OPEC, Unconventional Oil and Climate Change - On the importance of the order of extraction

Hassan Benchekroun[1]
Gerard van der Meijden[2]
Cees Withagen[3]

[1] McGill University
[2] Vrije Universiteit Amsterdam
[3] IPAG Business School (Paris)

OPEC, Unconventional Oil and Climate Change[*]

On the importance of the order of extraction

Hassan Benchekroun

McGill University

CIREQ

Gerard van der Meijden[♯]

Vrije Universiteit Amsterdam

Tinbergen Institute

Cees Withagen

IPAG Business School (Paris)

Vrije Universiteit Amsterdam

December 19, 2019

Abstract

We show that OPEC's market power contributes to climate change by enabling producers of relatively expensive and dirty oil to start producing before OPEC reserves are depleted. We examine the importance of this extraction *sequence* effect by calibrating and simulating a cartel-fringe model of the global oil market. While welfare net of climate damage under the cartel-fringe equilibrium can be significantly lower than under a first-best outcome, almost the entire welfare loss is due to the sequence effect of OPEC's market power. In our benchmark calibration, the cost of the sequence effect amounts to 15 trillion US$, which corresponds to 97 percent of the welfare loss. Moreover, we find that an increase in non-OPEC oil reserves decreases global welfare. In a counterfactual world without non-OPEC oil, global welfare would be 13 trillion US$ higher, 10 trillion US$ of which is due to lower climate damages.

JEL codes: Q31, Q42, Q54, Q58

Keywords: cartel-fringe, climate policy, non-renewable resource, Herfindahl rule

1 Introduction

What is the impact of imperfect competition in the oil market on climate change? This question is relevant given the sizable carbon footprint of oil and the prominent size of OPEC. Oil is responsible for close to a quarter of anthropogenic carbon emissions (IEA, 2016)[1] and, with OPEC producing 40 percent of global oil supply and owning 70 percent of world oil reserves (EIA, 2019b), it is not realistic to assume that OPEC is a price taker in the market of oil.

An old adage says that "the monopolist is the conservationist's best friend" (e.g., Dasgupta and Heal, 1979, p. 329). Indeed, we know from non-renewable resource economics that market power typically leads to higher initial resource prices and slower resource depletion. However, in the case of oil, the consequences of imperfect competition for the Earth's climate are more complex because different types of oil reserves with varying carbon contents are exploited. The reason is that imperfect competition does not only affect the speed, but also the order of extraction of different reserves of oil (cf. Benchekroun et al., 2009, 2010, 2019). Conventional OPEC oil is cheaper and its extraction is less carbon intensive than unconventional oil owned by relatively small oil producers (Malins et al., 2014; Fischer and Salant, 2017; OCI, 2019). Technically recoverable reserves and production of unconventional types of oil by non-OPEC countries have grown significantly over the last decade. The supply of oil sands from Canada has more than doubled, and shale oil production in the US has increased more than tenfold since 2007 (CAPP, 2017b; EIA, 2019b). Current recoverable reserves of Canadian oil sands and of US shale oil amount to 165 and 78.2 billion barrels, respectively (CAPP, 2017a; EIA, 2019c). In this paper, we take into account that when OPEC exercises market power it does not only slow down its rate of extraction—which tends to be good for the climate—but it also opens the door for earlier production by the fringe. As a result, OPEC's relatively cheaper and cleaner oil is extracted later, while the fringe's costlier and dirtier oil is extracted earlier. This 'sequence effect' leads to higher discounted extraction costs and climate damage.

Our paper is related to two strands of literature, the first one studying resource use under imperfect competition. We model the oil market as a situation where supply

---

[1]The other important fossil fuels that contribute to anthropogenic carbon emissions are coal with 28 percent and gas with 12 percent (IEA, 2016).

comes from a cartel and a large group of price-taking fringe members. Important contributions to the field of imperfect competition on non-renewable resource markets were made by Stiglitz (1976) on monopoly, Lewis and Schmalensee (1980) on oligopoly, and Gilbert (1978) and Newbery (1981) on dominant firms. Furthermore, Salant (1976), Groot et al. (2003), Benchekroun et al. (2009, 2010) and Benchekroun and Withagen (2012) have developed cartel-fringe models of the resource market. See also Withagen (2013) for a survey and the references therein. Our paper is closely related to Benchekroun et al. (2019), who built an oligopoly-fringe model of the oil market, taking into account the presence of a renewable substitute for oil. However, Benchekroun et al. (2019) ignored climate damages, implying that they had to remain silent on the sequence effect of market power for climate change. Furthermore, they did not calibrate their model and left out a welfare analysis. Hence, the current paper complements our earlier work.[2]

Second, our article relates to the literature on the sequence of extraction of multiple non-renewable resource deposits with different unit extraction costs. Herfindahl (1967) and Solow and Wan (1976) show that these deposits are optimally extracted in order of increasing marginal extraction costs. The principle of extracting cheap resources before the more expensive ones has become known as the Herfindahl rule. Over the last decades, several refinements of this rule were proposed. Kemp and Long (1980) show that in general equilibrium, the Herfindahl rule may break down due to a consumption smoothing motive. Other reasons for deviations from the Herfindahl rule are heterogeneous resource demand (Chakravorty and Krulce, 1994), extraction capacity constraints (Amigues et al., 1998; Holland, 2003), upper bounds on pollution stocks (Chakravorty et al., 2008) and supply cost uncertainty (Gaudet and Lasserre, 2011). We contribute to this literature by examining how a violation of the Herfindahl rule due to imperfect competition affects climate change through the timing of carbon emissions.

---

[2]While we follow a large strand of the literature and consider that OPEC acts as a cohesive cartel (see Withagen (2013) for a survey), there is recent empirical evidence for imperfect cartelization of OPEC (cf. Almoguera et al., 2011; Brémond et al., 2012; Kisswani, 2016; Okullo and Reynès, 2016). We have also examined the case where the cartel consists of subgroups that act as Cournot oligopolists (see Benchekroun et al. (2019) for the characterization of the equilibrium). The qualitative nature of the equilibrium and the policy implications remain unchanged, although the sequence effect becomes smaller (e.g., in case of 5 oligopolists 89 percent of the welfare loss of imperfect competition compared to the first-best is attributable to the sequence effect). We have therefore opted to keep the assumption of a cohesive cartel for the ease of exposition and economy of notation.

We quantify the effect of market power on climate damages and welfare. Furthermore, we determine the effects of a resource tax, and perform a sensitivity analysis for reserves, extraction costs, emission factors of the cartel and the fringe, and the specification of the demand function. Our analysis takes into account that conventional oil supplied by OPEC has lower marginal extraction costs and is cleaner than oil from deep-water drilling, oil sands, oil shale, and shale oil supplied by the fringe (Malins et al., 2014; Fischer and Salant, 2017; OCI, 2019). Our main findings are as follows.

First, when decomposing the global welfare loss under the cartel-fringe equilibrium into a 'conservation effect' (slower extraction due to a higher initial oil price) and a 'sequence effect' (front-loading of extraction of the relatively expensive and dirty resource), we find that the sequence effect, which so far has remained unexplored in the literature, is huge in our calibrated model. In the benchmark scenario, imperfect competition causes a social welfare loss of 14.5 percent of first-best welfare, almost all of which (97 percent, corresponding to 15 trillion US$) is imputable to the inefficient order of use of the resources, i.e., to the sequence effect. Furthermore, imperfect competition increases the discounted value of climate damages by 5.3 percent compared to the first-best. Without the sequence effect, imperfect competition would *decrease* climate damages by 4.8 percent compared to the first-best, due to the conservation effect.

Second, the recent increase in non-OPEC oil reserves and the decrease in their extraction costs have not only increased climate damages, but may also have lowered 'grey welfare' because the relatively expensive non-OPEC oil partially crowds out early extraction of cheap oil by the cartel. We numerically investigate conditions under which the recent boom in nonconventional reserves and the decrease in nonconventional oil extraction costs reduces global welfare. Starting from our benchmark calibration, each additional barrel of non-OPEC oil reserves lowers global welfare by 12 US$. Furthermore, in a counterfactual world without non-OPEC oil, global welfare would be 13 trillion US$ higher, 10 trillion US$ of which is due to lower climate damages.

Our findings are supportive of recent calls for a supply side approach to a climate treaty and for the need for policies that limit investments and extraction of fossil fuels (cf. Harstad, 2012; Erickson et al., 2018; Green and Denniss, 2018; Asheim et al., 2019). A successful supply side treaty has to take into account the heterogeneity of

reserves in terms of extraction costs and full-cycle greenhouse gas emissions, as well as the effects of market power on the timing of extraction of the different oil reservoirs.

Our numerical results are obtained within a calibrated stylized model. A caveat is therefore in order. The numbers we obtain are useful only to gain insight into the possible relative magnitudes of the different effects examined. But some remarks on the scope of our study are in order at this point as well. We only consider two types of oil reserves; this clarifies the exposition and the relevant mechanisms at the expense of more realism and more accurate estimates of the effects we measure. We consider linear extraction costs, thus in our model cumulative extraction is exogenous: Climate damage effects merely result from changes in the timing of extraction of different types of oil. Therefore, our analysis mainly applies to the extraction of relatively cheap oil that is available at roughly constant marginal costs and in finite amounts (and not to more expensive oil that is available in larger amounts and at higher, reserve-dependent extraction costs). Still, the initial aggregate proven oil reserves that we use in our calibrated model contain 839 tonnes of CO_2 (EIA, 2019b), which already is about 84 percent of the remaining carbon budget corresponding to the scenario of keeping the average global temperature rise below 2 degrees Celsius with a 50 percent probability (McGlade and Ekins, 2015). Our results show that even with fixed cumulative emissions, the change in the timing of extraction of the proven oil reserves due to imperfect competition, the shale oil revolution, and the introduction of a resource tax already generate substantial climate damage and welfare effects.

The importance of the inefficient order of use of the different oil reserves is corroborated by the recent findings of Asker et al. (2019). While we use a stylized model with two different types of reserves, they use a rich micro-dataset on production costs and reserves of 11,455 oil fields (constituting 99.9 percent of global reserves). They construct a counterfactual scenario for the period 1970-2100 (when all reserves are assumed depleted) in which these fields are extracted according to the Herfindahl rule, where from 2014 until 2100 it is assumed that oil demand increases at an annual rate of 1.3 percent and actual production satisfies the Herfindahl rule. Asker et al. (2019) find that the total costs of production misallocation between oil fields add up to 744 billion US$ (measured at 2014 prices), which equals 30 percent of the present value of actual extraction costs since 1970. Furthermore, they show that 22 percent of this

efficiency loss (i.e., 163 billion US$) can be attributed to OPEC's market power.[3] It is interesting to note that while both Asker et al. (2019) and our paper point to the importance of the inefficiencies due to OPEC's market power, we get to this conclusion from quite different approaches, an indication of the robustness of our results.

In contrast with Asker et al. (2019), in our paper the time path of aggregate oil supply is not exogenous. The extraction paths for the entire time horizon are obtained as equilibrium paths from a theoretical model of resource extraction that incorporates market power, competition by a fringe and the existence of a backstop technology. After fully characterizing the market equilibrium, we calibrate our model on the global oil market and examine different scenarios (e.g., first-best, perfect competition, cartel-fringe). Hence, we take into account that market power not only influences the order but also the speed of extraction. Moreover, while Asker et al. (2019) limit their attention to the production cost inefficiency due to OPEC's market power, we examine the repercussions of the order of extraction for climate change, due to differences in both extraction costs as well as carbon emissions factors between oil fields. Furthermore, we use our theoretical model to examine the implications of a resource tax and to perform a welfare analysis.

The remainder of the paper is structured as follows. Section 2 outlines the model. Section 3 characterizes the cartel-fringe equilibrium. Section 4 calibrates the model, quantifies the sequence effect, and discusses the welfare effects of increasing reserves and declining extraction costs of non-OPEC oil, and of a resource tax. Section 5 examines the robustness of our results with respect to non-linear demand functions. Finally, Section 6 concludes.

2   The model

A non-renewable resource is jointly supplied by a price-taking fringe and a cartel with market power. The fringe is endowed with an aggregate initial stock S_0^f and has a constant per unit extraction cost k^f. The initial stock of the cartel is denoted by S_0^c. The per unit extraction cost of the cartel is constant and denoted by k^c. Extraction

---

[3]The 163 billion US$ that Asker et al. (2019) report is in between the welfare costs of the sequence effect of 15 trillion US$ that we find when we model OPEC as a cohesive cartel and the welfare costs of the sequence effect amounting to 75 billion US$ if we would model OPEC as 14 Cournot oligopolists.

rates at time $t \geq 0$ by the fringe and the cartel are $q^f(t)$ and $q^c(t)$, respectively. The time argument will be dropped when possible. A perfect substitute for the resource can be produced, indefinitely, at marginal cost $b > 0$, by using a backstop technology. We abstract from technological progress (cf. Fischer and Salant, 2017), as well as from set-up costs. If $p \leq b$, inverse demand for the non-renewable resource is given by $p = \alpha - \beta(q^f + q^c)$, with $\alpha > 0$ and $\beta > 0$, where p denotes the price of the resource.[4] If $p > b$, demand for the non-renewable resource equals zero. Denote the interest rate by $r > 0$.

