phi} \cdot \left\{ w(0, z_t) - w(q_t^a, z_t) + \frac{1}{r} \cdot \left[x(0, z_{t+1}^a) - x(0, z_t) \right] \right\} + \frac{\eta}{\lambda} \cdot \pi(q_t^a, z_t). \quad (18)$$

The payments at least compensate the government for the current welfare loss and the additional stock-pollution damages in the future. The larger η, the higher the payments, and for $\eta = 1$, they eat up all of the resource owners' profit from positive extraction.

Given that cumulative extraction increases over time, differentiating (18) illustrates the development of payments for $z \geq \bar{z}^w$:

$$\begin{aligned} &\frac{\partial m^a(z_t)}{\partial z} \\ &= \frac{1-\eta}{\phi} \Bigg\{ \underbrace{\frac{\partial c(q_t^a, z_t)}{\partial z} + \frac{1}{r} \left[\frac{\partial x(0, z_{t+1}^a)}{\partial z} - \frac{\partial x(0, z_t)}{\partial z} \right]}_{>0} - \underbrace{\left[\frac{\partial w(q_t^a, z_t)}{\partial q} - \frac{1}{r} \frac{\partial x(0, z_{t+1}^a)}{\partial z} \right]}_{<0} \cdot \underbrace{\frac{\partial q_t^a}{\partial z}}_{<0} \Bigg\} \\ &\quad + \frac{\eta}{\lambda} \Bigg\{ \underbrace{-\frac{\partial c(q_t^a, z_t)}{\partial z}}_{<0} + \underbrace{\frac{\partial \pi(q_t^a, z_t)}{\partial q}}_{>0} \cdot \underbrace{\frac{\partial q_t^a}{\partial z}}_{<0} \Bigg\}. \end{aligned} \quad (19)$$

Firstly, marginal extraction costs and future stock-pollution damages increase in z. This directly increases the government's required compensation to implement $q^a > q^w = 0$, but it also reduces the firms' willingness to pay, such that the net effect on payments is unclear. Secondly, a higher z indirectly reduces both the welfare loss and the profits from cooperation, by reducing q^a. This speaks for declining payments. Thus, payments definitely decline over time if the bargaining power of the government is high enough for the decline in profits to dominate. By contrast, if the lobby receives all the gains from cooperation ($\eta = 0$), the effects work into opposing directions. Payments then definitely decline over time if the indirect effect on welfare always outweighs the direct one. Else, payments temporarily increase over time. However, the direct effect vanishes in the long run as extraction ceases, such that payments eventually decline. Note that a higher η both implies higher payments and makes it less likely that payments increase. Thus, they can only increase over time for $z \geq \bar{z}^w$ if they are small in the first place. We summarize these results:

Proposition 3 (Development of Payments for $z \geq \bar{z}^w$.) *For $z \in [\bar{z}^w, \bar{z}^a)$, we have $m^a(z) > 0$, $\frac{\partial m^a(z)}{\partial \eta} > 0$ and $\frac{\partial^2 m^a(z)}{\partial z \partial \eta} < 0$. For $z \to \bar{z}^a$, $m^a(z)$ asymptotically converges to* *zero. This convergence is definitely monotone if the bargaining power of the government is sufficiently high ($\eta = 1$ or $\eta \geq 1/(1+\mu)$ together with $\frac{\partial^2 x(q,z)}{\partial z^2} = 0$), or if the direct, negative effect of cumulative extraction is sufficiently small ($\frac{\partial c(q,z)}{\partial z} \to 0$ together with $\frac{\partial^2 x(q,z)}{\partial z^2} = 0$).*

Proof. See Appendix A. □

We turn to the development of payments for $z \leq \bar{z}^w$. In general, payments will change smoothly as z accumulates, but there are two threshold levels of z at which $\frac{\partial m^a(z)}{\partial z}$ can change discontinuously, namely, at $z = \bar{z}^w$ and at

$$z = \underline{z}^w \equiv \bar{z}^w - q^a(\underline{z}^w). \tag{20}$$

The derivative may first jump at $z = \underline{z}^w$, when the further increase in z stops undermining the lobby's *next-period* outside option in case of current cooperation, $\Pi^w(z^a_{t+1})$. Accordingly, its willingness to pay to ensure cooperation increases sharply. At $z = \bar{z}^w$, which is attained one period later, the further increase in z stops deteriorating the lobby's *current* outside option, $\pi(q^w_t, z_t) + \delta \cdot \Pi^w(z^w_{t+1})$. Accordingly, its willingness to pay to avoid non-cooperation decreases sharply, which may again lead to a discontinuity. These discontinuities can only be ruled out if $\eta = 0$, such that profits do not determine payments, or if $\frac{\partial q^w(\bar{z}^w)}{\partial z} = 0$, which implies that profits develop smoothly at $\underline{z}^w$ and $\bar{z}^w$. We summarize these results:

Proposition 4 (Development of Payments for $z = \underline{z}^w$ and $z = \bar{z}^w$.) *Suppose that $\eta = 0$ or $\frac{\partial q^w(\bar{z}^w)}{\partial z} = 0$. Then $\frac{\partial m^a(z)}{\partial z}$ is continuous for all $z \in [0, \bar{z}^a)$. Now suppose that $\eta > 0$ and $\frac{\partial q^w(\bar{z}^{w-})}{\partial z} < 0$. Then $\frac{\partial m^a(z)}{\partial z}$ jumps up at $z = \underline{z}^w$, and it jumps down at $z = \bar{z}^w$.*

Proof. See Appendix A. □

Finally, note that $\frac{\partial m^a(z)}{\partial z}$ is continues for all $z \in [0, \bar{z}^a)$ in the special case of identical convergence levels. This in turn is the case if stock-pollution damages and the first-unit flow-pollution damages are zero, $x(q,z) = x(q)$ and $x'(0) = 0$. The discontinuity in the development of payments thus arises because pollution costs reduce first-unit welfare, but not first-unit profit.

Summing up, we can characterize the development of payments quite generally for $z \geq \underline{z}^w$. However, we have already seen above that the development of the conflict of interest is more complex for the time in which both the government and the lobby want positive extraction, and this holds a fortiori for the development of payments. We therefore turn to specific functional forms in the next section.

Table 1: Explicit functions.

Functions		Explicit forms
$u(q)$	$=$	$\left(\rho_q - \frac{\rho_{qq}}{2}q\right)q$
$p(q) = u'(q)$	$=$	$\rho_q - \rho_{qq}q$
$c(q,z)$	$=$	$\left(\kappa_{qz}z + \kappa_q + \frac{\kappa_{qq}}{2}q\right)q$
$x(q,z)$	$=$	$\chi_z z + \frac{\chi_{zz}}{2}z^2 + \chi_q q + \frac{\chi_{qq}}{2}q^2$

5 Explicit Example

We now derive the extraction paths and payments for a linear-quadratic specification. The assumed functions are summarized in Table 1. Collecting terms, we have

$$w(q,z) = (\beta_w - \gamma_w z)\,q - \frac{\alpha_w}{2}q^2 + \Xi, \tag{21a}$$

$$\pi(q,z) = (\beta_\pi - \gamma_\pi z)\,q - \frac{\alpha_\pi}{2}q^2, \tag{21b}$$

$$\frac{1}{1+\mu}w(q,z) + \frac{\mu}{1+\mu}\pi(q,z) = (\beta_a - \gamma_a z)\,q - \frac{\alpha_a}{2}q^2 + \frac{\Xi}{1+\mu}, \tag{21c}$$

where

$$\alpha_w \equiv \kappa_{qq} + \rho_{qq} + \chi_{qq} + \frac{\chi_{zz}}{r}, \qquad \alpha_\pi \equiv \kappa_{qq} + 2\rho_{qq}, \qquad \alpha_a \equiv \frac{\alpha_w + \mu\alpha_\pi}{1+\mu}, \tag{22a}$$

$$\beta_w \equiv \rho_q - \kappa_q - \chi_q - \frac{\chi_z}{r}, \qquad \beta_\pi \equiv \rho_q - \kappa_q, \qquad \beta_a \equiv \frac{\beta_w + \mu\beta_\pi}{1+\mu}, \tag{22b}$$

$$\gamma_w \equiv \kappa_{qz} + \frac{\chi_{zz}}{r}, \qquad \gamma_\pi \equiv \kappa_{qz}, \qquad \gamma_a \equiv \frac{\gamma_w + \mu\gamma_\pi}{1+\mu}, \tag{22c}$$

and $\Xi \equiv \frac{\delta}{1-\delta}\left[\chi_z(z+q) + \frac{\chi_{zz}}{2}(z+q)^2\right] - \frac{1}{1-\delta}\left[\chi_z z + \frac{\chi_{zz}}{2}z^2\right]$, which contains the present value of the additional stock-pollution costs caused by continuing extraction for the current period. In (22), the placeholder parameters are defined in such a way that they contain the instantaneous effects of current extraction *and* the costs that this extraction causes in the future if no additional extraction takes place. We assume all coefficients to be positive if not stated otherwise.

To prepare the dynamic optimization, we define

$$0 < \psi_i \equiv \frac{2\gamma_i}{\alpha_i + \sqrt{\alpha_i^2 + \frac{4}{r}\gamma_i(\alpha_i - \gamma_i)}} \leq \frac{\gamma_i}{\alpha_i} < 1 \qquad \text{for } i = w, \pi, a, \tag{23}$$

where the second inequality is implied by Assumption 2. With the linear-quadratic functions, the extraction paths depend linearly on z in the following way:

Proposition 5 (Explicit Example: Extraction Paths) *The welfare-maximizing extrac-*

tion, the profit-maximizing extraction and the bargained extraction are given by:

$$q^i(z) = \begin{cases} \psi_i(\bar{z}^i - z) & \text{if } z < \bar{z}^i, \\ 0 & \text{if } z \geq \bar{z}^i, \end{cases} \qquad \text{for } i = w, \pi, a, \tag{24}$$

where $\bar{z}^i = \beta_i/\gamma_i$. Cumulative extraction levels along paths starting in t develop as follows:

$$z^i_{t+s} = \begin{cases} \bar{z}^i - (1-\psi_i)^s(\bar{z}^i - z_t) & \text{if } z_t < \bar{z}^i, \\ z_t & \text{if } z_t \geq \bar{z}^i, \end{cases} \qquad \text{for } i = w, \pi, a, \tag{25}$$

where $s = 0, 1, 2, \ldots$. For $z \in [0, \bar{z}^w)$, we can distinguish four cases concerning the lobbying distortion $\Delta_{a,w}(z)$ and its development $\Delta'_{a,w}(z)$:

Case	*Relation*	$\Delta_{a,w}(z)$	$\Delta'_{a,w}(z)$
I	$\psi_w < \psi_a$	> 0	< 0
II	$\psi_w = \psi_a$	> 0	$= 0$
III	$\psi_a \bar{z}^a/\bar{z}^w > \psi_w > \psi_a$	> 0	> 0
IV	$\psi_w \geq \psi_a \bar{z}^a/\bar{z}^w > \psi_a$	$\lesseqqgtr 0 \Leftrightarrow z \lesseqqgtr \hat{z}(\geq 0)$	> 0

where

$$\hat{z} \equiv \frac{\psi_w \bar{z}^w - \psi_a \bar{z}^a}{\psi_w - \psi_a} = \underline{z}^w - \frac{\psi_a(1-\psi_w)}{(\psi_w - \psi_a)(1-\psi_a)}(\bar{z}^a - \bar{z}^w). \tag{26}$$

Thus, there is at most one $z < \underline{z}^w$ at which the bargained extraction and the welfare-maximizing extraction coincide. For $z \in [\bar{z}^w, \bar{z}^a)$, we then have $\Delta_{a,w}(z) = q^a(z) > 0$ and $\Delta'_{a,w}(z) < 0$, and for $z \geq \bar{z}^a$, there is no lobbying distortion, $\Delta_{a,w}(z) = q^a(z) = q^w(z) = 0$.

Proof. See Appendix B. □

An optimal extraction path is characterized by two properties. The first is the convergence level, that is, the level of cumulative extraction that would imply zero extraction. As explained in the general case for (15), $\bar{z}^\pi > \bar{z}^a > \bar{z}^w$ because the government takes first-unit pollution damages into account, such that the bargained extraction continues when it would be welfare-maximizing to stop. The second property is the amount of extraction given any level of cumulative extraction below the convergence level $\bar{z}^i$. Given $\bar{z}^i - z$, extraction is determined by the respective ψ_i term. Since it does not change the total amount of cumulative extraction in the long run, but only how rapidly this amount is approached, ψ_i represents the *speed of convergence*. A larger ψ_i implies that $q^i(z)$ is higher for a given z, but as z then increases, $q^i(z)$ also declines more rapidly.

What then determines the speed of convergence? Consider ψ_w. This term summarizes the decrease in marginal welfare due to effects both within the current period and in the future. The more an additional unit of extraction reduces marginal consumer surplus or increases marginal flow-pollution damages or marginal extraction costs, the more it pays off to stretch extraction over time and the smaller is ψ_w. In addition, the more the cumulative extraction increases the marginal extraction cost or the marginal stock-pollution cost, the more will an increase in z reduce the welfare-maximizing extraction; therefore, the respective parameters κ_{qz} and χ_{zz} increase ψ_w. (Note that these parameters also reduce the convergence level $\bar{z}^w$, which reduces extraction for a given level of z.)

Now consider ψ_π. On the one hand, resource owners do not care about flow pollution, which speaks for $\psi_\pi > \psi_w$. On the other hand, the parameter ρ_{qq} counts only once for marginal welfare, namely for the marginal consumer surplus, but it counts twice for marginal revenue via the price and its change. The larger this parameter, the more would the lobby prefer to stretch extraction over time compared to the government. If this *market-power effect* outweighs the *marginal flow-pollution effect* ($\rho_{qq} \geq \chi_{qq}$), we have $\psi_\pi < \psi_w$, which implies that a monopolist's extraction would be too slow from a social planner's point of view. Precisely, we have

$$\psi_w \gtreqless \psi_a \gtreqless \psi_\pi \quad \Leftrightarrow \quad \frac{\alpha_\pi}{\gamma_\pi} \gtreqless \frac{\alpha_a}{\gamma_a} \gtreqless \frac{\alpha_w}{\gamma_w} \quad \Leftrightarrow \quad \rho_{qq} \gtreqless \chi_{qq} - \frac{\chi_{zz}}{r} \frac{\kappa_{qq} + 2\rho_{qq} - \kappa_{qz}}{\kappa_{qz}}, \tag{27}$$

that is, $\psi_\pi < \psi_w$ if and only if the market-power effect outweighs the marginal-pollution effect, which consists of the effects of both marginal flow pollution and marginal stock pollution on the government's preferred speed of convergence. Thus, while a higher lobby influence due to a higher μ always increases the bargained convergence level $\bar{z}^a$, it increases the bargained speed of convergence ψ_a only if the marginal flow-pollution effect strongly exceeds the market-power effect.

The differences between the convergence levels and the speed-of-convergence parameters map into four possible cases concerning the lobbying distortion $\Delta_{a,w}(z)$. The initial sign and magnitude of $\Delta_{a,w}(z)$ depend on the preferred convergence levels and speeds of convergence of the bargaining parties, whereas its development just depends on the difference between the preferred speeds of convergence. For $\psi_a > \psi_w$ (Case I), $\Delta_{a,w}(z)$ is positive and decreases over time because the bargained extraction path is steeper than the welfare-maximizing one; however, by $\psi_a > \psi_w$ and $\bar{z}^a > \bar{z}^w$, the lobbying distortion remains positive for all $z < \bar{z}^w$. For $\psi_a = \psi_w$ (Case II), $\Delta_{a,w}(z)$ is also positive, due to the difference in the preferred convergence levels, but constant over time. For $\psi_a < \psi_w$, there are two cases. Either $\Delta_{a,w}(z)$ is initially positive and increases over time because the z accumulation reduces the resource owners' preferred extraction less than the welfare-maximizing one (Case III); or $\Delta_{a,w}(z)$ is initially negative, such that the government prefers a higher extraction than the lobby, but because the z accumulation again has a stronger impact on $q^w(z)$ than on $q^a(z)$, the difference shrinks over time until it turns around and the lobbying distortion becomes positive (Case IV). In all cases, the bargained cumulative extraction crosses the government's convergence level at some point; then $\Delta_{a,w}(z)$ is positive and declines over time.

Next, let us consider the payments. From Proposition 3, we know that they are positive after the government's convergence level $\bar{z}^w$ is reached, and that they then monotonically decline if the bargaining power of the government is high enough, but otherwise can be increasing from $\bar{z}^w$ onwards. In the long run, they definitely go to zero.[15] Furthermore, we know from Proposition 4 that the payments increase sharply one period before $\bar{z}^w$ is reached (if $\eta > 0$). The linear-quadratic functions now also allow us to characterize the development of payments for z levels at which both bargaining parties prefer positive extraction:

Proposition 6 (Explicit Example: Development of Payments for $z < \underline{z}^w$.) *For $z \in [0, \underline{z}^w)$, we have*

$$m^a(z) = \Theta_2 \left[\Theta_1 \left(\psi_a - \psi_w\right) \Delta_{a,w}(z) + \Delta_{a,w}(z)^2\right], \tag{28}$$

where $\Theta_1, \Theta_2 > 0$ with $\frac{\partial \Theta_1}{\partial \eta}, \frac{\partial \Theta_2}{\partial \eta} > 0$. Using the case distinction from Proposition 5, this implies:

Case	$\text{sign}[m^a(z)]$	$\text{sign}\left[\frac{\partial m^a(z)}{\partial z}\right]$
I	$+1$	-1
II	$+1$	0
III, IV for $z > \hat{z}$	$\text{sign}[z - (\hat{z} + \Theta_1)]$	$\text{sign}[z - (\hat{z} + \Theta_1/2)]$
IV for $z \leq \hat{z}$	$\text{sign}(\hat{z} - z)$	-1

and $\frac{\partial^2 m^a(z)}{\partial z^2} > 0$.

Proof. See Appendix B. □

Thus, the four cases from Proposition 5, which describe the lobbying distortion and its development, imply the following properties for the payments and their development. In Cases I and II, the bargained extraction always exceeds the welfare-maximizing one, $\Delta_{a,w}(z) > 0$, and payments are positive. For $\psi_a > \psi_w$ (Case I), the preferred quantities converge over time, $\Delta'_{a,w}(z) = -(\psi_a - \psi_w) < 0$, such that payments shrink. If the lobbying distortion is constant over time by $\psi_a = \psi_w$ (Case II), $\Delta'_{a,w}(z) = 0$, then the profit gain and the welfare loss from choosing the bargained extraction for the current period instead of the welfare-maximizing one are constant as well. Thus, payments are constant over time.

[15]With the linear-quadratic functions, there can be at most one maximum for $z > \bar{z}^w$. For sufficient conditions for a monotonic decrease, see Proposition B.1 in Appendix B.

By contrast, consider Case IV such that $\psi_a < \psi_w$. Payments are first positive and decreasing as long as the lobbying distortion is negative, $\Delta_{a,w}(z) < 0$, and gets weaker over time, $\Delta'_{a,w}(z) > 0$; they are then zero in the period in which the bargaining parties want to extract the same quantity, $\Delta_{a,w}(\hat{z}) = 0$. After that, when the lobbying distortion has changed its sign and starts increasing, payments first become negative until they reach a minimum and then start increasing, at some point getting positive (and increasing further).[16]

To understand this development, note that as long as $z = \hat{z}$ has not been crossed ($\Delta_{a,w}(z) < 0$), the lobby would always prefer q^a over q^w, including if the welfare-maximizing extraction path were chosen from the next period onwards. Intuitively, the welfare-maximizing path is too steep to maximize intertemporal profit, and a smaller present extraction flattens the future extraction path. This is reflected by initially positive payments that, however, decline with the absolute value of the lobbying distortion. Now in the time immediately after $z = \hat{z}$ has been crossed ($\Delta_{a,w}(z) > 0$), payments are negative. Recall that, by (17), the payments are determined by the impact that the bargained extraction has on current profits and welfare and on future profits and welfare if the welfare-maximizing extraction were chosen from the next period onwards. For z values not much higher than $\hat{z}$, both q^a and q^w are too high to maximize intertemporal profit along the welfare-maximizing extraction path, but since $q^a > q^w$ holds, the lobby would then prefer q^w over q^a if the welfare-maximizing extraction were chosen from the next period onwards. Consequently, the government has to compensate the lobby for not letting the negotiation fail, and the government is willing to do so because it anticipates the cooperation to continue and because the (anticipated) present value of payments to the government is always positive. The payments can become minimal and then turn positive before $\underline{z}^w$ is reached for two reasons: First, the welfare loss from deviating for one period from the welfare-maximizing extraction path increases in $\Delta_{a,w}(z)$ and, thus, over time. Second, the bargained extraction remains too high to maximize intertemporal profit along the welfare-maximizing extraction path, but when z approaches $\underline{z}^w$, the welfare-maximizing extraction becomes too low to maximize this profit, such that the lobby could eventually prefer q^a over q^w.

The remaining Case III can be understood as only the high-z branch of Case IV, such that in Case III, it is not possible that payments are positive and decreasing. Finally, note that, depending on the economy's parameters, any or all of the levels of z at which the development of payments changes its behavior can be negative or above $\underline{z}^w$, such that only a part of the U-shaped development of payments in Cases III and IV is relevant for the economy at hand.

Case III and the later part of Case IV are not only interesting because they include

[16] For general functional forms, $\eta > 0$ and $\Delta_{a,w}(z) = 0$ for some $z < \underline{z}^w$ is sufficient for temporarily negative payments; see Proposition A.1 in Appendix A.

negative payments, but also because in these cases, payments can increase over time while $z < \underline{z}^w$. The reason for this growth in payments is the intensifying lobbying distortion due to diverging preferred quantities. If, for example, $\eta = 0$, the payments just compensate the government for the welfare loss from deviating for one period from the welfare-maximizing extraction path. Then this loss and, thus, the payments decline initially with the declining difference $q^w - q^a$, become zero at $z = \hat{z}$, and increase afterwards with the increasing difference $q^a - q^w$.

6 Illustration

In this section, we illustrate the lobbying equilibrium for the four cases defined in Propositions 5 and 6. In each case, the lobbying distortion, which we can write as

$$\Delta_{a,w}(z) = \begin{cases} (\psi_a - \psi_w)(\bar{z}^a - z) + \psi_w(\bar{z}^a - \bar{z}^w) & \text{if } z < \bar{z}^w, \\ \psi_a(\bar{z}^a - z) & \text{if } z \in [\bar{z}^w, \bar{z}^a), \\ 0 & \text{if } z \geq \bar{z}^a, \end{cases} \tag{29}$$

using Proposition 5, and thus the payments develop in a qualitatively distinct way. We illustrate these cases using diagrams for specific parameter values, namely $r = 3\%$, $\rho_q = 200$, $\kappa_q = 100$, $\kappa_{qq} = 0$, $\kappa_{qz} = 1/10$, $\chi_q = 0$, $\chi_z = 9/10$ and $\chi_{zz} = 0$ so that $\bar{z}^\pi = 1000$ and $\bar{z}^w = 700$.[17] Initially, cumulative extraction is zero, $z_0 = 0$. We assume $\lambda = \phi = 1$, so that the lobby's policy weight is $\mu = 1$ and $\bar{z}^a = 850$, and that the bargaining power is symmetric, $\eta = 1/2$. The relation of the remaining economic parameters, ρ_{qq} and χ_{qq}, constitutes the four cases since for $\chi_{zz} = 0$, (27) becomes

$$\psi_w \gtreqless \psi_a \gtreqless \psi_\pi \qquad \Leftrightarrow \qquad \frac{\alpha_\pi}{\gamma_\pi} \gtreqless \frac{\alpha_a}{\gamma_a} \gtreqless \frac{\alpha_w}{\gamma_w} \qquad \Leftrightarrow \qquad \rho_{qq} \gtreqless \chi_{qq}. \tag{30}$$

In Case I, the marginal flow-pollution effect outweighs the market-power effect, $\chi_{qq} > \rho_{qq}$, implying $\psi_\pi > \psi_w$ and a positive lobbying distortion $\Delta_{a,w}(z)$. The bargained extraction is faster and higher than the welfare-maximizing one and it continues when it would be welfare-maximizing to stop due to first-unit flow-pollution costs and the present value of future stock-pollution costs, $\bar{z}^a > \bar{z}^w$.

