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Rapacious Oil Exploration in face of Regime Switches: Breakthrough Renewable Energy and Dynamic Resource Wars

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RAPACIOUS OIL EXPLORATION IN FACE OF REGIME SWITCHES:

Breakthrough Renewable Energy and Dynamic Resource Wars

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Abstract

Rapacious fossil fuel extraction occurs if fossil fuel producers fear that there is a probability that their under-the-ground assets becomes worth less. They show that rapacious depletion of oil reserves occurs if there is a probability of a breakthrough renewable energy coming to the market or a probability of climate policy finally becoming seriously ambitious. These are examples of one-way regime switches leading to the so-called Green Paradox. Two-way regimes switches also lead to rapacious oil depletion. They occur if there is a chance of being removed from office in a partisan political context with perennial election cycles or if there are dynamic resource wars with the hazard of being removed from office dependent on fighting efforts. This rapacity effect is stronger in societies with bad institutions and lack of political cohesiveness.

Keywords: regime switches, breakthrough renewable energy, Green Paradox, resource wars, contest success functions, political cohesiveness, confiscation risk, taxation, oil reserves uncertainty, exhaustible resources, exploration investment, hold-up problem

JEL codes: D81, H20, Q31, Q38

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1. Introduction

How do countries rich in natural resources react to the probability of new inventions leading to a low-cost breakthrough technology? And how do they react to the possibility chance that global warming increases the chance that countries importing fossil fuel finally impose a seriously ambitious climate policy? Typically, oil-rich countries will minimize the risk of economic obsolescence of their natural reserves by pumping them more quickly out of the ground. This accelerates global warming and will lead to the Green Paradox (Sinn, 2008). But such rapacious depletion of natural resources also occurs in other political and conflictual environments and is suggested by the following policy questions.

How does the presence of a large stock of natural resources affect the intensity of armed war? How does the threat of war affect the speed of resource extraction and prices of natural resources? How are resource wars affected by the cohesiveness of political institutions, the ease by which political parties can be removed from office, and fighting technology? How do costly attempts to stay in office ('fighting') affect the probability of staying in office, the speed of depletion of natural resources and efficiency? How does the risk of a benevolent government at some random future time being replaced by a populist resource-rent grabbing government affect the speed of extraction of natural resources? How do outcomes vary if there is a chance that the confiscating government will be removed from office again and the economy flips back to no confiscation? How do the inefficiencies resulting from stochastic political cycles affect depletion rates of natural resources and efficiency? Why are the inefficiencies resulting from confiscation less or absent if the timing of regime switches is known rather than stochastic?

Our objective is to provide answers to each of these questions in a tractable model of exhaustible resource extraction with one-way or two-way regime switches with endogenous hazard rates. Rapacious fossil fuel extraction occurs if fossil fuel producers fear that there is a probability that their under-the-ground assets becomes worth less. Our models of one-way and two-way regime switches dynamic resource wars build on the classic model of confiscation risk and natural resources of Long (1975). Inspired by the above questions, we highlight four sources of confiscation risk in relative contexts that lead to rapacious oil extraction.

First, there may a probability of a breakthrough renewable energy being invented that can be produced at lower cost than fossil fuel. Of course, this is excellent news for the fight against global warming once the invention has come to market. But as long as it has not, oil producers will in fear of the value of the value of their fossil fuel assets being wiped out pump up fossil fuel more aggressively and thereby accelerate global warming.

Second, there may a probability that there is a political change from the current lackluster climate policy to a more ambitious climate policy which puts a proper price on carbon emissions. This will also induce oil producers to aggressively deplete their fossil fuel reserves and thereby accelerate global warming. As already mentioned, both these cases are examples of the Green Paradox.

Third, the fear of being removed from office will in a partisan political economy model of perennial political cycles with exogenous hazards lead to more rapacious fossil fuel depletion too. Conflict over natural resources can be modelled as a two-way regime shift with perennial political cycles, where at any point of time there is a hazard that the incumbent gets thrown out of office by a rival political group. This political hazard increases with fighting by the opposition relative to that of the government.

Fourth, rapacious depletion of natural resources can occur in the context of dynamic resource wars where the key determinants of fighting and conflict and the rapacity of natural resource extraction are: lack of cohesiveness of the political system so that the incumbent can more easily channel funds to its clientele without giving it to the clientele of the opposition; more frequent elections or less government stability reduces resource wars but leads to more voracious depletion of reserves resources; a better fighting technology intensifies conflict; a large stock of natural resource wealth and low wages intensify conflict. Not the certainty of being kicked out of office, but the threat of being of office leads to rapacious resource depletion and harms efficiency. The point is that the incumbent depletes its reserves of natural resources too quickly relative to the Hotelling rule for fear of it being taken by the opposition. The resulting inefficiency induces a classic holdup problem, which discourages investment in exploration activities and aggravates the inefficiency associated with rapacious depletion of natural resources.

Before we develop our examples of the Green Paradox and of the political economy theory of dynamic resource wars with hazard rates depending on relative fighting intensities, we first set out as building blocks the theory of exhaustible resource extraction under confiscation risk and our model of perennial political conflict in economies with a benevolent and a rent-grabbing political party and exogenous hazards of being removed from office.

To obtain tractable solutions, we make two bold assumptions: isoelastic demand for natural resources and zero variable extraction costs. It is well known that then, without confiscation risk, the monopolistic resource extraction problem is efficient (Stiglitz, 1976). The monopolistic extraction rate is efficient even with a constant tax rate on oil revenues. These two bold assumptions thus highlight the inefficiencies that follow from confiscation risk, from perennial political cycles and from dynamic resource wars in a striking and analytically convenient manner.

We thus first offer in section 2 a tractable model of confiscation risk for a monopolistic owner of natural resource reserves. We refer to oil as shorthand for natural resources. The owner of the well pays a lump-sum fee upfront for the privilege of extracting oil, but faces a probability that some future resource-rent grabbing government will at some unknown future date start taxing oil revenue. The confiscation risk corresponds to a constant hazard rate, which leads to under-investment and rapacious depletion until confiscation takes place. At the moment the creaming off of oil revenue commences, the oil depletion rate jumps down and the oil price jumps up by a discrete amount. From that moment on, the rate of decline in the rate of oil depletion and the consequent rate of increase in the oil price follow the Hotelling rates, albeit starting from a lower level of oil reserves than would have been the case without confiscation risk. We show that this inefficiency is stronger if the probability of confiscation and the associated tax rate are higher. Since at the time of the regime switch the rate of oil depletion jumps down to below the level and the oil price jumps up above the level it would have been without confiscation risk, oil reserves are depleted more aggressively in the presence of looming confiscation risk but in Hotelling fashion as soon as the confiscation risk has gone and *confiscation has taken place*. It is thus the risk of confiscation that causes inefficiencies, not confiscation itself.

This model of confiscation risk builds on the literature on uncertainty about nationalization and speed of resource extraction (Long, 1975; Bohn and Deacon, 2000). We differ from these studies in modeling confiscation risk as a one-way regime switch resulting from a future tax grab rather than as future nationalization. [2] [3] Furthermore, we offer a tractable model with a closed-form analytical solution. Although variable extraction costs are zero, we allow for upfront costs of exploration investment (cf., Gaudet and Laserre, 1988).[4] We thus show that a higher risk of confiscation and a higher tax rate depress the level of exploration investment and cause a hold-up problem (e.g., Rogerson, 1992; Holmström and Roberts, 1998), which can be corrected with a subsidy.

Section 3 briefly explains how this canonical model of section 2 can easily be applied to understand the rapacious oil depletion and acceleration of global warming that is associated with the Green Paradox. Here it is the probability of a breakthrough in renewable energy or a more ambitious climate policy that is driving results.

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[2] If other assets are just as uncertain and unsafe as natural resources, the saving-consumption decision is distorted towards consumption but resource extraction is efficient (Konrad et al., 1994). In a recent analysis of confiscation risk of renewable resources the elasticity of resource demand determines whether expropriation risk boosts or curbs present extraction rates (cf., Laurent-Luchetti and Santaguni, 2012). The model with risk of 100% confiscation can be applied to the political economy of water management as is relevant in the Middle East, for example (Tsur and Zemel, 1998).

[3] Our model is related to the literature on collapses of the resource stock and changes in system dynamics - regime switches - in pollution control (e.g., Clarke and Reed, 1994; Tsur and Zemel, 1996; Naevdal, 2006; Polasky et al., 2011; de Zeeuw and Zemel, 2012), which in turn builds on the optimal maintenance schemes under potential machine failure (Kamien and Schwartz, 1971). This literature often uses linear models and quadratic preferences or preferences that are linear in the control, so that the nested Hamilton-Jacobi-Bellman (HJB) equations defining the model with regime switch can be solved analytically. Our model with isoelastic demand and zero variable oil extraction costs also permits an analytical solution.

[4] The approach of separating exploration investment from oil extraction decisions has also been used in a recent study of Ramsey taxation with oil resources (Daubanes and Laserre, 2012).

Section 4 generalizes these results by analyzing perennial political cycles with exogenous hazard rates. This is done by allowing for a positive and exogenous possibility that a confiscation regime reverts back to a no-confiscation regime. This makes oil depletion less rapid and thus reduces inefficiencies. We allow analyze the implications of oil discoveries and uncertainty about the stock of oil reserves.

Section 5 extends our model of political cycles with exogenous hazard rates developed in section 4 to a model of dynamic resource wars with two-way regime switch uncertainty and strategic behavior and uses it to explain the extent of fighting over the control of natural resources. We show that resource wars are more intense if the political system is less cohesive, oil reserves are high, the wage is low, and governments can be less frequently removed from office. Furthermore, oil extraction is more rapid if control of reserves is contested. Our model of dynamic resource wars contributes to a recent literature on the two-way link between resource extraction and conflict (Acemoglu et al., 2012; van der Ploeg and Rohner, 2012).

Natural resources are a prevalent feature of many wars in history and today (Westing, 1986; Collier, 2009). The immense empirical literature on conflict and natural resources (e.g., Collier and Hoeffler, 2004; Fearon, 2005) offers support for the effect of natural resources on conflict, but takes resource revenue as given. This ignores important endogeneity issues, because resource extraction and thus resource revenue are themselves influenced by conflict. Our contribution is to put forward a tractable model which makes use of the extensive literature on contest success functions (e.g., Tullock, 1967; Hirshleifer, 1991; Skaperdas, 1996; Konrad, 2009) to introduce conflict and resource wars into a setting of uncertainty about which of two factions hold office and controls the stock of natural resources.[5] We thus determine simultaneously both the speed of natural resource extraction and the intensity of conflict and subsequently analyze the impact of a more cohesive political system (cf., Besley and Persson, 2011ab), more frequent elections, the opportunity cost of fighting and fighting technology on these outcomes. In contrast to earlier studies on bargaining and war between sovereign states (e.g., Powell,

[5] Contest success functions have also been used to study the interstate conflicts over natural resources and its effects on trade (Garfinkel et al., 2011).