The fringe maximizes its discounted profits,

$$\int_0^\infty e^{-rt}(p(t) - k^f)q^f(t)dt, \tag{1}$$

taking the price path as given, subject to its resource constraint

$$\dot{S}^f(t) = -q^f(t), S^f(t) \geq 0 \text{ for all } t \geq 0, \text{ and } S^f(0) = S_0^f. \tag{2}$$

The cartel is aware of its influence on the equilibrium price and maximizes

$$\int_0^\infty e^{-rt}(\alpha - \beta(q^f(t) + q^c(t)) - k^c)q^c(t)dt, \tag{3}$$

taking the time path of q^f as given, subject to its resource constraint

$$\dot{S}^c(t) = -q^c(t), S^c(t) \geq 0 \text{ for all } t \geq 0, \text{ and } S^c(0) = S_0^c. \tag{4}$$

Moreover, the existence of the perfect substitute effectively implies an upper limit on the price the cartel can ask, yielding the additional constraint

$$\alpha - \beta(q^f(t) + q^c(t)) \leq b, \tag{5}$$

since b is the price at which consumers are indifferent between the non-renewable resource and the substitute. We assume that $k^c < k^f < b < \alpha$.

---

[4]Section 5 considers the case of non-linear demand functions resulting from a more general class of utility functions, namely the class of Hyperbolic Absolute Risk Aversion (HARA) utility of functions.

3 Cartel-fringe equilibrium

In this section, we first introduce the equilibrium concept. Subsequently, we discuss the different sequences of extraction phases that can occur in the equilibrium of the game.

3.1 Equilibrium concept

The cartel chooses an extraction path, taking the extraction path of the fringe as given while the fringe takes the price path as given and chooses its extraction path.

Definition 1 *A vector of functions* $(q^c, q^f) : [0, \infty) \to \mathbb{R}_+^2$ *with* $q^c(t) \geq 0$ *and* $q^f(t) \geq 0$ *for all* $t \geq 0$ *is a Cartel-Fringe Equilibrium (CFE) if*

(i) each extraction path of the vector (q^c, q^f) *satisfies the corresponding resource constraint,*

(ii)

$$\int_0^\infty e^{-rs} \left[\alpha - \beta \left(q^c(s) + q^f(s) \right) - k^c \right] q^c(s) ds$$
$$\geq \int_0^\infty e^{-rs} \left[\alpha - \beta \left(\hat{q}^c(s) + q^f(s) \right) - k^c \right] \hat{q}^c(s) ds$$

for all $\hat{q}^c$ *satisfying the resource constraint, and*

(iii)

$$\int_0^\infty e^{-rs} \left[p\left(s \right) - k^c \right] q^f(s) ds \geq \int_0^\infty e^{-rs} \left[p\left(s \right) - k^c \right] \hat{q}^f(s) ds,$$

where $p\left(s \right) = \alpha - \beta \left(q^c(s) + q^f(s) \right)$*, for all* $\hat{q}^f$ *satisfying the resource constraint.*

A full characterization of the cartel-fringe equilibrium is provided in Benchekroun et al. (2019).[5] Hence, we restrict ourselves to explaining its main properties. In a CFE, different phases of resource extraction may exist. By F, C, S and L we denote phases with only the fringe supplying, only the cartel supplying at a price strictly below b, simultaneous supply at a price strictly below b, and supply by the cartel at price b (i.e., limit pricing), respectively. We use the symbol '$\to$' to indicate the sequence of phases,

---

[5]Benchekroun et al. (2019) actually characterize an *oligopoly*-fringe equilibrium with n symmetric oligopolists. Our model is a special case of theirs, with $n = 1$.

e.g., $S \rightarrow F$ means that a phase with simultaneous use is preceding a phase with only the fringe supplying at a price strictly below b. We use the notation $t \in \Phi$ to refer to a moment where the phase of resource extraction is Φ with $\Phi \in \{F, C, S, L\}$.

The sequence of different extraction phases crucially depends on the initial resource stocks and on the cartel's marginal profit at the prices k^f (i.e., when the resource price equals marginal extraction cost of the fringe) and b (i.e., when the resource price equals the price of renewables). We denote the cartel's marginal profit as

$$\Pi(q^f, q^c) \equiv \alpha - \beta \left(q^f + 2q^c \right) - k^c. \tag{6}$$

Let us define demand at price k^f as $\tilde{q} \equiv (\alpha - k^f)/\beta$ and demand at the limit price b as $\hat{q} \equiv (\alpha - b)/\beta$. Marginal profit of the cartel at these prices reads, respectively,

$$\tilde{\Pi} \equiv \Pi(0, \tilde{q}) = 2k^f - \alpha - k^c, \tag{7a}$$
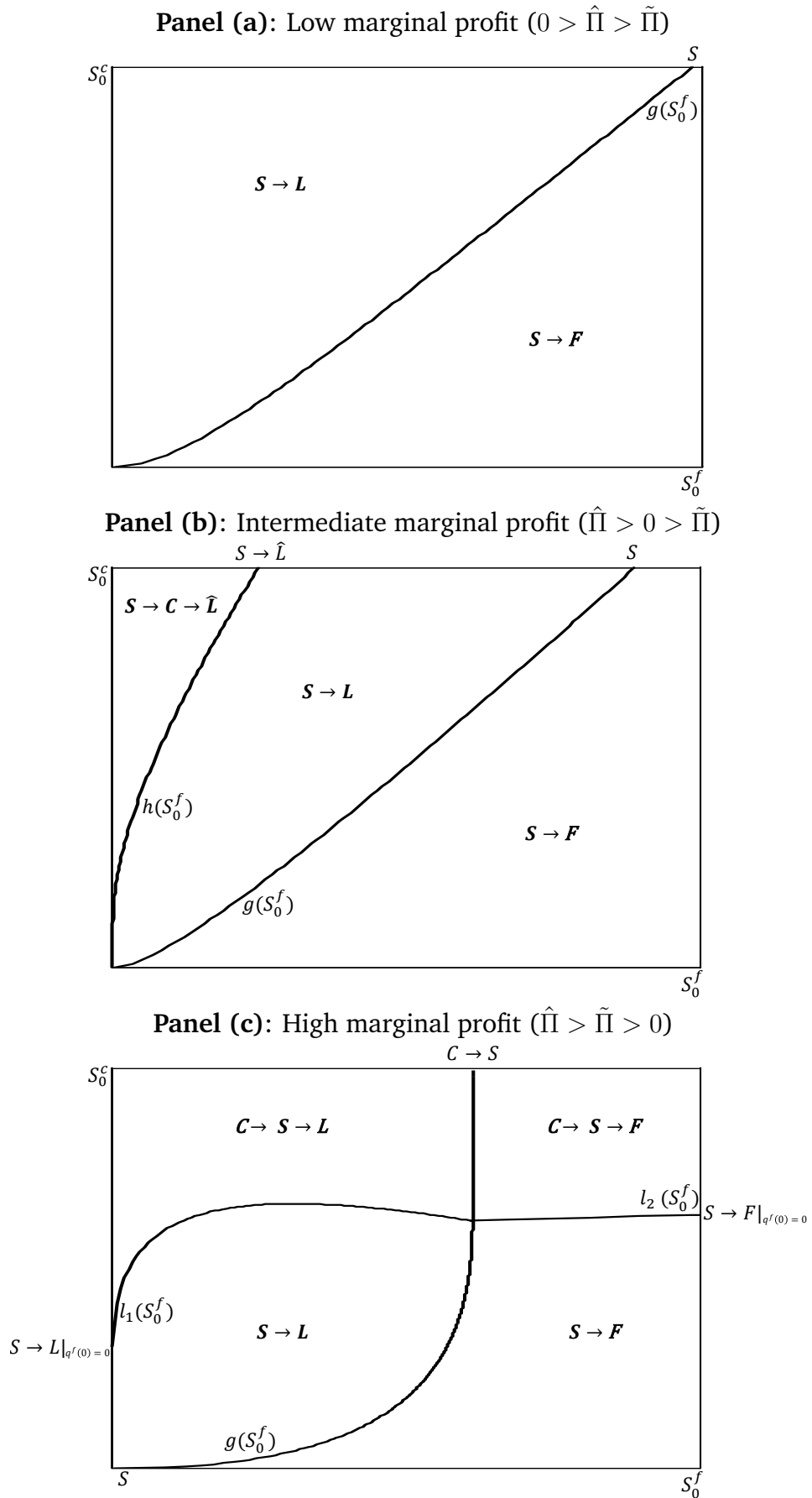
$$\hat{\Pi} \equiv \Pi(0, \hat{q}) = 2b - \alpha - k^c. \tag{7b}$$

Since $k^f < b < \alpha$, we have $\hat{\Pi} > \tilde{\Pi}$. Figure 1 shows the equilibrium sequence for different combinations of the initial resource stocks when $0 > \hat{\Pi} > \tilde{\Pi}$ ('low marginal profit', panel (a)), $\hat{\Pi} > 0 > \tilde{\Pi}$ ('intermediate marginal profit', panel (b)), and $\hat{\Pi} > \tilde{\Pi} > 0$ ('high marginal profit', panel (c)).

It is clear from Figure 1 that the equilibrium always features a regime with simultaneous use. This is an important result, as it drives the 'sequence effect': The existence of a simultaneous use phase implies that in the CFE extraction of the relatively expensive and dirty resources is front-loaded in time, compared to the first-best and the perfectly competitive equilibrium, which both are characterized by the equilibrium sequence $C \rightarrow F$, as shown in Appendix A. However, in the cartel-fringe equilibrium a transition from C to F would imply a downward jump in the cartel's extraction level and hence an upward jump in its marginal profits. It would then be better for the cartel to gradually lower its market share during a phase with simultaneous use.

Furthermore, for low and intermediate marginal profit levels (i.e., $0 > \tilde{\Pi}$ as in panels (a) and (b) of Figure 1), a CFE always starts with a simultaneous use phase. The intuition behind this outcome is that, in these cases, marginal profit of the cartel is negative as long as the market price is lower than the marginal extraction cost of the

Figure 1: Extraction sequences in the cartel-fringe equilibrium

Panel (a): Low marginal profit $(0 > \hat{\Pi} > \tilde{\Pi})$

Panel (b): Intermediate marginal profit $(\hat{\Pi} > 0 > \tilde{\Pi})$

Panel (c): High marginal profit $(\hat{\Pi} > \tilde{\Pi} > 0)$

fringe. Hence, if the cartel would initially be sole supplier it would choose an extraction rate such that the price would be higher than the fringe's marginal extraction cost. But then the net price of the fringe would grow at a rate lower than the rate of interest if the cartel would be sole supplier. Hence, the fringe prefers extraction over conservation: It will enter the market and a phase with simultaneous supply will result. Similarly, if the fringe would be the sole supplier initially, marginal profits of the cartel would be positive and growing at a rate lower than the rate of interest. Therefore, the cartel will start supplying immediately. So, as long as both the cartel and the fringe have a positive stock, there will be simultaneous supply.

In the remainder of this section, we will discuss the extraction sequences in the CFE for the different marginal profit scenarios shown in the three panels of Figure 1.

Low marginal profit. If marginal profit is negative for $p \leq b$ (the case depicted in panel (a)), the cartel will perform a limit-pricing strategy as soon as the fringe's stock is depleted. Hence, if the relative initial stock of the cartel is large enough the equilibrium sequence reads $S \to L$. However, if the relative initial stock of the cartel is small, the stock of the cartel will be depleted before the stock of the fringe and the equilibrium sequence is $S \to F$. The strictly increasing locus $g(S_0^f)$ gives combinations of S_0^c and S_0^f for which there is simultaneous use throughout with depletion of both resource stocks at the same instant of time.

