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**Conference Paper**

## Should the Global Community Welcome or Mourn New Oil Discoveries?

Beiträge zur Jahrestagung des Vereins für Socialpolitik 2017: Alternative Geld- und Finanzarchitekturen - Session: Environmental Economics, Natural Resources and Climate Change I, No. A17-V1

**Provided in Cooperation with:**

Verein für Socialpolitik / German Economic Association

*Suggested Citation:* Weichenrieder, Alfons (2017) : Should the Global Community Welcome or Mourn New Oil Discoveries?, Beiträge zur Jahrestagung des Vereins für Socialpolitik 2017: Alternative Geld- und Finanzarchitekturen - Session: Environmental Economics, Natural Resources and Climate Change I, No. A17-V1, ZBW - Deutsche Zentralbibliothek für Wirtschaftswissenschaften, Leibniz-Informationszentrum Wirtschaft, Kiel, Hamburg

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# Should the Global Community Welcome or Mourn New Oil Discoveries?

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This version: February 2017.

## Abstract

Oil discoveries affect global well-being through multiple channels. Focusing on the change in pollution, consumption and extraction cost paths, we build a multi-period model that allows us to assess whether oil windfalls may be welfare-enhancing. The assessment depends on the quality of the discovered resource, expressed as the extraction cost. Our findings suggest that even when faced with high environmental externalities and no internalization mechanism for them, new oil finds can be conducive to welfare. However, there may be no simple threshold below which the discovery is beneficial but rather multiple intervals into which the extraction costs may fall.

## 1 Introduction

Oil usage is facing a barrage of criticism for being one of the drivers of climate change. On the other hand, cheap energy is often considered a prerequisite for a thriving economy. Against this background, the question arises how new oil finds should be assessed by the global community. Every year, multiple new, often relatively small, oil discoveries are made and widely covered in the media.<sup>1</sup> Are these detrimental to welfare or just the opposite? Is more oil always worse? This paper discusses the driving factors that decide on how global well-being is affected by a marginal oil find.

The windfall of natural resources has received considerable attention in the political, macroeconomic and development context. Especially the low growth in resource-rich countries ("resource curse") has been subject to in-depth investigation, both theoretically and empirically, following the seminal paper by Sachs and Warner [12]. As a consequence, a literature has arisen on how to best manage windfall resources with prescriptions for public debt and investment decisions as well as the distribution of funds for consumption (see for example van der Ploeg and Venables [13]). There have also been attempts to quantify the effect of stock discovery on the profits of resource owners, e.g. non-identical natural resource oligopolists [3]. As for the welfare aspects, to our knowledge, there has only been one paper that explicitly attempted to model the influence of oil windfall on general well-being. In this study, Benckroun et al. [2] show that in the case of a dominant firm with competitive fringe, a new find may cause a welfare loss through a socially inefficient order of resource use. There have also been some attempts to empirically estimate the local welfare effects of windfalls [4] [11]. Despite increasing environmental concerns, to the best of the authors' knowledge, there have been no studies that assessed the impact of oil finds controlling for the potential externalities created. We would like to close this gap by modelling the main welfare channels through which an oil windfall affects welfare. As the country-level effects of the windfall have been thoroughly investigated already, we abstain from including them in our analysis. Therefore, we would like to answer the sort of question that Caselli and Michaels [4] pose, but in the modified context: Should the global community welcome or mourn further discoveries of oil?

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<sup>1</sup>In 2013 out of 400 monitored exploration wells drilled the previous year the industry discovered 20 billion barrels of conventional oil (and equivalent natural gas), against global consumption of 50 billion barrels worth. Worldwide, there was no single discovery reaching or exceeding one billion barrels ([8], p. 66).

The results of the study have important policy implications. In particular, they provide some guidance for whether the quest for new oil should be supported. Our findings suggest that, even on the eve of the renewables era, new oil findings have the potential to be welfare-enhancing.

In the next section, we discuss the assumption underlying our models and derive the first results in a static framework. This helps to develop the intuition for the results of the dynamic modelling as presented in Section 3. Section 4 concludes.

## 2 One Period Model

Throughout the paper, we assume that pollution is not internalized in the resource price and that there is an ordering of the resource units such that the extraction costs are an increasing and continuous function of the unit numbers.<sup>2</sup> Environmental costs are a continuous and increasing function of the amount consumed. The oil market is perfectly competitive<sup>3</sup> and so the price development is governed by a set of Hotelling conditions adjusted to our model. The last assumption may be seen as a strong one given that the empirical evidence on oil market structure is rather mixed (Griffin [5], Polasky [10]). We wish to emphasize, though, that this modeling choice in general stacks the deck against oil discoveries being conducive to welfare. Presence of market power tends to lead to lower oil extraction compared with the case of competitive firms. If the non-competitive industry undersupplies the resource compared to the first-best, the windfall will, in most cases, improve the outcome. In particular, this holds true for monopolies.<sup>4</sup> We discuss these contentions in more depth at the end of Section 2.