1993; Skaperdas, 1992; Acemoglu et al., 2012; Caselli et al., 2013)[6], we focus on conflict over the control of natural resources within the boundaries of a state.

Section 6 summarizes our results and offers some suggestions for further research.

2. Confiscation risk as regime switch

The problem for the owner of the oil reserves is to choose its level of exploration investment and extraction path to maximize the present value of its profits,

(1) $$\underset{R,I}{\text{Max}}\ \mathrm{E}\left[\int_0^\infty (1-\tau(t))\,p(t)R(t)\,\mathrm{e}^{-rt}\,dt\right]-qI$$

subject to the oil depletion equations,

(2) $$\dot{S}(t)=-R(t),\ \forall t\geq 0,\quad S(0)=S_0>0,\quad \int_0^\infty R(t)dt\leq S_0,$$

the oil exploration investment schedule,

(3) $$S_0=\Omega(I)=\omega_0 I^{\omega},\quad \Theta'>0,\Theta''<0,\omega_0>0,0<\omega<1,$$

the inverse oil demand curve ,

(4) $$p(t)=R(t)^{-1/\varepsilon},\ \forall t\geq 0,\quad \varepsilon>1,$$

the probability that confiscation has taken place in the interval ending at time *t*,

(5) $$\Pr(T\leq t)=1-\exp(-ht),\ \forall t\geq 0,\quad h\geq 0,$$

and the future tax (or confiscation) regime,

(6) $$\tau(t)=0,\quad 0\leq t<T,\qquad \tau(t)=\hat{\tau}>0,\quad T\geq t,$$

where $p, R, S, q, I, r,\ \tau$ and ε denote the price of oil, the oil depletion rate, the stock of oil reserves, the price of oil exploration investment, the volume of oil exploration

[6] Guns versus butter dilemmas and armaments races have also been studied in differential game analyses of the Richardson model of arms races (e.g., Brito, 1972; Intriligator, 1975; van der Ploeg and de Zeeuw, 1991).

investment, the market interest rate, the tax rate and the elasticity of oil demand, respectively, and $T > 0$ indicates the random date from which moment onwards confiscation takes place. The price of oil exploration investment (q) and the market rate of interest (r) are exogenously determined on world markets and constant over time. The concavity of $\Omega(.)$ ensures that there are decreasing returns to exploration investment. To ensure that marginal oil revenue is positive, we assume that the price elasticity of oil demand (ε) exceeds unity.

Aggregate oil demand is relatively inelastic, but the relevant elasticity for an individual oil-producing firm is much higher as it is less able to manipulate the price without losing market share to its direct competitors. Utility is given by $U(R) = R^{1-1/\varepsilon} / (1-1/\varepsilon)$ and corresponds to the area under the demand curve, so that $p = U'(R)$. With this demand function, marginal revenue is finite and thus oil reserves are fully exhausted asymptotically. The future confiscation rate or tax rate satisfies $0 < \hat{\tau} \leq 1$.

The probability that confiscation has not taken place before time t is $\Pr(T > t) = \exp(-ht)$. The exponential distribution has a constant hazard rate h. The conditional probability that confiscation has taken place satisfies $\Pr(T > s + t | T > s) = \Pr(T > t), \forall s, t \geq 0.$ So the conditional probability that confiscation does not take place for another three years given that confiscation has not already taken place in the first two years is the same as the initial probability that confiscation does not take place for another three years. The expected duration of the no-confiscation regime is the inverse of the hazard rate, $E[T] = 1/h$. The standard deviation of this duration is also $1/h$. One interpretation is that $1/h$ is the expected time it takes for a new political regime to come in on a platform of creaming off the oil revenue earned by the well owner.

Using the principle of dynamic programming, we work backward in time and first solve the problem from unknown time T onwards when taxation takes place, then solve the problem of oil extraction before confiscation has taken place, and finally solve for the optimal level of exploration investment. We denote the problems of oil extraction *after* and *before* confiscation with the superscripts A and B, respectively, and solve them for a given S_0 in section 2.1 and 2.2, respectively. We characterize the outcomes in section 2.3 and discuss the effects on profits and welfare in section 2.4. Section 2.5 then solves for the optimal level of exploration investment *I*.

2.1. After the regime switch

Marginal oil revenue must equal the scarcity rent, λ, which according to the Hotelling rule must rise at a rate equal to the market interest rate, *r*:

(7) $$\lambda = (1-\hat{\tau})(1-1/\varepsilon)R^{A^{-1/\varepsilon}}, \quad \dot{\lambda}/\lambda = r.$$

It follows from (7) and the inverse demand function (4) that the price paths and oil depletion paths are efficient despite the oil owner being a monopolist and oil revenues being taxed:

(8) $$\dot{p}^A / p^A = r > 0, \quad \dot{R}^A / R^A = -\varepsilon r < 0,$$

since oil demand is isoelastic and extraction costs are zero. Using (8) in (2), we solve for the optimal paths of oil depletion rates, oil reserves and the oil price after the regime switch:

(9) $$\begin{aligned} &R^A(t) = \varepsilon r S(t) = \varepsilon r e^{-\varepsilon r(t-T)} S(T), \quad S^A(t) = e^{-\varepsilon r(t-T)} S(T) \le S(T) \le S_0, \\ &\quad p^A(t) = e^{r(t-T)} \left(\varepsilon r S(T)\right)^{-1/\varepsilon}, \quad \forall t > T. \end{aligned}$$

Substituting (9) in (1), we get the present value of profits of the oil firm after the switch:

(10) $$V^A(S(t)) = \int_t^\infty (1-\hat{\tau}) R^A(s)^{1-1/\varepsilon} e^{-r(s-t)} ds = (1-\hat{\tau})(\varepsilon r)^{-1/\varepsilon} S(t)^{1-1/\varepsilon}, \quad \forall t \ge T.$$

where $V^A(.)$ corresponds to the value function after the regime switch. The present value of oil profits is negatively affected by the tax rate. The paths in (9) are efficient, since the tax rate, $\hat{\tau}$, operates as a lump-sum tax. Hence, the effects of taxation on expected profits (10) are similar to the effects of confiscation, and thus we can use them interchangeably.

2.2. Before the regime switch

The HJB equation associated with the dynamic programming problem before the regime switch is (see appendix for a mathematical derivation):

(11) $$\underset{R^B}{\text{Max}}\left[p(R^B)R^B - V_S^B(S)R^B \right] - h\left[V^B(S) - V^A(S) \right] = rV^B(S),$$

where $V^B(S)$ denotes the value function (the present value of profits to go excluding the cost of the initial outlay on exploration investment) before the switch. Equation (11) states that maximum oil rents *minus* the expected loss in value terms of switching to a regime of confiscation must equal the return from investing proceeds at the market rate of interest. The maximization of oil rents in (11) requires the condition that marginal oil revenue must equal the marginal value of oil reserves in the crust of the earth:

(12) $$(1 - 1/\varepsilon)p^B = V_S^B(S).$$

Making use of (4) and (12), we get the optimal oil depletion rate before the regime switch:

(13) $$R^B = \left(\frac{V_S^B(S)}{1 - 1/\varepsilon} \right)^{-\varepsilon}.$$

Upon substitution of (12) and (13) in (11), we write the HJB equation as:

(14) $$\frac{1}{\varepsilon}\left(\frac{V_S^B(S)}{1 - 1/\varepsilon} \right)^{1-\varepsilon} - h\left[V^B(S) - V^A(S) \right] = rV^B(S).$$

To solve equation (14), we postulate the value function $V^B(S) = KS^{1-1/\varepsilon}$, substitute it with (10) into (14), and use the method of undetermined coefficients to solve for K. The postulated value function indeed satisfies (14) if K satisfies the nonlinear equation:

(15) $$\frac{1}{\varepsilon}K^{1-\varepsilon} + h(1-\hat{\tau})(\varepsilon r)^{-1/\varepsilon} = (r+h)K.$$

From (12) and then (9), we get:

(16) $$p^B(t) = KS(t)^{-1/\varepsilon} \quad \text{and} \quad R^B(t) = K^{-\varepsilon}S(t),\ 0 \le t < T.$$

Solving for the time paths from (16) and (2), we obtain:

(17) $$p^B(t) = e^{Lt/\varepsilon}(LS_0)^{-1/\varepsilon}, \quad R^B(t) = Le^{-Lt}S_0, \quad S^B(t) = e^{-Lt}S_0, \quad 0 \le t < T,$$

where $L \equiv K^{-\varepsilon}$. To characterize our results, we first note from (15) that $K = (\varepsilon r)^{-1/\varepsilon}$ and $L = \varepsilon r$ if $h = 0$ and that $K = (1-\hat{\tau})(\varepsilon r)^{-1/\varepsilon} < (\varepsilon r)^{-1/\varepsilon}$ and $L = (1-\hat{\tau})^{-\varepsilon}\varepsilon r > \varepsilon r,\ \forall 0 < \hat{\tau} < 1$ if $h \to \infty$. We then totally differentiate equation (15):

$$(15') \qquad \begin{aligned} &dK = \frac{-(L-\varepsilon r)(K/\varepsilon h)dh - h(\varepsilon r)^{-1/\varepsilon}d\hat{\tau}}{r+h+(1-1/\varepsilon)L} \quad \Rightarrow \\ &K = K(h,\hat{\tau}),\ K_h < 0, K_{\hat{\tau}} < 0, \quad L = L(h,\hat{\tau}),\ L_h > 0, L_{\hat{\tau}} > 0, \quad \forall 0 < \hat{\tau} < 1. \end{aligned}$$

Note that $L(\infty,\hat{\tau}) > L(0,\hat{\tau})$ and sign(K) = − sign($L - \varepsilon r$) implies that indeed $K_h < 0$ for all $0 < \hat{\tau} < 1$.[7] We thus arrive at the following proposition.

Proposition 1: *After the regime switch the oil depletion rate and oil reserves decline at the rate εr and the oil price rises at the rate r with the corresponding time paths given by (9). Before the regime switch the oil depletion rate and oil reserves decline at the rate L > εr and the oil price rises at the rate $L/\varepsilon > r$ with the time paths given by (17). A higher confiscation risk and a higher tax rate boost the speed of oil depletion and depress the expected value of profits to go.*

A higher risk of confiscation and anticipation of a future oil tax thus reduce expected profits to go, raise the initial oil depletion rate and depress the initial oil price, more so if the chance of a regime switch and the expected tax are high. Subsequently, oil prices rise at a higher rate than the market interest rate and oil use and reserves decline faster than the Hotelling rates.[8] The ratio of oil reserves to production before the regime switch, $1/L$, is smaller than the ratio after the switch, $1/\varepsilon r$. This reflects a too rapid depletion rate.