Intermediate marginal profit. If marginal profit is positive at $p = b$ but negative for $p \leq k^f$ (the case depicted in panel (b)), the cartel does not necessarily choose for limit pricing directly after depletion of the fringe's stock. When the initial stock of the cartel is large enough, an intermediate C-phase occurs, as shown in the upper left region of the figure. Still, a final limit-pricing phase is present. Without such a final phase, marginal profit of the cartel would jump up to $b - k^c > \hat{\Pi}$ after depletion of its stock (when resource supply jumps down to zero), implying that it would be better off by conserving the last unit of the resource and selling it at the end of the extraction horizon at $p = b$. Hence, a final limit-pricing phase arises. Postponing extraction in this way remains profitable until marginal profit at the beginning equals marginal profits at the end of the final limit-pricing phase (discounted back to the beginning): $\hat{\Pi} = (b - k^c)e^{-\hat{T}r}$, where $\hat{T}$ denotes the maximum duration of the final limit-pricing phase. Hence, the extraction

sequence in the upper left region of the figure reads $S \to C \to \hat{L}$, where $\hat{L}$ denotes the limit pricing phase with duration $\hat{T}$. The duration of the intermediate C-phase becomes lower if S_0^c is reduced. The strictly increasing locus $h(S_0^f)$ gives combinations of S_0^f and S_0^c for which the intermediate C-phase exactly vanishes. For even lower values of S_0^o, in between the $h(S_0^f)$ and the $g(S_0^f)$ loci in panel (b), there will be limit pricing with a duration smaller than $\hat{T}$ after the stock of the fringe is depleted: $S \to L$. As in panel (a), below the $g(S_0^f)$ locus the equilibrium sequence reads $S \to F$.

High marginal profit. Finally, if marginal profit is positive for all $p \leq b$ (the case depicted in panel (c)), it may be profitable for the cartel to drive down the price below the extraction cost of the fringe, implying that an initial C-phase may occur. This happens in the upper region of the figure. On the upper left, the extraction sequence reads $C \to S \to L$. The duration of the final limit-pricing phase goes down if S_0^f is increased. At the vertical $C \to S$ locus, the limit-pricing phase has exactly vanished. Moving further to the right in the figure, the initial stock of the fringe becomes large enough to end up with a positive remaining stock when the cartel's stock is depleted. Hence, there will be a final F-phase and the equilibrium reads $C \to S \to F$. The potentially non-monotonic $l_1(S_0^f)$ and strictly increasing $l_2(S_f^0)$ loci give combinations of S_0^f and S_0^c for which the initial C-phase exactly vanishes. Below these loci, the extraction sequence either reads $S \to L$ (to the left of the $g(S_0^f)$ locus), or $S \to F$ (to the right of it).

4   Welfare implications of the CFE

We now exploit our analysis above to examine the quantitative importance of imperfect competition and the order of extraction of different oil reserves and the repercussions for climate change and welfare. In our framework, the fact that the fringe may start extracting before the low cost resource is exhausted is a source of inefficiency. This inefficiency is further amplified when we consider the emissions of pollution generated by oil and their impact on climate change. In this section we calibrate our model to examine the relative importance, in terms of global welfare, of the inefficient order of use of oil reserves. Our calibrated model also allows us to examine the effect of

increases in the fringe's reserves and decreases in its extraction costs on global welfare. Furthermore, we have checked that in all cases that we investigate numerically, the CFE is subgame perfect.[6]

We define 'grey' welfare, W^G, as the discounted sum of consumer surplus and producer surplus:

$$W^G \equiv \int_0^T e^{-rt} \left[\alpha(q^c + q^f) - \frac{1}{2}\beta(q^c + q^f)^2 - k^c q^c - k^f q^f \right] dt + \frac{e^{-r\bar{T}}}{r} \frac{(\alpha - b)^2}{2\beta},$$

where T denotes the moment at which the last resource stock is depleted.[7]

The atmospheric stock of carbon, E, evolves according to

$$\dot{E}(t) = \omega^c q^c(t) + \omega^f q^f(t),$$

where ω^c and ω^f denote the emission factor of the cartel and the fringe, respectively. We follow Hoel (2011), Golosov et al. (2014) and Van der Ploeg (2016) by assuming that climate damages are linear in the stock of atmospheric carbon.[8] The discounted value of climate damage is given by:

$$D(t) = \int_t^\infty e^{-r(s-t)} \zeta E(s) ds,$$

where $\zeta > 0$ denotes the instantaneous and constant marginal damage of carbon. Hence, the social cost of carbon (SCC), i.e., the discounted value of current and future marginal damages, is equal to

$$SCC(t) = \int_t^\infty e^{-r(s-t)} \zeta ds = \frac{\zeta}{r}.$$

---

[6]To be precise, we have found that in all cases that we examine numerically, the open loop CFE coincides with the closed loop CFE (which is subgame perfect in Markov strategies, cf. Salo and Tahvonen (2001)) if the fringe is modeled as described by Benchekroun and Withagen (2012, p. 356): "Each fringe firm takes the price path as given and determines its extraction strategy which is allowed to depend on its own stock only; the cartel takes each fringe firm's strategy as given and determines a pricing strategy (or alternatively a production strategy) that depends on its own stock and all fringe's stocks."

[7]Alternatively, we could define a the quasi-linear utility function $U(q^c + q^f + x) = \alpha(q^c + q^f + x) - \frac{1}{2}\beta(q^c + q^f + x)^2 + M$ (which gives rise to our linear demand function), where x denotes renewables consumption and M expenditure on a *numeraire* good. This results in the same expression for W^G.

[8]Golosov et al. (2014) actually assume that marginal damages are proportional to output. However, with the logarithmic utility function and constant savings rate that they impose, this is equivalent to our assumption of constant marginal damages in the utility function.

Social welfare, W, is defined as the difference between grey welfare and climate damage: $W \equiv W^G - D$.

In determining supply, both the cartel and the fringe ignore the damage caused by their activity. Thus in our framework we have two sources of market failure: Imperfect competition and a negative climate externality. The evaluation of the impact of market failure cannot entirely be captured by the level of the industry's output alone; it should also take into account the composition of aggregate extraction. Indeed, for a given path of aggregate extraction, the equilibrium involves an S-phase during which extraction of the high cost source occurs before the low cost reserve is exhausted. We seek to determine the relative importance of this failure due to the inefficient order of use of resources. For this purpose we compare the CFE characterized above, with the outcomes of three scenarios: The socially optimal extraction of reserves also referred to as the first-best (FB), the perfectly competitive (PC) scenario where the cartel— the owner of the low cost reserves—is assumed to be price taker, and the 'Herfindahl scenario'. In this latter scenario, total extraction at each instant of time is the same as in the CFE, but we impose the order of resource use of the first-best; first extraction by the cartel until its stock is depleted and then extraction by the fringe until depletion. This allows us to decompose the deviation of the CFE from the first-best into a 'conservation effect' (i.e., the deviation of the Herfindahl scenario from the first-best) and a 'sequence effect' (i.e., the deviation of the CFE from the Herfindahl scenario).

4.1 Calibration

We calibrate our model by using data on proven oil reserves, global oil consumption, extraction costs, the oil price, the price elasticity of oil demand, and carbon emission factors for different types of oil. Proven reserves owned by OPEC are 1212 billion barrels (EIA, 2019b). In the rest of the world, proven reserves excluding shale oil equal 438 billion barrels (EIA, 2019b). Furthermore, according to the EIA (2013) the "increase in total resources due to inclusion of shale oil" is equal to 11 percent, which implies another 181.5 barrels of oil for the rest of the world. For the parameters of the demand function, we use $\alpha = 225.5$ US\$/bbl and $\beta = 4.3$ US\$/bbl to get an initial oil demand of 34 billion barrels and an initial price of 80 dollars per barrel (roughly equal to the average crude oil consumption and crude oil price over the last decade (EIA,

2019b)) and an initial price elasticity of demand of 0.55, which is within the range of long-run price elasticities reported by Hamilton (2009).[9]

Table 1: Benchmark calibration

parameters	description	value	unit
α	choke price	225.5	US\$/bbl
β	slope inverse demand function	4.3	US\$/bbl
b	renewables price	102.5	US\$/BOE
k^c	marginal extraction cost cartel	18	US\$/bbl
k^f	marginal extraction cost fringe	62.5	US\$/bbl
r	interest rate	0.028	perunage
S_0^c	initial stock cartel	1212	billion bbl
S_0^f	initial stock fringe	619.5	billion bbl
ω^c	emission factor cartel	0.11083	tC/bbl
ω^f	emission factor fringe	0.1525	tC/bbl
$SCC = \zeta/r$	social costs of carbon	250	US\$/tC
implied values	**description**	**value**	**unit**
$q^c(0) + q^f(0)$	initial oil consumption	34	billion bbl
$p(0)$	initial oil price	80	US\$/bbl
$\varepsilon q^c(0) + q^f(0))$	initial price elasticity of demand	0.55	elasticity

For the marginal extraction costs of OPEC, we use the Middle East and North African oil (MENA) estimate of 18 US\$ per barrel reported in Fischer and Salant (2017). For the unit extraction costs of the fringe, we use a weighted average (with the oil reserves as weights)[10] of the other types of oil in Fischer and Salant (2017), which gives 62.5 US\$ per barrel.[11] Similarly, for the relative emission factor of the fringe (compared to OPEC) we use a weighted average of the relative emission factors of the different types of oil (excluding the MENA oil) in Fischer and Salant (2017), yielding $\omega^f/\omega^c = 1.376$. For the carbon content of crude oil, we use $\omega^c = 0.11083$ ton carbon per barrel (EPA, 2015).

For the renewables unit cost parameter we use $b = 102.5$ US\$/BOE ('barrels of oil equivalent') to indeed get an initial oil use equal to 34 billion barrels in equilibrium.

---

[9]By using the price elasticity of demand $\varepsilon \equiv -\frac{dq/q}{dp/p} = \frac{\alpha - \beta q}{\beta q}$ together with the demand function, we obtain $\alpha = \frac{\varepsilon+1}{\varepsilon}p$ and $\beta = \frac{p}{\varepsilon q}$, yielding values for α and β in terms of the observed initial p, q, and ε.

[10]Fischer and Salant (2017) use estimates for the ultimately recoverable resources reported by the IEA (2013), instead of the proven oil reserves.

[11]Fischer and Salant (2017) include conventional oil, enhanced oil recovery (EOR) and deep-water drilling, heavy oil, oil sands, and oil shale in their analysis.

Our renewables unit cost corresponds to the unit costs of biofuels after 30 years in Fischer and Salant (2017).[12] For the social cost of carbon, we take 250 US$/tC (or 68 US$/tCO$_2$), which is within the Nordhaus-Stern range of about 31 to 85 US$/tCO$_2$ (Stern, 2007; Nordhaus, 2017).[13] For the interest rate, we take the average of the US long-term composite rate on government bonds over the period 2017-2019, which equals 2.8 percent (U.S. Department of the Treasury, 2019).[14]

An overview of our benchmark calibration and the implied equilibrium values is provided in Table 1.[15] Because we have expressed prices and costs in billion US$, welfare and climate damages are expressed in billion US$ as well. The equilibrium of the calibrated model is characterized by $\hat{\Pi} < 0$ and the sequence $S \to L$: The cartel follows a limit-pricing strategy as soon as the fringe's stock is depleted.

4.2 The effects of imperfect competition

In this section, we discuss the effects of imperfect competition by comparing the CFE with the outcome under perfect competition, the first-best, and the Herfindahl scenario (i.e., the CFE without the sequence effect). The perfectly competitive equilibrium and the first-best are characterized in Appendix A.

Figure 2 shows the time profiles of the oil price (panel (a)) and cumulative carbon emissions (panel (b)) for the benchmark calibration. The black solid and dashed curves represent the CFE and the perfectly competitive equilibrium, respectively. The solid grey curve corresponds to the first-best and the dotted curve represents the Herfindahl scenario. The curves in panel (a) show that the time profile of the resource price in the CFE is entirely located above the perfectly competitive one, and even above the one corresponding to the first-best. Still, panel (b) shows that initially cumulative carbon emissions grow more rapidly in the CFE than under perfect competition and the first-best. The reason is that although extraction is initially lower in the CFE due to the higher oil price (conservation effect), extraction of relatively dirty oil by the fringe

---

[12]In their benchmark scenario, Fischer and Salant (2017) assume that the backstop cost initially equals 115 US$/BOE and gradually falls over time, due to technological change.

[13]We have $SCC = \frac{\varsigma}{r}$. Hence, in the benchmark scenario we set $\zeta = 250 \cdot 0.028 = 7$ US$/tC.