Since we assume away extraction capacity problems, impose homogenous demand over time<sup>5</sup> and pursue partial equilibrium analysis, we reason that the Herfindahl rule applies in our case: resources will be extracted in strict sequence by order of cost. With that setup, the oil discoveries permanently affect the market outcomes.<sup>6</sup> A choke price for oil is assumed which may derive from existence of a constant marginal cost alternative.

The applied yardstick to measure optimality (welfare) is the sum of the consumer-producer surplus combined with the money measure of environmental externality. To keep units comparable, we assume that the marginal utility of income is essentially constant around the equilibrium allocation before the discovery.

Starting with a static model, we assume a small oil find of size  $d$ , where all newly found units have the same extraction cost,  $c^d$ .<sup>7</sup> We maintain the assumption that the new find is of such quality that its extraction is (strictly) less costly than that of the most expensive unit that would have been consumed in the absence of the discovery, as it otherwise induces no changes to the economy. Figure 1 shows an example of how the supply curve changes after the discovery (the old extraction path is depicted as a continuous curve; the windfall causes the shift of the cost curve marked with dashed curve).

The new find shifts total consumption amount from  $q_0$  to some  $q_d$  affecting welfare through four different channels. The additionally extracted resource increases the utility of the consumers, but this positive impact is subdued by concomitant additional extraction costs and elevated pollution levels. Finally, the extraction

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<sup>2</sup>For the deposits that have not yet been under exploitation, those costs will be 'full cycle' costs that incorporate the expenses connected to land grabbing and infrastructure creation (well building etc.), in addition to the 'cash cost' of exploitation. Consequently, reserves in sites under operation would tend to be the 'low cost' units. For some discussion on the ordering of the extracted units, see Holland [6].

<sup>3</sup>The assumption follows MacAvoy's [7] view that oil prices can be best explained by a model focusing on demand or supply market fundamentals rather than cartel behavior. The theoretical underpinning for that follows from the observation that potential monopoly power in extractive resource markets is reduced by the depletability of reserves [9].

<sup>4</sup>For other market structures, though, e.g. for a dominant firm with very small fringe like in [3], an inefficient order of resource extraction may result from a windfall, making the net welfare effect less clear.

<sup>5</sup>In our model, this is equivalent to assuming that, in every period, the expected demand schedule is constant and the shocks to demand are independent.

<sup>6</sup>Some of the latest papers have been reformulating the Hotelling's model, e.g. as a drilling problem where firms choose when to drill but production is constrained by available technology [1], or where firms are allowed to adjust the rate of field opening in addition to the rate of depletion, thus allowing for the price growth to be independent from the rate of interest [14]. However, we want to refrain from the technical side of the extraction and use the traditional modelling accordingly.

<sup>7</sup>Alternative cost structures of the windfall are conceivable and, with small modifications, should be compatible with our model.

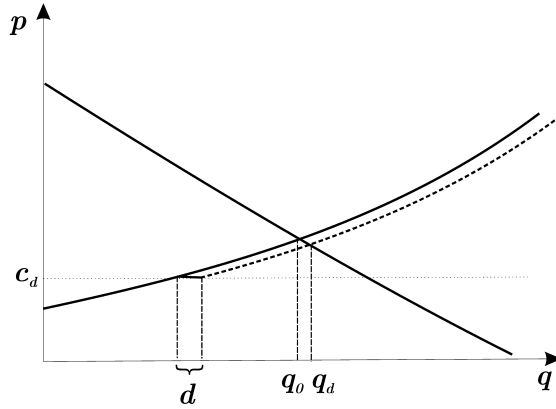


Figure 1: The change in cost schedule after a marginal discovery of oil.

costs for the initial equilibrium amount  $q_0$  decrease as the newly discovered units replace the most expensive ones.