Our model can be reinterpreted to understand the implications of the threat of nationalization where the hazard rate for that event is h. If the government fully

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[7] Since $\varepsilon > 1$, the left-hand side of (15) decreases in K and asymptotically tends to a positive value if $0 < \hat{\tau} < 1$. The right-hand side increases linearly in K, so (15) yields a unique and positive solution for K.

[8] The result that uncertainty about future taxation leads to more rapid extraction also occurs in a two-period model. Expected profits are $p(R(1))R(1) + \left[1-h+h(1-\hat{\tau})\right]p(R(2))R(2)/(1+r)$. With iso-elastic demand and zero extraction costs, we have $[p(2)-p(1)]/p(1) = (r+h\hat{\tau})/(1-h\hat{\tau}) > r$, hence a monopolist extracts to fast. Uncertainty about future carbon taxation in a growth model also leads to more rapid extraction, where it is known as the green paradox (Smulders et al., 2010).

compensates oil firms ($\hat{\tau}=0$), the efficient outcome prevails. If oil firms receive zero compensation, $\hat{\tau}=1$(cf., Long, 1975, Proposition 3.6), inefficiencies are largest. Typically, nationalization is associated with only partial compensation of oil firms, $0<\hat{\tau}<1$.

2.3. Oil depletion before and after the regime switch

Initially the path for the oil depletion rate exceeds the efficient path and the oil price path is below the efficient Hotelling path (as $L > \varepsilon r$). If the realized time of confiscation is long enough, the oil depletion rate before the switch can fall below and the oil price path can be above the efficient path. This occurs for all $t > T^*$, where T^* follows from $Le^{-LT^*}=\varepsilon r e^{-\varepsilon r T^*}$:

$$(18)\qquad T^* = \frac{\ln(L/\varepsilon r)}{L-\varepsilon r} = \frac{\ln(K(h,\hat{\tau})^{-\varepsilon}/\varepsilon r)}{K(h,\hat{\tau})^{-\varepsilon}-\varepsilon r} \equiv T^*(h,\hat{\tau})>0.$$

Since T^* depends negatively on L and positively on K,[9] we have $T_h^*(h,\hat{\tau})<0, T_{\hat{\tau}}^*(h,\hat{\tau})<0.$ A higher confiscation risk thus brings forward the date (provided confiscation has not taken place yet) that the oil depletion rate becomes lower than the efficient rate and the oil price higher. Suppose that confiscation takes place at date T. We know from (17) that just before we have $R^B(T-)=Le^{-LT}S_0$ and $p^B(T-)=e^{LT/\varepsilon}(LS_0)^{-1/\varepsilon}$. Using $S^A(T)=S^B(T)=e^{-LT}S_0$ in (9), we get:

$$(19)\qquad \begin{aligned} &R^A(T+)=\varepsilon r e^{-LT}S_0 < R^B(T-)=Le^{-LT}S_0, \\ &p^A(T+)=e^{LT/\varepsilon}(\varepsilon r S_0)^{-1/\varepsilon} > p^B(T-)=e^{LT/\varepsilon}(LS_0)^{-1/\varepsilon}. \end{aligned}$$

Once confiscation has taken place, the oil depletion rate jumps down and the oil price jumps up by a *discrete* amount. From then on oil depletion and reserves follow Hotelling paths, but are inefficient as they start out from fewer oil reserves than with no

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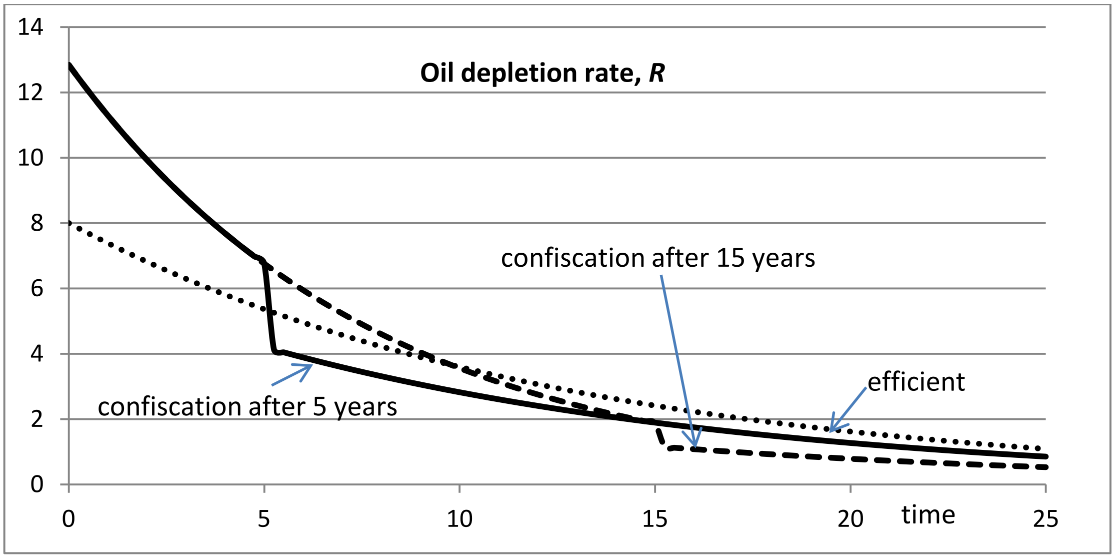
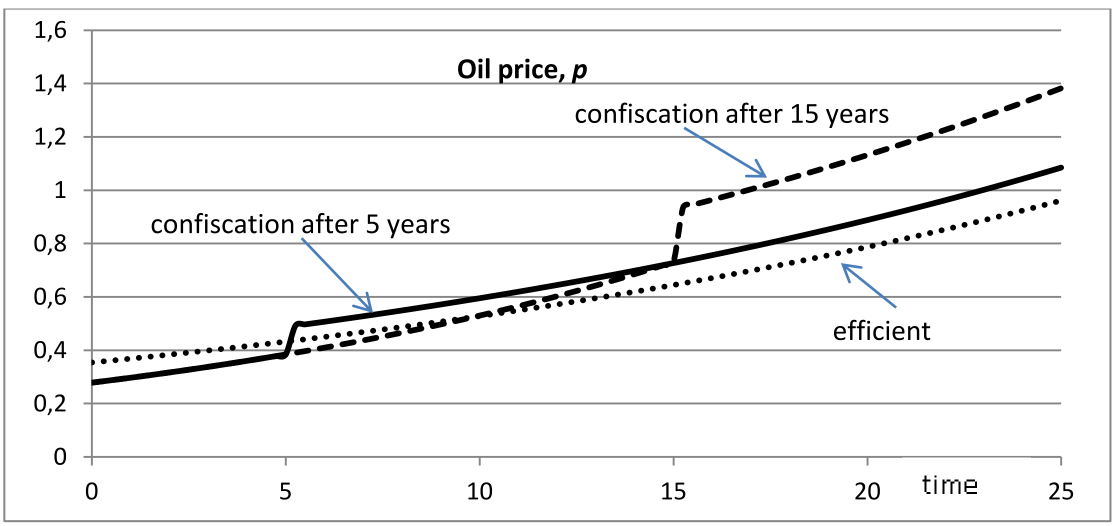
[9] Note that $\partial T^*/\partial L=[L-\varepsilon r-L\ln(L/\varepsilon r)]/[L(L-\varepsilon r)^2]$. The denominator of this expression is positive and the derivative of the numerator is $-\ln(L/\varepsilon r)<0$. Hence, as the numerator approaches zero as L approaches εr, we have that $\partial T^*/\partial L<0$ and thus $\partial T^*/\partial K>0$.

confiscation risk. Oil prices from then on rise at the interest rate, but starting from a higher level than with no confiscation risk.

Figure 1: Simulation of oil extraction under confiscation risk





To illustrate proposition 1, fig. 1 simulates the model with $\varepsilon = 2$, $r = 0.04$, $S_0 = 100$, $h = 0.1$ and $\hat{\tau} = 0.4$. This implies an expected date of confiscation of 10 with standard deviation of also 10 units of time. The solution to (15) is $K = 2.79$ and thus $L = 0.13$. We also find from (18) that the solution for the crossing time is $T^* = 9.77$. The reserves to production ratios before and after the regime switch are 7.7 and 12.5, respectively. The dashed lines indicate the efficient outcome, which prevails if there is no risk of confiscation or immediate confiscation at the rate $\hat{\tau}$. The dotted lines are the efficient Hotelling rates of extraction without confiscation risk. The solid lines indicate the inefficient outcomes that result if the realized date of confiscation is after $T = 5$.

Since $T = 5 < T^* = 9.77$, oil depletion rates are always higher than the efficient rates and oil prices under confiscation risk are always lower than under the efficient ones without confiscation risk. The dashed lines correspond to a later realized date of confiscation of $T = 15 > T^*$, so the oil depletion paths and oil price paths cross over with the efficient paths before confiscation takes place. The simulations confirm that the risk of confiscation pushes up oil depletion rates and pushes down oil prices in the period before confiscation. After confiscation, oil depletion jumps down and oil prices up and then continue at their less aggressive Hotelling rates.