[14]The long-term composite rate is the "unweighted average of bid yields on all outstanding fixed-coupon bonds neither due nor callable in less than 10 years" (U.S. Department of the Treasury, 2019).
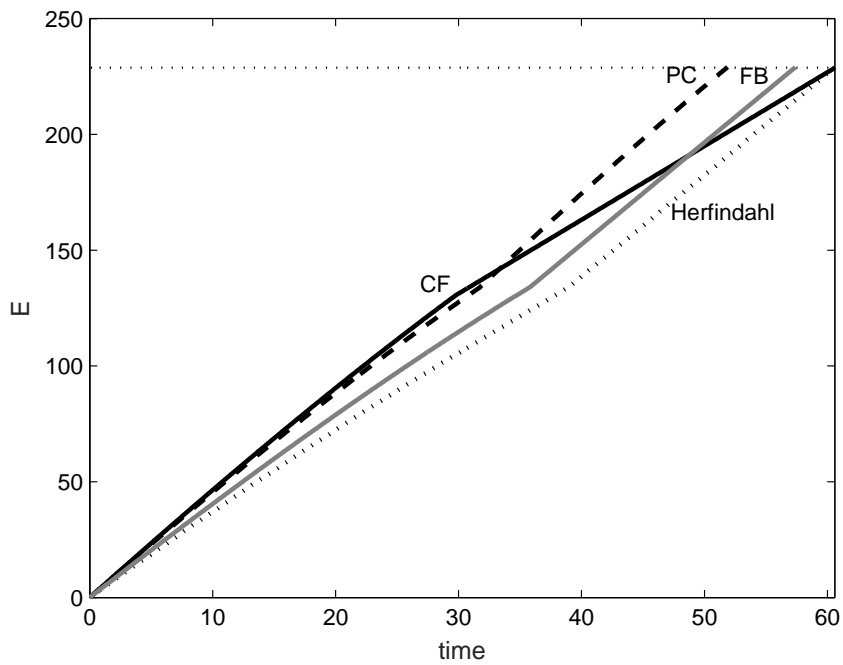
[15]We use tC to denote 'metric tonnes of carbon', GtC for 'gigatonnes of carbon', bbl for 'barrels of oil' (one barrel contains about 159 litres) and BOE for 'barrels of oil equivalent'.

Figure 2: Time profiles

Panel (a) - Oil price (US$/bbl)
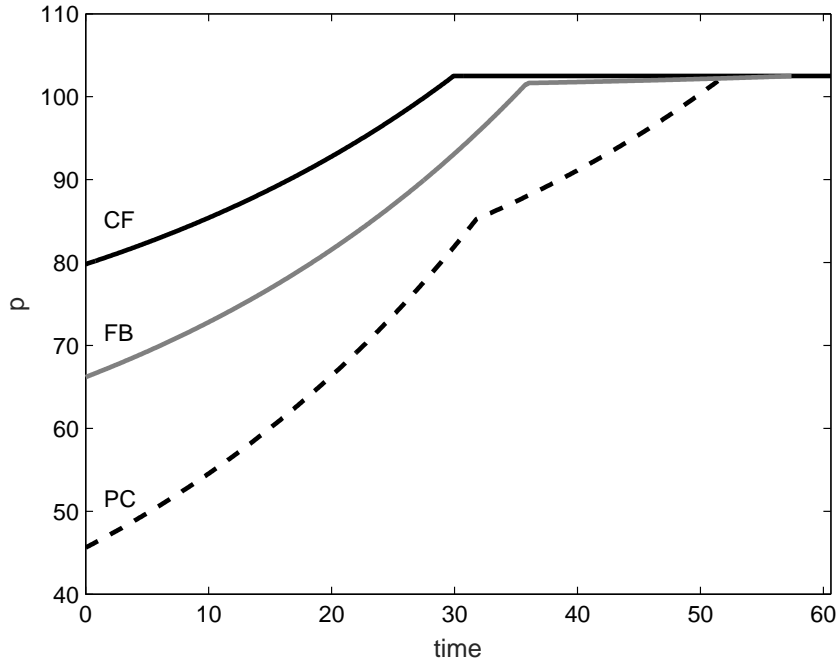
Panel (b) - Cumulative emissions (GtC)

Notes: The figure shows the time profiles of the oil price (panel (a)) and cumulative carbon emissions (panel (b)). The figure shows these time profiles for the cartel fringe (CF, solid black), perfectly competitive (PC, dashed black), first-best (FB, solid grey) equilibria, and the Herfindahl scenario (dotted black). Parameters are set at their benchmark values, as shown in Table 1.

is front-loaded in time in the CFE (sequence effect). The dotted curve shows that if we would eliminate the sequence effect, the CFE would generate a cumulative carbon emissions time profile below the one generated by each of the other cases.

**Figure 3:** Relative emission factors and climate damage
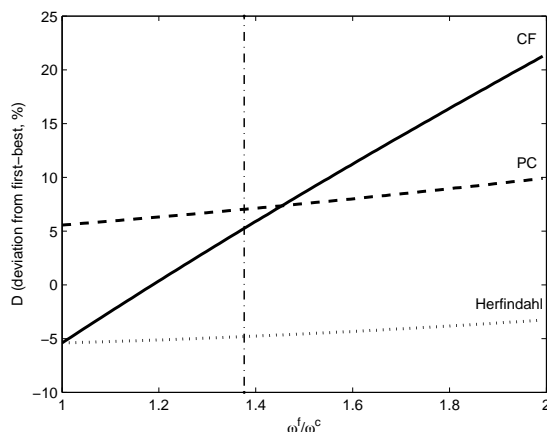
Notes: The figure shows percentage deviations of climate damage (expressed in US$) from the first-best for various values of ω^f/ω^c. The solid black curve corresponds to the cartel-fringe (CF) and the dashed black curve to the perfectly competitive (PC) equilibrium. The dotted curve represents the Herfindahl scenario. Parameters are set at their benchmark values, as shown in Table 1. The vertical line indicates the benchmark relative emission factor.

Figure 3 depicts how climate damage depends on the emission factor of the fringe compared to that of the cartel. The figure shows the deviation of climate damage from the first-best, in percentage terms. When the relative emission factor equals unity, the CFE coincides with the Herfindahl scenario, as the sequence effect becomes immaterial to climate change. Due to the conservation effect, climate damage is lower than under perfect competition, and even lower than in the first-best. However, by increasing the relative emission factor above 1.2, climate damage becomes higher than in the first-best, and eventually (above 1.45) higher than under perfect competition.

Figure 4 compares the levels of grey welfare (panel (a)), climate damage (panel (b)), and social welfare (panel (c)) between the different scenarios for various values of the interest rate, which is a crucial determinant of the welfare consequences of changes in the sequence of extraction.[16] Comparison of the CFE (solid line) and the Herfindahl scenario (dotted line) in the three panels learns that the difference in welfare and climate damage is mainly driven by the sequence effect. In our benchmark scenario

---

[16]We offset changes in the interest rate by changes in ζ in order to leave the $SCC = \zeta/r$ unaffected.

Figure 4: Welfare deviations from first-best
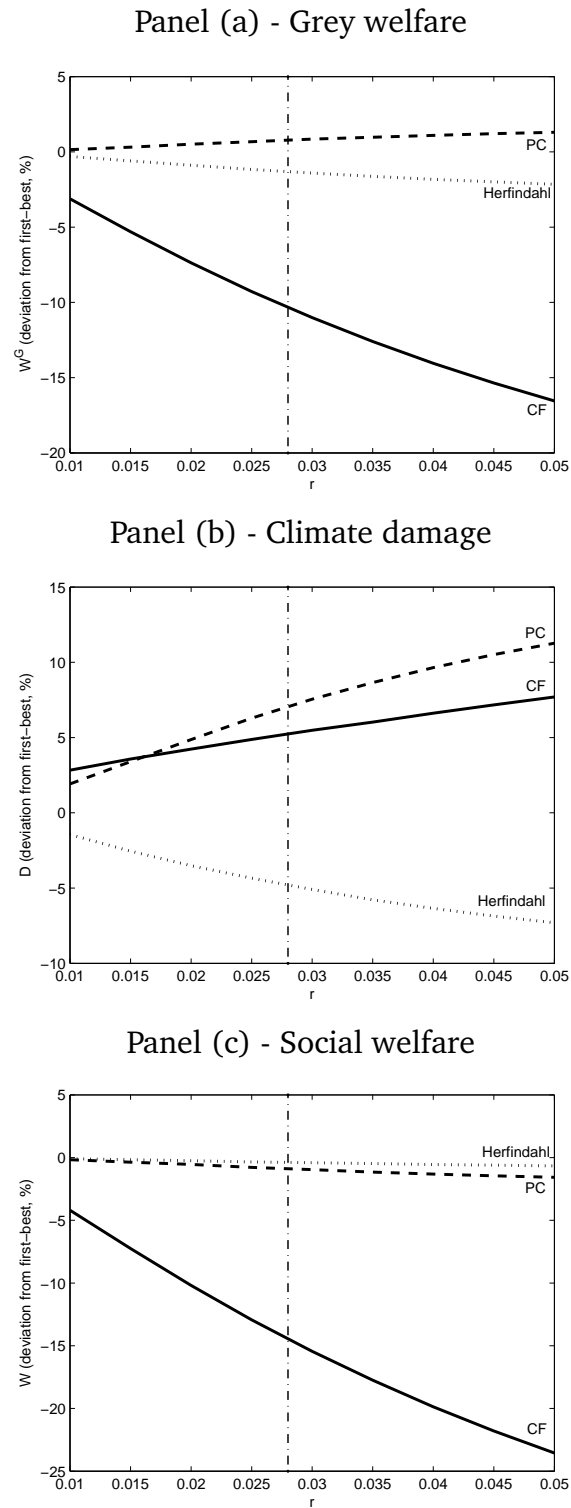
Panel (a) - Grey welfare

Panel (b) - Climate damage

Panel (c) - Social welfare

Notes: The figure shows percentage deviations of grey welfare (panel (a)), climate damage (panel (b)), and social welfare (panel (c)) from the first-best for various values of the interest rate. The solid black curves correspond to the cartel-fringe (CF) and the dashed black curves to the perfectly competitive (PC) equilibrium. The dotted curves represent the Herfindahl scenario. Parameters are set at their benchmark values, as shown in Table 1. The vertical lines indicate the benchmark interest rate.

18

with $r = 0.028$, the grey welfare loss in the CFE, compared to the first-best (as depicted in panel (a)), is 10.3 percent, of which only 1.3 percentage points remain in the Herfindahl scenario: 87.4 percent of the grey welfare loss is driven by the sequence effect. Furthermore, at $r = 0.028$ climate damage (panel (b)) is 5.3 percent higher in the CFE equilibrium than in the first-best, while the Herfindahl scenario would give a 4.8 percent *lower* climate damage than in the first-best. Panel (c) shows that social welfare at $r = 0.028$ is 14.5 percent lower in the CFE than in the first-best, of which only 0.4 percentage points remain in the Herfindahl scenario: 97 percent of the loss in social welfare is due to the sequence effect. In absolute terms, the social welfare loss due to the sequence effect corresponds to 15 trillion US\$ in our benchmark calibration. Panel (c) also shows that the difference between the CFE and the Herfindahl curve is increasing in the rate of interest. Intuitively, the higher the rate of interest, the more important timing becomes, and the larger will be the loss in welfare due to the violation of the Herfindahl rule in the CFE.

Figure 5: Importance of sequence effect: the role of extraction costs
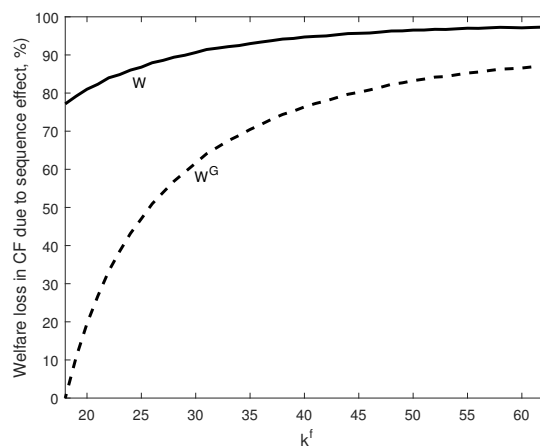
Notes: The figure shows the percentage of the welfare loss of the CFE (compared to the first-best) that can be attributed to the sequence effect, for various values of k^f. The solid line represents social welfare and the dashed line grey welfare. Parameters are set at their benchmark values, as shown in Table 1.

Figure 5 shows how the share of the welfare loss in the CFE (compared to the first-best) attributable to the sequence effect depends on the marginal extraction cost of the fringe. The solid (dashed) line depicts the percentage of the social (grey) welfare loss that can be attributed to the sequence effect. It is clear from the figure that if the marginal extraction costs of the fringe would be equal to those of the cartel, the

sequence effect in grey welfare would vanish. Still, because of the relatively high emission factor of the fringe, the sequence effect would remain important for climate damage and therefore for social welfare.

4.3   More and cheaper non-OPEC oil

Recently, oil reserves of non-OPEC countries have gone up substantially. The proven oil reserves of the US, for instance, have more than doubled from 19 to 39 billion barrels between 2010 and 2017 EIA (2019a). Furthermore, the average "well drilling and completion costs" in five US onshore areas evaluated by the US Energy Information Administration have gone down by 25 to 30 percent between 2012 and 2015 (EIA, 2016, p. 1). In this section, we model these developments as an increase in the initial resource stock and a decrease in the unit extraction costs of the fringe.