What is the net welfare impact of the discovery? To address this question, we note that the total extraction cost is  $C^d = dc^d$ , with  $c^d < c(q_0)$ . Denoting the total welfare with the discovery as  $W^d$  and without it as  $W^{nd}$ , we have:

$$W^{nd} \geq W^d$$

$$\int_0^{q_0} u(x) - e(x) - c(x) \, dx \geq \int_0^{q_d} u(x) - e(x) \, dx - \int_0^{q_d-d} c(x) \, dx - C^d,$$

where  $e(x)$  reflects the marginal environmental damage and  $c(x)$  the marginal extraction cost path before the discovery of new oil. Instead of creating the new cost curve, we see the newly found units as replacing the most expensive ones (from the 'old' extraction path), the total extraction costs are thus costs of the first  $q_d - d$  units plus  $C^d$ . Assuming that supply is less than perfectly inelastic, we know that the new extraction amount  $q_1$  is the same or higher than  $q_0$  and that  $q_1 - d < q_0$ . The latter comes from the observation that, if the consumption increases by more than the amount discovered, the costs (and therefore the price required by the sellers) would be higher than in the initial case, while the increased sales would translate into lower willingness-to-pay, which is a contradiction.

Using the envelope theorem, we conclude that, for the discovery to be welfare increasing, it needs to hold that:

$$c^d < c(q_0) - \frac{\partial q_0}{\partial d} e(q_0) = c(q_0) - \frac{c'(q_0)}{c'(q_0) - p'(q_0)} e(q_0), \quad (1)$$

with  $c^d$  being the unit extraction cost of the discovered resource. In accordance with condition (1), the difference between the extraction cost of the new unit and the one that was previously the most expensive must cover the additional environmental externalities caused by increased consumption.

The threshold unit cost,  $\bar{c}^d = c(q_0) - \frac{\partial q_0}{\partial d} e(q_0)$ , gives the highest extraction costs for the newly discovered units for which the find is (weakly) welfare-improving. The lower the threshold value, the more stringent the condition.

We notice that when the marginal extraction costs are constant around  $q_0$  the right-hand side of (1) simplifies to  $c(q_0)$ . In this case, the total amount of extracted oil remains unaffected so the newly discovered units simply replace the most expensive ones and the level of externality is unchanged.

**Proposition 1** *If the marginal cost around the old equilibrium point is constant,  $c'(q_0) = 0$ , the oil find has an unambiguously (weakly) positive welfare impact that comes in through decreased extraction costs.*

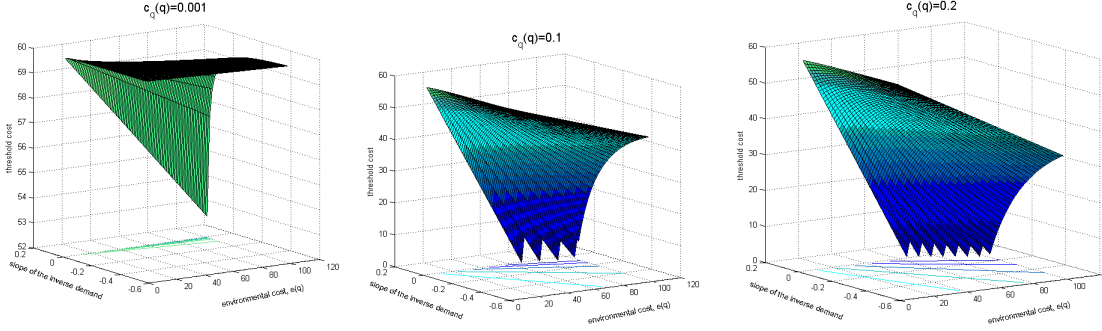


Figure 2: Threshold discovery unit costs for different environmental costs and responsiveness of demand.

In the case that marginal costs are increasing around  $q_0$ , i.e.,  $(c'(q_0) > 0)$ , the additional environmental costs become relevant as they deplete welfare. Unless  $p'(q_0) = -\infty$ , the threshold unit cost of discoveries,  $\bar{c}^d$ , for which the discovery is welfare-neutral, is reduced compared to the case of  $c'(q_0) = 0$ . The strength of this shift depends on the properties of demand. For more elastic demand (values of  $p'(q_0)$  closer to zero), the rise in total extraction is stronger than for the inelastic demand. This leads to relatively higher environmental costs and a lowered threshold unit cost of discoveries,  $\bar{c}^d$ .