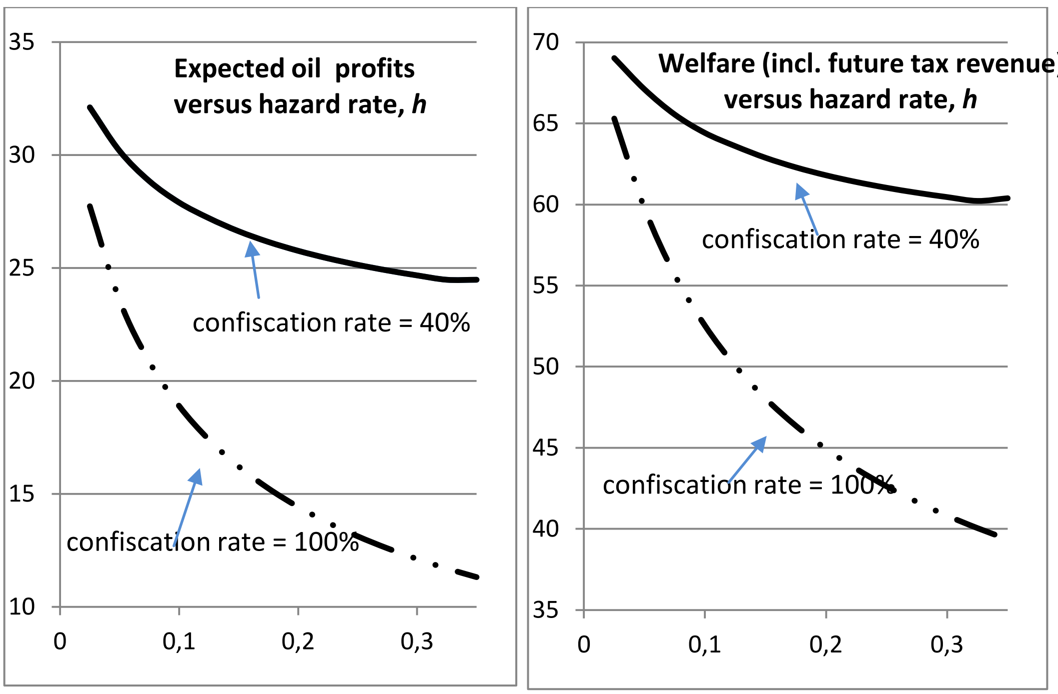
2.4. Expected profits and welfare

The expected present value of oil profits at time zero are $V^B(S_0) = KS_0^{1-1/\varepsilon}$. Welfare corresponds to the area under the oil demand curve, $KS_0^{1-1/\varepsilon}/(1-1/\varepsilon) > V^B(S_0)$, *plus* the expected value of confiscation revenues, $\mathrm{E}\left[\frac{\hat{\tau}}{1-\hat{\tau}}V^A(S(T))\right] = \hat{\tau}(\varepsilon r)^{-1/\varepsilon}\mathrm{E}\left[S(T)^{1-1/\varepsilon}\right]$ (cf., (10)). Substituting $S(T)$ from (17) and taking expectations using the exponential distribution function, we get welfare if future tax revenue is handed back as lump-sum subsidies:

$$\frac{K}{1-1/\varepsilon}S_0^{1-1/\varepsilon} + \hat{\tau}(\varepsilon r)^{-1/\varepsilon}S_0^{1-1/\varepsilon}\mathrm{E}\left[e^{-(1-1/\varepsilon)LT}\right] = \left[\frac{K}{1-1/\varepsilon} + \hat{\tau}\left(\frac{h}{h+(1-1/\varepsilon)L}\right)(\varepsilon r)^{-1/\varepsilon}\right]S_0^{1-1/\varepsilon}. \tag{20}$$

The left-hand panel of fig. 2 plots the expected present value of oil profits and welfare against the hazard rate, both for a 40% and a 100% confiscation rate. The highest feasible level of expected oil profits is 35.36, which occurs if there is no chance of confiscation (i.e., $\hat{\tau}$ or h is zero). Highest oil profits occur even if there is full or partial confiscation with certainty from time zero onwards. The expected present value of oil profits is plotted in the left panel and is lower for higher hazard and higher confiscation rates. It starts out with 35.36 if the hazard rate is zero and asymptotically approaches for a confiscation rate of 40% and 100% expected profits of 21.21 and zero, respectively, as the hazard rate approaches infinity.

Figure 2: Effects of hazard rate and confiscation rate on oil profits and net welfare



Welfare *excluding* the returned lump-subsidies from tax revenue are simply double the expected value of profits, since ε = 2. The right-hand panel in fig. 2 highlights the inefficiencies of the risk of confiscation; it indicates that welfare *including* the tax revenue that is handed back as lump-sum subsidies is depressed by higher hazard and confiscation rates.

2.5. Exploration investment and the hold-up problem

The final stage of solving the problem stated in section 2 is to solve for the optimal level of exploration investment, *I*. Using (3) and the value function at time zero,

$V^B(\Omega(I)) = K\Omega(I)^{1-1/\varepsilon}$, we find that this requires setting the marginal return on exploration investment to its cost:

$$(21) \qquad (1-1/\varepsilon)K\Omega(I)^{-1/\varepsilon}\Omega'(I) = q.$$

Total differentiation of (21) gives $q\left[[\Omega'(I)/\varepsilon\Omega(I)] - \Omega''(I)/\Omega'(I)\right]dI = -dq + (q/K)(K_h dh + K_\tau d\hat{\tau}),$ so the optimal outlay on exploration investment declines with its cost and the confiscation risk:

$$(22) \qquad I = I(h,\hat{\tau},q), \quad I_{h,}I_{\hat{\tau}}, I_q < 0.$$

A benevolent government faced with the hazard of being removed from office by a grabbing populist has a second-best rationale to subsidize exploration investment. If the subsidy rate is θ, then the optimality condition (21) becomes $(1-1/\varepsilon)K(h,\hat{\tau})\Omega(I)^{-1/\varepsilon}\Omega'(I) = q-\theta.$ Without confiscation risk and a monopolistic oil well owner, $(1-1/\varepsilon)K(0,\hat{\tau})\Omega(I)^{-1/\varepsilon}\Omega'(I) = q$ where $K(0,\hat{\tau}) = (\varepsilon r)^{-1/\varepsilon}$. Hence, the optimal exploration investment subsidy increases with the risk of confiscation and the confiscation rate:

$$(23) \qquad \theta = \left[(\varepsilon r)^{-1/\varepsilon} - K(h,\hat{\tau})\right](1-1/\varepsilon)\Omega(I)^{-1/\varepsilon}\Omega'(I) \equiv \theta(h,\hat{\tau},q) > 0, \quad \theta_h, \theta_{\hat{\tau}}, \theta_q > 0.$$

We have used (15′) and that $\partial\theta/\partial I = \left(\Omega'' - \varepsilon^{-1}\Omega'/\Omega\right)\Omega^{-1/\varepsilon} < 0$ and (22) to get the comparative statics results in (23).[10] Equations (22) and (23) thus give rise to the following proposition.

Proposition 2: *The inefficiencies induced by confiscation risk are exacerbated by a drop in exploration investment, especially if the risk of confiscation and the expected tax rate are higher. These inefficiencies can be eliminated by subsidizing exploration investment*

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[10] The first best has $K(0,\hat{\tau})(I)^{-1/\varepsilon}\Omega'(I) = q$ and corrects for the monopoly distortion in the exploration investment by setting the first-best subsidy to $\theta^{FB} = \left[(\varepsilon r)^{-1/\varepsilon} - (1-1/\varepsilon)K(h,\hat{\tau})\right]\Omega(I)^{-1/\varepsilon}\Omega'(I) \quad > \theta(h,\hat{\tau}).$ A subsidy is thus needed even with no confiscation risk, $\theta^{FB} = (\varepsilon r)^{-1/\varepsilon}\Omega(I)^{-1/\varepsilon}\Omega'(I)/\varepsilon > 0.$

at a rate that increases in the risk of confiscation, the expected tax rate and the cost of exploration investment.

A higher risk of confiscation and a higher expected tax rate depress expected profits to go of a given stock of oil reserves and, as a consequence, it is less attractive to undertake exploration investment so that the discovered stock of oil reserves is less. This inefficiency is corrected with an appropriate subsidy on exploration investment. A higher cost of exploration investment also depresses the discovered stock of oil reserves and thus necessitates a higher subsidy.

Proposition 2 implies a hold-up problem (e.g., Rogerson, 1992; Holmström and Roberts, 1998). One way to overcome this is to nationalize the oil firm (vertical integration), but this may lower efficiency. There may also be contractual solutions. Here an appropriate exploration investment subsidy implemented by benevolent government can get rid of the inefficiency in exploration investment caused by the risk of a populist rival taking over office. If confiscation risk is a proxy for bad property rights, this is not so simple.

3. Application: the Green Paradox

Well-intended climate policy can have undesirable unintended consequences (e.g., Sinn, 2008; Gerlagh, 2011; Grafton et al., 2010; Hoel, 2010). By levying a steeply rising carbon tax or subsidizing the use of renewables, oil well owners are encouraged to extract and sell their oil more quickly, thereby exacerbating carbon emissions and global warming. This counterintuitive result has been coined the Green Paradox. However, if oil extraction becomes more costly as fewer reserves are left, the total amount of oil extracted from the earth is endogenous and not all oil reserves are necessarily fully exhausted. Over time, oil will become less attractive relative to the carbon-free backstop. Hence, a rising schedule for the carbon tax or a renewables subsidy makes it more attractive to keep more oil reserves in the crust of the earth. This offsets and can overturn the Green Paradox, both in terms of green welfare and total welfare (van der Ploeg and Withagen, 2012). We used an alternative rationale for the Green Paradox not to hold. Our model also has two margins: how quickly to extract oil and how much oil in total to extract from the earth. We thus argue using the model of section 2 that the prospect of some breakthrough in the invention and bringing to the market of a carbon-free substitute induces oil to be pumped up more rapidly. As a result, carbon is more quickly emitted into the atmosphere and thus global warming is exacerbated. These effects are less strong if the carbon-free backstop is a worse substitute for oil (cf., Grafton et al., 2012). At the moment the carbon-free substitute becomes available, oil use jumps down by a discrete amount and the oil price jumps up by a discrete amount unless the cost reduction of renewables and the degree of substitutability is large enough in which case the oil price jumps down. From then on, the rate of decline in the rate of oil depletion and the rate of increase in the oil price follow Hotelling paths, albeit starting from a lower level of oil reserves than if there would have been no hazard of a cheaper substitute coming to the market. This inefficiency is stronger if the risk of discovery and drop in the price of the substitute are higher. Once the cheap carbon-free substitute is on the market, oil is depleted in Hotelling manner. Uncertainty about timing of the breakthrough causes inefficiencies, not the breakthrough itself.

However, the prospect of cost-effective renewables becoming available at some random moment in the future implies also that exploration investment is curbed and thus that the total stock of available oil reserves diminishes. The hold-up problem reduces the total of carbon emitted into the atmosphere and thus alleviates the problem of global warming. Subsidizing green R&D to speed up the introduction of breakthrough renewables leads to more rapid oil extraction before the breakthrough, but more oil is left in situ as exploration investment will be lower. The latter offsets the Green Paradox.