Figure 6 shows how welfare and climate damage depend on the fringe's reserves (left panels) and its marginal extraction costs (right panels). Panel (a) shows that the additional reserves would have led to higher grey welfare under perfect competition, in the first-best, and in the Herfindahl scenario. However, in the CFE, grey welfare is declining in the initial stock as long as this initial stock is smaller than 650 billion barrels of oil, due to the sequence effect. Panel (b) shows that the increase in climate damage due to the increase in non-OPEC oil reserves is larger in the CFE than in the other scenarios. It can be seen from panel (c) that an increase in non-OPEC reserves decreases social welfare, although it increases social welfare in the first-best and the Herfindahl scenario.[17] In our benchmark model, the fringe's initial stock equals 619.5 billion barrels. In a counterfactual world without non-OPEC oil, global welfare in the CFE would be 13 trillion US\$ higher, 10 trillion US\$ of which is due to lower climate damages. Panels (b), (d), and (f) show that a decrease in the fringe's marginal extraction costs leads to higher climate damages in the CFE. Nevertheless, grey welfare and social welfare still go up if the fringe's extraction costs fall: the sequence effect is

---

[17]The result that an increase in non-OPEC oil reserves is detrimental to welfare may not come as a surprise and may also arise in a simpler model where all firms are price takers and ignore the climate damage generated by their production. However, in our framework the increase in non-OPEC oil reserves is also detrimental to *grey* welfare: Even if we ignore the climate damages caused by non-OPEC oil, the net impact of the increase in these reserves on grey welfare may be negative, due to the violation of the Herfindahl rule. Intuitively, the additional non-OPEC oil that consists for a large share of relatively expensive nonconventional oil crowds out early extraction of relatively cheap OPEC oil, leading to higher discounted extraction costs.

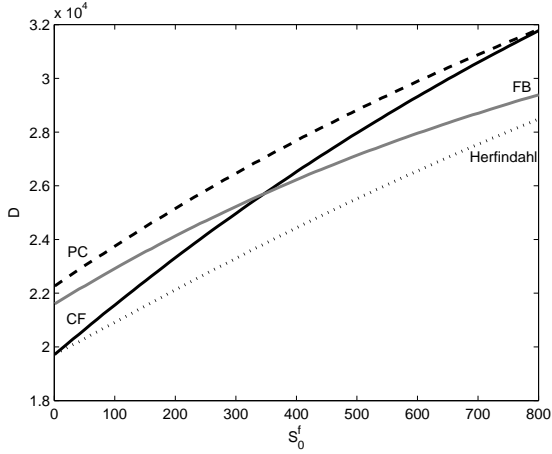# Figure 6: Welfare effects of more and cheaper non-OPEC oil
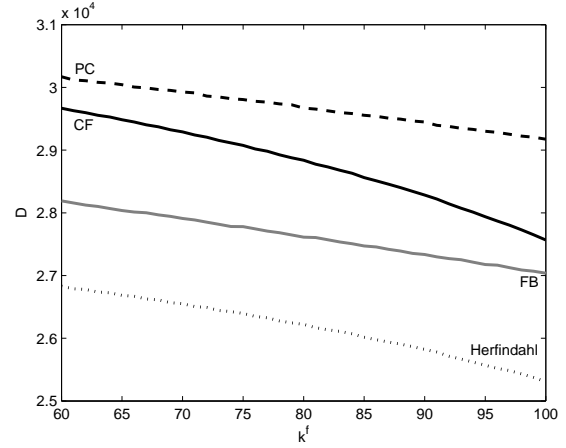
Panel (a) - Grey welfare vs. initial stock
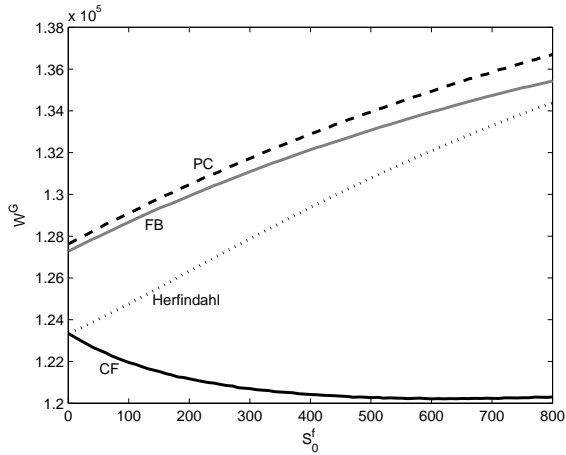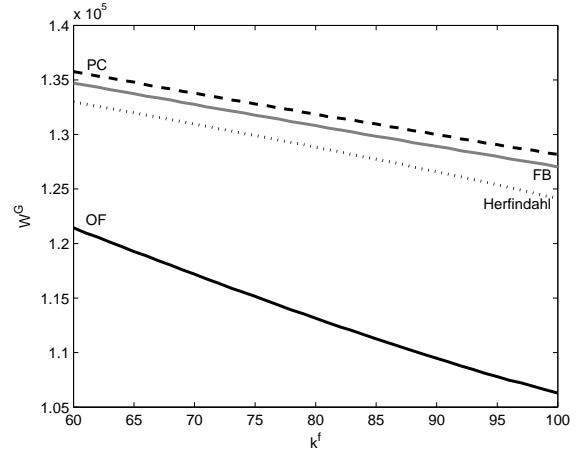
Panel (b) - Grey welfare vs. extraction costs

Panel (c) - Damage vs. initial stock

Panel (d) - Damage vs. extraction costs

Panel (e) - Social welfare vs. initial stock
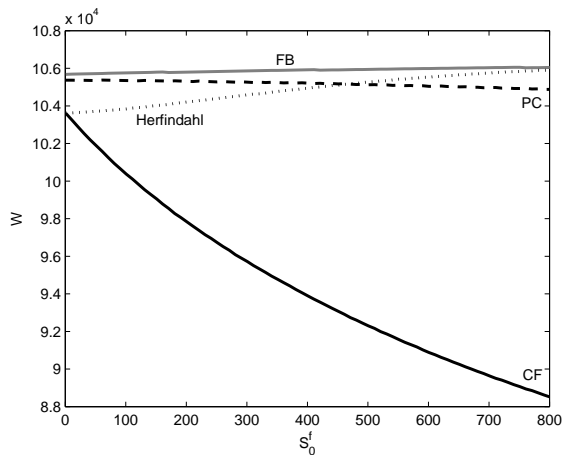
Panel (f) - Social welfare vs. extraction costs
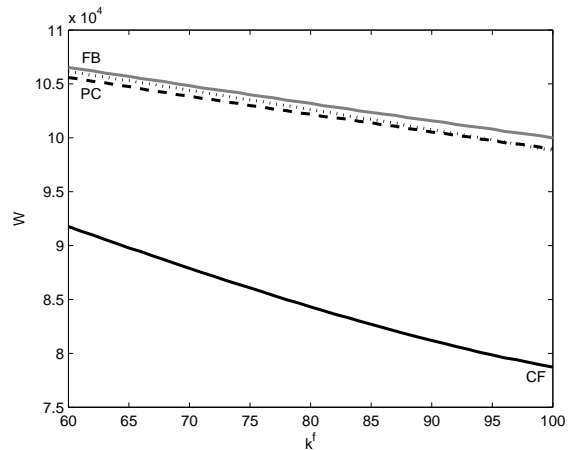
Notes: The figure shows grey welfare (panels (a) and (b)), climate damage (panels (c) and (d)) and social welfare (panels (e) and (f)) for various values of the fringe's initial resource stock and marginal extraction costs. Welfare and climate damages are expressed in billion US$'s. The solid curves correspond to the cartel-fringe (CF) equilibrium. The dashed black curves indicate the perfectly competitive equilibrium (PC) and the solid grey curves the first-best outcome (FB). The dotted curves represent the Herfindahl scenario. Parameters are set at their benchmark values, as shown in Table 1.

not strong enough to offset the beneficial impact of the fringe's lower extraction costs.

Finally, we want to examine the consequences of the recent 'shale oil revolution' in the US and Canada. This revolution has increased the recoverable reserves in the rest of the world (i.e., the fringe) from 438 to 619 billion barrels (EIA, 2013). Moreover, the average break even price of North-American shale oil has gone down by 22 US$ per barrel between 2015 and 2019 (Rystad Energy, 2019), suggesting that marginal extraction costs have gone down substantially as well. Assuming that the emission factor of shale oil equals the weighted average emission factor of the fringe's reserves,[18] we can use our model to examine the welfare effect of this recent shale oil revolution. The magnitude of the effects of the shale oil revolution on climate change depends obviously on the SCC. Furthermore, the sequence effect in the CFE is crucially affected by the rate of interest: The higher the rate of interest, the more important the timing of extraction becomes for welfare. Therefore, panel (a) of Figure 7 shows combinations of the SCC (expressed in US$) and the rate of interest for which the increase in the fringe's oil reserves (from 438 to 619.5 billion barrels) leads to an increase (grey area) and a decrease (white area) in social welfare. Similarly, panel (b) shows for which combinations of the SCC and the interest rate the fall in the fringe's marginal extraction costs from 84.5 to 62.5 (i.e., a fall with 22 US$ to our benchmark value) increases social welfare. Both panels clearly show that for high values of the SCC and the rate of interest (i.e., in the upper-right corners), the shale oil revolution causes a decline in social welfare.

The main conclusion of our welfare analysis so far is that almost all (97 percent) of the loss in social welfare under the cartel-fringe framework relative to the first-best is due to the inefficient order of use of the resources. Moreover, although the pure conservation effect of imperfect competition would imply 4.8 percent lower climate damages in the CFE than in the first-best, by taking this sequence effect into account, climate damages are actually 5.3 percent *larger* than in the first-best. A lot of attention in the literature and the policy debate on how to address climate change evolves around ways to reduce the use of polluting resources. The merit of policy options should be

---

[18]The actual emission factor of shale oil depends heavily on flaring. Brandt et al. (2016) report that emissions from shale oil wells in the Bakken Formation in the US in 2013 varied from 2 to 28 gCO_2eq/MJ over the different wells, compared to a US conventional crude oil mean of 8 gCO_2eq/MJ. If flaring would be completely controlled, production-weighted mean greenhouse gas emissions from the Bakken Formation would only be 3.5 gCO_2eq/MJ.

Figure 7: Welfare effects of the 'shale oil revolution'
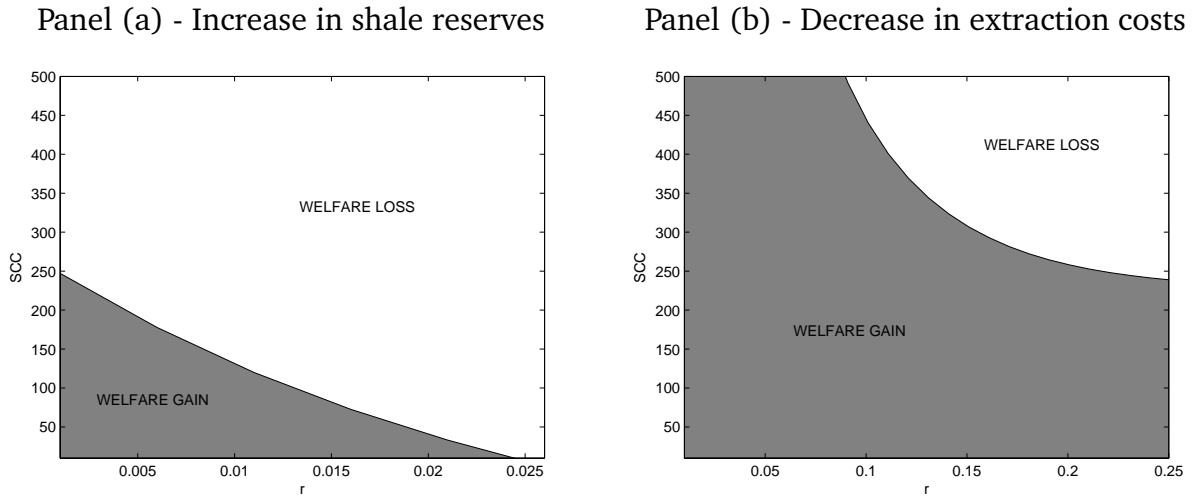
Panel (a) - Increase in shale reserves   Panel (b) - Decrease in extraction costs

Notes: The figure shows combinations of r and SCC (expressed in US$) for which the 'shale oil revolution' is beneficial for welfare (grey) or detrimental to welfare (white). Panel (a) shows the results for an increase in S_0^f from 438 to 619.5. Panel (b) depicts the outcomes for a decrease of k^f from 84.5 to 62.5. Parameters are set at their benchmark values, as shown in Table 1. For clarity reasons, the scale of the horizontal axis differs between the two panels.

evaluated while having this important feature of the climate change problem in mind. Below, we discuss the introduction of a resource tax while taking into account its impact on the order of use of the polluting resources.
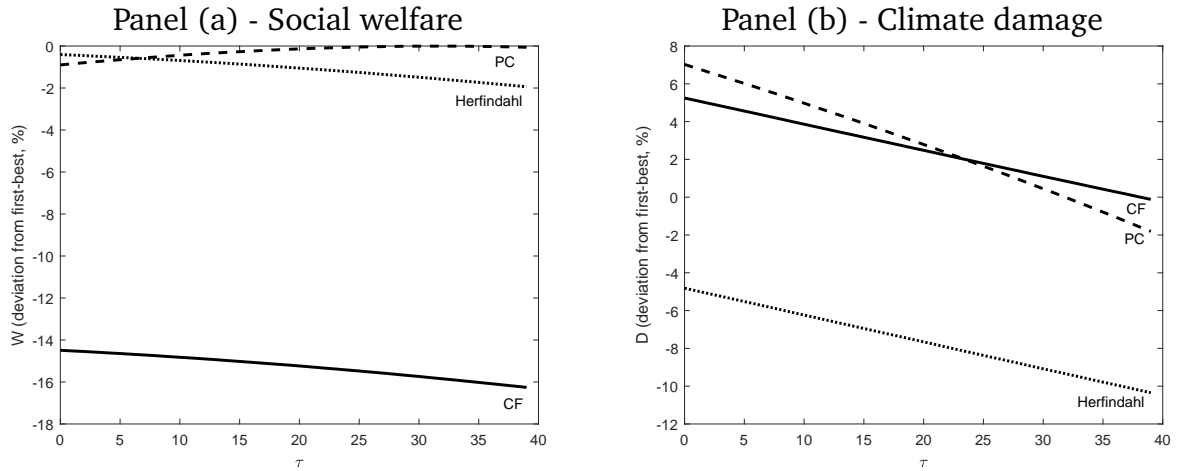
4.4 Resource tax

In this section, we analyze the welfare and climate effects of a resource tax at a specific rate τ within our benchmark calibrated framework.[19] Mathematically, introducing the tax in our model boils down to replacing α by $\alpha - \tau$ and b by $b - \tau$ at all occurrences in Sections 2 and 3.