**Proposition 2** *In case of a perfectly inelastic demand, any new oil find is (weakly) welfare increasing. With increasing elasticity the threshold unit cost drops until, in the extreme case of perfect elasticity of demand, it hits the difference between marginal cost of extraction in the scenario without the discovery and the marginal environmental cost.*

Figure 2 illustrates how the threshold unit cost  $\bar{c}^d$  depends on the parameter values. It shows how different demand slopes ( $p'(q)$  - on the  $x$  axis) and marginal environmental costs ( $e(q)$  - on the  $y$  axis) affect the threshold discovery unit cost ( $\bar{c}^d$  - on the  $z$  axis). The three panels were simulated for different slopes of the supply,  $c'(q)$ , the marginal costs of oil around  $q_0$  are assumed to be 60. The monotonicity in the variables is easily recognizable. The first panel illustrate the case of marginal cost increasing very slowly. Here, almost all finds of oil with extraction costs lower than the current extraction costs of 60, are conducive to welfare, only in the case of extremely elastic demand (slope of the inverse demand curve close to zero) the threshold costs,  $\bar{c}^d$ , is much lower.

How would a monopolisation of the oil supply affect our results? In a competitive market, the utility from a marginally increased consumption is offset by additional extraction costs and it consequently does not appear in condition (1). With non-competitive industry, on the other hand, the equilibrium marginal costs of extraction are lower than marginal utility and so the threshold condition (1) needs to be adjusted to reflect the (positive) difference between willingness to pay and producers' costs. As competitive firms supply (weakly) higher oil quantities relative to the monopolist, the extra environmental costs are also (weakly) higher there. Hence, when a discovery is found to be welfare-enhancing for competitive market, it is also socially desirable (or neutral) when the market is served by a monopolist.<sup>8</sup>

### 3 Dynamic Model

Now consider a two-period economy to investigate the dynamic effects of a marginal discovery. The profit maximization problem of the representative oil producer that acts as a price taker can be written as

$$\max_{q_1, q_2} p_1 q_1 - \int_0^{q_1} c(q) dq + (1+r)^{-1} [p_2 q_2 - \int_{q_1}^{q_2} c(q_1 + q) dq] - \lambda (q_1 + q_2 - Q_0).$$

<sup>8</sup>The possible neutrality comes from the cases where a find would be extracted with competitive industry but left in the ground for a non-competitive industry.

Here,  $q_1$  and  $q_2$  are the amounts extracted in the first and second periods and  $Q_0$  denotes total initial reserves at time 0. The first-order conditions are:  $p_1 - c(q_1) - (1+r)^{-1}[c(q_1 + q_2) - c(q_1)] = \lambda$  and  $(1+r)^{-1}[p_2 - c(q_1 + q_2)] = \lambda$ . Assuming that, at the end of the second period, some of the oil units will be too expensive to extract (otherwise, the problem becomes trivial), we set  $\lambda = 0$ . Consequently, the conditions that assure that the oil producer sells in both periods (interior solution) read:

$$p_2 = c(q_1 + q_2) \text{ and } p_2 = (1+r)p_1 - rc(q_1). \quad (2)$$

Combining them with market clearing conditions yields the equilibrium condition:

$$(1+r)p_1(q_1) - rc(q_1) = c(q_1 + q((1+r)p_1(q_1) - rc(q_1))). \quad (3)$$

With strictly monotonic demand and cost functions and a satiation level of demand, the solution to the problem exists and is unique. The left-hand side is a decreasing function of  $q_1$  as increased output during the first period suppresses the oil price and increases its extraction costs, while the right-hand side is an increasing function of  $q_1$ . Notice that we always have that  $q_1 > q_2$  as the profitability of the firm requires  $p(q_1) > c(q_1)$  in condition (2).

Now, assume a discovery is made that gives additional  $d$  units of oil with extraction costs  $c^d$  to the resource endowment of the firm,  $Q_0$ , giving rise to the new extraction cost schedule  $cn(\cdot)$ :

$$cn(q) = \begin{cases} c(q), & \text{if } q < q^{\hat{c}} \\ c^d & \text{if } q^{\hat{c}} < q < q^{\hat{c}} + d \\ c(q-d) & \text{otherwise} \end{cases}$$

where  $q^{\hat{c}} = c^{-1}(c^d)$  denotes the extraction unit which, under the old cost schedule, had the marginal extraction cost of  $c^d$ . The windfall moves  $q_1$  and  $q_2$  to new levels and the marginal cost of the most expensively extracted unit in the second period becomes  $c(q_1^d + q_2^d - d)$ , with upper index  $d$  marking the new levels in the case of the find.<sup>9</sup>

In the case of the unit extraction costs of the find,  $c^d$ , being less than  $cn(a)$ , implicitly defined by the equation  $(1+r)p_1(a) - rcn(a) = cn(a + q((1+r)p_1(a) - rcn(a)))$ , we denote the find as  $d_l$  and notice that the newly discovered units are extracted already in the first period. For the high extraction costs discovery,  $d_h$ , the find is physically extracted only in the second period.