We just give a sketch of how the model of section 2 needs to be modified to give these insights. There are two types of energy, viz. oil, R, and renewables, B. Before the breakthrough ($t < T$), renewables are infinitely elastically supplied at cost $\tilde{b}(t) = b.$ After the breakthrough ($t \geq T$), they are supplied at cost $\tilde{b}(t) = b - \Delta$ where $0 < \Delta \leq b$. The oil demand schedule is now

$$(4') \qquad R(t) = \Upsilon p(t)^{-\varepsilon} b^{\sigma},\ 0 \leq t < T, \quad R(t) = \Upsilon p(t)^{-\varepsilon} (b-\Delta)^{\sigma},\ \forall t \geq T, \quad \Upsilon, \sigma > 0, \quad \varepsilon > 1.$$

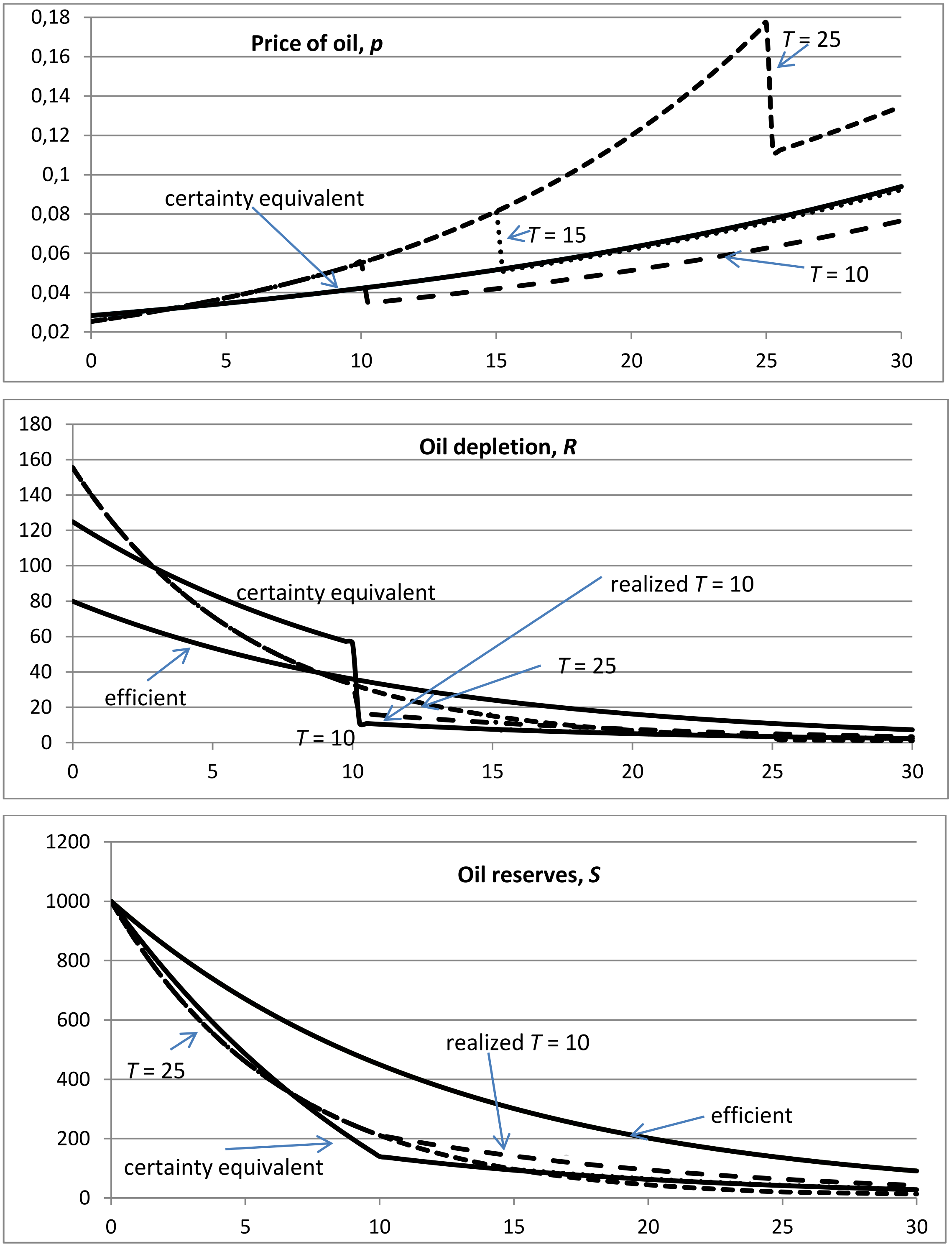
The probability that the breakthrough occurs in the interval ending at time t is (5). Oil and renewables are gross substitutes, so the constant cross price elasticity of oil demand (σ) is positive. The inverse demand function for oil is $p = (\Upsilon \tilde{b}^{\sigma} / F)^{1/\varepsilon} \equiv p(F, \tilde{b}).$ With these modifications, the results of section 2 can easily be translated to the insights given above.

Proposition 3: *After the breakthrough the oil depletion rate and oil reserves decline at the rate εr and the oil price rises at the rate r with the corresponding time paths given by (8). Before the breakthrough the oil depletion rate and oil reserves decline too rapidly at the rate $L \equiv K^{-\varepsilon} \Upsilon b^{\sigma} > \varepsilon r$ and the oil price rises too rapidly at the rate $L/\varepsilon > r$ with the time paths given by (16) where $K = K(b - \Delta, h), K_{b-\Delta} > 0, K_h < 0$ solves (14). At the time of the breakthrough, there is a discrete drop in the rate of oil extraction. If renewables enjoy a big enough cost reduction and are a good enough substitute, the oil price falls by a discrete amount.*

To illustrate proposition 3, fig. 3 offers some illustrative simulations. We set the own price elasticity of oil to $\varepsilon = 2$, the cross price elasticity of oil to $\sigma = 1$ and autonomous oil demand to $\Upsilon = 1.$ We set the interest rate to $r = 0.04$. The hazard rate for the breakthrough is set to $h = 0.1$, so the expected time it takes for the breakthrough is 10 years. Hence, $0.08 < L < 0.28$. The cost of renewables is set to 100 before the breakthrough and to 20 after the breakthrough, so $b = 100$ and $\Delta = 80$. Finally, the initial stock of oil reserves is set to $S_0 = 1000$.

With the parameters set to these values, the solution to (14) is $K = 0.802$ and thus $L = 0.155$. The speed of oil depletion, 0.155, is thus almost twice as high as the speed after the breakthrough, $\varepsilon r = 0.08$. Fig. 3 shows simulations with realized times of the breakthrough technology occurring at times 10, 15 and 25 by long dashes, dots and short dashes, respectively. We compare these with the certainty-equivalent paths which suppose that the breakthrough occurs with certainty at the expected date of the breakthrough $1/h$ and the efficient paths if the cost of renewables is constant from time zero onwards. The initial oil price if there is never a breakthrough is 0.0354 and if there is an immediate breakthrough the initial oil price is 0.0158. From then on oil prices follow a

Figure 3: Impact of threat of breakthrough renewables on oil extraction and prices



Hotelling path in each of these two cases. The paths for oil depletion rates and reserves do not depend on whether there is never or an immediate breakthrough. The certainty-equivalent path starts off with an oil price in between, 0.0283, and then also follows a Hotelling path. Oil depletion is affected by the certainty of a future breakthrough: until the breakthrough reserves are depleted at a rapid rate and thus at a lower rate afterwards.

Not knowing the date of the breakthrough also speeds up the rate of oil extraction before the breakthrough compared with the certainty-equivalent (and a fortiori the efficient) path. This means that initially oil depletion is higher and oil prices lower than in the certainty-equivalent path, but after some time as a consequence of the faster rate of oil depletion oil depletion is lower and oil prices higher than in the certainty-equivalent outcome. At the moment the breakthrough comes to market, both the rate of oil depletion and oil prices jump down and thereafter continue along their Hotelling paths, albeit from an inefficient base. If the cost reduction would have not been so substantial or the renewables would not have been such a good substitute, the oil price would have jumped up by a discrete moment of the breakthrough. A sufficient condition for this not to occur is from (17) that $\left(b/(b-\Delta)\right)^{\sigma} > (r+h)/h = 3.5.$

4. Political regime uncertainty and oil reserves uncertainty

We now extend our model of confiscation risk exposited in section 2 in the following two ways: (i) the regime switch may revert back again after some time; (ii) the stock of oil reserves is uncertain.[11] To allow for (i), we denote the incumbent government which does not confiscate by the superscript *B* and the populist confiscating challenger political rival by the superscript *A*. The hazard rate for *B* being removed from office is $h^B > 0$ and is supposed to be exogenous. The expected duration of *B*'s term of office is thus $1/h^B$. We suppose that, if the populist challenger *A* is in office, the hazard rate of being removed

[11] We have regime change uncertainty and oil stock uncertainty (cf., Zemel, 2012).

from office is $h^A > 0$.[12] In section 2 we had $h^A = 0$. To allow for (ii), we have the stochastic oil depletion equation:

$$(2') \qquad dS = -Rdt + \sigma S dW, \quad S(0) = S_0 > 0,$$

where $\sigma > 0$ and W is a Wiener process. Equation (2′) implies that relative changes in the stock of oil reserves are normally distributed and ensures that the stock always remains positive. The stochastic HJB equations for the two regimes are:

$$(24) \qquad \underset{R^B}{\text{Max}}\left[p(R^B)R^B - G(S)R^B - V_S^B(S)R^B \right] + 0.5\sigma^2 S^2 V_{SS}^B(S) + h^B V^A(S) = (r+h^B)V^B(S),$$

$$(25) \qquad \underset{R^A}{\text{Max}}\left[(1-\hat{\tau})p(R^A)R^A - G(S)R^A - V_S^A(S)R^A \right] + 0.5\sigma^2 S^2 V_{SS}^B(S) + h^A V^B(S) = (r+h^A)V^A(S).$$

Equation (24) extends the Principle of Optimality (11) for political party B and equation (25) gives the Principle of Optimality for the populist confiscating political party A. These two coupled HJB equations can be obtained analytically by guessing the value functions $V^B(S) = K^B S^{1-1/\varepsilon}$ and $V^A(S) = K^A S^{1-1/\varepsilon}$, and solving for K^B and K^A with the method of undetermined coefficients. Performing the maximization in (24) and (25) shows that the optimal depletion rates are $R^B = L^B S$ and $R^A = L^A S$ with $L^B \equiv (K^B)^{-\varepsilon}$ and $L^A \equiv (1-\hat{\tau})^{\varepsilon}(K^A)^{-\varepsilon}$. Substituting the postulated value functions and these depletion rates into equations (24) and (25) and dividing by $S^{1-1/\varepsilon}$, we get two algebraic equations:

$$(26) \qquad \frac{1}{\varepsilon}(K^B)^{1-\varepsilon} - \frac{1}{2}\sigma^2\left(\frac{1-1/\varepsilon}{\varepsilon}\right)K^B + h^B K^A = (r+h^B)K^B,$$

$$(27) \qquad \frac{1}{\varepsilon}(1-\hat{\tau})^{\varepsilon}(K^A)^{1-\varepsilon} - \frac{1}{2}\sigma^2\left(\frac{1-1/\varepsilon}{\varepsilon}\right)K^A + h^A K^B = (r+h^A)K^A.$$

Equations (26) and (27) can be solved for K^B and K^A, so the postulated value functions indeed satisfy equations (24) and (25).

[12] In general, the probability of the no-confiscation regime B coming to an end might depend positively on the stock of untapped oil reserves and the hazard of the confiscation regime A coming to an end might depend negatively on untapped oil reserves, but we abstract from this.