Figure 2 shows the paths of extraction (left-hand-side figure) and cumulative extraction (right-hand-side figure) for $\chi_{qq} = 5, \rho_{qq} = 2$. The dashed gray curves are the profit-maximizing paths and the dotted gray curves are the welfare-maximizing paths, if they were followed from $t = 0$ on. A profit-maximizing monopolist's convergence level,

[17] $\chi_{zz} = 0$ implies that the marginal-pollution effect and the marginal flow-pollution effect coincide, see (27). For $\chi_{zz} > 0$, the discussion gets more involved without sufficiently worthwhile additional insights. Note that marginal stock-pollution costs are still positive by $\chi_z > 0$.

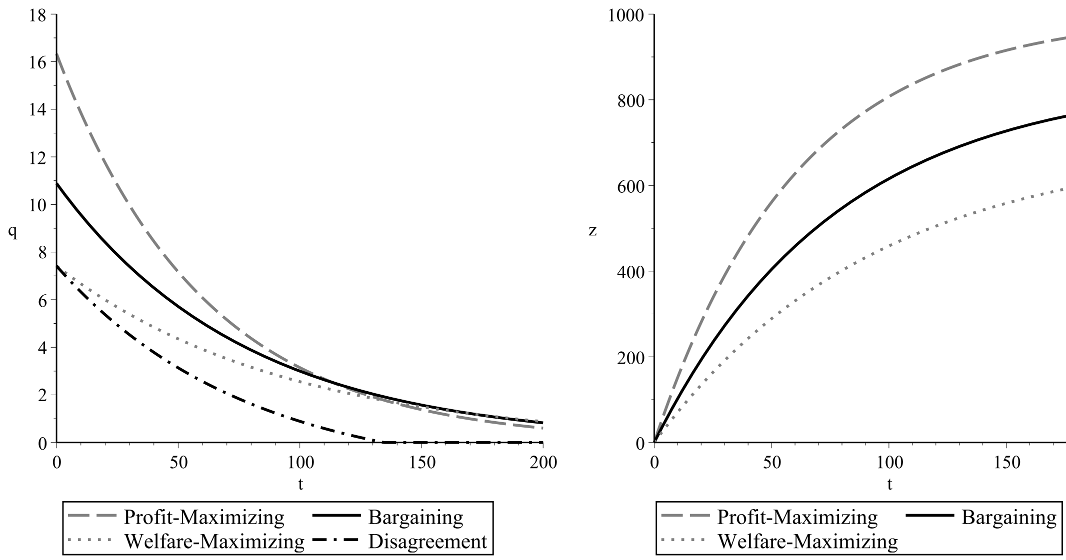


Figure 2: Extraction paths for $\psi_w < \psi_a$ (Case I).

$\bar{z}^\pi$, exceeds that of a welfare-maximizing social planner, $\bar{z}^w$. Moreover, by $\psi_w < \psi_\pi$, a monopolist would not smooth extraction as much over time as a social planner. Thus, q_t^π quickly decreases and cuts q_t^w from above. The bargained extraction path, $q^a(z)$, is a compromise between these extremes, shown as the black curve in Figure 2. The cumulative extraction converges to $\bar{z}^a$.

From the point of view of this lobbying equilibrium, q_t^π and q_t^w are only hypothetical reference paths once $q^a(z)$ has been chosen for a while. By contrast, the dash-dotted black curve represents the extraction $q^w(z)$ that the government would choose in the corresponding period after disagreement, given that z up to that period has been determined by the bargained extraction. Each point along that curve represents extraction in the first period of deviation from the lobbying equilibrium to the welfare-maximizing path, so that each point is the beginning of an extraction path converging to $q = 0$, while cumulative extraction would converge to $\bar{z}^w$ from then on. This only changes when $z \geq \bar{z}^w$; then the threat would be to choose $q = 0$ immediately and forever. In Case I, the lobbying distortion is positive and declines in z. This can also be seen in Figure 2: $q^w(z)$ is always below $q^a(z)$, and the vertical difference between the solid black curve and the dash-dotted curve is always declining.

Figure 3 shows the development of contribution payments. Because $\Delta_{a,w}(z) > 0$, choosing q_t^a instead of q_t^w implies a higher z in the future. This worsens the lobby's next-period outside option. However, the profit gain in the current period dominates, such that the payments are always positive, and they decline together with the lobbying distortion for $z < \underline{z}^w$ (see Proposition 6). Since $\frac{\partial q^w(\bar{z}^w)}{\partial z} = -\psi_w < 0$ and $\eta > 0$, we know from Proposition 4 that $\frac{\partial m^a(z)}{\partial z}$ jumps up at $z = \underline{z}^w$, and that it jumps down at $z = \bar{z}^w$. This can be seen in the figure, where payments increase between $\underline{z}^w$ and $\bar{z}^w$.

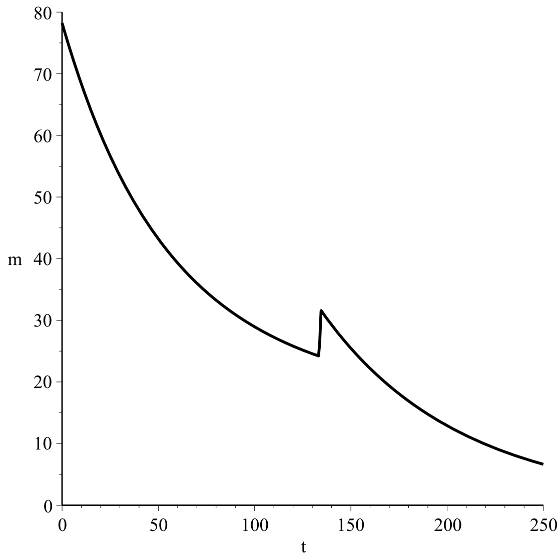


Figure 3: Contribution payment path for $\psi_w < \psi_a$ (Case I).

For $z \geq \underline{z}^w$, the increase in z due to current cooperation does not deteriorate the lobby's *next-period* outside option anymore, since $q^w(z + q^a)$ is zero in any way. The increase in z deteriorates its *current* outside option until $z = \bar{z}^w$, when $q^w(z)$ becomes zero. Thus, the lobby's willingness to pay for cooperation increases sharply at $z = \underline{z}^w$, and its willingness to pay to avoid non-cooperation drops at $z = \bar{z}^w$. For $z \geq \bar{z}^w$, we discussed above that payments could increase initially, but definitely vanish in the long run. With symmetric bargaining power, $\mu = 1$ and $\chi_{zz} = 0$, which we assumed for the figures, payments are always declining in z for $z \geq \bar{z}^w$ (see Proposition 3).[18]

Case II: $\psi_w = \psi_a$.

The developments of extraction and cumulative extraction for the second case are depicted in Figure 4. In this knife-edge case, the desired speed of convergence is identical: $\chi_{qq} = \rho_{qq}$ ($= 2$ in the figure) $\Leftrightarrow \psi_w = \psi_a = \psi_\pi$. Accordingly, the difference between $q^a(z)$ and $q^w(z)$ is driven solely by the difference between first-unit joint product and welfare or, equivalently, the difference between the convergence levels, as long as the government and the lobby group want positive extraction. Thus, for $z < \bar{z}^w$, (29) simplifies to $\Delta_{a,w}(z) = \psi_a \left(\bar{z}^a - \bar{z}^w\right)$, such that $\Delta'_{a,w}(z) = 0$; each period, q_t^a and q_t^w decrease by the same amount. Only when the non-negativity constraint becomes binding for the government, this cannot continue; q_t^w is then and remains zero, while q_t^a continues to decline.

Figure 5 shows the development of contribution payments. They remain at a positive, constant level as long as $q^w(z + q^a) > 0$ (see Proposition 6). Once $z \geq \underline{z}^w$, the

[18]In the example, payments are temporarily increasing in z for $z \geq \bar{z}^w$ if $\eta < 1/25$.

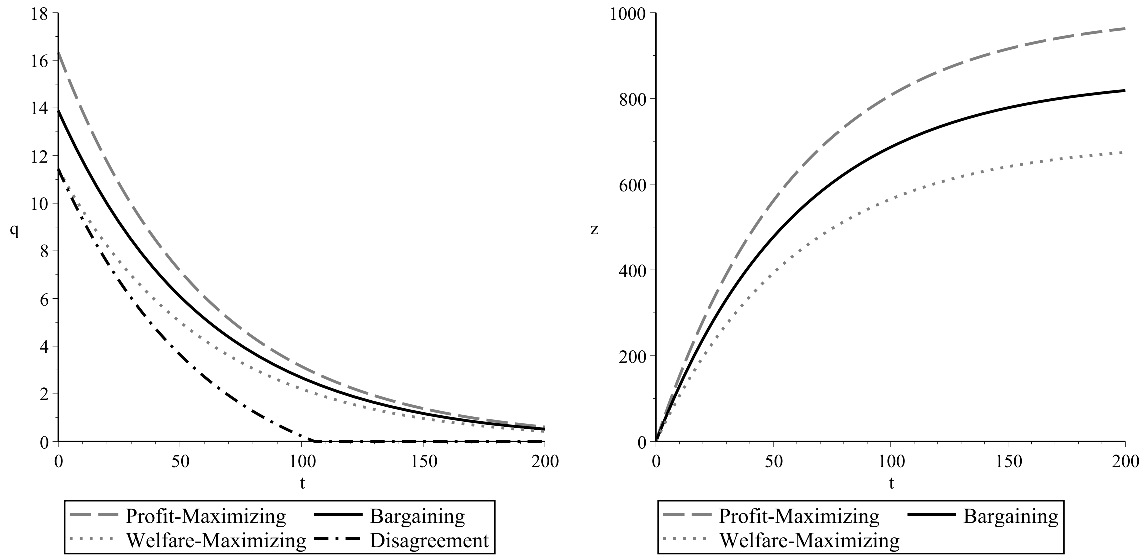


Figure 4: Extraction paths for $\psi_w = \psi_a$ (Case II).

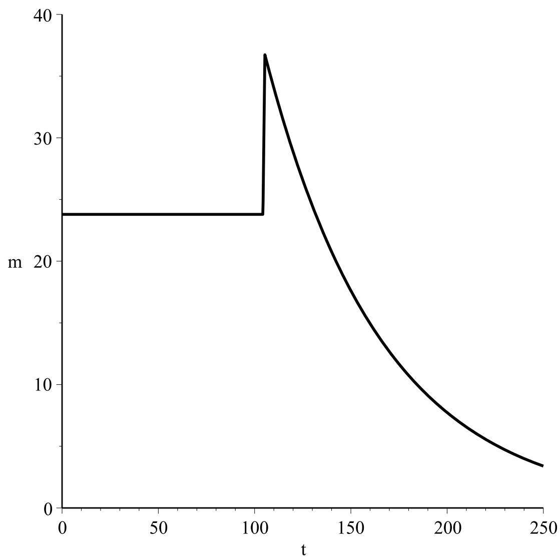


Figure 5: Contribution payment path for $\psi_w = \psi_a$ (Case II).

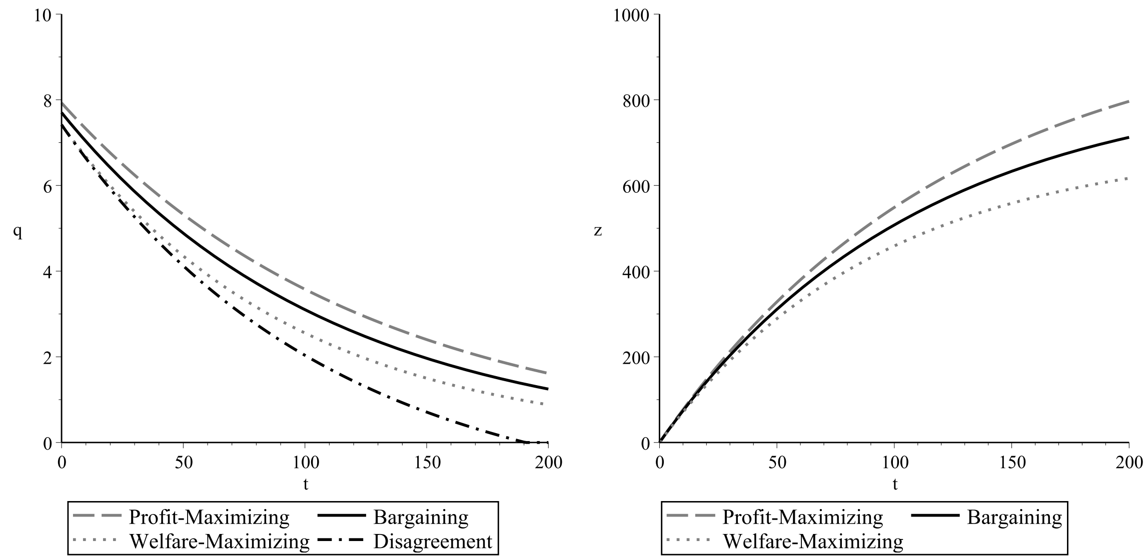


Figure 6: Extraction paths for $\psi_w > \psi_a$ and $\psi_w \bar{z}^w < \psi_a \bar{z}^a$ (Case III).

payments display the same discontinuity and long-run behavior as in Case I.

Cases III and IV: $\psi_w > \psi_a$.

Now suppose $\alpha_w/\gamma_w < \alpha_\pi/\gamma_\pi \Leftrightarrow \psi_w > \psi_a$.[19] Because $\bar{z}^a > \bar{z}^w$, it then depends on the amount of cumulative extraction z whether the lobbying distortion $\Delta_{a,w}(z)$ is positive or negative (see Proposition 5). If $\Delta_{a,w}(z)$ is positive for $z = 0$, then it will remain so as z increases. We have

$$\Delta_{a,w}(0) > 0 \qquad \Leftrightarrow \qquad \psi_a \bar{z}^a - \psi_w \bar{z}^w > 0. \tag{31}$$

This defines Case III. By $\alpha_w/\gamma_w < \alpha_a/\gamma_a \Leftrightarrow \psi_w > \psi_a$, the government would in principle want a faster extraction than the bargained one, *given* $\bar{z}^i - z$. However, the additional pollution effects lower $\beta_w/\gamma_w = \bar{z}^w$ enough to outweigh this. The welfare-maximizing path would then imply extraction below q_t^a, which in turn is below q_t^π. Thus, the government would still reduce extraction in case of disagreement. In Figure 6 (where $\chi_{qq} = 2, \rho_{qq} = 5$), this can be seen the same way as in the previous cases. $\Delta_{a,w}(z) > 0$ and $\Delta'_{a,w}(z) > 0$ imply that the preferred extraction quantities diverge over time. Accordingly, and in contrast to Cases I and II, payments increase – see Figure 8a. Given that the bargaining parties can anticipate high payments in the future, payments may even be negative for small z values (see Proposition 6). Once $q^w(z + q^a) = 0$, the development of payments is similar to that in Cases I and II.

[19] In the more general case in which $\chi_{zz}/r > 0$, $\psi_w > \psi_a$ applies if the market-power effect strongly exceeds the marginal flow-pollution effect ($\rho_{qq} > \chi_{qq} + \chi_{zz}/r$ is sufficient) or if the increase in the marginal cost of stock pollution (χ_{zz}/r) is very large. Both would make the welfare-maximizing government want to extract more today and less tomorrow, compared to profit-maximizing firms.

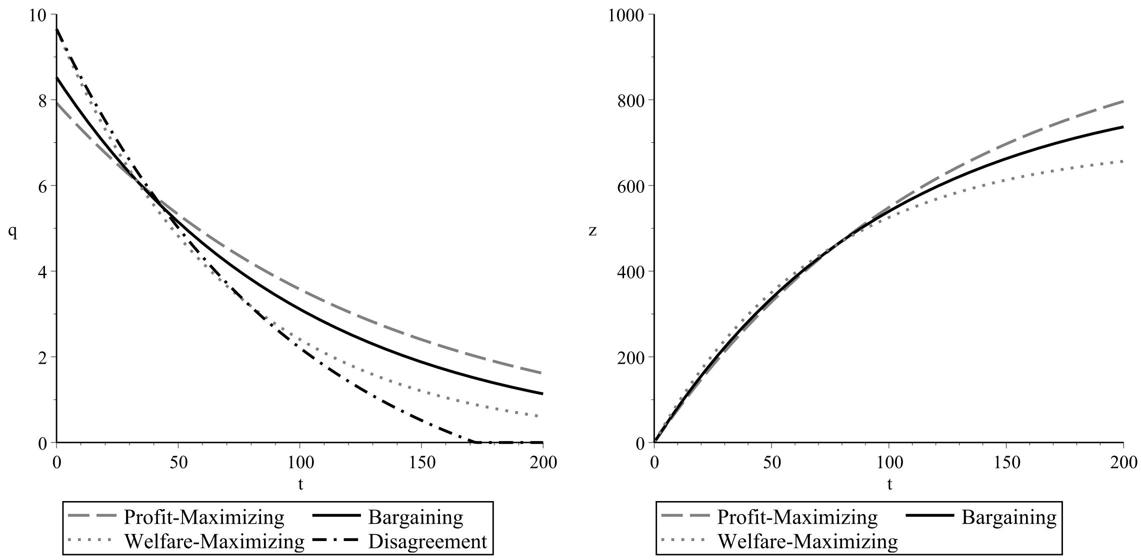


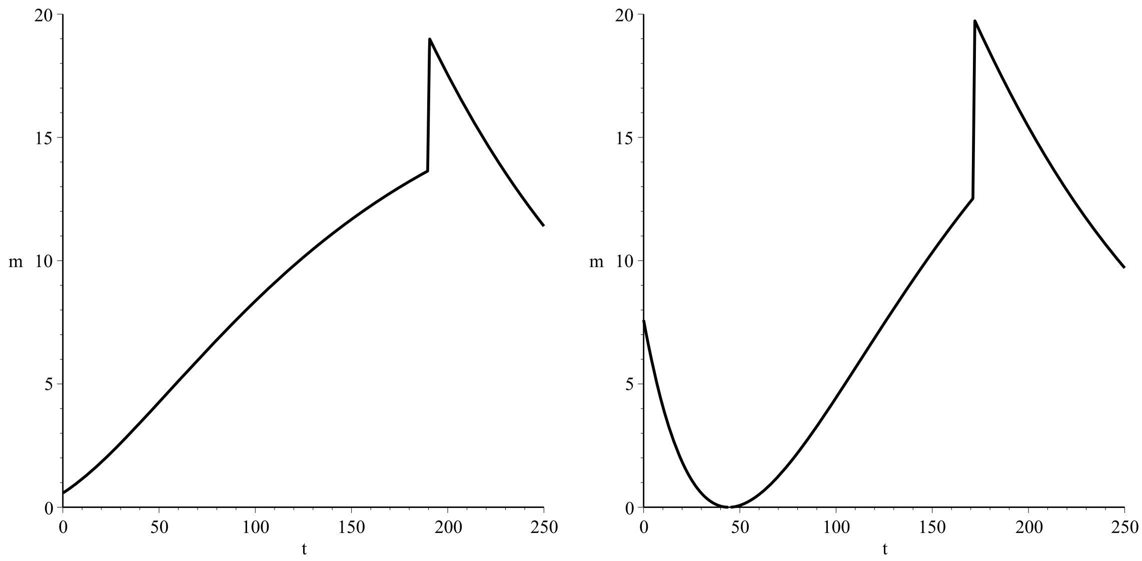
Figure 7: Extraction paths for $\psi_w > \psi_a$ and $\psi_w \bar{z}^w > \psi_a \bar{z}^a$ (Case IV).

If, on the other hand, $\psi_w \bar{z}^w > \psi_a \bar{z}^a$, we have Case IV. The government's preferred extraction exceeds the bargained extraction for small z: $\Delta_{a,w}(0) < 0$. But as time goes by, $q^w(z)$ again decreases more than $q^a(z)$. Thus, it becomes lower than the bargained extraction for large z, in particular for $z = \underline{z}^w < \bar{z}^a$. Put another way, in total, the lobby group would want to extract more than the government, but maximizing profits would imply a stronger postponing of extraction. Therefore, the lobbying distortion – the absolute value of $\Delta_{a,w}(z)$ – first declines until q_t^w and q_t^a coincide at the switching-level $\hat{z}$ from (26); afterwards, the two diverge again, until the non-negativity constraint on $q^w(z)$ becomes binding; see the left-hand-side of Figure 7 (where $\chi_{qq} = 0, \rho_{qq} = 5$).

Figure 8b shows the development of contribution payments. The curve first slopes downwards. Payments are zero when $\Delta_{a,w}(\hat{z}) = 0$. Afterwards, they turn negative as $\Delta_{a,w}(z)$ becomes positive (see Proposition 6). In the figure, the curve slopes upwards and the payments become positive before $q^w(z)$ starts to be constrained. In general, it is possible that the payments are still negative when z approaches $\underline{z}^w$ (see Proposition 6), but once it has crossed $\bar{z}^w$, the behavior resembles that of the other cases, and the payments are definitely positive again.

7 Discussion

Having illustrated the dynamics of the lobbying equilibrium, we will now discuss four points. Firstly, the relationship between the resource-extraction development and the development of payments; secondly, the empirical classification of the four cases; thirdly, the impact of demand shocks on the lobby payments; and fourthly, the influence of the lobby on environmental damages.



(a) $\psi_w \beta_w < \psi_a \beta_a$ (b) $\psi_w \beta_w > \psi_a \beta_a$

In Figure 8b, contribution payments are negative around $t = 44$.

Figure 8: Contribution payment paths for $\psi_w > \psi_a$ (Cases III and IV).

First, consider the relationship between the resource-extraction development and the development of payments. Intuitively, one may think that extraction quantities and payments are so closely linked that they must move in the same direction. However, the development of payments in fact depends on the development of the bargaining parties' outside options. Therefore, while extraction and payments initially decrease over time in Case I, they are constant in Case II, increasing or possibly first decreasing and then increasing in Case III, and first decreasing and then increasing in Case IV. Moreover, we have seen that the discontinuity in the lobby's next-period outside option implies a discontinuity in the payments as soon as the welfare-maximizing extraction starts being constrained to zero. Afterwards, payments can initially increase over time but vanish in the long run with the resource extraction. Thus, if an outside observer could see the payments, she should note that declining payments do not imply that an end of resource extraction is in sight, nor do they immediately indicate a waning lobby influence or a permanently lower conflict of interest between resource owners and the general public.

Furthermore, payments turn negative when the bargained extraction starts to exceed the welfare-maximizing extraction in Case IV, and they can initially be negative in Case III. In both cases, deviating for *only* the current period from the welfare-maximizing path reduces intertemporal profit, and this profit loss outweighs the corresponding welfare loss, such that the government has to compensate the lobby to continue cooperation. Ruling out direct payments from politicians to lobbyists, this compensation can be interpreted as money from the state coffers to the lobby.[20] Though such payments will usually be illegal, they may even exist in countries with strong institutions.[21]

Next, we discuss how fossil fuels (coal, oil and gas) can be characterized using our four cases, based on a rough calibration of the linear-quadratic model's parameters to empirical properties of the global markets. In this calibration, conducted in Appendix C, we define the stock-pollution costs of a fossil fuel by its climate impact because the climate impact is straightforward to calculate and takes center stage in policy debates.