The quality of the discovery has a discrete impact on the change in the extraction. The associated adjustments in the extraction path are derived in the appendix and can be written as:

$$\begin{aligned} \frac{\partial q_1}{\partial d_l} &= \frac{rc'(q_1) + (1 - rm'(p_2))c'(q_1)c'(q_1 + q_2)}{\varpi}, \\ \frac{\partial q_2}{\partial d_l} &= m'(p_2) \frac{\partial q_1}{\partial d_l} [(1+r)p'(q_1) - rc'(q_1)] + rm'(p_2)c'(q_1) \end{aligned} \quad (4)$$

and

$$\begin{aligned} \frac{\partial q_1}{\partial d_h} &= \frac{c'(q_1 + q_2)}{\varpi}, \\ \frac{\partial q_2}{\partial d_h} &= m'(p_2) \frac{\partial q_1}{\partial d_h} [(1+r)p'(q_1) - rc'(q_1)], \end{aligned} \quad (5)$$

where  $\varpi = rc'(q_1) - (1+r)p'(q_1) + c'(q_1 + q_2)[1 + m'(p_2)(p'(q_1)(1+r) - rc'(q_1))]$  and  $m' = \partial q_2 / \partial p_2$  is the slope of the demand curve. Consequently, all the derivatives are non-negative but smaller than unity with  $\frac{\partial q_1}{\partial d_l} > \frac{\partial q_1}{\partial d_h}$ <sup>10</sup> and  $\frac{\partial q_2}{\partial d_h} > \frac{\partial q_2}{\partial d_l}$ . The total change is stronger for the  $d_l$  discovery:  $\frac{\partial q_1}{\partial d_l} + \frac{\partial q_2}{\partial d_l} > \frac{\partial q_1}{\partial d_h} + \frac{\partial q_2}{\partial d_h}$ .

<sup>9</sup>We maintain the assumption that the discovery,  $d$ , must be relatively small. We assume that it does not exceed the amount extracted in any of the periods in the old equilibrium.

<sup>10</sup>As  $1 - rm'(p_2)c'(q_1) > 1$ .

It may appear somewhat surprising that the size of adjustment of production is not a continuous function of the quality of discovery, but rather has two discrete manifestations. This becomes intuitive, however, when we consider the decision of the representative oil producer. The quality of the finding – conditional on being above or below the threshold quality  $cn(a)$  – does not influence his production decision, as it has no effect on marginal cost. It affects the average costs only (and, consequently, the profit levels) in the two periods.

A finding of low quality (high  $c^d$ ) is physically extracted in the second period; therefore, the associated extraction cost savings are achieved in the second period as well. On the other hand, the costs of additionally extracted units in the first period  $\frac{\partial q_1}{\partial d_h}d$ , together with a slight decrease in the oil price compared to the counterfactual scenario of no discovery, curb the relative profitability of period one. Those intertemporal adjustments are the reason why low quality findings result in different extraction paths than in the case of a high quality discovery (low  $c^d$ ), where new units are already physically extracted in the first period. Here, the savings in extraction cost, compared to the counterfactual scenario, are made in the first period, while the profitability of the second period is negatively affected.

Given those intertemporal shifts, the steepness of the supply curve,  $c'(q_1)$ , affects the quantity adjustment differently for  $d_l$  and  $d_h$ . For the case of discovery of "cheap" oil ( $d_l$ ), the company extracts a relatively large fraction of the extra oil in the first period. Even so, its marginal cost,  $c(q_1^d)$ , is lower than in the no-discovery scenario,  $c(q_1)$ , and those "savings" in marginal costs are stronger, the steeper the supply curve around  $q_1$ . The equilibrium conditions thus require that  $\frac{\partial \frac{\partial q_1}{\partial d_l}}{\partial c'(q_1)} \geq 0$ . However, when "expensive" oil is found, increasing the production in the first period implies extraction of units that are more expensive than previously. The steeper the supply curve, the more reluctant the company would be to do that, so we conclude that  $\frac{\partial \frac{\partial q_1}{\partial d_h}}{\partial c'(q_1)} \leq 0$ .

Obviously, in the case of zero interest rates, only the sum, and not the distribution of profits between the periods, matter. Consequently, with  $r = 0$  any discovery will have the same impact on the extraction paths. This is visible when comparing solutions (4) and (5).