If the challenger is never removed from office (h^A = 0), equation (27) gives $K^A = (1-\hat{\tau})\left[\varepsilon r + 0.5\sigma^2(1-1/\varepsilon)\right]^{-1/\varepsilon}$ and $L^A = (1-\hat{\tau})^{-\varepsilon}\left[\varepsilon r + 0.5\sigma^2(1-1/\varepsilon)\right]$. If also σ = 0, we get (10). Like a higher interest rate, oil reserves uncertainty (σ > 0) boosts the speed of oil extraction, lowers the reserves to production ratio and depresses the after-calamity value to go. Also, if the incumbent is never removed from office (h^B = 0), $L^B = \varepsilon r + 0.5\sigma^2(1-1/\varepsilon) \geq \varepsilon r$ so oil reserves uncertainty increases the rate at which oil is extraction and curbs expected profits to go for the incumbent. Oil extraction under the non-confiscating is more rapid than under the confiscating government, since then the fear of confiscation is higher. In general, we can solve equations (26) and (27) for $K^A = K^A(h^A, h^B, \hat{\tau}, r, \sigma)$ and $K^B = K^B(h^A, h^B, \hat{\tau}, r, \sigma)$ and establish $K^i_{h^A} > 0$, $K^i_{h^B}, K^i_r, K^i_\sigma, K^i_{\hat{\tau}} < 0, i = A, B$ so depletion is faster under both regimes if the hazard of switching to the confiscation regime, the interest rate, oil reserves uncertainty and the confiscation rate are higher and slower if the hazard of switching to the no-confiscation regime is bigger.

Proposition 4: *A lower chance of the no-confiscation government and a higher chance of the confiscation government being kicked out of office boost oil profits and makes oil depletion less aggressive in both regimes. Political uncertainty benefits rent-grabbing governments. Uncertainty about oil reserves makes oil depletion more aggressive and curbs oil profits.*

To illustrate this proposition, table 1 offers some numerical results again with ε = 2, r = 0.04, S_0 = 100, h = 0.1 and $\hat{\tau}$ = 0.4. Row (1) confirms the benchmark outcomes of section 3 with zero probability of reverting back to the no-confiscation regime and no uncertainty about the level of oil reserves. Still abstracting from oil stock uncertainty, comparison of rows (2) and (3) with each other and with row (1) indicates that a higher chance of reverting back to the no-confiscation regime, h^A, increases oil profits under both the no-confiscation regime A and the confiscation regime B. The prospect of returning back to no confiscation someday leads to *less* aggressive oil depletion rates in both regimes as can be witnessed from the lower $L^A = R^A/S$ and $L^B = R^B/S$ for higher h^A.

Table 1: Effects of political regime and oil stock uncertainty ($\hat{\tau} = 0.4$)

	$L^A = R^A/S$	$L^B = R^B/S$	$V^A = 10\ K^A$	$V^B = 10\ K^B$
(1) $\sigma = 0$, $h^A = 0 < h^B = 0.1$	0.247	0.598	21.22	27.92
(2) $\sigma = 0$, $h^A = h^B = 0.1$	0.220	0.570	26.78	30.74
(3) $\sigma = 0$, $h^A = 0.3 > h^B = 0.1$	0.206	0.552	30.63	32.76
(4) $\sigma = 0$, $h^A = 0.1 < h^B = 0.3$	0.230	0.607	24.57	27.10
(5) $\sigma = 0$, $h^A = h^B = 0.3$	0.215	0.579	28.15	29.79
(6) $\sigma = 1$, $h^A = h^B = 0.1$	0.331	0.787	11.83	16.15

Comparing rows (4) and (2) of table 1 indicates that a higher probability of switching to a confiscation regime lowers expected oil profits in both the no-confiscation regime and in the confiscation regime. The reason is that oil depletion rates have become *more* aggressive in both regimes as can be witnessed from the higher L^A and L^B.

There are no effects of more regime (or political) uncertainty, defined as an equal increase in both hazard rates, if $\hat{\tau} = 0.$ However, if $\hat{\tau} = 0.4,$ comparing rows (5) and (2) indicates that oil depletion is more aggressive under the no-confiscation regime of the initial incumbent but less aggressive under the confiscation regime. Hence, expected oil profits are curbed under no confiscation but boosted under the confiscation regime.

Introducing uncertain oil reserves ($\sigma = 1$), comparing row (6) and row (2) confirms that uncertainty about the stock of oil reserves leads to more aggressive oil depletion rates in each regime than in the case of certainty. Hence, expected oil profits are lower in both regimes.[13] [14] Stochastic variations reduce the value of untapped oil reserves and, as the

[13] If oil firms face stochastic oil reserves as described by (24) and extraction costs, the fact that oil reserves can be perfectly observed implies that it is impossible for oil reserves to suddenly fall to zero and the expected rate of change of the value of oil is unaffected by uncertainty albeit that oil extraction rates will be affected by uncertainty (Pindyck, 1980). Equations (18)-(19) in Pindyck (1980) give the rate of change in oil depletion

$$E_t[dR]/dt = [r(p-k) - 0.5\sigma^2 p''(R)\partial R/\partial S]/p'(R) < 0$$

for the competitive case with constant extraction cost $k > 0$, which makes depletion *less* rapid for higher σ. Prudence can, in contrast, make oil depletion less aggressive (e.g., van der Ploeg, 2010).

variance increases with oil reserves, there is a bigger incentive to deplete oil reserves more aggressively.

One can show that the inefficiency in exploration investment (see section 2.5) is curbed by the probability of the no-confiscation regime flipping back and by less uncertainty about oil reserves. One could allow the hazards of the populist confiscating government getting and staying into office to increase in the stock of oil in the ground, $h^A = h^A(S), h^{A}{}' > 0, h^B = h^B(S), h^{B}{}' < 0.$ If oil reserves are still high, the bias of excessively fast extraction of oil is exacerbated in both regimes. As oil reserves are depleted, these political biases disappear.

5. Dynamic resource wars: strategic, two-way regime switches

We now extend our model of perennial political turnover developed in section 4 to a model of general regime switch uncertainty with strategically determined hazard rates. This allows us to analyze the dynamic interactions between natural resource extraction and resource wars as well as to understand the political determinants of resource extraction and political turnover. Our objective is to understand the two-way interaction between natural resource extraction and conflict when there is uncertainty about who controls natural resources. We suppose there are two rival factions *A* and *B* which fight with each other about the control of oil. By diverting labor away from productive activities, they stage a costly fight but can thereby increase their grip on office and thus on the proceeds of oil or try to remove the incumbent from office to gain control of oil. In contrast to the 2-period analysis of van der Ploeg and Rohner (2012), we offer an infinite-horizon analysis of ongoing conflict with repeated switches of government regime.

5.1. The model

We denote by an asterisk outcomes for factions *A* and *B* if they are out of office. If *A* is the incumbent, the factions *A* and *B* fight f^A and f^{B*} units of time, respectively. They then

[14] More aggressive harvesting also occurs in renewable resource markets with reserves uncertainty when demand is isoelastic and extraction costs are zero (Pindyck, 1984; van der Ploeg, 1987).

have $N - f^A$ and $N - f^{B*}$ units of time left for work, where N is the exogenous labor supply of each faction. If B is the incumbent, factions A and B fight, respectively, f^{A*} and f^B units of time and work $N - f^{A*}$ and $N - f^B$ units of time. The opportunity cost of fighting is the wage W. The hazard rates of faction A being replaced by B and of faction B by A depend on relative fighting efforts and are, respectively, given by:

$$(28) \qquad h^A = \frac{2H(f^{B*})^{\phi}}{(f^A)^{\phi} + (f^{B*})^{\phi}}, \quad h^B = \frac{2H(f^{A*})^{\phi}}{(f^{A*})^{\phi} + (f^B)^{\phi}}, \qquad H > 0, \quad 0 < \phi \le 1.$$

Equations (28) imply that by fighting more intensively each faction improves chances of entering office and gaining control of oil reserves. Further, rebels who do not fight, never gain access to office. If both the incumbent and the rebels fight with the same intensity, the hazard of being removed from office is H. An incumbent's hazard of being removed from office if it does not make any effort to fend off rebels is twice as high, $2H$, but it could be any factor (especially if there are more political factions). Our way of specifying hazard rates is closely connected to the contest success functions used in the literature on contests and conflict (e.g., Tullock, 1967; Hirshleifer, 1991; Skaperdas, 1996; Konrad, 2009), which finds that conflict increase in the stakes and decisiveness of conflict technology.[15]

Three key parameters characterize outcomes. The first parameter is H which stands for how fast elections take place or for government instability. The second parameter ϕ indicates *fighting technology,* which is subject to non-increasing returns to scale ($\phi \le 1$). A high value of ϕ implies that the effect of fighting for the incumbent on the probability of being removed from office and for the rebels of gaining office is high. The third crucial parameter $0 < \kappa \le 0.5$ is the *cohesiveness* of the political system (cf., Besley and Persson, 2011ab). This parameter indicates how big a share of oil revenue the incumbent gives to the rival rebel faction rather than keeping the oil revenue for itself.

[15] This literature also finds that less productive groups fight harder and have a higher winning chance than richer groups. Our model confirms these results if we let the wage differ for the two factions.

The incumbent fights to try to stay in office and sets the rate of oil extraction. The contender only fights to gain office and control of oil. Using (28) and abstracting from reserves uncertainty, we write the HJB equations which the value functions corresponding to the non-cooperative subgame-perfect Nash equilibrium outcome for if faction *A* is in office, V^A(S), and for if it is not in office, $V^{A*}(S)$, have to satisfy:

$$\begin{gathered} rV^A(S) = \\ \underset{f^A, R^A}{\mathrm{Max}} \left\{ (1-\kappa) p(R^A) R^A - V_S^A(S) R^A + W(N - f^A) - h^A \left[V^A(S) - V^{A*}(S) \right] \right\}, \end{gathered} \tag{29}$$

$$\begin{gathered} rV^{A*}(S) = \\ \underset{f^{A*}}{\mathrm{Max}} \left\{ \kappa p(R^B) R^B - V_S^{A*}(S) R^B + W(N - f^{A*}) + h^B \left[V^A(S) - V^{A*}(S) \right] \right\}, \end{gathered} \tag{30}$$

where h^A and h^B depend on relative fighting efforts and are given by (28).

Equation (29) states that maximum oil rents (net of any share of oil revenue transferred to the rival faction and the shadow cost of oil) *plus* income from productive activities *minus* the expected loss of losing office equals the return from investing oil proceeds at the market rate of interest. Equation (30) states a similar principle for the contender: oil rents received from the incumbent *plus* wage income *plus* the expected gain of entering office must equal the market rate of return. There are two similar equations describing the value functions for if faction *B* is in office, V^B(S), and if it is not in office, $V^{B*}(S)$.