In case of coal, we find the first-unit profit to be low whereas the climate impact is high, such that there is a large divergence between the preferred convergence levels ($\bar{z}^{\pi}/\bar{z}^{w} = 3.34$). Consequently, the government of our model would always prefer to extract less coal than the resource-owner lobby group.[22] Furthermore, the relative importance of the market-power effect and the marginal flow-pollution effect can be estimated by inspecting the price elasticity of coal demand and the empirical pollution impact. While there is a world market for coal, local coal demand elasticities may be influenced by the necessity of inland transport that may hinder competition. For instance, in the United States, the average transportation cost accounted for 41% of the average delivered cost of coal shipments to power plants in 2018 (EIA, 2019). The pollution impact depends on the population density and on the pollution-abatement technology (Biegler and Zhang, 2009, Chapter 2.3). For example, more than 80% of SO_2 emissions from coal power stations are filtered out in the United States, but less than 60% in China and 45% in India (Lin et al., 2018).

Based on these considerations, Case I applies if flow pollutants are important but supply alternatives are available. This may be the case in coastal regions of developing or emerging economies, where an initially strong conflict of interest between profit maximization and welfare maximization would then be expected to fade over time. Based on our calibration, the European Union, with a high level of pollution-abatement technology, is of Case II ($\alpha_w/\alpha_\pi \approx 1$), but due to the knife-edge nature of this case, this statement is rather uncertain. The coal industry in the United States, which has a lower population density than Europe and high transportation cost, may then represent Case III. The case of Australia, with the lowest population density of all OECD countries, is definitely Case III ($\alpha_w/\alpha_\pi = 0.72$) in our calibration. For countries such as the United States and Australia, our calibration would thus imply an increasing lobbying distortion

[20]For this interpretation to fit the model exactly, the marginal disutility from using state money to pay a lobby must coincide with the marginal utility from receiving money from the lobby (instead of letting the lobby pay a royalty to the state).

[21]Due to a lack of observability, evidence is hard to come by, but even the European Commission's 'Research Fund for Coal and Steel' was accused of paying the wage of a lobbyist of the 'European Association For Coal and Lignite' (EURACTIVE, 2019).

[22]$\bar{z}^{\pi}/\bar{z}^{w} > 2$ is sufficient; see Proposition C.1 in Appendix C.

if the coal lobby is influential, and more generally an increasing conflict of interest between profit maximization and welfare maximization, up to the point at which welfare maximization would demand an end to coal.

The price per energy unit of oil is about four times higher than that for coal, whereas its climate impact is lower. Consequently, the difference between the preferred convergence levels is much smaller ($\bar{z}^\pi/\bar{z}^w = 1.07$). Furthermore, the price elasticity of oil demand is smaller than that of coal. Thus, the market-power effect is five times stronger in the former case than in the latter. There is no consensus on whether the marginal flow-pollution effect of oil is weaker than that for coal. However, even if the former were 50% higher than the latter, the market-power effect would definitely outweigh the marginal-pollution effect in Australia ($\alpha_w/\alpha_\pi = 0.55$) and in the European Union ($\alpha_w/\alpha_\pi = 0.60$). Together with the small difference between the preferred convergence levels, oil is typically Case IV.[23]

This fits the observation that supply restraint due to market power of oil companies was a concern several decades ago, whereas the conflict of interest turned around at some point, such that there are complaints that governments are not curbing oil consumption enough to get environmental problems under control nowadays.

Finally, the marginal extraction costs of gas are comparably high, such that the first-unit profit is low, but its climate impact is also low. Consequently, the conflict of interest on total extraction is in-between that in case of oil and coal ($\bar{z}^\pi/\bar{z}^w = 2.34$). Nevertheless, it is high enough to ensure that the government always prefers to extract less than the lobby. Furthermore, the price per energy unit and the price elasticity of gas demand are about twice those of coal, which implies that the market-power effect is about the same. However, the flow-pollution damages are much smaller, such that gas in Australia ($\alpha_w/\alpha_\pi = 0.52$) and in the European Union ($\alpha_w/\alpha_\pi = 0.62$) are definitely Case III.[24]

Note that Proposition 5 implies (for $z_0 = 0$)

$$\bar{z}^w = [1 - (1 - \psi_a)^{T^w}]\bar{z}^a \qquad \Leftrightarrow \qquad T^w = \frac{\ln(1 - \bar{z}^w/\bar{z}^a)}{\ln(1 - \psi_a)}, \tag{32}$$

where T^w is the point in time when it would be welfare-maximizing to stop extraction along the equilibrium extraction path. Based on our calibration, the climate impact (which corresponds to the stock-pollution costs in our model) is highest for coal and lowest for gas. Furthermore, the first-unit profit and, thus, $\bar{z}^w/\bar{z}^\pi$ is lowest for coal.

[23]The upper bound for the flow-pollution damages of oil in Australia and the European Union are 1.7 *USD/MBtu* and 3.7 *USD/MBtu*, respectively. If these damages are below 13.7 *USD/MBtu*, then Case IV will apply; see Appendix C.

[24]The calibrated flow-pollution damages of gas in Australia and the European Union are 0.1 *USD/MBtu* and 0.6 *USD/MBtu*, respectively. If these damages are below 2.2 *USD/MBtu*, then Case III will apply; see Appendix C.

Since the price of oil and the marginal extraction costs of gas are high, the first-unit profit of oil is much higher than that of gas. This outweighs the larger climate impact of oil, such that the long-run extraction in a lobbying equilibrium will exceed the welfare-maximizing level the least in case of oil and the most in case of coal. However, whether the point in time at which it would be welfare-maximizing to stop extraction is reached earlier or later for the different fuels also depends on the bargained speed of convergence, which we have seen to depend on the effects of flow pollution and market power. Based on our calibration, the marginal flow-pollution effect is weaker for gas than for oil and coal, but the market-power effect is much stronger for oil than for gas and coal. Consequently, ψ_a is lowest for oil and highest for coal. Thus, T^w is reached first for coal, then for gas and last for oil.

Moreover, our model allows to analyze the impact of demand shocks on lobby payments. For example, the shale gas revolution in the United States can be interpreted as a negative demand shock for coal. If the preferred extraction quantities converge over time, as in Case I, then a negative demand shock reduces the difference between the preferred quantities and, thus, the lobby payments. However, if they diverge over time, as in Case III and the later part of Case IV, then the bargained extraction declines by less than the welfare-maximizing one in response to a negative demand shock, which *raises* the payments within the periods.[25] Recalling that the coal industry in the United States may represent Case III, this may help to explain why its contribution payments rose steeply between 2007 and 2012 when the shale gas production rose by more than 25% in every single year and by 461% over the years (EIA, 2020*c*).

Finally, consider the lobby influence on environmental damages. As we have seen, the extraction functions $q^a(z)$ and $q^w(z)$ intersect either never or once. In Cases I–III, they never do, such that $q^a > q^w$ holds for all z, and the intertemporal environmental damages resulting from the bargaining definitely exceed those along the welfare-maximizing path. In Case IV, $q^a > q^w$ holds for z above the switching-level $\hat{z}$ from (26), but $q^a < q^w$ holds for small z. Only in the latter case can the intertemporal environmental damages resulting from the bargaining be below those along the welfare-maximizing path.[26] This depends on the parameters of the economy. If, for example, the environmental damages only depend on the flow of pollution and the preferred convergence levels of z coincide, $\chi_{qq} < \rho_{qq}$ implies that lobbying flattens the extraction path and reduces the environmental damages. If, on the other hand, flow-pollution effects are small, stock-pollution damages exist, and the future is important enough, then the higher total z accumulation in the Case-IV equilibrium increases the intertem-

[25] $\chi_{zz} = 0$ is sufficient; see Proposition B.2 in Appendix B.

[26] Note that $q^a(z) < q^w(z)$ implies $m^a(z) > 0$ and $\frac{\partial m^a(z)}{\partial z} < 0$; see Proposition 6. We thus know that lobbying increases intertemporal environmental damages in any period for which we either know that $q^a(z) > q^w(z)$, or observe that either $m^a(z) < 0$ or $\frac{\partial m^a(z)}{\partial z} > 0$, and in all future periods.

poral environmental damages.[27] The effects of lobbying on the environment resemble those of unilateral climate policy analyzed in the "green paradox" literature: Lobbying can reduce the current extraction ("weak green paradox"; see Gerlagh, 2011), but at the same time increase the intertemporal environmental damages (no "strong green paradox").

8 Resource Taxes

The lobbying-equilibrium policy and the welfare-maximizing policy have been derived as a direct choice of extraction quantities. In this section, we show that is also possible to implement the extraction paths via resource taxes. For equivalence to the quantity-choice equilibrium, we assume that each period's tax revenues are immediately distributed to the suppliers as lump-sum payments – both in the lobbying equilibrium and in the disagreement situation.

Assume that resource suppliers are so small that they take the price path including the resource tax as given, and only through their lobby organization's influence on policy can they internalize the effect of supply on the price. Then, along the lines of (14), the Euler equation of a representative resource supplier is

$$p(q_t) - \tau_t - \frac{\partial c(q_t, z_t)}{\partial q} = \delta \cdot \left[p(q_{t+1}) - \tau_{t+1} - \frac{\partial c(q_{t+1}, z_{t+1})}{\partial q} + \frac{\partial c(q_{t+1}, z_{t+1})}{\partial z} \right], \tag{33}$$

where τ_t is the resource tax of the current period. The tax can be used to implement the extraction path bargained between the lobby and the government. Comparing (14) and (33), it must hold that

$$\begin{aligned} \tau_t^a - \delta \tau_{t+1}^a = & \frac{1}{1+\mu} \cdot \frac{\partial x(q_t^a, z_t)}{\partial q} - \frac{\mu}{1+\mu} \cdot p'(q_t^a) \cdot q_t^a \\ & - \delta \cdot \left\{ \frac{1}{1+\mu} \cdot \left[\frac{\partial x(q_{t+1}^a, z_{t+1}^a)}{\partial q} - \frac{\partial x(q_{t+1}^a, z_{t+1}^a)}{\partial z} \right] - \frac{\mu}{1+\mu} \cdot p'(q_{t+1}^a) \cdot q_{t+1}^a \right\}. \end{aligned} \tag{34}$$

Solving for τ_t^a immediately yields the following tax path:

Proposition 7 (Tax Path) *The tax that implements the bargained extraction $q^a(z)$ by price-taking resource suppliers is given by:*

$$\tau_{t+s}^a = \frac{1}{1+\mu} \cdot \frac{\partial x(q_{t+s}^a, z_{t+s})}{\partial q} - \frac{\mu}{1+\mu} \cdot p'(q_{t+s}^a) \cdot q_{t+s}^a + \frac{1}{1+\mu} \cdot \sum_{\nu=1}^{\infty} \delta^\nu \cdot \frac{\partial x(q_{t+s+\nu}^a, z_{t+s+\nu}^a)}{\partial z}, \tag{35}$$

[27] For $\chi_{zz} = \chi_{qq} = 0$, lobbying increases intertemporal environmental damages if r is sufficiently low; see Proposition B.3 in Appendix B. In the example of Case IV, we find $D^a > D^w$ if $r < 2.75\%$.

which is positive for all $q^a(z) \geq 0$.

The first two terms correct for the effect of resource extraction on marginal flow-pollution costs and on marginal revenues via the price, respectively. The influence of these terms depends on the policy weights of the bargaining parties. The last term corrects for the future stock-pollution costs caused by current extraction, also multiplied by the government's relative policy weight.

Using the linear-quadratic specification from Section 5 yields:

Proposition 8 (Explicit Example: Tax Path) *The tax that implements the bargained extraction $q^a(z)$ by price-taking resource suppliers is defined by*

$$\tau^a(z) = \gamma_\pi(\bar{z}^\pi - \bar{z}^a) + \left[\frac{\gamma_\pi}{\gamma_a}\alpha_a - (\alpha_\pi - \rho_{qq})\right] q^a(z). \tag{36}$$

Proof. Substituting the linear-quadratic functions from Table 1 in (34) yields:

$$\tau^a_{t+s} = \frac{\chi_q + \frac{\chi_z}{r} + (\chi_{qq} + \mu\rho_{qq})q^a_{t+s} + \chi_{zz}\sum_{v=1}^{\infty}\delta^v z_{t+s+v}}{1+\mu}. \tag{37}$$

Using (25) and (23) yields:

$$\sum_{v=1}^{\infty}\delta^v z_{t+s+\nu} = \sum_{\nu=1}^{\infty}\delta^v[\bar{z}^a - (1-\psi_a)^\nu(\bar{z}^a - z_{t+s})] = \frac{\bar{z}^a}{r} - \frac{1-\psi}{\psi(r+\psi)}q^a_{t+s} = \frac{\bar{z}^a}{r} - \frac{\alpha_a - \gamma_a}{r\gamma_a}q^a_{t+s}. \tag{38}$$

Substituting into (37), using (22) and rearranging yields (36). □

The tax path consists of two parts. The first, $\gamma_\pi(\bar{z}^\pi - \bar{z}^a)$, corrects for the different convergence levels. The resource tax converges to this part in the long run, where it just keeps firms from extracting. The second part is proportional to

$$\frac{\gamma_\pi}{\gamma_a}\alpha_a - (\alpha_\pi - \rho_{qq}) = \frac{(\chi_{qq} + \frac{\chi_{zz}}{r} + \mu\rho_{qq})\kappa_{qz} - (\kappa_{qq} + \rho_{qq})\frac{\chi_{zz}}{r}}{(1+\mu)\kappa_{qz} + \frac{\chi_{zz}}{r}}. \tag{39}$$

Here, $\alpha_\pi - \rho_{qq}$ is the slope of a competitive resource supplier's marginal profit function, and γ_π/γ_a corrects for the difference in stock effects, such that the whole term ensures that the contemporaneous marginal profit decreases as fast as the contemporaneous marginal joint product of the government and the lobby. If the lobby's weight μ is very high, (39) goes to ρ_{qq} and $\bar{z}^a$ goes to $\bar{z}^\pi$, so that the resource suppliers are induced to act like a monopolist. If μ is zero, (39) is $\chi_{qq} - \frac{\chi_{zz}}{r}\frac{\alpha_w - \gamma_w}{\gamma_w}$ and $\bar{z}^a$ is $\bar{z}^w$. This shows that the resulting Pigouvian taxation in principle has to correct for the marginal flow-pollution effect, but less so as welfare maximization would call for a stronger reaction of extraction to the growing stock due to increasing marginal stock-pollution costs. (If $\mu = \chi_{zz} = 0$, then (39) becomes χ_{qq}.)

9 Conclusions

In this article, we analyze resource extraction determined by the bargaining of a government and a resource-owner lobby group. The resulting extraction is a compromise path between welfare maximization and profit maximization. The influence of the lobby increases with the government's preference for contribution payments and decreases with the lobby's cost of collecting them. Depending on how strongly resource extraction increases marginal pollution damages and decreases the resource price, extraction is either too fast or too slow, compared to welfare maximization, and the distance of the bargained extraction to the welfare-maximizing one may increase or decrease over time. Only when cumulative extraction has become so high that it would be welfare-maximizing to completely stop extraction, will the lobbying distortion decline over time in any case – in the very long run, as extraction costs increase ever further, the lobby's preferred extraction quantity also approaches zero. Extraction continues for too long, however, causing inefficiently high pollution. Note that this characterization of the evolving conflict of interest between profit maximization and welfare maximization applies more generally and is valid beyond the lobby model; if demand in a resource market is inelastic, then unregulated suppliers with market power may want to sell too little of the resource early on, and too much of it later.

We derive an analytical solution of our model with linear-quadratic functions. Along with the conflict of interest, the payments vanish in the very long run, but prior to that, they decline if the marginal flow-pollution effect strongly outweighs the market-power effect, remain constant if the preferred speeds of convergence coincide, and increase at least temporarily if the market-power effect is sufficiently strong. The payments necessary for a time-consistent agreement may temporarily turn negative if there is an intertemporal profit loss from cooperating for one period – that is, if the intertemporal profit would be higher if welfare maximization started in the current period rather than in the next. This is the case if the increased extraction strongly reduces the (welfare-maximizing) extraction that the government would choose in case of disagreement in the future, which in turn worsens the lobby's future bargaining position. Nonetheless, since the bargained extraction increases intertemporal profit and reduces intertemporal welfare, the present value of anticipated payments to the government is always positive.

Whenever lobbying increases extraction, it also raises the economy's inherited cumulative extraction a period later. Via reducing the welfare-maximizing extraction, this reduces the resource owners' profits if the bargaining should fail. The lobby always has to take this into account in the bargaining – until cumulative extraction becomes so high that welfare maximization implies zero extraction. Therefore, the lobby's willingness to pay increases sharply at this moment, which induces the jump in the payments.

Additionally, we demonstrate how the bargained extraction path can be implemented via resource taxes. These taxes account for current and future pollution costs and on the effect of resource extraction on marginal revenues via the price. Thereby, they reduce extraction within the periods and total extraction compared to a situation without regulation. With linear-quadratic functions, the resource taxes consist of a constant part, correcting for the difference in preferred convergence levels, and a part that is proportional to the bargained extraction, correcting for the difference in preferred speeds of convergence.

The analysis in this article contributes to our understanding of the political economy of resource extraction. Firstly, it is important to bear in mind that the conflict of interest between profit maximization and welfare maximization can operate in different directions, such that a lobby would either try to convince the government to increase or decrease extraction, and it can change over time. Secondly, if we can observe bribes or "contribution payments" that are very low, this does not necessarily indicate that the lobby influence is low in general; rather, it may indicate a temporary absence of a conflict of interest, but the divergence of interests afterwards is already anticipated by the bargaining parties.

In a dynamic relationship, the bargaining parties' expectations for the future are decisive, which includes the effect of cooperation on future bargaining positions. Therefore, if the bribable government expects to be replaced by a benevolent government in the future, the lobbying influence changes, but its negative impact on intertemporal welfare is not necessarily reduced. Finally, if money is exchanged for a favorable policy as it is in our setting, the bargained policy does not depend on the behavior in case of disagreement, as long as both parties expect their cooperation to continue. Accordingly, if a breakdown of bargaining does not impede the possibility to restart cooperation in the future, the lobby's payments are different than in our main model, but the equilibrium policy is the same. For an elaboration of these points, see Appendix E and Appendix D, respectively.

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Appendix

A Proofs of Section 4

Proof of Proposition 1. For $q > 0$, (10) yields the first-order conditions:

$$\eta \frac{\frac{\partial w(q^a(z),z)}{\partial q} + \delta \frac{\partial G^a(z+q^a(z))}{\partial z}}{G^a(z) - W^w(z)} + (1-\eta) \frac{\frac{\partial \pi(q^a(z),z)}{\partial q} + \delta \frac{\partial L^a(z+q^a(z))}{\partial z}}{L^a(z) - \Pi^w(z)} = 0, \tag{A.1a}$$

$$\eta \frac{\phi}{G^a(z) - W^w(z)} - (1-\eta) \frac{\lambda}{L^a(z) - \Pi^w(z)} = 0. \tag{A.1b}$$

Rearranging (A.1b) and substituting this into (A.1a), we obtain

$$\frac{1}{1+\mu} \left[\frac{\partial w(q^a(z), z)}{\partial q} + \delta \frac{\partial G^a(z + q^a(z))}{\partial z} \right] + \frac{\mu}{1+\mu} \left[\frac{\partial \pi(q^a(z), z)}{\partial q} + \delta \frac{\partial L^a(z + q^a(z))}{\partial z} \right] = 0, \tag{A.2}$$

where the payments in the intertemporal utility terms cancel out, so that the agreement policy can be written as in (11). Rearranging (A.1b) and collecting the payment terms yields (12a). Since q^a and q^w maximize $\frac{1}{1+\mu}W(z) + \frac{\mu}{1+\mu}\Pi(z)$ and $W(z)$, respectively, $M^a(z) \geq 0$ is required for the government to participate. (12b) follows from rearranging $M^a(z) = m^a(z) + \delta M^a(z + q^a(z))$. (13a) and (13b) follow from substituting (12a) into $G^a(z) = W^a(z) + \phi M^a(z)$ and $L^a(z) = \Pi^a(z) - \lambda M^a(z)$, respectively, and rearranging. □

To prepare the proof of Lemma A.2, we derive the effective bounds of intertemporal values:

Lemma A.1 (Effective Bounds of Intertemporal Values) *For a bargained extraction path maximizing* $\sum_{s=0}^{\infty} \delta^s \cdot \left[\frac{1}{1+\mu} w(q_{t+s}, z_{t+s}) + \frac{\mu}{1+\mu} \pi(q_{t+s}, z_{t+s}) \right]$ *with* $\mu \in [0, \infty)$*, this intertemporal joint product is bounded and profit* $\pi(q, z)$ *is positive for* $z < \bar{z}^a$ *and zero for* $z \geq \bar{z}^a$*. Intertemporal welfare is bounded for a welfare-maximizing extraction path and intertemporal profit is bounded for a profit-maximizing extraction path, and profit is positive below the respective convergence levels.*

Proof. By Assumption 2, $w(q,z)$ and $\pi(q,z)$ are strictly concave in q. Then, the unique myopic maximizer $\bar{q}^w(z) = \operatorname{argmax}_q w(q,z)$ is implicitly defined by the complementary-slackness conditions $\frac{\partial w(\bar{q}^w(z),z)}{\partial q} \leq 0$, $\bar{q}^w(z) \geq 0$ and $\bar{q}^w(z)\frac{\partial w(\bar{q}^w(z),z)}{\partial q} = 0$. Along the same lines, $\pi(q,z)$ has a unique myopic maximizer $\bar{q}^\pi(z)$, and $\frac{1}{1+\mu}w(q,z) + \frac{\mu}{1+\mu}\pi(q,z)$ with $\mu \in [0,\infty)$ has a unique myopic maximizer $\bar{q}^a(z) \in [0, \max[\bar{q}^w(z), \bar{q}^\pi(z)]]$.

A welfare-maximizing extraction path starting with z_t never includes $q_{t+s} > \bar{q}^w(z_{t+s})$ for any s, because $\bar{q}^w(z_{t+s})$ maximizes $w(q, z_{t+s})$ and adding to future cumulative extraction cannot increase welfare. We can thus assume $q \in [0, \bar{q}^w(z)]$ for welfare maximization. Since w is monotonously increasing in q up to $w(\bar{q}^w(z), z)$, it follows that $w(q,z) \in [w(0,z), w(\bar{q}^w(z),z)]$. By the Envelope theorem,

$$\frac{\mathrm{d}w(\bar{q}^w(z),z)}{\mathrm{d}z} = \frac{\partial w(\bar{q}^w(z),z)}{\partial z} = -\frac{\partial c(\bar{q}^w(z),z)}{\partial z} - \frac{\partial x(\bar{q}^w(z),z)}{\partial z} \leq 0, \qquad \text{(A.3)}$$

so that along a feasible path, $w(\bar{q}^w(z),z)$ is non-increasing and intertemporal welfare is bounded above. Moreover, since it is possible to choose $q_{t+s} = 0 \,\forall\, s$ such that $z_{t+s} = z_t \,\forall\, s$, maximized $\sum_{s=0}^{\infty} \delta^s \cdot w(q_{t+s}, z_{t+s})$ is bounded below by $w(0,z_t)/(1-\delta) = -x(0,z_t)/(1-\delta) < 0$.