After the characterization of the market reactions in the two periods above, our next step is to evaluate the welfare effect of a new find. The welfare is given by the expression:

$$\int_0^{q_1} u(x) - e(x) - c(x) dx + (1+r)^{-1} \left[ \int_0^{q_2} u(x) dx - \int_{\delta q_1}^{\delta q_1 + q_2} e(x) dx + \int_{q_1}^{q_1 + q_2} c(x) dx \right],$$

where  $\delta$  is the parameter of linear decay of pollutants and is decisive for how the timing of pollution affects the welfare. In the case of instantaneous decay,  $\delta = 0$ , it is only the flow of pollution that matters in a given period. For  $\delta = 1$ , on the other hand, once the pollutants are emitted, they stay in the environment forever.  $\delta \in (0, 1)$  allows for some persistence of pollutants over time. The perfectly competitive solution is the same as when maximizing the sum of consumer and producer surplus, while disregarding the environmental concerns. Therefore, we may apply the envelope theorem to some parts of the welfare function when investigating the effects of cost schedule change.

We find the windfall to be welfare-enhancing when savings in the extraction costs exceed the negative environmental effects (*env\_eff*) caused by extra consumption. The savings are to be understood as the difference between the cost of the marginal unit that was extracted before and the cost of the (cheaper) unit from the new deposit that now replaces that marginal unit (adjusted for intertemporal changes). Taking the high quality discovery, we have the following condition for a welfare increase:

$$\frac{r}{1+r} c(q_1) + \frac{1}{1+r} c(q_1 + q_2) - c^d > env\_eff_l. \quad (6)$$

The first term gives the effect of the shift of some of the costs to the next period, whereas the second element is the cost of the unit that is left in the earth after the discovery as it gets replaced by the newly found unit with cost  $\hat{c}$ . The condition for the low quality discovery needs to account for the fact that the newly found units will be used physically only in the second period and it reads:

$$\frac{1}{1+r}c(q_1 + q_2) - c^d > env\_eff_h. \quad (7)$$

The environmental effects will reflect the change in pollution burden due to the changes in the resource consumption path:

$$env\_eff_i = \frac{\partial q_1}{\partial d_i} e(q_1) + \frac{1}{1+r} e(\delta q_1 + q_2) \left[ \delta \frac{\partial q_1}{\partial d_i} + \frac{\partial q_2}{\partial d_i} \right] - \frac{\partial q_1}{\partial d_i} \frac{\delta}{1+r} e(\delta q_1) \text{ for } i = l, h. \quad (8)$$

Here, the first two terms point to the increased consumption in both periods and the last term prevents double counting of the costs.

Depending on the values of terms in equations (6),(7) and (8), it may be the case that a discovery with higher extraction costs could be welfare-enhancing as opposed to the better quality discovery. To verify this, assume two possible discoveries, one of  $d_{high\_c}$  type (with costs  $c_h^d$ ), the other of  $d_{low\_c}$  type (costs  $c_{low}^d$ ), but with both costs being close to  $cn(a)$  as previously defined. Should the externalities associated with resource consumption be substantial, the additional environmental burden could outweigh the cost savings made for  $d_{low\_c}$ . For the  $d_{high\_c}$  discovery, the extraction costs savings will fall by  $\frac{r}{1+r}c(q_1) + (c_{high}^d - c_{low}^d)$ , which, however, may be compensated by lower environmental costs.<sup>11</sup> In how far the environmental effects differ for the two types of finds depends to a large extent on the rate of decay of the pollutants,  $\delta$ , and the curvature of the environmental burden curve.

The encapsulated condition for an oil find to be welfare-enhancing is given by:

$$c_i^d < \mathbf{1}_{l\_c}(i) \left[ \frac{r}{1+r} c(q_1) \right] + \frac{c(q_1 + q_2)}{1+r} - \frac{\partial q_1}{\partial d_i} e(q_1) - \frac{e(\delta q_1 + q_2)}{1+r} \left( \delta \frac{\partial q_1}{\partial d_i} + \frac{\partial q_2}{\partial d_i} \right) + \frac{\partial q_1}{\partial d_i} \frac{\delta e(\delta q_1)}{1+r} \text{ for } i = l\_c, h\_c \quad (9)$$

Again, the derivation of expression (9) and the implicit reactions  $\frac{\partial q_1}{\partial d}$  and  $\frac{\partial q_2}{\partial d}$  have been delegated to the appendix. The low cost discovery shifts some of the costs that were previously borne in the first period to the second one (first term, with indicator function for  $l$  discovery). In general, a windfall makes sure that the most expensive of the previously extracted units are not used anymore (second term). On the other hand, through increased consumption, pollution in both periods increases, which is reflected in the third and fourth terms. The last term adjusts the changes in the stock of pollution inherited in the latter period to avoid double-counting. Condition (9) implies that the extraction costs of the newly discovered units need to be low enough to cover for all of these effects.