Figure 8 shows the effect of a resource tax on the percentage deviation of social welfare (panel (a)) and on the percentage deviation of climate damage (panel (b)) from the first-best. An important implication of our analysis is that a resource tax can be detrimental to welfare, as shown in panel (a). While a resource tax contributes,

---

[19]The constancy of the tax can be motivated by constant marginal damages of emissions. Note that the perfectly competitive equilibrium only coincides with the first-best if emission factors of the cartel/fringe and the fringe are the same and the resource tax rate equals the SCC multiplied by the common emission factor. With differing emission factors, the first-best cannot be reached by imposing a resource tax. In the calibrated model, the second-best resource tax rate (i.e., the top of the dashed curve in panel (a) of Figure 8) lies between 27 and 38 US$/bbl, the SCC of a unit of extraction by the cartel and fringe, respectively.

Figure 8: Welfare effects of a resource tax (percentage deviations from first-best)

Panel (a) - Social welfare

Panel (b) - Climate damage

Notes: The figure shows percentage deviations of social welfare (panel (a)) and climate damage (panel (b)) from the first-best for various values of the resource tax rate. The solid curves correspond to the cartel-fringe (CF) and the dashed curves to the perfectly competitive (PC) equilibrium. The dotted curves represent the Herfindahl scenario. Parameters are set at their benchmark values, as shown in Table 1.

as intended, to a reduction in climate damages (see panel (b)) it impacts the speed of extraction of oil reserves as well as the composition of the oil extracted.

From panel (b) of Figure 2 we see that pollution accumulates faster in the CF equilibrium than under the first best. A tempting policy response is to impose a resource tax to slow down production and the accumulation of pollution. However from Figure 8 panel (a) we get that social welfare is a decreasing function of the tax. The explanation lies in the fact that the 'fast' accumulation of pollution in the CF equilibrium, observed in Figure 2 panel (b), is due to the 'sequence effect', whereby the dirty reserves are exploited before the 'cleaner' reserves, rather than overproduction of the resource. Indeed from Figure 2 panel (a), in the benchmark scenario, the price path in the CF equilibrium is above the price path under the first-best indicating that total oil production in the CF equilibrium is below that of the first best. As a result, a resource tax is detrimental to welfare in our benchmark scenario.

5   Non-linear demand

In this section, we examine the robustness of our results to the specification of the demand function we have used. We consider different demands generated by the

general class of (HARA) utility functions

$$U(q) = \frac{1 - \varphi}{\varphi} \left[\left(\frac{\psi}{1 - \varphi} q + \chi \right)^\varphi - \chi^\varphi \right], \text{ with } \psi > 0, \ \chi \geq 0 \text{ and } \varphi > 0, \tag{8}$$

where $q \equiv q^c + q^f + x$ denotes energy demand, with x being the use of renewables. The corresponding energy demand function reads[20]

$$q = \frac{1 - \varphi}{\psi} \left[\left(\frac{p}{\psi} \right)^{\frac{1}{\varphi - 1}} - \chi \right]. \tag{9}$$

We numerically examine three special cases of the HARA class demand functions: (i) quadratic utility (yielding linear demand, as in the benchmark model), requiring $\varphi = 2$, $\chi > 0$ and $p < \chi \psi$; (ii) Cobb-Douglas utility (yielding CES demand), requiring $\chi = 0$ and $\varphi < 1$; and (iii) power utility (yielding 'shifted CES demand'), requiring $\varphi < 1$, $\chi > 0$ and $\psi = 1 - \varphi$ (cf. Kagan et al., 2015, p. 506).[21] In each case, the remaining two free parameters of the HARA utility function are chosen such that the demand function runs through $(p, q) = (80, 34)$ as in the benchmark model, and the price elasticity of demand equals 0.55 in this point. Figure 9 shows the percentage welfare loss (compared to the first-best) due to the sequence effect for interest rates varying from 0.01 to 0.05. The benchmark interest rate of 0.028 is indicated by the dashed-dotted vertical line. Panel (a) depicts social welfare and panel (b) grey welfare. The two graphs show that the sequence effect in the cases with non-linear demand (the dashed and dotted curves) is of the same order of magnitude as in the case with linear demand (the solid curves): the sequence effect accounts for more than 95 percent of the social welfare loss and for more than 80 percent of the grey welfare loss. Appendix B shows that the welfare effects of the 'shale oil revolution' (i.e., an increase in the fringe's stock and a decrease in its extraction costs) under CES and shifted CES demand are qualitatively similar to the welfare effects under linear demand.

---

[20]Note that HARA utility functions are characterized by a non-negative super-elasticity of demand $\frac{d\varepsilon}{dq} \frac{q}{\varepsilon}$, which implies that in the CFE the growth rate of $p - k^c$ is smaller than r. Hence, the growth rate of the oil price does not exceed the rate of interest. This prevents arbitrators from purchasing oil, hoarding it, and making capital gains (cf. Dasgupta and Heal, 1979, pp. 327-331).

[21]We use Euler's method together with time inversion and iteration over the duration of the limit pricing phase (in case the equilibrium reads $S \rightarrow L$) or the fringe's stock at the end of the S-phase (in case the equilibrium reads $S \rightarrow F$) to solve the system of differential equations derived from the necessary conditions. Details are available from the authors upon request.

Figure 9: Importance of sequence effect: HARA class demand functions

Panel (a) - Social welfare   Panel (b) - Grey welfare
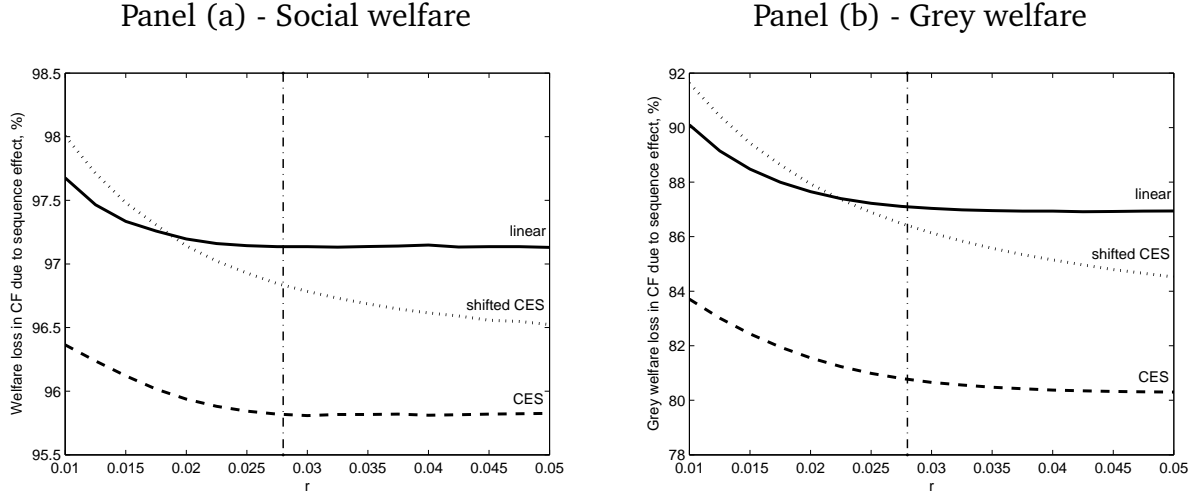
Notes: The figure shows the percentage of the social welfare loss (panel (a)) and the grey welfare loss (panel (b)) of the CFE (compared to the first-best) that can be attributed to the sequence effect. The solid line corresponds to linear demand ($\varphi = 2$, $\chi > 0$, $p < \chi\psi$), the dashed line to CES demand ($\chi = 0$, $\varphi < 1$), and the dotted line to shifted CES demand ($\varphi < 1$, $\chi > 0$, $\psi = 1 - \varphi$). The remaining parameters are set at their benchmark values, as shown in Table 1.

6 Conclusion

OPEC's market power has been shown to result in an inefficient order of use of the different oil reserves. A calibrated version of our model reveals that this source of inefficiency is responsible for almost the entire welfare loss of the cartel-fringe equilibrium compared to the first-best. It is also strong enough to make the recent shale oil revolution detrimental to global welfare. These distortions, which are rarely explicitly discussed during climate negotiations, could play a role in a solution to the climate change problem. Our results are established within a model where energy needs are met by oil (owned by a cartel and a fringe) and by renewables that are perfect substitutes for oil and that can be produced in unlimited amounts by using backstop technologies.

By decomposing the welfare and climate change consequences of imperfect competition into a *conservation* and a *sequence* effect, we have demonstrated that although the monopolist may be the conservationist's friend, they will certainly not become best friends. On the one hand, the conservation effect indeed slows down climate change by increasing the initial oil price. On the other hand, imperfect competition causes front-loading in time of relatively dirty unconventional oil, which aggravates climate

26

change. In our calibrated model, imperfect competition reduces social welfare by 14.5 percent compared to the first-best, 97 percent of which is due to the sequence effect. Furthermore, although the conservation effect lowers climate damages by 4.8 percent, by taking the sequence effect into account we have found that imperfect competition on balance *increases* climate damages by 5.3 percent.

Our results also have shown that the recent shale oil revolution not only increases climate damage, but also can lower grey welfare as it crowds out relatively cheap OPEC oil. If the interest rate and the social cost of carbon are large enough, the shale oil revolution causes a reduction in social welfare. Furthermore, without non-OPEC oil, global welfare in the CFE would be 13 trillion US$ higher, 10 trillion US$ of which is due to lower climate damages.

Our findings corroborate calls for a supply side approach to a climate treaty and for the need for policies that limit investments and extraction of fossil fuels (cf. Harstad, 2012; Erickson et al., 2018; Green and Denniss, 2018; Asheim et al., 2019). A successful supply side treaty will have to take the heterogeneity of fossil fuel suppliers into account, in particular market power and its repercussions on the timing of extraction of the different reserves.

This paper is a first to attempt to examine the importance of the sequence effect on climate change. Admittedly, our results were derived within a stylized model and under a number of assumptions made for tractability or ease of exposition. Two different streams of future research appear to be promising. The first is to examine the robustness of our conclusion under alternative scenarios. One relevant scenario would consider more sophisticated climate policies that recognize the cartel's market power and that are conditioned on the state of the climate and its evolution over time. Other natural extensions would be to introduce multiple pools with different extraction costs (cf. Fischer and Salant, 2017), stock-dependent unit extraction costs, extraction costs that are strictly convex in the quantity extracted, and unit cost of renewables that decline over time due to technical progress. The combination of stock-dependent extraction costs of the fringe and declining renewables costs is of particular interest. Our conjecture is that the conservation effect of market power will then lead to a reduction in cumulative extraction, because—compared to the perfectly competitive case—it takes more time to deplete the cartel's stock, leading to lower renewables unit cost at the time of depletion

of the cartel's stock. However, the sequence effect of market power potentially mitigates or even reverses this fall in cumulative extraction, as part of the fringe's stock will have been used already when the cartel's stock is depleted.