Along the same lines, intertemporal profit $\sum_{s=0}^{\infty} \delta^s \cdot \pi(q_{t+s}, z_{t+s})$ and the intertemporal joint product $\sum_{s=0}^{\infty} \delta^s \cdot \left[\frac{1}{1+\mu}w(q_{t+s}, z_{t+s}) + \frac{\mu}{1+\mu}\pi(q_{t+s}, z_{t+s})\right]$ are bounded above, and their maximized values are bounded below by $\pi(0,z_t)/(1-\delta) = 0$ and $-x(0,z_t)/\left[(1+\mu)(1-\delta)\right] < 0$. Moreover, since $u'(q) = p(q)$ is strictly decreasing in q, $c(q,z)$ is convex in q, and $0 = p(\bar{q}^w(z)) - \frac{\partial c(\bar{q}^w(z),z)}{\partial q} - \frac{\partial x(\bar{q}^w(z),z)}{\partial q} \leq p(\bar{q}^w(z)) - \frac{\partial c(\bar{q}^w(z),z)}{\partial q}$ holds, we have $\pi(\bar{q}^w(z),z) = p(\bar{q}^w(z))\bar{q}^w(z) - c(\bar{q}^w(z),z) > 0$ for $\bar{q}^w(z) > 0$ and, thus, $\pi(q,z) > 0$ for $0 < q \leq \bar{q}^w(z)$. Finally, since $\bar{q}^a(z) \in [0, \max[\bar{q}^w(z), \bar{q}^\pi(z)]]$ and $\pi(q,z) > 0$ for $0 < q \leq \bar{q}^\pi(z)$ holds, we have $\pi(q,z) > 0$ for $0 < q \leq \bar{q}^a(z)$. □

To prepare the proof of Proposition 2, we derive the Euler equation (14) and the binding non-negativity constraint (15).

Lemma A.2 (Euler Equations) *The Euler equation for the bargained extraction path is given by* (14)*, and the Euler equations for welfare maximization and profit maximization emerge es special cases for $\mu = 0$ and $\mu \to \infty$, respectively.*

Proof. By Lemma A.1, the maximum in (11) is well-defined (cf. Sydsæter et al., 2008, Sec. 12.3). The first-order condition of (11) is

$$\frac{1}{1+\mu}\left[\frac{\partial w(q^a,z)}{\partial q} + \delta\frac{\partial W^a(z+q^a)}{\partial z}\right] + \frac{\mu}{1+\mu}\left[\frac{\partial \pi(q^a,z)}{\partial q} + \delta\frac{\partial \Pi^a(z+q^a)}{\partial z}\right] = 0. \qquad \text{(A.4)}$$

Differentiating (11) and substituting (A.4) yields the envelope condition:

$$\frac{1}{1+\mu}\frac{\partial W^a(z)}{\partial z}+\frac{\mu}{1+\mu}\frac{\partial \Pi^a(z)}{\partial z}$$
$$=\frac{1}{1+\mu}\left[\frac{\partial w(q^a,z)}{\partial z}-\frac{\partial w(q^a,z)}{\partial q}\right]+\frac{\mu}{1+\mu}\left[\frac{\partial \pi(q^a,z)}{\partial z}-\frac{\partial \pi(q^a,z)}{\partial q}\right]. \quad \text{(A.5)}$$

Evaluating this for $z = z^a_{t+1} = z_t + q^a(z_t)$ and $q = q^a_{t+1} = q^a(z^a_{t+1})$ and substituting the result into (A.4) for $z = z_t$ and $q = q^a_t = q^a(z_t)$ yields the Euler equation:

$$\frac{1}{1+\mu}\frac{\partial w(q^a_t,z_t)}{\partial q}+\frac{\mu}{1+\mu}\frac{\partial \pi(q^a_t,z_t)}{\partial q}$$
$$=\delta\left\{\frac{1}{1+\mu}\left[\frac{\partial w(q^a_{t+1},z^a_{t+1})}{\partial q}-\frac{\partial w(q^a_{t+1},z^a_{t+1})}{\partial z}\right]+\frac{\mu}{1+\mu}\left[\frac{\partial \pi(q^a_{t+1},z^a_{t+1})}{\partial q}-\frac{\partial \pi(q^a_{t+1},z^a_{t+1})}{\partial z}\right]\right\}, \quad \text{(A.6)}$$

which is written more explicitly in (14). The Euler equations for welfare maximization and profit maximization then follow from $q^a_t(\mu = 0) = q^w_t$ and $q^a_t(\mu \to \infty) = q^\pi_t$. □

Lemma A.3 (Binding Non-negativity Constraints) *Suppose that cumulative extraction is at a level $z \geq \bar{z}^a$, where $\bar{z}^a$ is defined by*

$$\frac{1}{1+\mu}\left[\frac{\partial w(0,\bar{z}^a)}{\partial q}+\frac{1}{r}\frac{\partial w(0,\bar{z}^a)}{\partial z}\right]+\frac{\mu}{1+\mu}\left[\frac{\partial \pi(0,\bar{z}^a)}{\partial q}+\frac{1}{r}\frac{\partial \pi(0,\bar{z}^a)}{\partial z}\right]=0. \quad \text{(A.7)}$$

Then and only then, the non-negativity constraint $q^a \geq 0$ is binding, and this remains so in the future. The levels of cumulative extraction for which the non-negativity constraint starts binding for welfare maximization, $\bar{z}^w$, and profit maximization, $\bar{z}^\pi$, follow as special cases for $\mu = 0$ or $\mu \to \infty$, respectively.

Proof. Suppose zero extraction were chosen in all future periods. The intertemporal joint product evaluated in the current period then is $\frac{1}{1+\mu}\left[w(q_t,z_t)+w(0,z_t+q_t)/r\right]+\frac{\mu}{1+\mu}\left[\pi(q_t,z_t)+\pi(0,z_t+q_t)/r\right]$. Zero extraction in the current period is optimal if

$$\frac{1}{1+\mu}\left[\frac{\partial w(0,z_t)}{\partial q}+\frac{1}{r}\frac{\partial w(0,z_t)}{\partial z}\right]+\frac{\mu}{1+\mu}\left[\frac{\partial \pi(0,z_t)}{\partial q}+\frac{1}{r}\frac{\partial \pi(0,z_t)}{\partial z}\right]\leq 0. \quad \text{(A.8)}$$

By $\frac{\partial c(0,z)}{\partial z} = 0$ and by additive separability of $x(q,z)$, we have $\frac{\partial^2 w(0,z)}{\partial q \partial z} = \frac{\partial^2 \pi(0,z)}{\partial q \partial z} = \frac{\partial^2 \pi(0,z)}{\partial z^2} = 0$ and $\frac{\partial^2 w(0,z)}{\partial z^2} = -\frac{\partial^2 x(0,z)}{\partial z^2} \leq 0$, such that the left-hand side is weakly declining in z; thus, (A.8) must hold for $z \geq \bar{z}^a$. Because this applies in any future period, positive extraction cannot become optimal again later on. The derivations of $\bar{z}^w$ and $\bar{z}^\pi$ follow along the same lines. Reversing the arguments, the optimality of $q^a(z) > 0$, $q^w(z) > 0$ and $q^\pi(z) > 0$ for $z < \bar{z}^a$, $z < \bar{z}^w$ and $z < \bar{z}^\pi$, respectively, follows. □

Proof of Proposition 2 By Lemma A.3, we have $q^i(z) > 0$ for $z < \bar{z}^i$ and $q^i(z) = 0$ for $z \geq \bar{z}^i$. Suppose $\frac{\partial q^i(\bar{z}^i)}{\partial z} > 0$. Since $q^i(z) > 0$ for $z < \bar{z}^i$, this implies $q^i(\bar{z}^i) > 0$, which contradicts $q^i(\bar{z}^i) = 0$. Thus, $\frac{\partial q^i(\bar{z}^i)}{\partial z} \leq 0$. For $z < \bar{z}^a$, differentiating (14) with respect to z and rearranging yields:

$$\frac{\partial q^a_{t+1}}{\partial z} = \frac{\Gamma_t \frac{\partial q^a_t}{\partial z} + \Omega_t \left(1 + \frac{\partial q^a_t}{\partial z}\right)}{\Gamma_{t+1}\delta \left(1 + \frac{\partial q^a_t}{\partial z}\right)}, \tag{A.9}$$

where

$$\Gamma_t = -\frac{\partial^2 w(q^a_t, z_t)}{\partial q^2} + \frac{\partial^2 w(q^a_t, z_t)}{\partial q \partial z} + \mu \left[-\frac{\partial^2 \pi(q^a_t, z_t)}{\partial q^2} + \frac{\partial^2 \pi(q^a_t, z_t)}{\partial q \partial z}\right], \tag{A.10a}$$

$$\begin{aligned}\Omega_t = &-\frac{\partial^2 w(q^a_t, z_t)}{\partial q \partial z} + \delta \left[\frac{\partial^2 w(q^a_{t+1}, z^a_{t+1})}{\partial q \partial z} - \frac{\partial^2 w(q^a_{t+1}, z^a_{t+1})}{\partial z^2}\right] \\ &+ \mu \left\{-\frac{\partial^2 \pi(q^a_t, z_t)}{\partial q \partial z} + \delta \left[\frac{\partial^2 \pi(q^a_{t+1}, z^a_{t+1})}{\partial q \partial z} - \frac{\partial^2 \pi(q^a_{t+1}, z^a_{t+1})}{\partial z^2}\right]\right\}.\end{aligned} \tag{A.10b}$$

Assumption 2 implies $\Gamma_t > 0$ and Assumption 1 implies $\Omega_t > 0$.[28] By (A.9), $\frac{\partial q^a_t}{\partial z} \notin (-1, 0)$ then implies $\frac{\partial q^a_{t+1}}{\partial z} > 0$. $\frac{\partial q^a_{t+1}}{\partial z} > 0$ in turn implies $\frac{\partial q^a_{t+2}}{\partial z} > 0$, so that $\frac{\partial q^a_t}{\partial z} \notin (-1, 0)$ implies $\frac{\partial q^a_{t+s}}{\partial z} > 0$ for all $s = 1, 2, 3, \ldots$. Since $\frac{\partial q^a_{t+s}}{\partial z} \leq 0$ must hold for some $s = 1, 2, 3, \ldots$ to ensure that $\lim_{s \to \infty} z^a_{t+s} = \bar{z}^a$, $\frac{\partial q^a_t}{\partial z} \in (-1, 0)$ must hold. Since the derivatives of $w(q_t, z_t)$ and $\pi(q_t, z_t)$ are continuous, $\frac{\partial q^a_t}{\partial z}$ is continuous by (A.9). Since $q^a_t(\mu = 0) = q^w_t$ and $q^a_t(\mu \to \infty) = q^\pi_t$, $\frac{\partial q^w_t}{\partial z} \in (-1, 0)$ and $\frac{\partial q^\pi_t}{\partial z} \in (-1, 0)$ are also continuous, respectively. Finally, Salant, Eswaran and Lewis (1983) prove that Assumption 2 is sufficient for an infinite extraction time to be optimal.[29] □

Proof of Proposition 3. Using (A.5) and $\frac{\partial x(0, z_t)}{\partial z} = \frac{\partial x(q^a_t, z_t)}{\partial z}$ yields:

$$\begin{aligned}&\frac{\partial [W^a(z_t) + \mu \Pi^a(z_t) - W(z_t)|_{q=0}]}{\partial z} \\ &= \frac{\partial w(q^a_t, z_t)}{\partial z} - \frac{\partial w(q^a_t, z_t)}{\partial q} + \mu \frac{\partial \pi(q^a_t, z_t)}{\partial z} - \mu \frac{\partial \pi(q^a_t, z_t)}{\partial q} + \frac{\frac{\partial x(0, z_t)}{\partial z}}{1 - \delta}\end{aligned}$$

[28] If $\frac{\partial c(q,z)}{\partial q}$ were convex in z, then a (temporarily) steep extraction path, $\frac{\partial q^i(z)}{\partial z} < -1$, could be optimal to avoid higher marginal extraction costs in the future. By contrast, if $\frac{\partial c(q,z)}{\partial q}$ were concave in z, then a (temporarily) increasing extraction path, $\frac{\partial q^i(z)}{\partial z} > 0$, could be optimal because future extraction does not increase the stock-dependent costs as much as present extraction.

[29] In a continuous-time model, a strictly concave welfare (or profit) function is sufficient for an infinite extraction time to be optimal (Salant, Eswaran and Lewis, 1983, Appendix: Continuous-Time Analysis). In a discrete-time model, marginal extraction costs in the current period are always lower than in the next, which speaks in favor of a finite extraction time. Thus, Assumption 2 is slightly stronger than the standard assumption of a strictly concave welfare (or profit) function.

$$= -(1+\mu)\left\{\left[\frac{1}{1+\mu}\left(\frac{\partial w(q_t^a,z_t)}{\partial q} - \frac{1}{r}\frac{\partial x(q_t^a,z_t)}{\partial z}\right) + \frac{\mu}{1+\mu}\frac{\partial \pi(q_t^a,z_t)}{\partial q}\right] + \frac{\partial c(q_t^a,z_t)}{\partial z}\right\} < 0. \tag{A.11}$$

The square-bracketed term is the marginal joint product, which must be positive along the bargained extraction path. Rearranging (17) for $q^w = 0$ yields:

$$m^a(z_t) = \frac{\eta}{\phi}\left\{W^a(z_t) + \mu\Pi^a(z_t) - W(z_t)|_{q=0} - \delta\left[W^a(z_{t+1}^a) + \mu\Pi^a(z_{t+1}^a) - W(z_{t+1}^a)|_{q=0}\right]\right\}$$
$$+ \frac{1}{\phi}\left[W(z_t)|_{q=0} - w(q_t^a,z_t) - \delta W(z_{t+1}^a)|_{q=0}\right]. \tag{A.12}$$

Since $\frac{\partial[W^a(z_t)+\mu\Pi^a(z_t)-W(z_t)|_{q=0}]}{\partial z} < 0$, $m^a(z_t)$ is increasing in η for $z \geq \bar{z}^w$.

Substituting (2), (4) and (6) into (A.12) and differentiating yields:

$$\frac{\partial m^a(z_t)}{\partial z} = \frac{\eta}{\phi}\Bigg\{-(1+\mu)\frac{\partial c(q_t^a,z_t)}{\partial z} - \frac{1}{r}\left[\frac{\partial x(0,z_{t+1}^a)}{\partial z} - \frac{\partial x(0,z_t)}{\partial z}\right]$$
$$+ (1+\mu)\left[\frac{1}{1+\mu}\left(\frac{\partial w(q_t^a,z_t)}{\partial q} - \frac{1}{r}\frac{\partial x(q_t^a,z_t)}{\partial z}\right) + \frac{\mu}{1+\mu}\frac{\partial \pi(q_t^a,z_t)}{\partial q}\right]\cdot\frac{\partial q_t^a}{\partial z}\Bigg\}$$
$$+ \frac{1}{\phi}\Bigg\{\frac{\partial c(q_t^a,z_t)}{\partial z} + \frac{1}{r}\left[\frac{\partial x(0,z_{t+1}^a)}{\partial z} - \frac{\partial x(0,z_t)}{\partial z}\right]$$
$$- \left[\frac{\partial w(q_t^a,z_t)}{\partial q} - \frac{1}{r}\frac{\partial x(0,z_{t+1}^a)}{\partial z}\right]\cdot\frac{\partial q_t^a}{\partial z}\Bigg\}. \tag{A.13}$$

The first line on the right-hand side is negative. The square-bracketed term in the second line on the right-hand side is the marginal joint product, which must be positive along the bargained extraction path, such that the second line is negative. Thus, $\frac{\partial m^a(z_t)}{\partial z}$ is decreasing η for $z \geq \bar{z}^w$. The square-bracketed term in the fourth line on the right-hand side is marginal welfare, which is negative for $z \geq \bar{z}^w$, such that the fourth line is negative. If $\eta(1+\mu) \geq 1$ and $\frac{\partial^2 x(0,z)}{\partial z^2} = 0$, such that $\frac{\partial x(0,z_{t+1}^a)}{\partial z} = \frac{\partial x(0,z_t)}{\partial z}$, then the sum of the first and the third line on the right-hand side is non-positive. If $\frac{\partial c(q,z)}{\partial z} \to 0$ and $\frac{\partial^2 x(0,z)}{\partial z^2} = 0$, then the third line on the right-hand side goes to zero. In both cases, $m^a(z_t)$ is decreasing in z for $z \geq \bar{z}^w$. □

Proof of Proposition 4. Differentiating (17) and rearranging yields:

$$\frac{\partial m^a(z_t)}{\partial z} = \frac{\eta}{\lambda}\left[\frac{\partial \pi(q_t^a,z_t)}{\partial q}\frac{\partial q_t^a}{\partial z} + \frac{\partial \pi(q_t^a,z_t)}{\partial z} + \delta\frac{\partial \Pi^w(z_t+q_t^a)}{\partial z}\left(1+\frac{\partial q_t^a}{\partial z}\right) - \frac{\partial \Pi^w(z_t)}{\partial z}\right]$$
$$- \frac{1-\eta}{\phi}\left[\frac{\partial w(q_t^a,z_t)}{\partial q}\frac{\partial q_t^a}{\partial z} + \frac{\partial w(q_t^a,z_t)}{\partial z} + \delta\frac{\partial W^w(z_t+q_t^a)}{\partial z}\left(1+\frac{\partial q_t^a}{\partial z}\right) - \frac{\partial W^w(z_t)}{\partial z}\right]. \tag{A.14}$$

The derivatives of $\pi(q_t,z_t)$ and $w(q_t,z_t)$ are continuous, $\frac{\partial W^w(z)}{\partial z}$ is continuous by the envelope theorem and $\frac{\partial q_t^a}{\partial z}$ is continuous for $z \neq \bar{z}^a$ by Proposition 2. Thus, $\frac{\partial m^a(z_t)}{\partial z}$ is continuous for $z \neq \bar{z}^a$ if $\frac{\partial \Pi^w(z_t)}{\partial z}$ is continuous. Differentiating (8) yields:

$$\frac{\partial \Pi^w(z_t)}{\partial z} = \frac{\partial \pi(q_t^w, z_t)}{\partial z} + \delta \frac{\partial \Pi^w(z_t + q_t^w)}{\partial z} + \left[\frac{\partial \pi(q_t^w, z_t)}{\partial q} + \delta \frac{\partial \Pi^w(z_t + q_t^w)}{\partial z}\right] \frac{\partial q_t^w}{\partial z}. \quad \text{(A.15)}$$

Continuity depends on $\frac{\partial q_t^w}{\partial z}$, which is continuous for $z \neq \bar{z}^w$ by Proposition 2. Thus, $\frac{\partial \Pi^w(z_t)}{\partial z}$ is continuous for $z \neq \bar{z}^w$, such that $\frac{\partial m^a(z_t)}{\partial z}$ is continuous for $z \notin \{\underline{z}^w, \bar{z}^w, \bar{z}^a\}$.

For $z \in [\bar{z}^w, \bar{z}^a)$, such that $q^w(z) = 0$, we have $\frac{\partial \pi(0,z)}{\partial z} = 0$ and $\frac{\partial q^w(z)}{\partial z} = 0$, which implies

$$\lim_{z \to \bar{z}^{w+}} \frac{\partial \Pi^w(z)}{\partial z} = 0. \quad \text{(A.16a)}$$

For $z \to \bar{z}^{w-}$, such that $q^w(z) \to 0$, we have $\frac{\partial \pi(0,z)}{\partial q} > 0$, $\frac{\partial \pi(0,z)}{\partial z} = 0$ and $\frac{\partial q^w(z)}{\partial z} \leq 0$ by Proposition 2, which implies

$$\begin{aligned}
\lim_{z \to \bar{z}^{w-}} \frac{\partial \Pi^w(z)}{\partial z} &= \lim_{z \to \bar{z}^{w-}} \left[\frac{\partial \pi(q^w(z), z)}{\partial q} \frac{\partial q^w(z)}{\partial z} + \delta \frac{\partial \Pi^w(z + q^w(z))}{\partial z} \left[1 + \frac{\partial q^w(z)}{\partial z}\right]\right] \\
\Rightarrow \frac{\partial \Pi^w(\bar{z}^{w-})}{\partial z} &= \frac{\partial \pi(0, \bar{z}^{w-})}{\partial q} \frac{\partial q^w(\bar{z}^{w-})}{\partial z} + \delta \frac{\partial \Pi^w(\bar{z}^{w-})}{\partial z} \left[1 + \frac{\partial q^w(\bar{z}^{w-})}{\partial z}\right] \\
\Leftrightarrow \frac{\partial \Pi^w(\bar{z}^{w-})}{\partial z} &= \frac{\frac{\partial \pi(0, \bar{z}^{w-})}{\partial q} \frac{\partial q^w(\bar{z}^{w-})}{\partial z}}{1 - \delta \left[1 + \frac{\partial q^w(\bar{z}^{w-})}{\partial z}\right]} \leq 0. \quad \text{(A.16b)}
\end{aligned}$$

Using (A.16) in (A.14) yields:

$$\lim_{z \to \underline{z}^{w+}} \frac{\partial m^a(z)}{\partial z} - \lim_{z \to \underline{z}^{w-}} \frac{\partial m^a(z)}{\partial z} = -\frac{\eta}{\lambda} \frac{\frac{\partial \pi(0, \bar{z}^{w-})}{\partial q} \frac{\partial q^w(\bar{z}^{w-})}{\partial z}}{1 - \delta \left[1 + \frac{\partial q^w(\bar{z}^{w-})}{\partial z}\right]} \delta \left[1 + \frac{\partial q^a(\underline{z}^w)}{\partial z}\right] \geq 0, \quad \text{(A.17a)}$$

$$\lim_{z \to \bar{z}^{w+}} \frac{\partial m^a(z)}{\partial z} - \lim_{z \to \bar{z}^{w-}} \frac{\partial m^a(z)}{\partial z} = \frac{\eta}{\lambda} \frac{\frac{\partial \pi(0, \bar{z}^{w-})}{\partial q} \frac{\partial q^w(\bar{z}^{w-})}{\partial z}}{1 - \delta \left[1 + \frac{\partial q^w(\bar{z}^{w-})}{\partial z}\right]} \leq 0, \quad \text{(A.17b)}$$

where $\frac{\partial q^a(\underline{z}^w)}{\partial z} \in (-1, 0)$ by Proposition 2. If and only if $\eta > 0$ and $\frac{\partial q^w(\bar{z}^{w-})}{\partial z} < 0$, (A.17a) and (A.17b) hold as strict inequalities, such that $\frac{\partial m^a(z)}{\partial z}$ jumps up at $z = \underline{z}^w$, and it jumps down at $z = \bar{z}^w$. □

Proposition A.1 (Negative Payments for $z < \underline{z}^w$.) *Suppose that $\eta = 0$. Then $m^a(z) > 0$ holds for all $z \in [0, \underline{z}^w)$. Now suppose that $\eta > 0$ and $q^a < q^w$ for some $z \in [0, \underline{z}^w)$. Then $m^a(z) < 0$ holds for some $z \in [0, \underline{z}^w)$.*

Proof. For $\eta = 0$, (17) becomes

$$m^a(z_t) = \frac{1}{\phi} \cdot \left[w(q_t^w, z_t) + \delta W^w(z_t + q_t^w) - w(q_t^a, z_t) - \delta W^w(z_t + q_t^a)\right]. \quad \text{(A.18)}$$

Since q^w maximizes $w(q_t, z_t) + \delta W^w(z_t + q_t)$, (A.18) is positive, such that $m^a(z) > 0$ holds for all $z \in [0, \underline{z}^w)$. Differentiating (17) yields:

$$\begin{aligned}\frac{\partial m^a(z_t)}{\partial z} = \frac{\eta}{\lambda} \cdot \Bigg\{ & \frac{\partial \pi(q_t^a, z_t)}{\partial z} - \frac{\partial \pi(q_t^w, z_t)}{\partial z} + \left[\frac{\partial \pi(q_t^a, z_t)}{\partial q} \frac{\partial q_t^a}{\partial z} - \frac{\partial \pi(q_t^w, z_t)}{\partial q} \frac{\partial q_t^w}{\partial z} \right] \\ & + \delta \left[\frac{\partial \Pi^w(z_{t+1}^a)}{\partial z} - \frac{\partial \Pi^w(z_{t+1}^w)}{\partial z} \right] + \delta \left[\frac{\partial \Pi^w(z_{t+1}^a)}{\partial z} \frac{\partial q_t^a}{\partial z} - \frac{\partial \Pi^w(z_{t+1}^w)}{\partial z} \frac{\partial q_t^w}{\partial z} \right] \Bigg\} \\ + \frac{1-\eta}{\phi} \cdot \Bigg\{ & \frac{\partial w(q_t^w, z_t)}{\partial z} - \frac{\partial w(q_t^a, z_t)}{\partial z} + \left[\frac{\partial w(q_t^w, z_t)}{\partial q} \frac{\partial q_t^w}{\partial z} - \frac{\partial w(q_t^a, z_t)}{\partial q} \frac{\partial q_t^a}{\partial z} \right] \\ & + \delta \left[\frac{\partial W^w(z_{t+1}^w)}{\partial z} - \frac{\partial W^w(z_{t+1}^a)}{\partial z} \right] + \delta \left[\frac{\partial W^w(z_{t+1}^w)}{\partial z} \frac{\partial q_t^w}{\partial z} - \frac{\partial W^w(z_{t+1}^a)}{\partial z} \frac{\partial q_t^a}{\partial z} \right] \Bigg\}. \end{aligned} \tag{A.19}$$