**Proposition 3** *If the marginal costs around the old equilibrium points are constant,  $c'(q_1) = c'(q_1 + q_2) = 0$ , the oil find has an unambiguously positive welfare effect that comes in through the channel of decreased extraction costs.*

Having  $c'(q_1) = c'(q_1 + q_2) = 0$  implies that the discovery will not affect the amount of extracted units ( $\frac{\partial q_1}{\partial d} = \frac{\partial q_2}{\partial d} = 0$ ),<sup>12</sup> with the only change being which units are extracted. As the most expensive units are exchanged with the cheaper ones, welfare increases.

**Proposition 4** *The more persistent the pollutant (the higher the  $\delta$ ), the harder it is for a discovery to be welfare-enhancing.*

Not only does a slower decay of pollutants cause the net present cost of pollution to increase, it also makes the pollution in early periods especially harmful. Since a discovery non-negatively influences both the sum of extracted oil and the extraction in the first period, lower costs  $c^d$  are required for the welfare superiority of the windfall.

Our framework could easily be transformed to accommodate multi-period analysis. The intuition from propositions (1) and 2 concerning the elasticities of demand and supply extends to the model. The welfare superiority condition with  $T$  periods quickly grows in complexity as it needs to encompass  $T$  different cases

<sup>11</sup>Both the amount of oil extracted in the first period and the total oil consumption are lower for the  $d_{high\_c}$  find.

<sup>12</sup>Derivation of those terms is shown in the appendix.



(differing in the quality of the discovery and thus the period in which the newly found unit gets physically extracted). For a discovery that is used already in the first period, the condition reads:

$$c^d < \sum_{t=1}^{T-1} \frac{r}{(1+r)^t} c\left(\sum_{i=1}^t q_i\right) + \frac{1}{(1+r)^{T-1}} c\left(\sum_{i=1}^T q_i\right) - \sum_{t=1}^T \frac{\partial q_t}{\partial d} EnvEffect_t \quad (10)$$

where  $EnvEffect_t$  gives the discounted sum of all the pollution costs associated with the increase in  $q_t$ . The environmental effect consists of the intermediate harm caused by pollution and the costs associated with a higher pollution stock in future periods,

$$EnvEffect_t = - \sum_{i=t}^T \left(\frac{\delta}{1+r}\right)^{i-1} \left(e\left(\sum_{j=1}^i \delta^{i-j} q_j\right) + \delta \sum_{i=t}^{T-1} \left(\frac{\delta}{1+r}\right)^i \left(e\left(\sum_{j=1}^i \delta^{i-j+1} q_j\right)\right).\right.$$

## 4 Discussion

Even though the end of the oil era and a transition to renewable resources is impatiently awaited by many, new oil discoveries may still be welcomed by the international community. We derive conditions for an oil find to be welfare-enhancing when looking at 'global' effects - the change in utility, total extraction costs and environmental externalities. While we believe our model captures main welfare channels for oil finds, there are some aspects that are left out of the study and that could influence our findings. Primarily, even though we look at the effect of an oil find on the extraction of oil, we do not model the oil search process and do not allow endogenous field openings. A worthwhile future extension of our study would be to incorporate investments into oil finds in order to discuss under what circumstances these should be encouraged or discouraged given the trade-offs that have been discussed in this paper. Again, we should expect that the size of the environmental externality and the slope of the preexisting marginal cost curve are important in addressing this question.

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## 5 Appendix:

To investigate how the social outcome is influenced by the windfall, compare welfare with and without the discovery,  $W^d$  and  $W^{nd}$ . First, start with the situation when the extraction cost of the newly discovered units is lower than  $\bar{c}$ , where  $\bar{c}$  equals  $cn(a)$ , implicitly defined by the equation  $(1+r)p_1(a) - rcn(a) = cn(a + q((1+r)p_1(a) - rcn(a)))$ . This condition is decisive for whether the windfall will be extracted in the first or second period.

$$\begin{aligned}
W^{nd} < W^d &\iff \\
\int_0^{q_1} u(x) - e(x) - c(x) \, dx + (1+r)^{-1} & \left[ \int_0^{q_2} u(x) \, dx - \int_{\delta q_1}^{\delta q_1 + q_2} e(x) \, dx + \int_{q_1}^{q_1 + q_2} c(x) \, dx \right] \\
&< \\
\int_0^{q_1^d} u(x) - e(x) \, dx - \int_0^{q_1^d - d} c(x) \, dx - C^d + (1+r)^{-1} & \left[ \int_0^{q_2^d} u(x) \, dx - \int_{\delta q_1^d}^{\delta q_1^d + q_2^d} e(x) \, dx - \int_{q_1^d - d}^{q_1^d + q_2^d - d} c(x) \, dx \right]
\end{aligned}$$