The second stream of future research relates to the policy implications of the sequence effect and the conflicting interests of the different owners of oil reserves, in particular during the negotiation and the design of climate change mitigation options in a global context. While there is a successful and growing literature on strategic interactions between resource users on one-hand and resource owners on the other (e.g., Liski and Tahvonen, 2004; Harstad, 2012; Kagan et al., 2015), there is none that tackles the interactions between two (or several) groups of resource owners and resource users. Such triangular (or multilateral) interactions may well turn out to be key in reaching a sustainable solution to curbing carbon emissions. For example, a possible solution for the problem of inefficient order of use of resources is to allow for the possibility that resource users and owners of the 'cleaner' resource buy out the 'dirtier' reserves or compensate their owners to induce them to halt their extraction (cf. Harstad, 2012; Eichner and Pethig, 2017a,b). This is obviously not a simple task; nevertheless it is definitely worth further investigation.

References

ALMOGUERA, P. A., C. C. DOUGLAS AND A. M. HERRERA, "Testing for the cartel in OPEC: non-cooperative collusion or just non-cooperative?," *Oxford Review of Economic Policy* 27 (Spring 2011), 144–168.

AMIGUES, J.-P., P. FAVARD, G. GAUDET AND M. MOREAUX, "On the Optimal Order of Natural Resource Use When the Capacity of the Inexhaustible Substitute Is Limited," *Journal of Economic Theory* 80 (May 1998), 153–170.

ASHEIM, G. B., T. FÆHN, K. NYBORG, M. GREAKER, C. HAGEM, B. HARSTAD, M. O. HOEL, D. LUND AND K. E. ROSENDAHL, "The case for a supply-side climate treaty," *Science* 365 (2019), 325–327.

ASKER, J., A. COLLARD-WEXLER AND J. DE LOECKER, "(Mis)Allocation, Market Power, and Global Oil Extraction," *American Economic Review* 109 (April 2019), 1568–1615.

BENCHEKROUN, H., A. HALSEMA AND C. WITHAGEN, "On nonrenewable resource oligopolies: The asymmetric case," *Journal of Economic Dynamics and Control* 33 (November 2009), 1867–1879.

———, "When additional resource stocks reduce welfare," *Journal of Environmental Economics and Management* 59 (January 2010), 109–114.

BENCHEKROUN, H., G. VAN DER MEIJDEN AND C. WITHAGEN, "An oligopoly-fringe non-renewable resource game in the presence of a renewable substitute," *Journal of Economic Dynamics and Control* 105 (2019), 1 – 20.

BENCHEKROUN, H. AND C. WITHAGEN, "On price taking behavior in a nonrenewable resource cartel-fringe game," *Games and Economic Behavior* 76 (2012), 355–374.

BRANDT, A. R., T. YESKOO, M. S. MCNALLY, K. VAFI, S. YEH, H. CAI AND M. Q. WANG, "Energy Intensity and Greenhouse Gas Emissions from Tight Oil Production in the Bakken Formation," *Energy & Fuels* 30 (2016), 9613–9621.

BRÉMOND, V., E. HACHE AND V. MIGNON, "Does OPEC still exist as a cartel? An empirical investigation," *Energy Economics* 34 (2012), 125–131.

CAPP, "Canadian Oil and Natural Gas, `http://www.capp.ca/canadian-oil-and-natural-gas/oil-sands`," *Canadian Association of Petroleum Producers* (2017a).

———, "Crude Oil Forecast, Markets & Transportation - Production & Supply Data, `http://www.capp.ca/publications-and-statistics/publications/302698`," *Canadian Association of Petroleum Producers* (2017b).

CHAKRAVORTY, U. AND D. L. KRULCE, "Heterogeneous Demand and Order of Resource Extraction," *Econometrica* 62 (November 1994), 1445–1452.

CHAKRAVORTY, U., M. MOREAUX AND M. TIDBALL, "Ordering the Extraction of Polluting Nonrenewable Resources," *American Economic Review* 98 (June 2008), 1128–1144.

DASGUPTA, P. AND G. HEAL, *Economic Theory and Exhaustible Resources* (Cambridge Economic Handbooks, University Press, Oxford, 1979).

EIA, "Technically Recoverable Shale Oil and Shale Gas Resources: An Assessment of 137 Shale Formations in 41 Countries Outside the United States," *U.S. Energy Information Administration* (2013).

———, "Trends in U.S. Oil and Natural Gas Upstream Costs," *U.S. Energy Information Administration* (2016).

———, "Crude Oil Proved Reserves, Reserves Changes, and Production, `https://www.eia.gov/dnav/pet/PET_CRD_PRES_DCU_NUS_A.htm`," *U.S. Energy Information Administration* (2019a).

———, "International Energy Statistics, `http://www.eia.gov/beta/international/data/browser`," *U.S. Energy Information Administration* (2019b).

———, "World Shale Resource Assessments, `https://www.eia.gov/analysis/studies/worldshalegas/`," *U.S. Energy Information Administration* (2019c).

EICHNER, T. AND R. PETHIG, "Buy coal and act strategically on the fuel market," *European Economic Review* 99 (2017a), 77 – 92.

———, "Trade in fossil fuel deposits for preservation and strategic action," *Journal of Public Economics* 147 (2017b), 50–61.

EPA, "Inventory of US Greenhouse Gas Emissions and Sinks," *U.S. Environmental Protection Agency* (2015).

ERICKSON, P., M. LAZARUS AND G. PIGGOT, "Limiting fossil fuel production as the next big step in climate policy," *Nature Climate Change* (11 2018).

FISCHER, C. AND S. W. SALANT, "Balancing the carbon budget for oil: The distributive effects of alternative policies," *European Economic Review* (2017).

GAUDET, G. AND P. LASSERRE, "The Efficient Use Of Multiple Sources Of A Nonrenewable Resource Under Supply Cost Uncertainty," *International Economic Review* 52 (02 2011), 245–258.

GILBERT, R. J., "Dominant Firm Pricing Policy in a Market for an Exhaustible Resource," *Bell Journal of Economics* 9 (Autumn 1978), 385–395.

GOLOSOV, M., J. HASSLER, P. KRUSELL AND A. TSYVINSKI, "Optimal Taxes on Fossil Fuel in General Equilibrium," *Econometrica* 82 (January 2014), 41–88.

GREEN, F. AND R. DENNISS, "Cutting with both arms of the scissors: the economic and political case for restrictive supply-side climate policies," *Climatic Change* (03 2018).

GROOT, F., C. WITHAGEN AND A. DE ZEEUW, "Strong time-consistency in the cartel-versus-fringe model," *Journal of Economic Dynamics and Control* 28 (November 2003), 287–306.

HAMILTON, J. D., "Causes and Consequences of the Oil Shock of 2007-08," *Brookings Papers on Economic Activity* 40 (2009), 215–283.

HARSTAD, B., "Buy Coal! A Case for Supply-Side Environmental Policy," *Journal of Political Economy* 120 (2012), 77–115.

HERFINDAHL, O. C., "Depletion and economic theory," in M. Gaffney, ed., *Extractive resources and taxation* (Madison University of Wisconsin Press, 1967), 63–90.

HOEL, M., "The Supply Side of CO 2 with Country Heterogeneity," *Scandinavian Journal of Economics* 113 (December 2011), 846–865.

HOLLAND, S. P., "Set-up costs and the existence of competitive equilibrium when extraction capacity is limited," *Journal of Environmental Economics and Management* 46 (November 2003), 539–556.

IEA, "World Energy Outlook," *International Energy Agency, Paris* (2013).

———, "CO_2 emissions from fuel combustion," *International Energy Agency, Paris* (2016).

KAGAN, M., F. VAN DER PLOEG AND C. WITHAGEN, "Battle for Climate and Scarcity Rents: Beyond the Linear-Quadratic Case," *Dynamic Games and Applications* (December 2015), 1–30.

KEMP, M. C. AND N. V. LONG, "On Two Folk Theorems Concerning the Extraction of Exhaustible Resources," *Econometrica* 48 (April 1980), 663–673.

KISSWANI, K., "Does OPEC act as a cartel? Empirical investigation of coordination behavior," *Energy Policy* 97 (2016), 171–180.

LEWIS, T. R. AND R. SCHMALENSEE, "On Oligopolistic Markets for Nonrenewable Natural Resources," *The Quarterly Journal of Economics* 95 (1980), 475–491.

LISKI, M. AND O. TAHVONEN, "Can carbon tax eat OPEC's rents?," *Journal of Environmental Economics and Management* 47 (January 2004), 1 – 12.

MALINS, C., S. GALARZA, A. BARAL, A. BRANDT AND G. HOWORTH, "The Development of a Greenhouse Gas Emissions Calculation Methodology for Article 7a of the Fuel Quality Directive," Report to the directorate general for climate action of the european commission, Washington D.C.: The International Council on Clean Transportation (ICCT), 2014.

MCGLADE, C. AND P. EKINS, "The geographical distribution of fossil fuels unused when limiting global warming to $2°$ C," *Nature* 517 (January 2015), 187–190.

NEWBERY, D. M. G., "Oil Prices, Cartels, and the Problem of Dynamic Inconsistency," *Economic Journal* 91 (September 1981), 617–46.

NORDHAUS, W. D., "Revisiting the social cost of carbon," *Proceedings of the National Academy of Sciences* 114 (2017), 1518–1523.

OCI, "Oil Climate Index, http://oci.carnegieendowment.org/#total-emissions," *Carnegie Endowment for International Peace* (2019).

OKULLO, S. J. AND F. REYNÈS, "Imperfect cartelization in OPEC," *Energy Economics* 60 (2016), 333 – 344.

RYSTAD ENERGY, "Global liquids cost curve, https://www.rystadenergy.com/newsevents/news/press-releases/Rystad-Energy-ranks-the-cheapest-sources-of-supply-in-the-oil-industry-/," *Press Releases* (2019).

SALANT, S. W., "Exhaustible Resources and Industrial Structure: A Nash-Cournot Approach to the World Oil Market," *Journal of Political Economy* 84 (1976), pp. 1079–1094.

SALO, S. AND O. TAHVONEN, "Oligopoly equilibria in nonrenewable resource markets," *Journal of Economic Dynamics and Control* 25 (May 2001), 671–702.

SOLOW, R. M. AND F. Y. WAN, "Extraction Costs in the Theory of Exhaustible Resources," *Bell Journal of Economics* 7 (Autumn 1976), 359–370.

STERN, N., *The Economics of Climate Change: The Stern Review.* (Cambridge University Press, UK, 2007).

STIGLITZ, J. E., "Monopoly and the Rate of Extraction of Exhaustible Resources," *The American Economic Review* 66 (1976), 655–661.

VAN DER PLOEG, F., "Second-best carbon taxation in the global economy: The Green Paradox and carbon leakage revisited," *Journal of Environmental Economics and Management* 78 (2016), 85–105.

U.S. DEPARTMENT OF THE TREASURY, "Daily Treasury Long Term Rate Data, https://www.treasury.gov/resource-center/data-chart-center/interest-rates/Pages/TextView.aspx?data=longtermrate," *Department of the Treasury* (2019).

WITHAGEN, C., "Cartel-versus-Fringe Models," in J. F. Shogren, ed., *Encyclopedia of Energy, Natural Resource, and Environmental Economics* (Waltham: Elsevier, 2013), 260 – 267.

Appendix

A Perfectly competitive equilibrium and first-best

The Hamiltonian associated with the fringe's problem reads

$$\mathcal{H}^f = e^{-rt}(p(t) - k^f)q^f + \lambda^f[-q^f]. \tag{A.1}$$

The necessary conditions include

$$p(t) = \alpha - \beta(q^f(t) + q^c(t)) \leq k^f + \lambda^f(t)e^{rt}, \tag{A.2a}$$

$$[k^f + \lambda^f(t)e^{rt} - \alpha + \beta(q^f(t) + q^c(t))]q^f(t) = 0, \tag{A.2b}$$

$$\dot{\lambda}^f(t) = 0. \tag{A.2c}$$

For $t \in F$ we have

$$p(t) = \alpha - \beta q^f(t) = k^f + \lambda^f e^{rt}, \tag{A.3a}$$

$$p(t) = \alpha - \beta q^f(t) \leq k^c + \lambda^c e^{rt}, \tag{A.3b}$$

$$q^f(t) = \frac{1}{\beta}(\alpha - k^f - \lambda^f e^{rt}), \tag{A.3c}$$

where λ^f is the fringe's shadow price of the resource stock. Hence, (A.2a)-(A.2c) say that in an equilibrium with positive supply of the fringe, the producer price satisfies Hotelling's rule: The net price, $p - k^f$, increases over time at a rate equal to the interest rate. The shadow price of the resource stock is constant over time since extraction costs do not depend on the stock.