Since $q^a(\underline{z}^w) = \bar{z}^w - \underline{z}^w > q^w(\underline{z}^w)$ holds, $q^a < q^w$ for some $z \in [0, \underline{z}^w)$ implies $q^a = q^w$ for some $z \in [0, \underline{z}^w)$. For $q^a = q^w$, (17) becomes $m^a(z)|_{q^a=q^w} = 0$ and (A.19) becomes

$$\begin{aligned} & \frac{\partial m^a(z_t)}{\partial z}\Big|_{q_t^a = q_t^w} \\ &= \frac{\eta}{\lambda} \cdot \left[\frac{\partial \pi(q_t^w, z_t)}{\partial q} + \delta \frac{\partial \Pi^w(z_{t+1}^w)}{\partial z} \right] \left(\frac{\partial q_t^a}{\partial z} - \frac{\partial q_t^w}{\partial z} \right) \\ &\quad - \frac{1-\eta}{\phi} \cdot \left[\frac{\partial w(q_t^w, z_t)}{\partial q} + \delta \frac{\partial W^w(z_{t+1}^w)}{\partial z} \right] \left(\frac{\partial q_t^a}{\partial z} - \frac{\partial q_t^w}{\partial z} \right) \\ &= \frac{\eta(1+\mu)}{\phi} \cdot \left[\frac{\partial w(q_t^w, z_t)}{\partial q} + \mu \frac{\partial \pi(q_t^w, z_t)}{\partial q} + \delta \left[\frac{\partial W^w(z_{t+1}^w)}{\partial z} + \mu \frac{\partial \Pi^w(z_{t+1}^w)}{\partial z} \right] \right] \left(\frac{\partial q_t^a}{\partial z} - \frac{\partial q_t^w}{\partial z} \right) \\ &\quad - \frac{1}{\phi} \cdot \left[\frac{\partial w(q_t^w, z_t)}{\partial q} + \delta \frac{\partial W^w(z_{t+1}^w)}{\partial z} \right] \left(\frac{\partial q_t^a}{\partial z} - \frac{\partial q_t^w}{\partial z} \right). \end{aligned} \tag{A.20}$$

Since q^w maximizes $w(q, z) + \delta W^w(z + q)$, the second line of (A.20) is zero, and since q^a maximizes $w(q, z) + \mu\pi(q, z) + \delta \left[W^a(z + q) + \mu\Pi^a(z + q)\right]$ and $q^a(\underline{z}^w) > q^w(\underline{z}^w)$ implies $\left(\frac{\partial q^a}{\partial z} - \frac{\partial q^w}{\partial z}\right)\Big|_{q^a=q^w} > 0$ for some $q^a = q^w$, the first line of (A.20) cannot be zero, such that $\frac{\partial m^a(z)}{\partial z}\Big|_{q^a=q^w} \neq 0$. $m^a(z)|_{q^a=q^w} = 0$ and $\frac{\partial m^a(z)}{\partial z}\Big|_{q^a=q^w} \neq 0$ then implies that $m^a(z)$ changes its sign at $q^a = q^w$, such that $m^a(z) < 0$ holds for some $z \in [0, \underline{z}^w)$. □

B Proofs of Section 5

We guess that there exist constants Y_0^i and Y_1^i such that the following state-dependent extraction functions solve the maximizations $q^w(z) = \operatorname{argmax}_q w(q, z) + \delta W^w(z + q)$,

$q^\pi(z) = \text{argmax}_q\, \pi(q,z) + \delta\Pi^\pi(z+q)$ and (11) for the functions (21):

$$q^i(z) = \begin{cases} Y_0^i + Y_1^i z & \text{if } Y_0^i + Y_1^i z > 0, \\ 0 & \text{if } Y_0^i + Y_1^i z \leq 0, \end{cases} \qquad \text{for } i = w, \pi, a. \tag{B.1}$$

Thus, we expect the linear-quadratic utility functions to lead to extraction functions that are linear in the state z as long as positive extraction is optimal. For stability of the dynamic system (cf. Gandolfo, 2009, Chapter 3), we conjecture that

$$0 < 1 + Y_1^i \leq 1 \qquad \text{for } i = w, \pi, a \tag{B.2}$$

must hold. To solve for the coefficients, we first use them to state the intertemporal value functions $W^i(z)$ and $\Pi^i(z)$ in an explicit form.

Lemma B.1 (Intertemporal Values) *Suppose that $q^i(z)$ from* (B.1) *is the optimal extraction function for $i = w, \pi, a$. Then,*

$$W^i(z) = \frac{\beta_w + \frac{Y_0^i}{Y_1^i}\gamma_w}{1 - \delta\left(1 + Y_1^i\right)} q^i(z) - \frac{\frac{\alpha_w}{2} + \frac{1}{Y_1^i}\gamma_w}{1 - \delta\left(1 + Y_1^i\right)^2} q^i(z)^2 - \frac{\chi_z z + \frac{\chi_{zz}}{2} z^2}{1 - \delta}, \tag{B.3a}$$

$$\Pi^i(z) = \frac{\beta_\pi + \frac{Y_0^i}{Y_1^i}\gamma_\pi}{1 - \delta\left(1 + Y_1^i\right)} q^i(z) - \frac{\frac{\alpha_\pi}{2} + \frac{1}{Y_1^i}\gamma_\pi}{1 - \delta\left(1 + Y_1^i\right)^2} q^i(z)^2. \tag{B.3b}$$

Proof. First suppose that $Y_0^i + Y_1^i z \leq 0$, implying $q^i(z) = 0$ forever because $Y_1^i \leq 0$ by (B.2) and z cannot decrease. (21a), (21b) and (21c) become $w(0,z) = -(\chi_z z + \chi_{zz} z^2/2)$, $\pi(0,z) = 0$ and $[w(0,z) + \mu\pi(0,z)]/(1+\mu) = w(0,z)/(1+\mu)$, respectively. Then, $W^i(z) = -(\chi_z z + \chi_{zz} z^2/2)/(1-\delta)$, $\Pi^i(z) = 0$ and $[W^i(z) + \mu\Pi^i(z)]/(1+\mu) = W^i(z)/(1+\mu)$, which is consistent with (B.3). Let us turn to the unconstrained case. Substituting (B.1) into the equation of motion (1) yields $z_{t+1}^i = z_t^i + Y_0^i + Y_1^i z_t^i$. Hence,

$$z_{t+s}^i = z_t^i + \sum_{\nu=0}^{s-1} q_{t+\nu}^i = z_t^i + sY_0^i + Y_1^i \sum_{\nu=0}^{s-1} z_{t+\nu}^i. \tag{B.4}$$

After some substitutions and rearrangements, we obtain

$$z_{t+s}^i = \left(1 + Y_1^i\right)^s z_t^i + Y_0^i \sum_{\nu=0}^{s-1} \left(1 + Y_1^i\right)^\nu = \left(1 + Y_1^i\right)^s \left(\frac{Y_0^i}{Y_1^i} + z_t^i\right) - \frac{Y_0^i}{Y_1^i}. \tag{B.5}$$

Substituting into (B.1) yields:

$$q_{t+s}^i = \left(1 + Y_1^i\right)^s \left(Y_0^i + Y_1^i z_t\right). \tag{B.6}$$

Using (21a), we then obtain:

$$\begin{aligned}
w(q_{t+s}^i, z_{t+s}^i) &= \frac{Y_0^i}{Y_1^i}\chi_z - \left(\frac{Y_0^i}{Y_1^i}\right)^2 \chi_{zz} \\
&+ \left(\beta_w + \frac{Y_0^i}{Y_1^i}\gamma_w + \frac{Y_1^i - r}{rY_1^i}\chi_z - \frac{Y_0^i}{Y_1^i}\frac{2(Y_1^i - r)}{rY_1^i}\chi_{zz}\right)\left(1+Y_1^i\right)^s\left(Y_0^i + Y_1^i z_t^i\right) \\
&- \left(\frac{\alpha_w}{2} + \frac{1}{Y_1^i}\gamma_w - \frac{1}{Y_1^i}\frac{(2+Y_1^i)Y_1^i - r}{rY_1^i}\chi_{zz}\right)\left[\left(1+Y_1^i\right)^s\left(Y_0^i + Y_1^i z_t^i\right)\right]^2. \qquad \text{(B.7)}
\end{aligned}$$

Substituting this into $\sum_{s=0}^{\infty}\delta^s \cdot w(q_{t+s}^i, z_{t+s}^i)$ then yields (B.3a). (B.3b) can be obtained in the same manner using (21b) and substituting the result into $\sum_{s=0}^{\infty}\delta^s \cdot \pi(q_{t+s}^i, z_{t+s}^i)$.□

Proof of Proposition 5 $q^w(z)$ maximizes $w(q,z) + \delta W^w(z+q)$. Substituting (21a) and (B.3a), we derive a first-order condition for q, into which we again substitute $q^w(z) = Y_0^w + Y_1^w z$:

$$\begin{aligned}
&\beta_w - \gamma_w z - \alpha_w\left(Y_0^w + Y_1^w z\right) \\
&+ \delta\left[\frac{Y_1^w\beta_w + Y_0^w\gamma_w}{1-\delta\left(1+Y_1^w\right)} - \frac{Y_1^w\alpha_w + 2\gamma_w}{1-\delta\left(1+Y_1^w\right)^2}\left[Y_0^w + Y_1^w\left[Y_0^w + \left(1+Y_1^w\right)z\right]\right]\right] = 0. \qquad \text{(B.8)}
\end{aligned}$$

This condition must also hold for $z = z + q^w(z) = z + Y_0^w + Y_1^w z$. This generates two equations in two unknowns. These contain quadratic terms, but only $Y_0^w = \psi_w \bar{z}^w$ and $Y_1^w = -\psi_w$ fulfill (B.2). $Y_0^i = \psi_i \bar{z}^i$ and $Y_1^i = -\psi_i$ for $i = \pi, a$ are derived in the same way, maximizing $\pi(q,z) + \delta\Pi^\pi(z+q)$ and $[w(q,z) + \delta W^a(z+q) + \mu[\pi(q,z) + \Pi^a(z+q)]]/(1+\mu)$, respectively. Using these equations in (B.2) yields $0 < 1 - \psi_i \leq 1$, which is fulfilled by (23), and using them in (B.5) and (B.6) yields (24) and (25).

Using (24) for $i = w, a$ in (16) yields (29). For $z < \bar{z}^w$, $\Delta_{a,w}(z)$ is positive if $\psi_a \geq \psi_w$ (Cases I and II) or if $\psi_a < \psi_w$ and $\psi_a \bar{z}^a > \psi_w \bar{z}^w$ (Case III). If $\psi_a < \psi_w$ and $\psi_a \bar{z}^a \leq \psi_w \bar{z}^w$ (Case IV), then $\Delta_{a,w}(z) \gtreqless 0 \Leftrightarrow z \gtreqless \hat{z}$ from (26). For $z < \bar{z}^w$, $\Delta'_{a,w}(z) = -(\psi_a - \psi_w)$ is negative in Case I, zero in Case II and positive in Cases III and IV. For $z \in [\bar{z}^w, \bar{z}^a)$, $\Delta_{a,w}(z)$ is positive and $\Delta'_{a,w}(z) = -\psi_a$ is negative, and for $z \geq \bar{z}^a$, we have $\Delta_{a,w}(z) = \Delta'_{a,w}(z) = 0$. □

To prepare the proofs of Propositions 6 and B.1, we derive the intertemporal payments and the payments within the periods.

Lemma B.2 (Payments) *The present value of payments is*

$$\begin{aligned}
&M^a(z) \\
&= \frac{\eta(1+\mu)}{\phi}\left\{\frac{\frac{\gamma_a}{\psi_a} - \frac{\alpha_a}{2}}{1-\delta(1-\psi_a)^2}q^a(z)^2 - \left[\frac{\frac{\gamma_a}{\psi_w} - \frac{\alpha_a}{2}}{1-\delta(1-\psi_w)^2}q^w(z)^2 - \frac{\gamma_a(\bar{z}^w - \bar{z}^a)}{1-\delta(1-\psi_w)}q^w(z)\right]\right\}
\end{aligned}$$

$$+\frac{1}{\phi}\left\{\frac{\frac{\gamma_w}{\psi_w}-\frac{\alpha_w}{2}}{1-\delta(1-\psi_w)^2}q^w(z)^2-\left[\frac{\frac{\gamma_w}{\psi_a}-\frac{\alpha_w}{2}}{1-\delta(1-\psi_a)^2}q^a(z)^2-\frac{\gamma_w(\bar{z}^a-\bar{z}^w)}{1-\delta(1-\psi_a)}q^a(z)\right]\right\}. \quad \text{(B.9)}$$

The payments in any single period are

$$m^a(z)=\begin{cases}\Theta_2\left[\Theta_1\left(\psi_a-\psi_w\right)\left[q^a(z)-q^w(z)\right]+\left[q^a(z)-q^w(z)\right]^2\right] & \textit{if } z<\underline{z}^w,\\ \frac{\gamma_w}{\phi}\left(\bar{z}^a-\bar{z}^w\right)q^a(z)+\Theta_3 q^a(z)^2-\Theta_4 q^w(z)-\Theta_5 q^w(z)^2 & \textit{if } z\in\left[\underline{z}^w,\bar{z}^w\right),\\ \frac{\gamma_w}{\phi}\left(\bar{z}^a-\bar{z}^w\right)q^a(z)+\Theta_3 q^a(z)^2 & \textit{if } z\in\left[\bar{z}^w,\bar{z}^a\right),\end{cases} \quad \text{(B.10)}$$

where

$$\Theta_1\equiv\frac{1}{\phi}\frac{\eta(1+\mu)\delta\left(1-\delta\right)}{1-\delta\left(1-\psi_w\right)^2}\frac{\gamma_a\left(\bar{z}^a-\bar{z}^w\right)}{1-\delta\left(1-\psi_w\right)}\frac{\psi_w}{1-\delta\left(1-\psi_a\right)}\Big/\Theta_2 \qquad >0, \quad \text{(B.11a)}$$

$$\Theta_2\equiv\frac{1}{\phi}\frac{1-\delta}{1-\delta\left(1-\psi_w\right)^2}\left[\eta\left(1+\mu\right)\left(\frac{\gamma_a}{\psi_a}-\frac{\alpha_a}{2}\right)+\frac{\gamma_w}{\psi_w}-\frac{\alpha_w}{2}\right] \qquad >0, \quad \text{(B.11b)}$$

$$\Theta_3\equiv\frac{1}{\phi}\left[\eta\left(1+\mu\right)\left(\frac{\gamma_a}{\psi_a}-\frac{\alpha_a}{2}\right)-\frac{\gamma_w}{\psi_a}+\frac{\alpha_w}{2}\right], \quad \text{(B.11c)}$$

$$\Theta_4\equiv\frac{1}{\phi}\eta(1+\mu)\frac{\gamma_a\left(\bar{z}^a-\bar{z}^w\right)}{1-\delta\left(1-\psi_w\right)} \qquad >0, \quad \text{(B.11d)}$$

$$\Theta_5\equiv\frac{1}{\phi}\frac{1}{1-\delta\left(1-\psi_w\right)^2}\left[\eta\left(1+\mu\right)\left(\frac{\gamma_a}{\psi_w}-\frac{\alpha_a}{2}\right)-\frac{\gamma_w}{\psi_w}+\frac{\alpha_w}{2}\right], \quad \text{(B.11e)}$$

and where $\frac{\partial\Theta_1}{\partial\eta},\frac{\partial\Theta_2}{\partial\eta},\frac{\partial\Theta_3}{\partial\eta},\frac{\partial\Theta_4}{\partial\eta}>0$.

Proof. Substituting (B.3) as well as $Y_0^i=\psi_i\bar{z}^i$ and $Y_1^i=-\psi_i$ from the proof of Proposition 5 for $i=w,a$ into (12a), using (22) and simplifying yields (B.9). Substituting (B.9) into (12b), using q^w and q^a from Proposition 5 and simplifying yields (B.10). $0<\psi_i\leq\frac{\gamma_i}{\alpha_i}<1$ from (23) and $\bar{z}^a<\bar{z}^w$ prove $\Theta_1,\Theta_2,\Theta_4,\frac{\partial\Theta_2}{\partial\eta},\frac{\partial\Theta_3}{\partial\eta},\frac{\partial\Theta_4}{\partial\eta}>0$. Finally, differentiating (B.11a) yields

$$\frac{\partial\Theta_1}{\partial\eta}\frac{\eta}{\Theta_1}=\frac{1}{\phi}\frac{1-\delta}{1-\delta\left(1-\psi_w\right)^2}\left(\frac{\gamma_w}{\psi_w}-\frac{\alpha_w}{2}\right)\Big/\Theta_2>0. \quad \text{(B.12)}$$

□

Proof of Proposition 6 Substituting $\Delta_{a,w}(z)=q^a(z)-q^w(z)$ into the first line of (B.10) yields (28), and differentiating (28) yields

$$\frac{\partial m^a(z)}{\partial z}=-\Theta_2\left[\Theta_1\left(\psi_a-\psi_w\right)^2+2\left(\psi_a-\psi_w\right)\Delta_{a,w}(z)\right], \quad \text{(B.13a)}$$

$$\frac{\partial^2 m^a(z)}{\partial z^2}=2\Theta_2\left(\psi_a-\psi_w\right)^2>0. \quad \text{(B.13b)}$$

In Case I, $\psi_a>\psi_w$ and $\Delta_{a,w}(z)>0$ hold, such that (28) is positive and (B.13a) is negative, which together with $\frac{\partial\Theta_1}{\partial\eta},\frac{\partial\Theta_2}{\partial\eta}>0$ implies $\frac{\partial m^a(z)}{\partial\eta}>0$ and $\frac{\partial^2 m^a(z)}{\partial z\partial\eta}<0$. In Case

II, $\psi_a = \psi_w$ and $\Delta_{a,w}(z) > 0$ hold, such that (28) is positive and (B.13a) is zero, which together with $\frac{\partial \Theta_1}{\partial \eta}, \frac{\partial \Theta_2}{\partial \eta} > 0$ implies $\frac{\partial m^a(z)}{\partial \eta} > 0$ and $\frac{\partial^2 m^a(z)}{\partial z \partial \eta} = 0$.

Using $\hat{z}$ from (26) in (28) and (B.13a) yields

$$m^a(z) = \Theta_2 \left(\psi_a - \psi_w\right)^2 \left(\hat{z} - z\right) \left(\hat{z} + \Theta_1 - z\right), \tag{B.14a}$$

$$\frac{\partial m^a(z)}{\partial z} = \Theta_2 \left(\psi_a - \psi_w\right)^2 \left(\hat{z} + \Theta_1/2 - z\right) (-2) . \tag{B.14b}$$

In Case III and in Case IV for $z > \hat{z}$, $\psi_a < \psi_w$ and $\hat{z} - z < 0$, such that $\text{sign}[m^a(z)] = \text{sign}[z - (\hat{z} + \Theta_1)]$ and $\text{sign}\left[\frac{\partial m^a(z)}{\partial z}\right] = \text{sign}[z - (\hat{z} + \Theta_1/2)]$. In Case IV for $z \leq \hat{z}$, $\psi_a < \psi_w$ and $\hat{z} - z \geq 0$, such that $\text{sign}[m^a(z)] = \text{sign}(\hat{z} - z)$ and $\frac{\partial m^a(z)}{\partial z} < 0$. □

Proposition B.1 (Development of Payments for $z \geq \bar{z}^w$) *For $z \in [\bar{z}^w, \bar{z}^a)$, we have $m^a(z) > 0$, $\frac{\partial m^a(z)}{\partial \eta} > 0$ and $\frac{\partial^2 m^a(z)}{\partial z \partial \eta} < 0$. For $z \to \bar{z}^a$, $m^a(z)$ asymptotically converges to zero. For this convergence to be monotone,*

$$\eta \geq \underline{\eta} \equiv \frac{1}{2(1+\mu)} \left(1 - \frac{\alpha_w - \frac{\alpha_a}{2} - \frac{\gamma_w - \gamma_a}{\psi_a}}{\frac{\gamma_a}{\psi_a} - \frac{\alpha_a}{2}} \right) = - \frac{\gamma_w}{2(1+\mu)} \frac{\frac{\alpha_w}{\gamma_w} - \frac{1}{\psi_a}}{\frac{\gamma_a}{\psi_a} - \frac{\alpha_a}{2}} \tag{B.15}$$

is necessary and sufficient. For this inequality to hold, $\eta \geq 1/[2(1+\mu)]$ together with $\chi_{zz} = 0$ is sufficient; $\alpha_w/\gamma_w \geq 1/\psi_a (\geq \alpha_a/\gamma_a)$ is sufficient, and it is necessary if $\eta = 0$. If the inequality does not hold, $m^a(z)$ is increasing for $z = \bar{z}^w$ and declining for large z, in particular for $z \geq (\bar{z}^a + \bar{z}^w)/2$.

Proof. The first two sentences of the proposition follow from Proposition 3. Using $\Theta_3 > -\gamma_w/\psi_a$ in the third line of (B.10) and differentiating yields

$$\frac{\partial m^a(z)}{\partial z} < - \frac{2\gamma_w \psi_a}{\phi} \left(z - \frac{\bar{z}^a + \bar{z}^w}{2} \right), \tag{B.16}$$

so that the payments are declining if $z \geq (\bar{z}^a + \bar{z}^w)/2$. They are always declining if $\frac{\partial m^a(\bar{z}^w)}{\partial z} \leq 0$, which yields (B.15). If $\chi_{zz} = 0$, then $\alpha_w - \frac{\alpha_a}{2} - \frac{\gamma_w - \gamma_a}{\psi_a}$ becomes $[\alpha_w/2 + \mu(\kappa_{qq}/2 + \chi_{qq})]/(1+\mu) > 0$, so that $\eta \geq 1/[2(1+\mu)]$ together with $\chi_{zz} = 0$ is sufficient for (B.15) to hold. Finally, $\alpha_w/\gamma_w \geq 1/\psi_a (\geq \alpha_a/\gamma_a)$ is sufficient for (B.15) to hold, and it is necessary for (B.15) to hold if $\eta = 0$. □

Proposition B.2 (Impact of Demand Shocks on Payments) *A positive demand shock (a greater ρ_q) raises the payments within the periods for $z \in [\bar{z}^w, \bar{z}^a)$ and for $z < \underline{z}^w$ in Case I. In Case II, it raises the payments if $\chi_{zz} > 0$, and it leaves the payments unaffected if $\chi_{zz} = 0$. In Cases III and IV, $\chi_{zz} = 0$ implies $\frac{\partial m^a(z)}{\partial \rho_q} \gtreqless 0 \Leftrightarrow z \lesseqgtr \hat{z} + \Theta_1/2$, such that a positive demand shock reduces the payments if $\frac{\partial m^a(z)}{\partial z} > 0$.*

Proof. Differentiating (B.10) yields

$$\frac{\partial m^a(z)}{\partial \rho_q} = \begin{cases} \Theta_2\Theta_1\left(\psi_a-\psi_w\right)\Delta_{a,w}(z)\cdot\frac{\gamma_w-\gamma_a}{\gamma_a\gamma_w\left(\bar{z}^a-\bar{z}^w\right)} & \\ \quad +\Theta_2\left[\Theta_1\left(\psi_a-\psi_w\right)+2\Delta_{a,w}(z)\right]\cdot\left(\frac{\psi_a}{\gamma_a}-\frac{\psi_w}{\gamma_w}\right) & \text{if } z<\underline{z}^w, \\ \gamma_w q^a(z)\cdot\frac{\gamma_w-\gamma_a}{\gamma_a\gamma_w}+\left[\gamma_w\left(\bar{z}^a-\bar{z}^w\right)+2\Theta_3 q^a(z)\right]\cdot\frac{\psi_a}{\gamma_a} & \text{if } z\in\left[\bar{z}^w,\bar{z}^a\right). \end{cases} \tag{B.17}$$

Since $\gamma_w \geq \gamma_a$, $\frac{\partial m^a(z)}{\partial \rho_q}$ is positive for $z \in [\bar{z}^w, \bar{z}^a)$. For $z < \underline{z}^w$, it is positive in Case I (where $\psi_a > \psi_w$ and $\Delta_{a,w}(z) > 0$), and it is positive [zero] in Case II (where $\psi_a = \psi_w$ and $\Delta_{a,w}(z) > 0$) if $\gamma_w > \gamma_a$ [$\gamma_w = \gamma_a$]. Now suppose $\gamma_w = \gamma_a \Leftrightarrow \chi_{zz} = 0$, such that substituting (B.13a) into (B.17) yields

$$\frac{\partial m^a(z)}{\partial \rho_q} = -\frac{1}{\gamma_a}\cdot\frac{\partial m^a(z)}{\partial z} \qquad \text{if } z<\underline{z}^w. \tag{B.18}$$

Thus, $\frac{\partial m^a(z)}{\partial \rho_q} \gtreqless 0$ in Cases III and IV if $\gamma_w = \gamma_a$ and $\frac{\partial m^a(z)}{\partial z} \lesseqgtr 0 \Leftrightarrow z \lesseqgtr \hat{z} + \Theta_1/2$. □

To prepare the proof of Proposition B.3, we derive the intertemporal environmental damages.