5.2. Non-cooperative outcomes for conflict and resource extraction

The Nash non-cooperative outcome supposes that, if faction *A* is in office, it takes as given rebel fighting efforts, f^{B*}, when choosing its optimal fighting efforts, f^A, and oil depletion rate, R^A. Similarly, if *A* is the rebel faction, it takes fighting efforts of the incumbent, f^B, as given when deciding on its fighting efforts, f^{A*}. Fighting efforts for faction *A* thus follow from setting the marginal expected gain from fighting to its opportunity cost, both if *A* is in office and has control of oil and if *A* is out of office:

$$(31)\qquad \left(\frac{2\phi H(f^{A})^{\phi-1}(f^{B*})^{\phi}}{\left[(f^{A})^{\phi}+(f^{B*})^{\phi}\right]^{2}}\right)\left[V^{A}(S)-V^{A*}(S)\right]= \left(\frac{2\phi H(f^{A*})^{\phi-1}(f^{B})^{\phi}}{\left[(f^{A*})^{\phi}+(f^{B})^{\phi}\right]^{2}}\right)\left[V^{A}(S)-V^{A*}(S)\right]=W,$$

and similarly for faction *B*. Equations (31) yield two reaction functions for if faction *A* is in and out of office indicating that *A* will fight more if *B* fights more (both if *A* is in and out of office). The intersection with the complementary reaction functions for faction *B* gives the non-cooperative Nash equilibrium. Since we assume that the cohesiveness parameter, fighting technology and the wage are the same for both factions and the hazard rates are given by symmetric contest functions, the non-cooperative Nash equilibrium outcome is symmetric. We thus get from (31) the following fighting intensities:

$$(32)\qquad f^{A}=f^{A*}=\phi H\,\frac{V^{A}(S)-V^{A*}(S)}{2W},\quad f^{B}=f^{B*}=\phi H\,\frac{V^{B}(S)-V^{B*}(S)}{2W}.$$

Fighting increases if the expected gain from staying in or getting into office ($V^A - V^{A*}$) is high relative to the opportunity cost of fighting (W). Further, fighting is more intense if fighting technology suffers from less decreasing returns to scale (higher ϕ) and it is easier to remove government from office (higher H). The result that fighting efforts are the same whether one is in office or out of office is a result of the specific functional form chosen for the hazard rates in (28). Substituting equations (32) into (28) and using symmetry, we have in equilibrium that $h^A = h^B = H$ and thus the HJB equations for faction *A* become:

$$(29')\qquad rV^{A}(S)= \underset{R^{A}}{\mathrm{Max}}\left\{(1-\kappa)p(R^{A})R^{A}-V_{S}^{A}(S)R^{A}+WN-(1+0.5\phi)H\left[V^{A}(S)-V^{A*}(S)\right]\right\},$$

$$(30')\qquad rV^{A*}(S)=\kappa p(R^{B})R^{B}-V_{S}^{A*}(S)R^{B}+WN+(1-0.5\phi)H\left[V^{A}(S)-V^{A*}(S)\right].$$

There are similar HJB equations for faction *B*. From (29′) we find that the optimal rate of oil depletion if faction *A* holds political office comes from setting marginal oil revenue (net of cohesiveness payments) to its marginal social cost:

(33) $\quad (1-\kappa)(1-1/\varepsilon)\,p(R^A) = V_S^A(S).$

Equation (33) implies that the oil price is high and thus the rate of oil depletion low if oil is scarce (low *S*), oil demand is not so elastic and monopoly power is strong (low ε),and cohesiveness of the political system is stronger (high κ). To solve the simultaneous HJB equations (29′) and (30′) together with (33), we guess that the value functions are given by $V^B(S) = V^A(S) = KS^{1-1/\varepsilon} + WN/r$ and $V^{B*}(S) = V^{A*}(S) = K^* S^{1-1/\varepsilon} + WN/r$ with *K* and K^* constants to be determined. Using these value functions, we find from (33) and its counterpart for faction *B* the optimal oil price and thus from (4) the corresponding optimal oil depletion rates,

(34) $\quad p^A = p^B = \dfrac{KS^{-1/\varepsilon}}{1-\kappa}, \quad R^A = R^B = (1-\kappa)^{\varepsilon} K^{-\varepsilon} S.$

Substituting (34) into (29′) and (30′) and then equating coefficients on $S^{1-1/\varepsilon}$, we get:

(35) $\quad rK = (1-\kappa)^{\varepsilon} K^{1-\varepsilon}/\varepsilon - (1+0.5\phi)H(K-K^*),$

(36) $\quad rK^* = \kappa(1-\kappa)^{\varepsilon-1}K^{1-\varepsilon} - (1-1/\varepsilon)(1-\kappa)^{\varepsilon}K^{-\varepsilon}K^* + (1-0.5\phi)H(K-K^*).$

These two nonlinear algebraic equations can be solved for *K* and K^*, which can then be substituted into (34) to get oil prices and depletion rates and also (from (32)) equilibrium fighting efforts:

(37) $\quad f^A = f^{A*} = f^B = f^{B*} = \phi H \dfrac{K-K^*}{2W} S^{1-1/\varepsilon}.$

If the political system is perfectly cohesive in the sense that all rents are shared equally between parties independent of whether they are in office or not (κ =0.5), it is easy to establish from equations (35)-(36) that the solution is $K = K^* = 0.5(\varepsilon r)^{-1/\varepsilon}$ and thus $R = \varepsilon r S$ and from (37) $f^A = f^B = 0$, regardless of the value of admissible ϕ. Hence, a perfectly cohesive political system is efficient and ensures that there is no armed conflict. If the possibility of removing factions from political office, i.e., the hazard rate *H* is zero, equation (35) gives $K = K^* = (1-\kappa)(\varepsilon r)^{-1/\varepsilon}$ (whilst K^* is irrelevant) and (34) gives $p^A = p^B = (\varepsilon r S)^{-1/\varepsilon}$ and $R^A = R^B = \varepsilon r S.$ Hence, if factions cannot be removed from office, the outcome is also efficient irrespective of the degree of political cohesion, κ.

Proposition 5: *Resource wars are intensified if oil reserves are high and workers are paid poorly. Conflict is less intense, depletion of oil reserves is less rapid and the expected payoff to factions improves if a greater share of oil revenue is given to rebels (bigger κ). Conflict is more intense yet oil depletion less rapid if government stability is higher (lower H). Decreasing returns in fighting technology (lower ϕ) leads to less intense resource wars and less rapid oil depletion.*

Proof: Defining $R^A / S = R^B / S = (1-\kappa)^{\varepsilon} K^{-\varepsilon} \equiv L,$ we rewrite (35) and (36) as follows:

$$(35') \quad \begin{aligned} &(\varepsilon-1)L^2 + \Xi L - \varepsilon^2 r(r+2H) = 0 \ \text{ with} \\ &\Xi \equiv \varepsilon[2(r+H) - \varepsilon r] - \varepsilon^2(1+0.5\phi)H\left(\frac{1-2\kappa}{1-\kappa}\right), \end{aligned}$$

$$(36') \quad K^* = \left[\frac{\varepsilon\left(\frac{\kappa}{1-\kappa}\right)L + \varepsilon(1-0.5\phi)H}{\varepsilon[r + (1-0.5\phi)H] + (\varepsilon-1)L} \right] K.$$

Picking the positive solution to equation (35′) gives the equilibrium speed of oil extraction,

$$(38) \quad \frac{R^A}{S} = \frac{R^B}{S} = L = \frac{\sqrt{\Xi^2 + 4(\varepsilon-1)\varepsilon^2 r(r+2H)} + \Xi}{2(\varepsilon-1)} > 0,$$

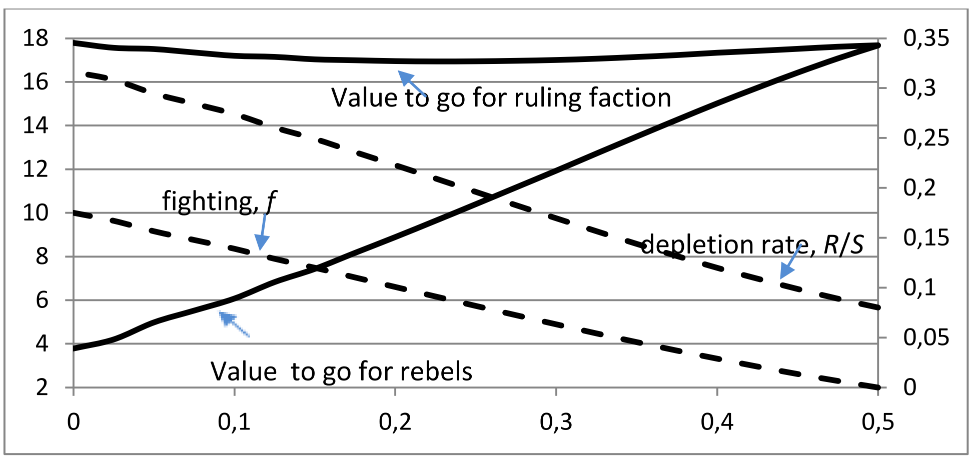
and thus K, K^* (from (36′), fighting efforts (from (37)) and values to go for each of the factions follow. Total differentiation of (35′) yields:

$$(39) \quad \begin{aligned} &[2(\varepsilon-1)L + \Xi]dL = \\ &-\varepsilon^2(1+0.5\phi)H d\kappa + 0.5H\varepsilon^2\left(\frac{1-2\kappa}{1-\kappa}\right)d\phi + \varepsilon^2\left[2r + 0.5\phi\left(\frac{1-2\kappa}{1-\kappa}\right)L\right]dH. \end{aligned}$$

At the solution to the quadratic equation (35′) the derivative of the quadratic slopes upwards, so that $2(\varepsilon-1)L + \Xi > 0$ and thus $\partial L / \partial \kappa < 0, \partial L / \partial \phi > 0$ and $\partial L / \partial H > 0.$ Q.E.D.

We numerically illustrate proposition 4 in fig. 4, which plots the effects of the share given to rebels, κ on the horizontal axis, on fighting, oil depletion rates (right-hand vertical axis) and values to go with parameters set to $\varepsilon = 2$, $r = 0.04$, $S_0 = 100$, $H = 0.1$, $N = 0.2$ and $W = 8$. Resource wars are thus indeed more intense if less of oil revenue is given to rebels; fighting goes from zero to as much as 10 as the share of oil revenues given to rebels goes from half to zero. The rate of depleting oil reserves rises fourfold from 0.08 to 0.32 as the political system moves from full to zero cohesiveness. The payoff to the rebels increases as they get a greater share of oil revenues (from 3.8 to 17.7 excluding wages paid for productive and army activities, $WN/r = 40$). Interestingly, the payoff to the faction holding control of oil reserves is hardly affected. The payoff to the incumbent first falls as the share of oil revenue given to rebels increases from $0 \le \kappa < 0.24$ but then rises with the share of revenue given to rebels for $0.24 \le \kappa < 1$. The reason is that the loss in payoff of sharing the revenue is for high enough degrees of cohesiveness dominated by the efficiency gains from less voracious depletion of oil reserves and less intense fighting. As a greater share of oil revenue is shared between the factions, the average payoff to the two factions, $(V + V^*)/2 + WN/r$, always rises steeply and resource wars are curbed.