In the perfectly competitive equilibrium, the cartel takes the price path as given. Hence, the Hamiltonian associated with the cartel's problem reads

$$\mathcal{H}^c = e^{-rt}(p(t) - k^c)q^c + \lambda^c[-q^c]. \tag{A.4}$$

The necessary conditions include

$$p(t) = \alpha - \beta(q^f(t) + q^c(t)) \leq k^c + \lambda^c e^{rt}, \tag{A.5a}$$

$$[k^c + \lambda^c e^{rt} - \alpha + \beta(q^c(t) + q^c(t))]q^c(t) = 0, \tag{A.5b}$$

$$\dot{\lambda}^c = 0. \tag{A.5c}$$

For $t \in C$ we have

$$p(t) = \alpha - \beta q^c(t) = k^f + \lambda^c e^{rt}, \tag{A.6a}$$

$$p(t) = \alpha - \beta q^c(t) \le k^c + \lambda^f e^{rt}, \tag{A.6b}$$

$$q^c(t) = \frac{1}{\beta}(\alpha - k^c - \lambda^c e^{rt}). \tag{A.6c}$$

Throughout a phase of simultaneous use, (A.2a) and (A.5a) must hold with equality, which is not possible because $k^f > k^c$. Hence, simultaneous use cannot occur in a perfectly competitive equilibrium. A limit-pricing phase requires a constant price, which contradicts (A.5b). Furthermore, the equilibrium sequence $F \to C$ can be excluded, because, according to (A.2b), during the initial phase the net price $p - k^f$ grows at the rate of intrest, implying that the net price $p - k^c$ would grow at a rate lower than the rate of interest (because $k^f > k^c$). Hence, the cartel prefers current extraction over future extraction and will undercut the fringe's price. Therefore, the unique equilibrium sequence under perfect competition reads $C \to F$. Thus, by integrating (A.3c) and (A.6c) over time, denoting the transition time by T_1 and the depletion time by T_2, using the terminal condition $\lambda^f = (b - k^f)e^{-rT_2}$, the price continuity condition $k^c + \lambda^c e^{rT_1} = k^f + \lambda^f e^{rT_1}$, and the resource constraints of the cartel and the fringe, we find that the perfectly competitive equilibrium is described by

$$r\beta S_0^f = (b - k^f)\left(r(T_2 - T_1) - 1 + e^{-r(T_2 - T_1)}\right) + (\alpha - b)r(T_2 - T_1), \tag{A.7a}$$

$$r\beta S_0^c = -(k^f - k^c)\left(1 - e^{-rT_1}\right) - (b - k^f)\left(e^{-r(T_2 - T_1)} - e^{-rT_2}\right) + (\alpha - k^c)rT_1. \tag{A.7b}$$

In the perfectly competitive equilibrium described by (A.7a)-(A.7b) the only remaining market failure is the climate externality. Hence, the competitive equilibrium coincides with the first-best if carbon is priced at a rate equal to the SCC. This requires a per unit tax on oil equal to $\tau = \frac{\omega^c \zeta}{r}$ during C and $\tau = \frac{\omega^f \zeta}{r}$ during F. By imposing these optimal tax rates, by integrating (A.3c) and (A.6c) over time, denoting the first-best transition

time by T_1^* and the first-best depletion time by T_2^*, using the terminal condition $\lambda^f = (b - \frac{\omega^f \zeta}{r} - k^f)e^{-rT_2}$, the social cost continuity condition $k^c + \lambda^c e^{rT_1^*} + \frac{\omega^c \zeta}{r} = k^f + \lambda^f e^{rT_1^*} + \frac{\omega^f \zeta}{r}$, and the resource constraints of the cartel and the fringe, we find that the first-best is described by

$$r\beta S_0^f = \left(b - \frac{\zeta\omega^f}{r} - k^f\right)\left(r(T_2^* - T_1^*) - 1 + e^{-r(T_2^* - T_1^*)}\right) + (\alpha - b)r(T_2^* - T_1^*),$$

$$r\beta S_0^c = -\left(k^f - k^c + \frac{\zeta(\omega^f - \omega^c)}{r}\right)\left(1 - e^{-rT_1^*}\right) + (\alpha - \frac{\zeta\omega^c}{r} - k^c)rT_1^*$$
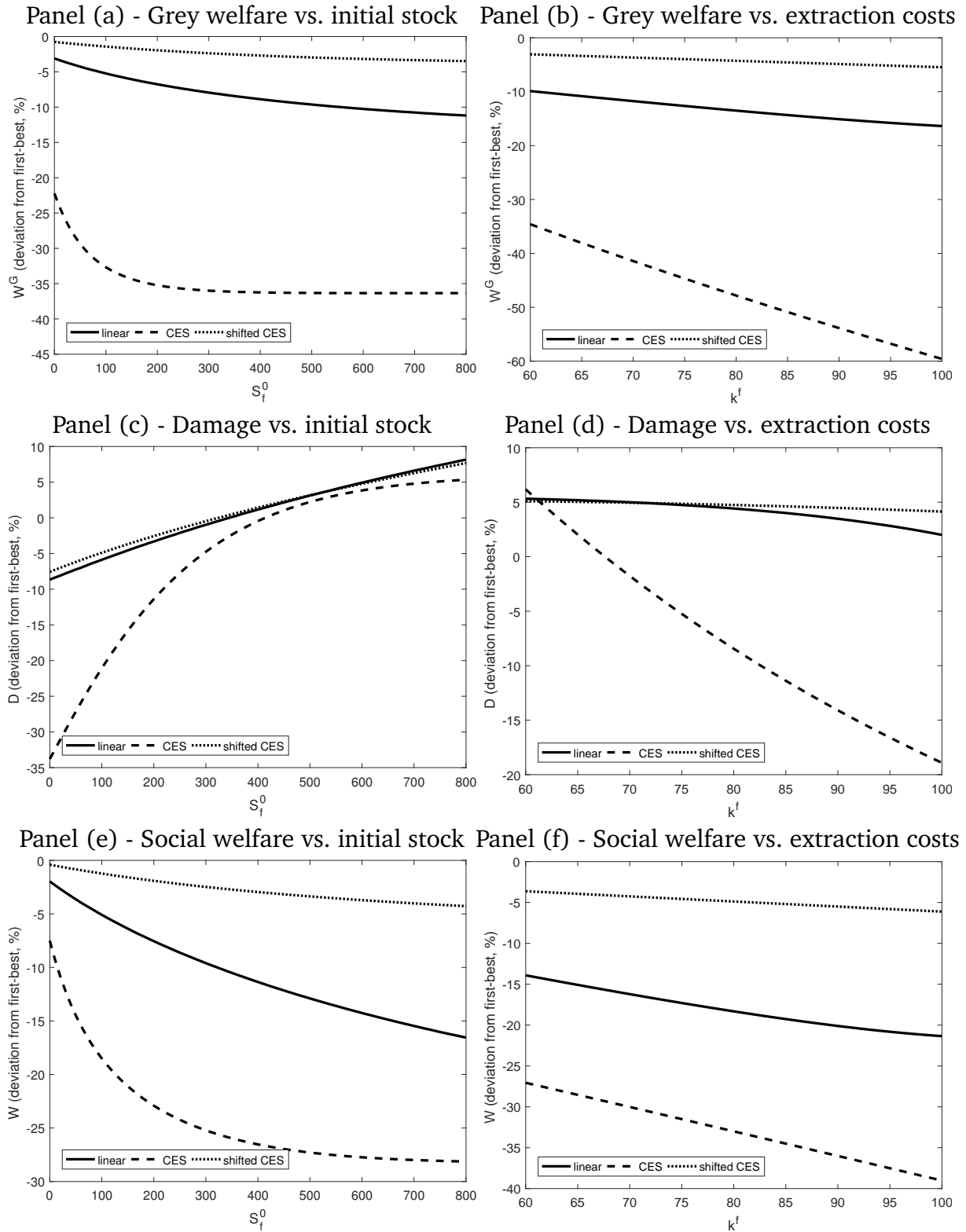$$- \left(b - \frac{\zeta\omega^f}{r} - k^f\right)\left(e^{-r(T_2^* - T_1^*)} - e^{-rT_2^*}\right).$$

B Non-linear demand

This appendix contains a robustness analysis of the welfare effects of more and cheaper non-OPEC oil, allowing for nonlinear (CES and shifted CES) demand functions. The results are shown in Figure B.1. The panels on the left show the effect of the fringe's initial reserve and the panels on the right the effect of its marginal extraction costs. The figure shows that the welfare and climate damage deviations from the first-best in the case with CES and shifted CES demand (represented by the dashed and dotted curves, respectively) are qualitatively similar to those in our benchmark case with linear demand (represented by the solid curves).

Figure B.2 shows the effects of the shale oil revolution (defined as an increase in the fringe's reserves from 438 to 619 billion barrels and a decrease in its unit extraction costs from 84.5 to 62.5 US$ per barrel) for the three different demand functions. The figure shows curves for which the welfare effect of the shale revolution equals zero. Above (below) these curves, the welfare effect is negative (positive). The solid, dashed and dotted curves correspond to linear, CES and shifted CES demand, respectively. Panel (a) shows the effect of an increase in reserves and panel (b) depicts the effect of a decrease in extraction costs. Note that the CES and shifted CES curves in panel (b) almost coincide. The benchmark equilibrium characterized by $SCC = 250$ and $r = 0.028$ is located well above each of the curves in panel (a) and well below each of the curves in panel (b). Hence, the welfare effect of the shale oil revolution is qualitatively similar for each of the three demand functions.

Figure B.1: Welfare effects of the 'shale revolution': HARA class demand functions

Panel (a) - Grey welfare vs. initial stock

Panel (b) - Grey welfare vs. extraction costs

Panel (c) - Damage vs. initial stock

Panel (d) - Damage vs. extraction costs

Panel (e) - Social welfare vs. initial stock

Panel (f) - Social welfare vs. extraction costs

Notes: The figure shows percentage deviations of grey welfare (panels (a) and (b)), climate damage (panels (c) and (d)) and social welfare (panels (e) and (f)) from the first best, for various values of the fringe's initial resource stock and marginal extraction costs. The solid line corresponds to linear demand ($\varphi = 2$, $\chi > 0$, $p < \chi\psi$), the dashed line to CES demand ($\chi = 0$, $\varphi < 1$), and the dotted line to shifted CES demand ($\varphi < 1$, $\chi > 0$, $\psi = 1 - \varphi$). The remaining parameters are set at their benchmark values, as shown in Table 1.

Figure B.2: Welfare effects of the 'shale oil revolution': HARA class demand functions
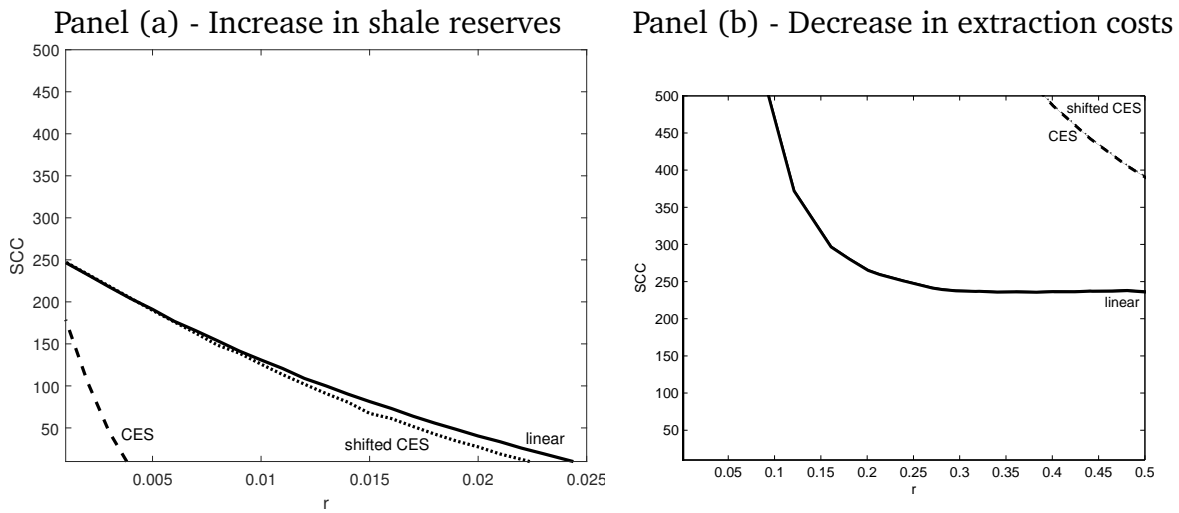
Panel (a) - Increase in shale reserves

Panel (b) - Decrease in extraction costs

Notes: The figure shows combinations of r and SCC (expressed in US$) for which the 'shale oil revolution' is beneficial for welfare (below the curve) or detrimental to welfare (above the curve). Panel (a) shows the results for an increase in S_0^f from 438 to 619.5. Panel (b) depicts the outcomes for a decrease of k^f from 84.5 to 62.5. The solid, dashed and dotted curves correspond to linear, CES and shifted CES demand, respectively. Parameters are set at their benchmark values, as shown in Table 1. For clarity reasons, the scale of the horizontal axis differs between the two panels.