Lemma B.3 (Intertemporal Environmental Damages) *The present value of environmental damages for $i = w, \pi, a$ is*

$$D^i(z) = \frac{\frac{\chi_{qq}+\frac{\chi_{zz}}{r}}{2}-\frac{\chi_{zz}}{r}\frac{1}{\psi_i}}{1-\delta(1-\psi_i)^2}q^i(z)^2+\frac{\chi_q+\frac{\chi_z}{r}+\frac{\chi_{zz}}{r}\bar{z}^i}{1-\delta(1-\psi_i)}q^i(z)+\frac{\chi_z z+\frac{\chi_{zz}}{2}z^2}{1-\delta}. \tag{B.19}$$

Proof. Using (24) and (25) in $\sum_{s=0}^{\infty}\delta^s\left[\chi_z z^i_{t+s}+\chi_{zz}/2(z^i_{t+s})^2+\chi_q q^i_{t+s}+\chi_{qq}/2(q^i_{t+s})^2\right]$ for $i = w, \pi, a$ and evaluating yields (B.19). □

Proposition B.3 (Impact of Lobbying on the Intertemporal Environmental Damages for $z = 0 < \bar{z}^w$ and $\chi_{zz} = \chi_{qq} = 0$) *For $z = 0 < \bar{z}^w$ and $\chi_{zz} = \chi_{qq} = 0$, lobbying increases the intertemporal environmental damages if $\chi_q, \chi_z, \kappa_q, \kappa_{qq}$ and μ are sufficiently high and ρ_q, ρ_{qq} and r are sufficiently low.*

Proof. Substituting $z = \chi_{zz} = \chi_{qq} = 0$ into (B.19) for $i = a$ and differentiating yields

$$\begin{aligned} \left.\frac{\partial D^a(0)}{\partial \mu}\right|_{\chi_{zz}=\chi_{qq}=0} &= \frac{\psi_a\left(\chi_q+\frac{\chi_z}{r}\right)}{\gamma_a(1+\mu)^2[1-\delta\left(1-\psi_a\right)]}\cdot\frac{\frac{\rho_{qq}}{1+\mu}+\sqrt{\alpha_a^2+\frac{4}{r}\gamma_a\left(\alpha_a-\gamma_a\right)}}{\sqrt{\alpha_a^2+\frac{4}{r}\gamma_a\left(\alpha_a-\gamma_a\right)}} \\ &\cdot\left[\chi_q+\frac{\chi_z}{r}-\frac{\left(\rho_q-\kappa_q\right)\rho_{qq}}{\frac{\rho_{qq}}{1+\mu}+\sqrt{\left(\kappa_{qq}+\rho_{qq}+\frac{\mu\rho_{qq}}{1+\mu}\right)^2+\frac{4}{r}\kappa_{qz}\left(\kappa_{qq}+\rho_{qq}+\frac{\mu\rho_{qq}}{1+\mu}-\kappa_{qz}\right)}}\right]. \end{aligned} \tag{B.20}$$

The fractions in the first line are positive. The second line increases with $\chi_q, \chi_z, \kappa_q, \kappa_{qq}$ and μ, and declines with ρ_q, ρ_{qq} and r, which proves the proposition. □

C Calibration for Section 6

In this section, we denote (crude) oil by o, (natural) gas by g and coal by k, and let $\epsilon \equiv -\frac{\partial q}{\partial p}\frac{q}{p}$ denote the absolute value of the price elasticity of demand. Current prices are 11.00 *USD/MBtu* for oil, 4.47 *USD/MBtu* for gas, and 2.49 *USD/MBtu* for coal (BP, 2020, pp. 26, 39, 49; median values).[30] The global yearly consumption of oil is $208 \cdot 10^9$ *MBtu*, that of gas is $138 \cdot 10^9$ *MBtu*, and that of coal is $150 \cdot 10^9$ *MBtu* (BP, 2020, pp. 20, 36, 47). The survey of Huntington, Barrios and Arora (2019, Table 1) finds a long-term oil demand price elasticity of 0.15 in developing countries and of 0.43 in OECD countries, such that we set $\epsilon^o = 0.3$. Furthermore, it reports an average long-term gas demand price elasticity of 1.36 in developing countries and of 0.96 in OECD countries, whereas the meta-analysis of Labandeira, Labeaga and López-Otero (2017, Table A4) finds an overall long-term gas demand price elasticity of 0.68. By taking the average of these values, we assume $\epsilon^g = 1$. Huntington, Barrios and Arora (2019, p. 11) note that "coal demand estimates are very much underrepresented in the available literature". However, there are some estimates of China's long-term coal demand price elasticity in the range of 0.3–0.7 (Ma et al., 2008; Bloch, Rafiq and Salim, 2015; Burke and Liao, 2015), and since China dominates the global coal market with a share of global coal consumption of more than 50% (BP, 2020, p. 47), we assume that $\epsilon^k = 0.5$ holds for the global price elasticity. From $p = \rho_q - \rho_{qq}q$ and $\epsilon = 1/(\rho_q/p - 1)$, we then get $\rho_q = p \cdot (1/\epsilon + 1)$ and $\rho_{qq} = p/(\epsilon q)$ and, thus, $\rho_q^o = 47.7\,\textit{USD/MBtu} > \rho_q^g = 8.94\,\textit{USD/MBtu} > \rho_q^k = 7.47\,\textit{USD/MBtu}$ and $\rho_{qq}^o = 171 \cdot 10^{-12}\,\textit{USD/MBtu}^2 > \rho_{qq}^k = 33.2 \cdot 10^{-12}\,\textit{USD/MBtu}^2 > \rho_{qq}^g = 32.4 \cdot 10^{-12}\,\textit{USD/MBtu}^2$.

The marginal production cost of oil increases from 2.98 *USD/MBtu* to 12.1 *USD/MBtu* for the next $208 \cdot 10^{11}$ *MBtu*, that of gas increases from 4.63 *USD/MBtu* to 6.63 *USD/MBtu* for the next $138 \cdot 10^{11}$ *MBtu*, and that of coal increases from 1.87 *USD/MBtu* to 4.15 *USD/MBtu* for the next $150 \cdot 10^{11}$ *MBtu* of resources (IEA, 2013, pp. 228, 231, 233; average values). $\frac{\partial c(q,z)}{\partial q} = \kappa_q + \kappa_{qz}z$ then implies $\kappa_q^g = 4.63\,\textit{USD/MBtu} > \kappa_q^o = 2.98\,\textit{USD/MBtu} > \kappa_q^k = 1.87\,\textit{USD/MBtu}$ and $\kappa_{qz}^o = 426 \cdot 10^{-15}\,\textit{USD/MBtu}^2 > \kappa_{qz}^k = 152 \cdot 10^{-15}\,\textit{USD/MBtu}^2 > \kappa_{qz}^g = 145 \cdot 10^{-15}\,\textit{USD/MBtu}^2$.

We use the social cost of carbon as an example for the intertemporal stock-pollution costs χ_z/r. While estimates vary strongly, we employ the value estimated by the United States Interagency Working Group from 2016, $\chi_z/r = 42\,\textit{USD/tCO}_2$ (IWG, 2016, p. 4). Oil, gas and coal emit $73.2\,\textit{kgCO}_2\textit{/MBtu}$, $53.1\,\textit{kgCO}_2\textit{/MBtu}$ and $93.3\,\textit{kgCO}_2\textit{/MBtu}$ (EIA, 2020*b*), which implies $\chi_z^k/r = 3.92\,\textit{USD/MBtu} > \chi_z^o/r = 3.07\,\textit{USD/MBtu} > \chi_z^g/r = 2.23\,\textit{USD/MBtu}$.

The parameter values calculated so far are summarized in columns 2–6 of Table 2.

[30] *MBtu* = million British thermal units, 1 barrel oil $= 5.8$ *MBtu*, $1\,m^3$ gas $= 0.035$ *MBtu*, 1 tonne coal $= 27.8$ *MBtu*, 1 *EJ* $= 948 \cdot 10^6$ *MBtu*; see IEA (2013, pp. 231–233) and IEA (2021).

Table 2: Parameter values of fossil fuels.

	ρ_q	ρ_{qq}	κ_q	κ_{qz}	χ_z/r	$\bar{z}^\pi/\bar{z}^w$	χ_{qq}	α_w/α_π
o	47.7	$176 \cdot 10^{-12}$	2.98	$426 \cdot 10^{-15}$	3.07	1.07	$\bar{x}^o \cdot 9.35 \cdot 10^{-12}$	$0.5 + 0.027\bar{x}^o$
g	8.94	$32.4 \cdot 10^{-12}$	4.63	$145 \cdot 10^{-15}$	2.23	2.07	$\bar{x}^g \cdot 14.5 \cdot 10^{-12}$	$0.5 + 0.224\bar{x}^g$
k	7.47	$33.2 \cdot 10^{-12}$	1.87	$152 \cdot 10^{-15}$	3.92	3.33	$\bar{x}^k \cdot 13.3 \cdot 10^{-12}$	$0.5 + 0.200\bar{x}^k$

Using these parameter values in $\bar{z}^\pi/\bar{z}^w = (\rho_q - \kappa_q)/(\rho_q - \kappa_q - \chi_z/r)$, we then obtain the seventh column. Furthermore, we show that $\alpha_w/\gamma_w \geq \rho_{qq}/\kappa_{qz} \geq 2$, which is the case for all fossil fuels, is sufficient to exclude Case IV if $\bar{z}^\pi/\bar{z}^w > 2$, which is the case for gas and coal:

Proposition C.1 (Relation between welfare-maximizing and profit-maximizing extraction) *Suppose that $\chi_{zz} = 0$ and $\alpha_w/\gamma_w \geq 2$ hold. If $\bar{z}^\pi/\bar{z}^w > 2$, then the welfare-maximizing extraction is smaller than the profit-maximizing extraction for all $z \in [0, \bar{z}^\pi)$.*

Proof. $\psi_w(\bar{z}^w - z) < \psi_\pi(\bar{z}^\pi - z)$ for $\psi_w \leq \psi_\pi$ since $\bar{z}^w < \bar{z}^\pi$. From (23), we obtain

$$\frac{\alpha_\pi/\gamma_\pi}{\alpha_w/\gamma_w} > \frac{\psi_w}{\psi_\pi} \quad \Leftrightarrow \quad \left(\frac{\alpha_\pi}{\gamma_\pi} - \frac{\alpha_w}{\gamma_w}\right)\left[\frac{\alpha_\pi}{\gamma_w} - \frac{\alpha_w}{\gamma_w} + \frac{\alpha_w/\gamma_w(\alpha_w/\gamma_w - 2)}{\alpha_w/\gamma_w - 1}\right] > 0. \tag{C.1}$$

Thus, $\alpha_\pi/\gamma_\pi > \alpha_w/\gamma_w \geq 2$ is sufficient for $\frac{\alpha_\pi/\gamma_\pi}{\alpha_w/\gamma_w} > \frac{\psi_w}{\psi_\pi}$. For $\chi_{zz} = 0$, we have $\frac{\alpha_\pi/\gamma_\pi}{\alpha_w/\gamma_w} = \frac{\kappa_{qq}+2\rho_{qq}}{\kappa_{qq}+\rho_{qq}+\chi_{qq}} \leq 2$ and, thus, $\psi_w/\psi_\pi \leq 2$ for $\alpha_w/\gamma_w \geq 2$. Consequently, $\bar{z}^\pi/\bar{z}^w > 2$ implies $\psi_w\bar{z}^w < \psi_\pi\bar{z}^\pi$, which in turn implies $\psi_w(\bar{z}^w - z) < \psi_\pi(\bar{z}^\pi - z)$ for $\psi_w > \psi_\pi$. □

From the flow-pollution cost function $x(q) = \chi_{qq}/2q^2$, we get $\chi_{qq} = 2\bar{x}/q$, where $\bar{x} \equiv x(q)/q$ is the average flow-pollution damage per unit of production. From

$$\frac{\alpha_w}{\alpha_\pi} = \frac{\rho_{qq} + \chi_{qq}}{2\rho_{qq}} = 0.5 + \frac{\chi_{qq}}{2\rho_{qq}} = 0.5 + \frac{\bar{x}}{\rho_{qq}q} = 0.5 + \frac{\bar{x}\epsilon}{p}$$

we then obtain the ninth column of Table 2. From this column, we obtain

$$\frac{\alpha_w^o}{\alpha_\pi^o} \gtreqless 1 \Leftrightarrow \bar{x}^o \gtreqless 18.5, \qquad \frac{\alpha_w^g}{\alpha_\pi^g} \gtreqless 1 \Leftrightarrow \bar{x}^g \gtreqless 2.23, \qquad \frac{\alpha_w^k}{\alpha_\pi^k} \gtreqless 1 \Leftrightarrow \bar{x}^k \gtreqless 2.50$$

Biegler and Zhang (2009) calculate the Australian health and CO_2 damage costs from coal and gas power stations based on ExternE (2005), and compare them to the respective European Union's damage costs from ExternE (2005). The health damage costs from Australian coal power stations due to PM_{10}, SO_2 and NO_x are 13.20 *AUD/MWh*, while their CO_2 damage costs are 29 *AUD/MWh* at a social cost of carbon of 31.35 *AUD/tCO* $=$ 26.41 *USD/tCO* and, thus, 46.12 *AUD/MWh* at a social cost of carbon of 42 *USD/tCO* (Biegler and Zhang, 2009, p. 34, 48). The health damage costs from European Union's hard coal power stations are 17 *EUR/MWh*, while their CO_2 damage costs are $17\,\textit{EUR/MWh}$ at a social cost of carbon of $19\,\textit{EUR/tCO} = 26.41\,\textit{USD/tCO}$ and, thus, $27.04\,\textit{EUR/MWh}$ at a social cost of carbon of $42\,\textit{USD/tCO}$ (Biegler and Zhang, 2009, p. 23, 34, 47). Thus,

$$\frac{\alpha_w^k}{\alpha_\pi^k} = 0.5 + 0.200 \cdot 13.20 \cdot \frac{3.92}{46.12} = 0.72$$

holds for Australia, where 13.20 are the health damage costs from secondary energy, $3.92/46.12$ is the ratio of CO_2 damage costs from primary to secondary energy, and $13.20 \cdot 3.92/46.12 = 1.12$ are then the health damage costs from primary energy, and

$$\frac{\alpha_w^k}{\alpha_\pi^k} = 0.5 + 0.200 \cdot 17 \cdot \frac{3.92}{27.04} = 0.99$$

holds for the European Union, where 2.46 are then the health damage costs from primary energy. The health damage costs from gas power stations are much smaller than those from coal power stations (Biegler and Zhang, 2009, p. 47). Consequently, we find that $\alpha_w^g/\alpha_\pi^g = 0.52$ holds for Australia and $\alpha_w^g/\alpha_\pi^g = 0.62$ holds for the European Union (Biegler and Zhang, 2009, p. 23, 34, 47, 48), where 0.09 and 0.56 are then the health damage costs from primary energy, respectively. The main driver of the higher health damage costs in the European Union compared to Australia is the higher population density (Biegler and Zhang, 2009, Chapter 2.3). Europe and Australia can thus be considered as representative cases for high and low health damage costs among OECD countries, respectively.[31]

The health damage costs from oil are not considered in Biegler and Zhang (2009). Burtraw, Krupnick and Sampson (2012) summarize the literature, stating that the best primary studies and the broader literature "support a rank order of fossil fuels wherein the coal fuel cycle is more damaging than the oil fuel cycle, which is more damaging than the natural gas fuel cycle. This difference would be magnified with consideration of climate change impacts." However, they also refer to the surveys of Sundqvist and Söderholm (2002) and Sundqvist (2004), who find that the median total damage costs from oil power stations are 43% and 40% higher than those from coal power stations, respectively. We use $\bar{x}^o = 1.5\bar{x}^k$ as an upper bound for the health damage costs from oil and then find that $\alpha_w^o/\alpha_\pi^o < 0.55$ holds for Australia and $\alpha_w^o/\alpha_\pi^o < 0.60$ holds for the European Union, where 1.68 and 3.69 are then the health damage costs from primary energy. Furthermore, we find that $\bar{x}^o < 13.7$ is sufficient for $\psi_w \bar{z}^w > \psi_\pi \bar{z}^\pi$ to hold in

[31] The population density of all OECD countries is 38 people/km^2, that of Australia is the lowest of all OECD countries with 4 people/km^2, and that of the European Union is 112 people/km^2. Outside the European Union, only South Korea (529 people/km^2), Israel (410 people/km^2), Japan (347 people/km^2) and Switzerland (215 people/km^2) have a higher population density (World Bank, 2021). However, Israel plans to phase out coal until 2025 and Switzerland has already done so (PPCA, 2021).

the case of oil by using the parameter values from Table 2 and a lower bound of ψ_w/ψ_π established in the following proposition for $r = 0$:

Proposition C.2 (Relation between welfare-maximizing and profit-maximizing speeds of convergence) *Suppose that $\alpha_w/\gamma_w \geq 2$ holds. If $\alpha_\pi/\gamma_\pi > \alpha_w/\gamma_w$, then $\psi_w/\psi_\pi \in \left[\frac{\sqrt{\alpha_\pi/\gamma_\pi - 1}}{\sqrt{\alpha_w/\gamma_w - 1}}, \frac{\alpha_\pi/\gamma_\pi}{\alpha_w/\gamma_w}\right] (> 1)$ increases with the discount rate.*

Proof. From (23), we obtain

$$\frac{\partial(\psi_w/\psi_\pi)}{\partial r} = \frac{\frac{\alpha_w/\gamma_w}{\psi_\pi}\left(\frac{\alpha_\pi/\gamma_\pi}{\alpha_w/\gamma_w} - \frac{\psi_w}{\psi_\pi}\right)}{r\sqrt{(\alpha_\pi/\gamma_\pi)^2 + \frac{4}{r}(\alpha_\pi/\gamma_\pi - 1)}\sqrt{(\alpha_w/\gamma_w)^2 + \frac{4}{r}(\alpha_w/\gamma_w - 1)}}. \tag{C.2}$$

From the proof of Proposition C.1, we know that $\alpha_\pi/\gamma_\pi > \alpha_w/\gamma_w \geq 2$ is sufficient for the numerator and, thus, the derivative to be positive. $\psi_w/\psi_\pi|_{r=0} = \frac{\sqrt{\alpha_\pi/\gamma_\pi - 1}}{\sqrt{\alpha_w/\gamma_w - 1}}$ and $\psi_w/\psi_\pi|_{r\to\infty} = \frac{\alpha_\pi/\gamma_\pi}{\alpha_w/\gamma_w}$ prove the interval in the proposition. □

Summarizing, we find that the energy sources map into our four-cases distinction as follows. (We neglect the knife-edge Case II.) Coal can be understood as Case I (III) if $\bar{x}^k > (<) 2.50$, and Gas can be understood as Case I (III) if $\bar{x}^g > (<) 2.23$. Oil is Case I if $\bar{x}^o > 18.5$, and it is definitely Case IV if $\bar{x}^o < 13.7$. For $\bar{x}^o \in [13.7, 18.5]$, oil is Case III if the discount rate is sufficiently small and otherwise Case IV.

D Recursive Nash Bargaining Solution

The Nash bargaining solution discussed in Section 4 presupposes that the government and the lobby never return to cooperation if negotiations fail. The present value of payments reflects the additional profit and the lost welfare due to the cooperation, compared to permanent welfare maximization. In equilibrium, there are always gains from cooperating and thus cooperation is time-consistent. Nevertheless, it might not be consistent to assume that, once negotiations failed, it will never take place again. Arguably, such a behavior would require commitment to non-cooperation.

To cope with this issue, Sorger (2006) proposes the *recursive Nash bargaining solution*. It assumes that if bargaining failed, the government and the lobby would choose non-cooperative strategies, but only for that period. The bargaining parties rationally expect themselves to cooperate again a period later because there will again be gains from cooperating. In contrast to the model in Section 4, the strategies in case of disagreement must take into account how bargaining positions are changed a period later. Because the parties never commit themselves to future behavior, the recursive Nash bargaining solution is time-consistent.

In the recursive Nash bargaining solution, we denote the agreement outcome by the superscript ar and the disagreement outcome by d. We thus need to define strategies for both bargaining parties' choice variables, m and q, for the cases of agreement and disagreement. Payments have no direct intertemporal effect, implying $m^d(z) = 0$. Moreover, the problem is still stationary, and (11) in Proposition 1, according to which the bargained extraction is independent of the outside options and maximizes a weighted sum of intertemporal welfare and intertemporal profit, still applies. Thus, the bargained extraction does not depend on the non-cooperative solution and is the same as in our earlier model: $q^{ar}(z) = q^a(z)$.