Figure 4: Effects of the share of oil revenue given to rebels, κ



In general, if oil revenues are not equally shared with the rebels and the hazard rate is strictly positive, oil depletion will be too rapid and there will be welfare losses resulting from the drop in productive output as factions go to war, especially in less cohesive political systems. Lack of political cohesiveness means that oil depletion rates are higher and the incumbent with control of oil enjoys higher value than the rebels.

Table 2 confirms that conflict is more intense, despite the speed of depleting oil reserves being unaffected, if the stake (oil reserves, *S*) is high and the opportunity cost of fighting (the wage, *W*) is low. A higher oil stake increases payoff to both ruling and the rebel factions. A lower wage leaves payoffs from oil unaffected, but depresses of course the wage component of payoffs. Fighting is less intense if rebels are more patient (lower *r* of 0.02 instead of 0.04) in which case oil depletion is less rapid and payoffs to both the ruling and the rebel faction (as does human capital) increase.

Table 2: Sensitivity of speed of oil extraction and fighting efforts

	V	V^*	$V + V^*$	$L = R/S$	f
Benchmark: $\kappa = 0.25$, $\phi = 1$, $H = 0.1$	16.94	10.40	27.34	0.196	0.082
$S(0) = 200$	23.96	14.71	38.67	0.196	0.116
$W = 4$	16.94	10.40	27.34	0.196	0.163
$r = 0.02$	20.59	14.23	34.82	0.133	0.079
$H = 0.2$	14.56	10.06	24.62	0.265	0.056
$\phi = 0.75$	17.68	11.26	28.94	0.180	0.060

If the possibility of being removed from office is more imminent and easier (higher *H*), the ruling faction can take less advantage of the oil stake and thus there is less appetite for fighting. Still, oil depletion is more rapid, thus exacerbating the inefficiencies as manifested in a lower joint payoff to go. In table 2 payoffs to both the ruling and the rebel faction falls. Hence, oil-rich countries with few elections and where the incumbent is hard to be removed from office and with well paid workers have less conflict than oil-rich countries with regular, hotly contested elections and poorly paid workers.

Table 2 also confirms that decreasing return to scale in fighting technology (lower ϕ) induces less intense resource wars and lower rates of oil depletion. As a result, payoffs to both ruling and rebel factions increase. Worse fighting technology can thus make factions better off in countries that are rich in oil.

6. Conclusion

Unintended consequences occur when government try to implement well-intended climate policies. Often discusses examples of this are the rapacious depletion of fossil fuel and the acceleration of global warming that occur when markets expect a rapidly rising carbon tax or a renewable subsidy. We have offered a new rationale for such Green Paradox effects based on one-way regime switches that occur when the market expects that there is a probability that at some future date a low-cost breakthrough in renewable energy comes to market. Similar Green Paradox effects occur if the market assigns a probability that climate policy becomes more ambitious at some future date. These insights are examples of one-way confiscation risks. But in a political context or in a situation of dynamic resource wars two-regime switches can occur where the probability of a regime switch may itself be endogenous.

Dynamic resource wars are a prevalent feature both of history and the present day. To understand such wars it is vital to understand the two-way link between resource extraction and conflict. Using a dynamic model with two-way political regime switches, resource extraction and fighting, we show that fighting is more intense and oil extraction more aggressive if the political system is less cohesive in the sense that the ruling faction gives a smaller share of oil revenue to rebels.[16] Conflict is also more intense if oil reserves are high, workers and soldiers are paid badly, factions are impatient, and fighting technology is more effective. And resource wars are more intense if there is not much change-over of governments, although the depletion of oil reserves is then less rapid. With the ruling faction being challenged by rebels over the control of natural resources, resource extraction becomes more voracious, especially if fighting technology is more effective.

Our dynamic model of resource wars is based on a political economy model where a benevolent and a populist rent-grabbing party alternate in office and control of natural resources. A higher probability of the populist regime being replaced by the benevolent,

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[16] This contrasts with the central case of inelastic oil demand discussed in Acemoglu et al. (2012), where oil extraction is too slow and incentives for war are mitigated.

no-confiscation regime boosts the present value of oil profits under both the populist and the benevolent regime. The prospect of returning to no confiscation someday leads to *less* aggressive oil depletion rates in both regimes. In contrast, a higher probability of switching from a benevolent to a populist, confiscation regime lowers expected oil profits in both the no-confiscation and the confiscation regime as oil depletion rates have become *more* aggressive in both regimes. Political uncertainty leads to regime switch uncertainty which curbs expected oil profits under the no-confiscation regime but boosts profits under the confiscation regime. However, oil stock uncertainty induces more aggressive oil depletion rates and lower expected oil profits in both regimes.

Both our model of resource wars and our political model of two-way regime switches build on the theory of confiscation risk facing a resource-owning monopolist. To get tractable results, we have assumed isoelastic demand and zero variable oil extraction costs. Extraction rates are then efficient and oil prices follow Hotelling paths even if confiscation has taken place and oil revenue is taxed. The risk of confiscation, not confiscation itself, leads to faster depletion of reserves and oil prices rising more rapidly than the Hotelling paths.[17] These inefficiencies are exacerbated by a hold-up problem, since the risk of creaming off oil profits depresses outlays on exploration investment. This can be corrected for with an appropriate subsidy on exploration investment, which increases in the confiscation risk.

Various extensions are of interest. If the probability of confiscation decreases as untapped oil reserves fall, the benevolent incumbent will pump oil even more vigorously to make it less likely to be booted out by a populist contender.[18] If the demand elasticity increases (decreases) as oil demand falls, the monopolistic rate of oil depletion will be too slow (rapid) from an efficiency point of view thereby reducing (increasing) incentives to fight

[17] Our model of confiscation risk is related to the analysis of the effects of an uncertain time at which a resource cartel is broken up and whether this leads to cartel to overproduce (Benchekroun et al., 2006), the interplay between political risk and foreign investment (Cherian and Perotti, 2001), and the role of wealth distribution and wealth accumulation on switches between regimes of bad and good property rights (e.g., Tornell, 1997; Leonard and Long, 2011).

[18] In contrast, in climate economics, if the hazard rate for a tipping point increases as the stock of atmospheric CO_2 rises, the climate policy will be more *precautionary* to lower the risk of a tipping point (de Zeeuw and Zemel, 2012).

about the control of natural resources.[19] If oil exploration becomes more expensive as less accessible fields are explored, the speed of oil depletion will be more conservative and thus incentives for war will be higher. If the political system is not very cohesive, bribing rebels will help to stave off conflict. If resource production is capital (labor) intensive, higher (lower) resource prices boost the return on capital and lower the wage and thus intensify war and conflict (Dal Bo and Dal Bo, 2011; Dube and Vargas, 2013). It is of interest to examine how this influences the rate of natural resource extraction in general equilibrium. Capturing the notorious volatility of oil prices with Geometric Brownian motion with mean reversion, the hazard rate for moving to a confiscation regime whether it is the outcome of a political process or of war might increase with the oil price (e.g., the hazard rate could be zero if the oil price is below a certain level and one if the oil price is above that level). Finally, a more general equilibrium analysis of regime switches facing oil well owners and of resource wars will allow for the potential effect of conflict on exchange rates and the potential erosion of the value of natural resource exports.

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[19] Linear demand functions $R = \alpha - p$ result from quadratic utility, say $U = \alpha R - 0.5R^2$, and imply an increasing demand elasticity and more conservative oil depletion (cf., Stiglitz, 1976). This also occurs with semi-loglinear demand functions (i.e., preferences with constant absolute risk aversion). In contrast, power utility functions with a subsistence need for oil, $U(R) = (R - \overline{R})^{1-1/\hat{\varepsilon}} / (1 - 1/\hat{\varepsilon}),\ \overline{R} > 0,$ imply $R = \overline{R} + p^{-\hat{\varepsilon}}$ and $\varepsilon = \hat{\varepsilon} / (1 + \overline{R}p^{\hat{\varepsilon}}) < \varepsilon,$ so the demand elasticity falls in the price and depletion of reserves is too rapid. In general, results depend on whether preferences are submodular or supermodular.

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Appendix: Derivation of the HJB equation (11)

Since the probability of a regime shift in an infinitesimally small time period Δt is $h\Delta t$, the Principle of Optimality from the perspective of time zero can be written as follows:

$$\text{(A1)} \qquad e^{-rt}V^B\left(S(t)\right) = \underset{R^B}{\text{Max}}\left[\int_t^{t+\Delta t} e^{-rs}p\left(R^B(s)\right)R^B(s)ds + (1-h\Delta t)e^{-r(t+\Delta t)}V^B\left(S(t+\Delta t)\right) + h\Delta t e^{-r(t+\Delta t)}V^A\left(S(t+\Delta t)\right)\right].$$

Multiplying both sides by e^{rt}, rearranging and dividing by Δt, we rewrite (A1) as:

$$\text{(A2)} \qquad \underset{R^B}{\text{Max}}\left[\frac{\int_t^{t+\Delta t} e^{-r(s-t)}p\left(R^B(s)\right)R^B(s)ds}{\Delta t} - he^{-r\Delta t}V^B\left(S(t+\Delta t)\right) + he^{-r\Delta t}V^A\left(S(t+\Delta t)\right) \frac{\left(e^{-r\Delta t}-1\right)V^B\left(S(t+\Delta t)\right)}{\Delta t} + \frac{V^B\left(S(t+\Delta t)\right) - V^B\left(S(t)\right)}{\Delta t}\right] = 0.$$

Evaluating the integral in (A2) for infinitesimally small Δt and taking the limit as $\Delta t \to 0$ whilst using l'Hôpital's Rule for $\lim_{\Delta t \to 0} \frac{\exp(-r\Delta t)-1}{\Delta t} = -r$, and taking terms that do not depend on $R^B(t)$ outside the square brackets, we get:

$$\text{(A3)} \qquad \underset{R^B}{\text{Max}}\left[p\left(R^B(t)\right)R^B(t) - \dot{V}^B\left(S(t)\right)\right] - hV^B\left(S(t)\right) + hV^A\left(S(t)\right) - rV^B\left(S(t)\right) = 0.$$

Substituting $\dot{V}^B = V_S^B\dot{S}$ and using (2), rearranging and dropping the time index, we get (11).