Thus, the lobby's and the government's intertemporal utilities in case of disagreement consist of profit or welfare in the period of disagreement, respectively, plus the resulting future intertemporal utility along the lobbying-equilibrium extraction path:

$$G^d(z) = w(q^d(z), z) + \delta \cdot \Big[W^a(z + q^d(z)) + \phi \cdot M^{ar}(z + q^d(z))\Big] \,, \tag{D.1a}$$

$$L^d(z) = \pi(q^d(z), z) + \delta \cdot \Big[\Pi^a(z + q^d(z)) - \lambda \cdot M^{ar}(z + q^d(z))\Big] \,, \tag{D.1b}$$

where $W^a(z)$ and $\Pi^a(z)$ are identical to the values in the Nash bargaining solution of Section 4. We can derive the intertemporal payment function as we derived $M^a(z)$ in Proposition 1:

$$M^{ar}(z) = \frac{1-\eta}{\phi} \cdot \Big[G^d(z) - W^a(z)\Big] + \frac{\eta}{\lambda} \cdot \Big[\Pi^a(z) - L^d(z)\Big] \,. \tag{D.2}$$

Let z^d_{t+s} denote the amount of cumulative extraction in period $t+s$ if the government has chosen $q^d(z)$ in $[t, \dots, t+s-1]$. Moreover, define $q^d_t \equiv q^d(z_t)$ and the values of intertemporal profit and welfare implied by permanent disagreement as $\Pi^{d\infty}(z_t) \equiv \sum_{s=0}^{\infty} \delta^s \cdot \pi(q^d_{t+s}, z^d_{t+s})$ and $W^{d\infty}(z_t) \equiv \sum_{s=0}^{\infty} \delta^s \cdot w(q^d_{t+s}, z^d_{t+s})$. Then, repeatedly inserting (D.1) into (D.2) yields:

$$\begin{aligned} M^{ar}(z_t) &= \frac{1-\eta}{\phi} \cdot \Big[W^{d\infty}(z_t) - W^a(z_t)\Big] + \frac{\eta}{\lambda} \cdot \Big[\Pi^a(z_t) - \Pi^{d\infty}(z_t)\Big] \\ &\quad - \lim_{s\to\infty} \delta^s \cdot \left[\frac{1-\eta}{\phi} \cdot G^{ar}(z^d_{t+s}) + \frac{\eta}{\lambda} \cdot L^{ar}(z^d_{t+s})\right] \\ &= \frac{1-\eta}{\phi} \cdot \Big[W^{d\infty}(z_t) - W^a(z_t)\Big] + \frac{\eta}{\lambda} \cdot \Big[\Pi^a(z_t) - \Pi^{d\infty}(z_t)\Big] \,. \end{aligned} \tag{D.3}$$

Substituting this into (D.1) and rearranging yields:

$$\begin{aligned} G^d(z) = W^{d\infty}(z) + \eta(1+\mu) \cdot \delta \cdot \Bigg\{ &\frac{1}{1+\mu} \Big[W^a(z + q^d(z)) - W^{d\infty}(z + q^d(z))\Big] \\ &+ \frac{\mu}{1+\mu} \cdot \Big[\Pi^a(z + q^d(z)) - \Pi^{d\infty}(z + q^d(z))\Big] \Bigg\}, \end{aligned} \tag{D.4a}$$

$$L^d(z) = \Pi^{d\infty}(z) + \frac{(1-\eta)(1+\mu)}{\mu} \cdot \delta \cdot \left\{ \frac{1}{1+\mu} \left[W^a(z+q^d(z)) - W^{d\infty}(z+q^d(z)) \right] + \frac{\mu}{1+\mu} \cdot \left[\Pi^a(z+q^d(z)) - \Pi^{d\infty}(z+q^d(z)) \right] \right\}, \quad \text{(D.4b)}$$

where the curly-bracketed terms represent the future gains of cooperation in case of disagreement in the current period. The government chooses $q^d(z)$ so as to maximize (D.4a). If the lobby gets all the future gains of cooperation ($\eta = 0$), the government chooses $q^d(z) = q^w(z)$, which would maximize intertemporal welfare if this extraction path were continued in the next period. A period later, it will then have to be compensated for the difference to maximal welfare. Else, if the government gets some of the future gains of cooperation ($\eta > 0$), it has a mixed motivation of maximizing welfare and impairing the lobby's future outside option. Then, $q^d(z)$ exceeds (is lower than) $q^w(z)$ if the gains of cooperation increase (decline) with the future cumulative extraction.

Along the lines of (15), the non-negativity constraint on the government's disagreement extraction q^d would be binding if $z \geq \bar{z}^d$, with the convergence level $\bar{z}^d$ defined by

$$\frac{\partial w(0,\bar{z}^d)}{\partial q} + \delta \cdot \frac{\partial W^{d\infty}(0,\bar{z}^d)}{\partial z} = -\eta(1+\mu) \cdot \delta \cdot \left\{ \frac{1}{1+\mu} \cdot \left[\frac{\partial W^a(\bar{z}^d)}{\partial z} - \frac{\partial W^{d\infty}(0,\bar{z}^d)}{\partial z} \right] + \frac{\mu}{1+\mu} \cdot \left[\frac{\partial \Pi^a(\bar{z}^d)}{\partial z} - \frac{\partial \Pi^{d\infty}(0,\bar{z}^d)}{\partial z} \right] \right\}. \quad \text{(D.5)}$$

If the future gains of cooperation increase with the future cumulative extraction, $\bar{z}^d$ exceeds $\bar{z}^w$, and vice versa. $\bar{z}^d$ can exceed $\bar{z}^a$ if the future gains of cooperation increase with the future cumulative extraction. Then, q^d is always positive along the lobbying-equilibrium extraction path.[32]

Comparing intertemporal utilities between the recursive Nash bargaining solution and our earlier model, we note that bargained intertemporal welfare and profit are the same, so that the present values of payments make the difference. From (D.3) and Proposition 1,

$$M^{ar}(z) - M^a(z) = \frac{1-\eta}{\phi} \cdot \left[W^{d\infty}(z) - W^w(z) \right] + \frac{\eta}{\lambda} \cdot \left[\Pi^w(z) - \Pi^{d\infty}(z) \right]. \quad \text{(D.6)}$$

Since $W^w(z)$ is maximized intertemporal welfare, the welfare difference cannot be positive. However, the profit difference can be positive, depending on whether the lobby prefers $q^d(z)$ or $q^w(z)$. Only if profits are lower in case of permanent disagreement than in case of welfare maximization, the difference in payments can be positive.[33] If

[32]For the explicit example, see Proposition F.1 in Appendix F.
[33]For the explicit example, see Proposition F.2 in Appendix F.

$q^d(z) = q^w(z)$, the payments and thus the intertemporal utilities coincide. This is definitely the case if $\eta = 0$, see (D.4a), or if $z \geq \bar{z}^d$ and $z \geq \bar{z}^w$, because then extraction in case of disagreement is zero in both solution concepts. The outside option then is zero extraction and payments forever in our earlier model, and postponing extraction and payments for one period in the recursive Nash bargaining solution.

Along the lines of (17), we derive the payments within the periods:

$$m^{ar}(z_t) = \frac{1-\eta}{\phi} \cdot \left[w(q_t^d, z_t) - w(q_t^a, z_t)\right] + \frac{\eta}{\lambda} \cdot \left[\pi(q_t^a, z_t) - \pi(q_t^d, z_t)\right]$$
$$+ \delta \cdot \left\{ \frac{1-\eta}{\phi} \cdot \left[W^{d\infty}(z_{t+1}^d) - W^{d\infty}(z_{t+1}^a)\right] + \frac{\eta}{\lambda} \cdot \left[\Pi^{d\infty}(z_{t+1}^a) - \Pi^{d\infty}(z_{t+1}^d)\right] \right\}. \quad \text{(D.7)}$$

If the non-cooperative convergence level is lower than the lobbying-equilibrium convergence level, $\bar{z}^d < \bar{z}^a$, the payment function $m^{ar}(z)$ has two kink points.[34] The first is at $z = \underline{z}^d \equiv \bar{z}^d - q^a$, when the future disagreement extraction becomes zero in case of agreement in the current period, and the second at $z = \bar{z}^d$, when the current extraction in case of disagreement becomes zero. By contrast, if the non-cooperative convergence level exceeds the lobbying-equilibrium convergence level, $\bar{z}^d \geq \bar{z}^a$, $m^{ar}(z)$ develops smoothly.

We return to the linear-quadratic example of Section 5. The bargained extraction, $q^a(z)$, is the same as in our earlier model and thus stated in Proposition 5, and intertemporal welfare and profit, $W^a(z)$ and $\Pi^a(z)$, are stated in Lemma B.1 with $Y_0^i = \psi_i \bar{z}^i$ and $Y_1^i = -\psi_i$ from the proof of Proposition 5 for $i = a$.

The recursive Nash bargaining solution is derived in Appendix F. Resource extraction in case of disagreement, $q^d(z)$, is linear in cumulative extraction, but we can only implicitly define the speed of convergence, $\psi_d \leq \psi_w$, which we do in Lemma F.2.

We define

$$\bar{z}^d \equiv \bar{z}^a - \frac{\bar{z}^a - \bar{z}^w}{1 + \frac{\eta(1+\mu)\delta\gamma_a(\psi_d - \psi_a)}{[1-\delta(1-\psi_a)]\gamma_w}}. \quad \text{(D.8)}$$

Then the extraction path in case of disagreement depends linearly on z in the following way:

Proposition D.1 (Explicit Example: Recursive Nash Bargaining Disagreement Extraction Path) *The extraction in case of disagreement is given by:*

$$q^d(z) = \begin{cases} \psi_d(\bar{z}^d - z) & \text{if } z \leq \bar{z}^d, \\ 0 & \text{if } z > \bar{z}^d. \end{cases} \quad \text{(D.9)}$$

[34] Given that $\frac{\partial q^d(\bar{z}^d)}{\partial z} < 0$ (cf. Proposition 4), $\eta > 0$ is not necessary for the discontinuity if $\bar{z}^d \neq \bar{z}^w$.

Proof. The function is derived in Appendix F, in particular in Lemma F.1 and F.2. The relation between $\bar{z}^d$, $\bar{z}^w$ and $\bar{z}^a$ is summarized in Proposition F.1. □

Next, let us consider the payments. For $z > \bar{z}^d$ (and $z > \bar{z}^w$), we discussed above that payments in the recursive Nash bargaining solution and those in our earlier model coincide. Furthermore, $m^{ar}(z)$ has two kink points at $z = \underline{z}^d$ and $z = \bar{z}^d$ if the non-cooperative convergence level is lower than the lobbying-equilibrium convergence level. For $z < \underline{z}^d$, we can characterize the development of payments as follows:

Proposition D.2 (Explicit Example: Recursive Nash Bargaining Development of Payments for $z < \underline{z}^d$.) *For $z \in [0, \underline{z}^d)$, we have*

$$m^{ar}(z) = \tilde{\Theta}_2 \left[q^a(z) - q^d(z)\right]^2, \tag{D.10}$$

where $\tilde{\Theta}_2 > 0$ with $\frac{\partial \tilde{\Theta}_2}{\partial \eta} > 0$.

Proof. The function is derived in Appendix F, in particular in Lemma F.3. □

Because we can only implicitly define ψ_d, we now illustrate the differences between our model approaches for specific parameter values. First, the disagreement extraction in the recursive Nash bargaining solution is lower than in our earlier model for Case I if the future gains of cooperation are not too important – that is, if $\eta < \gamma_w/[\delta\gamma_a(1+\mu)]$ (see Proposition F.1). Payments then decline over time in both approaches before the respective non-cooperative convergence level is reached. For the special case of $\eta = \gamma_w/[\gamma_a(1+\mu)]$, the present value of payments is definitely higher in the recursive Nash bargaining solution than in our earlier model in Case I (see Proposition F.2).[35] Then, $q^d < q^w$ leads to lower profits in case of disagreement in the recursive Nash bargaining solution than in our earlier model, and this loss outweighs the respective welfare loss, so that $M^{ar} > M^a$. For Case II, we find that $q^d = q^w$, so that $m^{ar} = m^a$, and for Cases III and IV, we find that $M^{ar} < M^a$ for the special case of $\eta \leq \gamma_w/[\gamma_a(1+\mu)]$ and $\bar{z}^w = \bar{z}^\pi$ (see Proposition F.2). Finally, the payment functions $m^{ar}(z)$ and $m^a(z)$ are quadratic functions of the difference between the bargained extraction and the extraction in case of disagreement (compare (B.10) in Appendix B to (F.12) in Appendix F).

Summing up, we find that the assumptions about behavior in case of disagreement lead to the same policy. However, it depends on the economic parameters whether the flexibility to return to the bargaining table benefits the government or the lobby. Thus, depending on the market conditions, the government would either have an interest in committing to welfare maximization in case of disagreement or to remain flexible.

[35] In Section 6, we use $\eta = 1/2$, $\mu = 1$ and $\chi_{zz} = 0$, so that $\eta = \gamma_w/[\gamma_a(1+\mu)]$.

E Short-lived Governments

Suppose that the mixed-motivation government of the previous sections is in power in the current period, but that it will be ousted and succeeded by a purely welfare-maximizing government (or social planner) with probability $1-\sigma$ after each period. Once it has lost power, it cannot return to office. We denote the outcome of the Nash bargaining between the lobby and the short-lived government by the superscript as. Furthermore, suppose that the outside option is a permanent termination of cooperation as in Section 4. Then, extraction in case of disagreement is $q^w(z)$ and the respective intertemporal utilities are given by (7) and (8). For example, the choice may be to implement better institutions in case of disagreement. Then, the government's and the lobby's expected intertemporal utilities are

$$G^{as}(z) = g(q^{as}(z), m^{as}(z), z) + \delta\cdot[\sigma\cdot G^{as}(z+q^{as}(z)) + (1-\sigma)\cdot W^w(z+q^{as}(z))], \quad \text{(E.1a)}$$
$$L^{as}(z) = l(q^{as}(z), m^{as}(z), z) + \delta\cdot[\sigma\cdot L^{as}(z+q^{as}(z)) + (1-\sigma)\cdot \Pi^w(z+q^{as}(z))]. \quad \text{(E.1b)}$$

Along the lines of Proposition 1, the bargaining maximizes

$$\frac{1}{1+\mu}\cdot\{w(q,z)+\delta\cdot[\sigma\cdot W^{as}(z+q)+(1-\sigma)\cdot W^w(z+q)]\} \\ + \frac{\mu}{1+\mu}\cdot\{\pi(q,z)+\delta\cdot[\sigma\cdot\Pi^{as}(z+q)+(1-\sigma)\cdot\Pi^w(z+q)]\}, \quad \text{(E.2)}$$

where $W^{as}(z) = w(q^{as}(z),z)+\delta\cdot\{\sigma\cdot W^{as}(z+q^{as}(z))+(1-\sigma)\cdot W^w(z+q^{as}(z))\}$ and $\Pi^{as}(z)$ is defined equivalently. The expected intertemporal payments $M^{as}(z) = m^{as}(z)+\delta\cdot\sigma\cdot M^{as}(z+q)$ share the expected surplus along the lines of Proposition 1:

$$M^{as}(z) = \frac{\eta}{\lambda}\cdot\{\pi(q^{as}(z),z)+\delta\cdot[\sigma\cdot\Pi^{as}(z+q^{as}(z))+(1-\sigma)\cdot\Pi^w(z+q^{as}(z))]-\Pi^w(z)\} \\ -\frac{1-\eta}{\phi}\cdot\{w(q^{as}(z),z)+\delta\cdot[\sigma\cdot W^{as}(z+q^{as}(z))+(1-\sigma)\cdot W^w(z+q^{as}(z))]-W^w(z)\}. \quad \text{(E.3)}$$

The payment in a given period thus is $m^{as}(z) = M^{as}(z)-\delta\cdot\sigma\cdot M^{as}(z+q^{as}(z))$.

For $\sigma=1$, we are in our earlier model from Section 4. For $\sigma<1$, the government and the lobby take into account that the bargaining ends with probability $1-\sigma$ after each period. σ affects the equilibrium of this model in two ways. Firstly, σ directly increases the future probability of continuing the lobbying equilibrium, which makes current continuation more valuable, and secondly, it changes the jointly optimal bargained extraction, $q^{as}\neq q^a$. While the model with explicit functions can be solved implicitly for $\sigma\in(0,1)$ (similar to that in Section D), we focus on the extreme case of $\sigma=0$, so that the government and the lobby cooperate for only one period. For this case, q^{as} and m^{as} can be derived explicitly. We discuss the solution for q^{as} and its difference to q^a below; for the explicit formula of m^{as}, see Appendix G.

We define

$$\psi_{as} \equiv \psi_a + \frac{(\psi_a - \psi_w)^2 (1 - \psi_a \alpha_a / \gamma_a)}{2\psi_w (1 - \psi_a \alpha_a/\gamma_a) + \psi_a^2 \alpha_a / \gamma_a}, \tag{E.4a}$$

$$\bar{z}^{as} \equiv \bar{z}^w + \frac{(\bar{z}^a - \bar{z}^w)\, \psi_a^2 (2 - \psi_w \alpha_w / \gamma_w)}{\psi_w^2 (1 - \psi_a \alpha_a / \gamma_a) + \psi_a^2}, \tag{E.4b}$$

where $\psi_{as} \gtreqless \psi_w \Leftrightarrow \psi_a \gtreqless \psi_w$, $\psi_{as} > \psi_a \Leftrightarrow \psi_a \neq \psi_w$, $\bar{z}^{as} > \bar{z}^w$ and $\bar{z}^{as} \gtreqless \bar{z}^a \Leftrightarrow \psi_a \gtreqless \psi_w$. Then resource extraction in the period of cooperation depends linearly on z in the following ways:

Proposition E.1 (Explicit Example: Short-lived Government Extraction) *For $\sigma = 0$, the bargained extraction is given by:*

$$q^{as}(z) = \begin{cases} \psi_{as} \cdot (\bar{z}^{as} - z) & \text{if } z \leq \bar{z}^w, \\ \frac{\gamma_a}{\alpha_a} \cdot (\bar{z}^a - z) & \text{if } z \in (\bar{z}^w, \bar{z}^{as}], \\ 0 & \text{if } z > \bar{z}^{as}. \end{cases} \tag{E.5}$$

For $z \leq \bar{z}^w$, $q^{as} > q^a > q^w$ if $\psi_a > \psi_w$, and $q^{as} = q^a > q^w$ if $\psi_a = \psi_w$. If $\psi_a < \psi_w$, the relation between q^{as}, q^a and q^w depends on z, with switching levels of z along the lines of (26)*. For $z \in (\bar{z}^w, \bar{z}^{as}]$, $q^{as} > q^a \geq q^w = 0$.*

Proof. The proof follows along the lines of the proof of Proposition 5. The relation between q^{as}, q^a and q^w follows from (24) and (E.5) together with (22), (23) and (E.4). □

If the non-negativity constraint on q^w is binding, but that on q^{as} is not, q^{as} is chosen so as to maximize $\frac{1}{1+\mu} \cdot w(q, z) + \frac{\mu}{1+\mu} \cdot \pi(q, z)$. Then q^{as} exceeds q^a, because there is only one period of extraction. Furthermore, the gains of cooperation and the welfare loss and, thus, the payments in the period of cooperation are higher for $\sigma = 0$ than for $\sigma = 1$ (see Proposition G.1).

If the non-negativity constraint on q^w is not binding, we have to distinguish between three cases, $\psi_a > \psi_w$, $\psi_a = \psi_w$ and $\psi_a < \psi_w$. If $\psi_a > \psi_w$, q^{as} exceeds q^a. In every future period, q^w will be below q^a, so that there is a strong incentive to extract more in the period of cooperation. Then, the profit gain and welfare loss are again higher for $\sigma = 0$ than for $\sigma = 1$, and this effect outweighs the respective changes in the future outside options, which is confirmed by higher payments in the period of cooperation for $\sigma = 0$ than for $\sigma = 1$ (see Proposition G.1).[36]

[36] For the special case of $\bar{z}^w = \bar{z}^\pi = \bar{z}^a$, intertemporal welfare is smaller with a short-lived government than with a government that is in power forever if $\psi_a \geq (1 + 2\psi_w)/3$, see Proposition G.2 in Appendix G.

For $\psi_a = \psi_w$, the q and m values in the period of cooperation are independent of whether $\sigma = 0$ or $\sigma = 1$. In every future period, q^a exceeds q^w by a constant amount, so that higher current extraction does not affect the future lobbying distortion. Since the distortive influence of the lobby is the same in the period of cooperation for $\sigma = 0$ and for $\sigma = 1$, but this influence vanishes in the next period for $\sigma = 0$ but not for $\sigma = 1$, intertemporal welfare is greater with a short-lived government than with a government that is in power forever.

If $\psi_a < \psi_w$, the bargained speed of convergence, ψ_{as}, and the bargained convergence level, $\bar{z}^{as}$, are compromise values between ψ_a and ψ_w as well as between $\bar{z}^a$ and $\bar{z}^w$. We find that the gains of cooperation from cooperating one period are higher for $\sigma = 0$ than for $\sigma = 1$. Whether the respective welfare loss is also higher depends on the parameter values as well as on the amount of cumulative extraction (see Proposition G.1).[37]

To summarize, while a higher probability of remaining in power clearly implies a longer deviation from welfare maximization, the distortive influence of the lobby can definitely be higher in the periods of cooperation if the probability of remaining in power is lower.

F Proofs of Appendix D

Similar to (B.1), we guess that there exist constants Y_0^d and Y_1^d such that the following state-dependent extraction function maximizes $G^d(z)$ from (D.4a) for the functions (21):

$$q^d(z) = \begin{cases} Y_0^d + Y_1^d z & \text{if } Y_0^d + Y_1^d z > 0, \\ 0 & \text{if } Y_0^d + Y_1^d z \leq 0, \end{cases} \tag{F.1}$$

where the stability condition is

$$0 < 1 + Y_1^d \leq 1. \tag{F.2}$$

To solve for the coefficients, we first use them to state the intertemporal value functions $W^{d\infty}(z)$ and $\Pi^{d\infty}(z)$ in an explicit form.

Lemma F.1 (Recursive Nash Bargaining Permanent-Disagreement Values) *Suppose that $q^d(z)$ from* (F.1) *is the disagreement extraction function. Then,*

$$W^{d\infty}(z) = \frac{\beta_w + \frac{Y_0^d}{Y_1^d}\gamma_w}{1 - \delta\left(1 + Y_1^d\right)} q^d(z) - \frac{\frac{\alpha_w}{2} + \frac{1}{Y_1^d}\gamma_w}{1 - \delta\left(1 + Y_1^d\right)^2} q^d(z)^2 - \frac{\chi_z z + \chi_{zz} z^2}{1 - \delta}, \tag{F.3a}$$

[37] For the special case of $\bar{z}^w = \bar{z}^\pi = \bar{z}^a$, intertemporal welfare is greater with a short-lived government than with a government that is in power forever, see Proposition G.2 in Appendix G.

$$\Pi^{d\infty}(z) = \frac{\beta_\pi + \frac{Y_0^d}{Y_1^d}\gamma_\pi}{1-\delta\left(1+Y_1^d\right)} q^d(z) - \frac{\frac{\alpha_\pi}{2} + \frac{1}{Y_1^d}\gamma_\pi}{1-\delta\left(1+Y_1^d\right)^2} q^d(z)^2 \tag{F.3b}$$

Proof. The proof follows along the lines of the proof of Lemma B.1. □

To prove Proposition D.1 and to prepare the proof of Proposition F.1, we derive the disagreement extraction.

Lemma F.2 (Recursive Nash Bargaining Disagreement Extraction) *In the disagreement extraction function* (F.1)*, the coefficients are* $Y_0^d = \psi_d \bar{z}^d$ *and* $Y_1^d = -\psi_d$*, where* $\psi_d \leq \psi_w$ *is implicitly defined by*

$$\eta\left(1+\mu\right)\left(1-\psi_d\right)\left(\psi_a-\psi_d\right)^2 - \frac{\alpha_w-\gamma_w}{\alpha_a-\gamma_a}\left(1-\psi_a\right)\left(\frac{1-\delta(1-\psi_w)}{\delta(1-\psi_w)}+\psi_d\right)\left(\psi_w-\psi_d\right) = 0, \tag{F.4}$$

and $\bar{z}^d$ *is defined in* (D.8). $\psi_w \gtreqless \psi_a$ *implies* $\psi_d \gtreqless \psi_a$.

Proof. $q^d(z)$ maximizes $G^d(z)$ from (D.4a). Substituting $W^a(z)$ and $\Pi^a(z)$ from Lemma B.1 with $Y_0^a = \psi_a \bar{z}^a$ and $Y_1^a = -\psi_a$ from the proof of Proposition 5 and $W^{d\infty}(z)$ and $\Pi^{d\infty}(z)$ from Lemma F.1, we can derive a first-order condition for q, into which we substitute $q^a(z)$ from Proposition 5 and $q^d(z) = Y_0^d + Y_1^d z$:

$$\begin{aligned}
&\beta_w - \gamma_w z - \alpha_w\left(Y_0^d + Y_1^d z\right) \\
&+ \delta\left[\frac{Y_1^d\beta_w + Y_0^d\gamma_w}{1-\delta\left(1+Y_1^d\right)} - \frac{Y_1^d\alpha_w + 2\gamma_w}{1-\delta\left(1+Y_1^d\right)^2}\left[Y_0^d + Y_1^d\left[Y_0^d + \left(1+Y_1^d\right)z\right]\right]\right] \\
&+ \eta\left(1+\mu\right)\delta\left\{\frac{\left(\psi_a\alpha_a - 2\right)\gamma_a}{1-\delta\left(1-\psi_a\right)^2}\psi_a\left[\bar{z}^a - \left[Y_0^d + \left(1+Y_1^d\right)z\right]\right]\right. \\
&\quad\left. + \frac{Y_1^d\alpha_a + 2\gamma_a}{1-\delta\left(1+Y_1^d\right)^2}\left[Y_0^d + Y_1^d\left[Y_0^d + \left(1+Y_1^d\right)z\right]\right] - \frac{Y_1^d\beta_a + Y_0^d\gamma_a}{1-\delta\left(1+Y_1^d\right)}\right\} = 0.
\end{aligned} \tag{F.5}$$

This condition must also hold for $z = z + q^a(z) = z + \psi_a\left(\bar{z}^a - z\right)$. This generates two equations in two unknowns. Subtracting the first from the second and rearranging yields:

$$\begin{aligned}
&\frac{\gamma_a(\bar{z}^a - z)}{1-\delta\left(1-\psi_a\right)}\frac{\delta\left(1-\delta\right)}{1-\delta\left(1+Y_1^d\right)^2}\left\{\eta\left(1+\mu\right)\left(1+Y_1^d\right)\left(\psi_a+Y_1^d\right)^2\right. \\
&\quad\left. - \frac{\alpha_w-\gamma_w}{\alpha_a-\gamma_a}\left(1-\psi_a\right)\left[\frac{1-\delta(1-\psi_w)}{\delta(1-\psi_w)} - Y_1^d\right]\left(\psi_w+Y_1^d\right)\right\} = 0.
\end{aligned} \tag{F.6}$$

In line with the previous sections, we define $Y_1^d \equiv -\psi_d$ as stated in Lemma F.2. Together with (F.6), this yields (F.4). Substituting $Y_1^d = -\psi_d$ in (F.2) yields $0 < 1-\psi_d \leq 1$. Thus, the first term in (F.4) is non-negative, so that the second term must also be non-negative for the equality to hold. This yields $\psi_d \leq \psi_w$. Differentiating (F.4) with respect to η and ψ_d yields

$$\begin{aligned}(1+\mu)\left(1-\psi_d\right)\left(\psi_a-\psi_d\right)^2 \mathrm{d}\eta - \Bigg\{ & \eta\,(1+\mu)\left(2+\psi_a-3\psi_d\right)\left(\psi_a-\psi_d\right) \\ & - \frac{\alpha_w-\gamma_w}{\alpha_a-\gamma_a}\left(1-\psi_a\right)\left(\frac{1-\delta(1-\psi_w^2)}{\delta(1-\psi_w)}+2\psi_d\right)\Bigg\} \mathrm{d}\psi_d = 0. \end{aligned} \tag{F.7}$$

Solving (F.4) for η, substituting into (F.7) and rearranging yields

$$\frac{\mathrm{d}\psi_d}{\mathrm{d}\eta} = \frac{(1+\mu)\left(\alpha_a-\gamma_a\right)(1-\psi_w)\left(1-\psi_d\right)^2\left(\psi_a-\psi_d\right)^3}{(\alpha_w-\gamma_w)(1-\psi_a)\Lambda}, \tag{F.8}$$

where

$$\begin{aligned}\Lambda \equiv\; & 2\psi_w^2(\psi_w-\psi_d)^2 + \Big\{(4\psi_a^2-2\psi_a\psi_d-\psi_d^2)(\psi_a-\psi_d) + (12\psi_a^2-10\psi_a\psi_d)(\psi_w-\psi_a) \\ & + (12\psi_a-4\psi_d)(\psi_w-\psi_a)^2 + 4(\psi_w-\psi_a)^3\Big\}(1-\psi_w) + 2(\psi_w^2-\psi_a\psi_d)(1-\psi_w)^2 \\ & + r[2(\psi_w-\psi_d)^2 + (2\psi_w-\psi_a-\psi_d)(1-\psi_w)]. \end{aligned} \tag{F.9}$$

Since $\psi_d \leq \psi_w$, $\psi_d|_{\eta=0} = \psi_w$ and $\frac{\mathrm{d}^2\psi_d}{\mathrm{d}\eta^2} = 0$ hold, $\frac{\mathrm{d}\psi_d}{\mathrm{d}\eta} \leq 0$ must hold. If $\psi_w \geq \psi_a > \psi_d$, then $\Lambda > 0$ and $\frac{\mathrm{d}\psi_d}{\mathrm{d}\eta} > 0$, which contradicts $\frac{\mathrm{d}\psi_d}{\mathrm{d}\eta} \leq 0$. Thus, $\psi_w = \psi_a$ implies $\psi_d = \psi_a$. If $\psi_w > \psi_a = \psi_d$, then $\frac{\mathrm{d}\psi_d}{\mathrm{d}\eta} = 0$, which contradicts $\psi_w > \psi_d$. Thus, $\psi_w > \psi_a$ implies $\psi_d > \psi_a$. To derive $Y_0^d \equiv \psi_d \bar{z}^d$, we solve (F.5) for Y_0^d. This equation depends on $\left(Y_1^d\right)^4$. The curly-bracketed term in (F.6) defines $\left(Y_1^d\right)^3$, so that we can derive $\left(Y_1^d\right)^4$ by multiplying with Y_1^d. Substituting $\left(Y_1^d\right)^4$ and afterwards $\left(Y_1^d\right)^3$ into the equation for Y_0^d yields, together with $Y_1^d = -\psi_d$, (D.8). □

Proposition F.1 (Relation between $\bar{z}^d$, $\bar{z}^w$ and $\bar{z}^a$) *The relation between $\bar{z}^d$, $\bar{z}^w$ and $\bar{z}^a$ is given as follows:*

$$\bar{z}^a > \bar{z}^d > \bar{z}^w \qquad \text{if } \psi_w \geq \psi_d > \psi_a, \tag{F.10a}$$

$$\bar{z}^a > \bar{z}^d = \bar{z}^w \qquad \text{if } \psi_w = \psi_d = \psi_a, \tag{F.10b}$$

$$\bar{z}^a > \bar{z}^w > \bar{z}^d \qquad \text{if } \psi_a > \psi_w \geq \psi_d \text{ and } 1 + \frac{\eta\,(1+\mu)\,\delta\gamma_a\,(\psi_d-\psi_a)}{[1-\delta\,(1-\psi_a)]\gamma_w} > 0, \tag{F.10c}$$

$$\bar{z}^d > \bar{z}^a > \bar{z}^w \qquad \text{if } \psi_a > \psi_w \geq \psi_d \text{ and } 1 + \frac{\eta\,(1+\mu)\,\delta\gamma_a\,(\psi_d-\psi_a)}{[1-\delta\,(1-\psi_a)]\gamma_w} < 0. \tag{F.10d}$$

The future gains of cooperation are increasing in z if (F.10a) *or* (F.10d) *hold, they stay constant if* (F.10b) *holds and they are declining in z if* (F.10c) *holds. $\eta < \gamma_w/[\delta\gamma_a(1+\mu)]$ is sufficient for the last inequality in* (F.10c) *to hold and $\eta > \gamma_w/[\delta\gamma_a(1+\mu)]$ is necessary for the last inequality in* (F.10d) *to hold.*

Proof. (F.10) follows from (D.8) together with Lemma F.2. From the discussion of (D.5), we know that $\bar{z}^d \gtreqless \bar{z}^w$ is equivalent to increasing, constant and declining future gains of cooperation. This and (F.10) prove the penultimate sentence in the lemma. For (F.10c) and (F.10d), note that

$$1+\frac{\eta\,(1+\mu)\,\delta\gamma_a\,(\psi_d-\psi_a)}{[1-\delta\,(1-\psi_a)]\gamma_w}\gtrless 0 \quad\Leftrightarrow\quad \psi_d \gtrless \frac{\eta\,(1+\mu)-[1-\delta\,(1-\psi_a)]\,\gamma_w/(\delta\psi_a\gamma_a)}{\eta\,(1+\mu)}\psi_a.$$

The numerator on the right side of the equivalence increases with ψ_a and goes to $\eta\,(1+\mu)-\gamma_w/(\delta\gamma_a)$ for $\psi_a\to 1$. This proves the last sentence in the lemma. □

To prove Proposition D.2 and to prepare the proof of Proposition F.2, we derive the intertemporal payments and the payments within the periods.

Lemma F.3 (Recursive Nash Bargaining Payments) *The present value of payments is*

$$\begin{aligned} M^{ar}(z)=\frac{\eta(1+\mu)}{\phi}\Bigg\{&\frac{\frac{\gamma_a}{\psi_a}-\frac{\alpha_a}{2}}{1-\delta(1-\psi_a)^2}q^a(z)^2\\ &-\left[\frac{\frac{\gamma_a}{\psi_d}-\frac{\alpha_a}{2}}{1-\delta(1-\psi_d)^2}q^d(z)^2-\frac{\gamma_a(\bar{z}^d-\bar{z}^a)}{1-\delta(1-\psi_d)}q^d(z)\right]\Bigg\}\\ +\frac{1}{\phi}\Bigg\{&\frac{\frac{\gamma_w}{\psi_d}-\frac{\alpha_w}{2}}{1-\delta(1-\psi_d)^2}q^d(z)^2-\frac{\gamma_w(\bar{z}^d-\bar{z}^w)}{1-\delta(1-\psi_d)}q^d(z)\\ &-\left[\frac{\frac{\gamma_w}{\psi_a}-\frac{\alpha_w}{2}}{1-\delta(1-\psi_a)^2}q^a(z)^2-\frac{\gamma_w(\bar{z}^a-\bar{z}^w)}{1-\delta(1-\psi_a)}q^a(z)\right]\Bigg\}. \end{aligned} \tag{F.11}$$

The payments in any single period are

$$m^{ar}(z)=\begin{cases}\tilde{\Theta}_2\left[q^a(z)-q^d(z)\right]^2 & \textit{if } z<\underline{z}^d,\\ \frac{\gamma_w}{\phi}\left(\bar{z}^a-\bar{z}^w\right)q^a(z)+\Theta_3 q^a(z)^2-\tilde{\Theta}_4 q^d(z)-\tilde{\Theta}_5 q^d(z)^2 & \textit{if } z\in[\underline{z}^d,\bar{z}^d),\\ \frac{\gamma_w}{\phi}\left(\bar{z}^a-\bar{z}^w\right)q^a(z)+\Theta_3 q^a(z)^2 & \textit{if } z\in[\bar{z}^d,\bar{z}^a),\end{cases} \tag{F.12}$$

where

$$\begin{aligned}\tilde{\Theta}_2\equiv\frac{1}{\phi}\frac{1-\delta}{1-\delta\,(1-\psi_d)^2}\Bigg\{&\eta\,(1+\mu)\left(\frac{\gamma_a}{\psi_a}-\frac{\alpha_a}{2}\right)+\frac{\gamma_w}{\psi_w}-\frac{\alpha_w}{2}\\ &-\frac{[1-\delta(1-\psi_a)(1-\psi_w)]\gamma_w}{[1-\delta(1-\psi_w)]\psi_w}\frac{\psi_w-\psi_d}{\psi_a-\psi_d}\Bigg\}>\Theta_2 \textit{ if } \psi_w>\psi_a,\end{aligned} \tag{F.13a}$$

$$\tilde{\Theta}_4\equiv\frac{1}{\phi}\eta(1+\mu)\frac{\gamma_a\left(\bar{z}^a-\bar{z}^d\right)}{1-\delta\,(1-\psi_a)}, \tag{F.13b}$$

$$\tilde{\Theta}_5\equiv\frac{1}{\phi}\frac{1}{1-\delta\,(1-\psi_d)^2}\left[\eta\,(1+\mu)\left(\frac{\gamma_a}{\psi_d}-\frac{\alpha_a}{2}\right)-\frac{\gamma_w}{\psi_d}+\frac{\alpha_w}{2}\right], \tag{F.13c}$$

and where Θ_2 *and* Θ_3 *are defined in* (B.11b) *and* (B.11c).

Proof. Substituting (B.3) for $Y_0^a = \psi_a \bar{z}^a$ and $Y_1^a = -\psi_a$ from the proof of Proposition 5 as well as (F.3a) and (F.3a) from Lemma F.2 into (D.3), using (22) and simplifying yields (F.12). Substituting (F.11) into (D.7), using q^a and q^d from Propositions 5 and D.1 and simplifying yields (B.10). Finally, $\tilde{\Theta}_2 > \Theta_2$ if $\psi_d > \psi_a$ follows from $\psi_d \leq \psi_w$. □

Proposition F.2 (Difference in Payments for $z \leq \min(\bar{z}^w, \bar{z}^d)$) *Suppose $z \leq \min(\bar{z}^w, \bar{z}^d)$. Then $M^{ar}(z) = M^a(z)$ if $\psi_w = \psi_a$, $M^{ar}(z) > M^a(z)$ if $\psi_w < \psi_a$ and $\eta \in [\gamma_w/[\gamma_a(1+\mu)], \gamma_w/[\delta\gamma_a(1+\mu)]]$, and $M^{ar}(z) < M^a(z)$ if $\psi_w > \psi_a$, $\bar{z}^a \to \bar{z}^w$ and $\eta \leq \gamma_w/[\gamma_a(1+\mu)]$.*

Proof. By Lemma F.2 and (F.10b), $\psi_w = \psi_a$ implies $\psi_d = \psi_w$ and $\bar{z}^d = \bar{z}^w$, such that $q^d(z) = q^w(z)$ and, thus, $M^{ar}(z) = M^a(z)$ by (D.6). Furthermore, $\psi_w \neq \psi_a$ implies $\psi_d \neq \psi_w$ and $\bar{z}^d \neq \bar{z}^w$ and, thus, $M^{ar}(z) < M^a(z)$ for $\eta = 0$ by (D.6). Thus, if $M^{ar}(z) < (>) M^a(z)$ holds for some η and some parameter relation of Proposition F.1, then it also holds for a smaller (larger) η if the parameter relation does not change. Substituting (B.9) and (F.11) into (D.6) for $\eta = \gamma_w/[\gamma_a(1+\mu)]$ and rearranging yields:

$$M^{ar}(z) - M^a(z) = \frac{1}{\phi}\Bigg\{ \frac{\frac{\gamma_w}{2}\left(\frac{\alpha_w}{\gamma_w} - \frac{\alpha_a}{\gamma_a}\right)}{1-\delta(1-\psi_w)^2}[\psi_w(\bar{z}^w - z)]^2 - \frac{\frac{\gamma_w}{2}\left(\frac{\alpha_w}{\gamma_w} - \frac{\alpha_a}{\gamma_a}\right)}{1-\delta(1-\psi_d)^2}[\psi_d(\bar{z}^d - z)]^2$$
$$+ \frac{\gamma_w(\bar{z}^a - \bar{z}^w)}{1-\delta(1-\psi_w)}\psi_w(\bar{z}^w - z) - \frac{\gamma_w(\bar{z}^a - \bar{z}^w)}{1-\delta(1-\psi_d)}\psi_d(\bar{z}^d - z)\Bigg\}. \quad \text{(F.14)}$$

For any $X > 0$, $\frac{X^2}{1-\delta(1-X)^2}$ and $\frac{X}{1-\delta(1-X)}$ are increasing in X. $\psi_w < \psi_a$ implies $\alpha_w/\gamma_w > \alpha_a/\gamma_a$ by (27) and $\bar{z}^w \geq \bar{z}^d$ for $\eta \leq \gamma_w/[\delta\gamma_a(1+\mu)]$ by (F.10c), such that the first and the second line of (F.14) are positive. Therefore, $M^{ar}(z) > M^a(z)$ for $\eta = \gamma_w/[\gamma_a(1+\mu)]$ and $\psi_w < \psi_a$ and, thus, for $\eta \in [\gamma_w/[\gamma_a(1+\mu)], \gamma_w/[\delta\gamma_a(1+\mu)]]$ and $\psi_w < \psi_a$. $\psi_w > \psi_a$ implies $\frac{\alpha_w}{\gamma_w} < \frac{\alpha_a}{\gamma_a}$ by (27) and $\bar{z}^a \to \bar{z}^w$ implies $\bar{z}^d \to \bar{z}^w$ by (D.8), such that the first line of (F.14) is negative and the second line of (F.14) goes to zero. Thus, $M^{ar}(z) < M^a(z)$ for $\eta = \gamma_w/[\gamma_a(1+\mu)]$, $\psi_w > \psi_a$ and $\bar{z}^a \to \bar{z}^w$ and, thus, for $\eta \leq \gamma_w/[\gamma_a(1+\mu)]$, $\psi_w > \psi_a$ and $\bar{z}^a \to \bar{z}^w$. □

G Proofs of Appendix E

Similar to (B.10), we can derive the payments in the period of cooperation:

$$m^{as}(z) =$$
$$\frac{1}{\phi}\begin{cases} \frac{1-\delta}{1-\delta(1-\psi_w)^2}\left[\eta(1+\mu)\left[\frac{(\alpha_a-\gamma_a)\psi_w}{r} + \frac{\alpha_a}{2}\right] + \frac{\gamma_w}{\psi_w} - \frac{\alpha_w}{2}\right][q^{as}(z) - q^w(z)]^2 & \text{if } z \leq \bar{z}^w, \\ \gamma_w(\bar{z}^a - \bar{z}^w)\, q^{as}(z) + \left[\eta(1+\mu)\frac{\alpha_a}{2} + \frac{\alpha_w}{2} - \frac{\alpha_a\gamma_w}{\gamma_a}\right] q^{as}(z)^2 & \text{if } z \in (\bar{z}^w, \bar{z}^{as}]. \end{cases} \quad \text{(G.1)}$$

Using this, we characterize the difference in payments:

Proposition G.1 (Difference in Payments between $\sigma = 0$ and $\sigma = 1$) *For $z \leq \underline{z}^w$, $m^{as} - m^a$ is positive if $\psi_a > \psi_w$, and it is zero if $\psi_a = \psi_w$. If $\psi_a \neq \psi_w$, $m^{as} - m^a$ is increasing in η. For $z \in (\bar{z}^w, \bar{z}^{as}]$, $m^{as} - m^a$ is positive.*

Proof. Substituting (B.10) and (G.1) into $m^{as}(z) - m^a(z)$ and rearranging yields

$$m^{as}(z) - m^a(z) = \\ \frac{1}{\phi}\begin{cases} \eta\,(1+\mu)\,\frac{\delta^2(1-\delta)(1-\psi_a)^2(\psi_a-\psi_w)^4\gamma_a}{2[1-\delta(1-\psi_a)]\left[1-\delta(1-\psi_w)^2\right][1-\delta+2\delta(1-\psi_a)\psi_w+\delta\psi_a^2]\psi_a} \\ \quad\cdot\left[\frac{[1-\delta(1-\psi_w)(1-\psi_a)](\psi_a\bar{z}^a-\psi_w\bar{z}^w)-(\psi_a-\psi_w)\psi_a\bar{z}^a}{[1-\delta(1-\psi_w)](1-\psi_a)(\psi_a-\psi_w)} - z\right]^2 \\ \quad+\frac{1-\delta}{1-\delta(1-\psi_w)^2}\left(\frac{\gamma_w}{\psi_w}-\frac{\alpha_w}{2}\right)\left\{[q^{as}(z)-q^w(z)]^2-[q^a(z)-q^w(z)]^2\right\} & \text{if } z \leq \underline{z}^w, \\ \gamma_w\,(1-\psi_a\alpha_a/\gamma_a)\,(z-\bar{z}^w)\,q^{as}(z) \\ \quad+\left[\eta\,(1+\mu)\,\frac{\alpha_a(1-\psi_a\alpha_a/\gamma_a)^2}{2}+\frac{\alpha_w\left[1-(\psi_a\alpha_a/\gamma_a)^2\right]}{2}\right]q^{as}(z)^2 & \text{if } z \in (\bar{z}^w, \bar{z}^{as}]\,. \end{cases} \tag{G.2}$$

If $\psi_a > \psi_w$, the second and the third line of (G.2) are positive and, by Proposition E.1, $q^{as} > q^a > q^w$, which implies that the fourth line of (G.2) is positive, such that $m^{as} > m^a$. If $\psi_a = \psi_w$, the second line of (G.2) is zero and, by Proposition E.1, $q^{as} = q^a$, which implies that the fourth line of (G.2) is zero, such that $m^{as} = m^a$. The derivative of $m^{as} - m^a$ with respect to η is positive for $z \leq \underline{z}^w$ and $\psi_a \neq \psi_w$, and it is positive for $z \in [\bar{z}^w, \bar{z}^{as})$, which proves the second sentence in the proposition. The last line of (G.2) is positive, such that $m^{as} > m^a$ for $z \in [\bar{z}^w, \bar{z}^{as})$. □

Finally, we can state the difference in intertemporal welfare for $\bar{z}^w = \bar{z}^\pi = \bar{z}^a$.

Proposition G.2 (Difference in Intertemporal Welfare between $\sigma = 0$ and $\sigma = 1$ for $\bar{z}^w = \bar{z}^\pi = \bar{z}^a$) *Suppose $\bar{z}^w = \bar{z}^\pi = \bar{z}^a$. Then, $\psi_w \geq \psi_a$ is sufficient for $W^{as} > W^a$, and $\psi_a \geq (1 + 2\psi_w)/3$ is sufficient for $W^{as} < W^a$.*

Proof. Taking the difference of $W^{as} = w(q^{as}(z), z) + \delta W^w(z + q^{as}(z))$ and W^a, using (24), (B.3a) with $Y_0^i = \psi_i \bar{z}^i$ and $Y_1^i = -\psi_i$ from the proof of Proposition 5 for $i = w, a$, (E.4) and (E.5), and rearranging yields

$$\begin{aligned} W^{as} - W^a = {} & \frac{\delta(1-\delta)\gamma_w(1-\psi_a)(\psi_a-\psi_w)^2(\bar{z}^a-z)^2}{2\psi_w[1-\delta(1-\psi_w)][1-\delta(1-\psi_a)^2][1-\delta(1-\psi_a)(1+\psi_a-2\psi_w)]} \\ & \cdot\Big\{(1-\psi_a)[1-\delta(1-\psi_a)^2]^2 + 2[1-\delta^2(1-\psi_a)^4](\psi_w-\psi_a) \\ & \quad + \delta(1-\psi_a)[3+\delta(1-\psi_a)^2](\psi_w-\psi_a)^2\Big\} \end{aligned} \tag{G.3a}$$

$$= -\frac{\delta(1-\delta)\gamma_w(1-\psi_a)(\psi_a-\psi_w)^2(\bar{z}^a-z)^2}{27\psi_w[1-\delta(1-\psi_w)][1-\delta(1-\psi_a)^2][1-\delta(1-\psi_a)(1+\psi_a-2\psi_w)]}$$
$$\cdot \Big\{\delta(1-\psi_w)^3[5-4\delta(1-\psi_w)^2]+3[\delta(1-\psi_w)^2+[3-2\delta(1-\psi_w)^2]^2]\Psi$$
$$+ 12\delta(1-\psi_w)[2-\delta(1-\psi_w)^2]\Psi^2+4\delta[1+\delta(1-\psi_w)^2]\Psi^3\Big\}, \tag{G.3b}$$

where $\Psi \equiv \psi_a - \psi_w - (1-\psi_a)/2$. $\psi_w - \psi_a \geq 0$ is sufficient for (G.3a) being positive, and $\Psi \geq 0$ is sufficient for (G.3b) being negative, which proves the proposition. □

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