Rearranging we get:

$$\begin{aligned}
C^d - \int_{q_1^d - d}^{q_1} c(x) \, dx + (1+r)^{-1} & \left[ \int_{q_1^d - d}^{q_1} c(x) \, dx - \int_{q_1^d + q_2^d - d}^{q_1 + q_2} c(x) \, dx \right] \\
&< \\
\int_{q_1}^{q_1^d} u(x) - e(x) \, dx + (1+r)^{-1} & \left[ \int_{q_2}^{q_2^d} u(x) \, dx - \int_{\delta q_1^d}^{\delta q_1^d + q_2^d} e(x) \, dx + \int_{\delta q_1}^{\delta q_1 + q_2} e(x) \, dx \right].
\end{aligned}$$

Simplifying we obtain:

$$\begin{aligned}
& C^d - \frac{r}{1+r} \int_{q_1^d-d}^{q_1} c(x) \, dx - \frac{1}{1+r} \int_{q_1^d+q_2^d-d}^{q_1+q_2} c(x) \, dx \\
& < \\
& \int_{q_1}^{q_1^d} u(x) - e(x) \, dx + (1+r)^{-1} \left[ \int_{q_2}^{q_2^d} u(x) \, dx - \int_{\delta q_1+q_2}^{\delta q_1^d+q_2^d} e(x) \, dx + \int_{\delta q_1}^{\delta q_1^d} e(x) \, dx \right].
\end{aligned}$$

If we approximate the integrals around  $q_1$  and  $q_2$  and divide both sides by  $d$ , the size of discovery<sup>13</sup>, we have

$$\begin{aligned}
& c^d - \frac{r}{1+r} \left[ 1 - \frac{\partial q_1}{\partial d} \right] c(q_1) - \left[ 1 - \frac{\partial q_1}{\partial d} - \frac{\partial q_2}{\partial d} \right] \frac{c(q_1+q_2)}{1+r} \\
& < \\
& \frac{\partial q_1}{\partial d} u(q_1) - \frac{\partial q_1}{\partial d} e(q_1) + \frac{1}{1+r} \left[ \frac{\partial q_2}{\partial d} u(q_2) - \left( \delta \frac{\partial q_1}{\partial d} + \frac{\partial q_2}{\partial d} \right) e(\delta q_1+q_2) + \delta \frac{\partial q_1}{\partial d} e(\delta q_1) \right].
\end{aligned}$$

From the first-order condition of the firm we know that in the second period  $c(q_1+q_2) = p_2 = u(q_2)$  so we use this relationship to get:

$$\begin{aligned}
& c^d - \frac{r}{1+r} \left[ 1 - \frac{\partial q_1}{\partial d} \right] c(q_1) - \frac{c(q_1+q_2)}{1+r} \left[ 1 - \frac{\partial q_1}{\partial d} \right] \\
& < \\
& \frac{\partial q_1}{\partial d} u(q_1) - \frac{\partial q_1}{\partial d} e(q_1) - \frac{e(\delta q_1+q_2)}{1+r} \left[ \delta \frac{\partial q_1}{\partial d} + \frac{\partial q_2}{\partial d} \right] + \frac{\delta}{1+r} \frac{\partial q_1}{\partial d} e(\delta q_1).
\end{aligned}$$

From (3) we recall that in the firm's optimum:  $\frac{1}{1+r} c(q_1+q_2) + \frac{r}{1+r} c(q_1) = p_1$ . Consequently, we can further simplify and obtain the final condition for the supremacy of windfall:

$$(1+r)c^d - rc(q_1) - c(q_1+q_2) < -\frac{\partial q_1}{\partial d} (1+r)e(q_1) - e(\delta q_1+q_2) \left[ \delta \frac{\partial q_1}{\partial d} + \frac{\partial q_2}{\partial d} \right] + \delta \frac{\partial q_1}{\partial d} e(\delta q_1).$$

In order to find  $\frac{\partial q_1}{\partial d}$  and  $\frac{\partial q_2}{\partial d}$ , we use the relevant version of Hotelling rule that in our case is given by:  $(1+r)p_1 - rc(q_1 - d_l) = p_2$ . It can be rewritten as an equilibrium condition as

$$(1+r)p(q_1) - rc(q_1 - d_l) - c(q_1 + m((1+r)p(q_1) - rc(q_1 - d_l)) - d_l) = 0,$$

where  $m(\cdot)$  denotes the demand function and  $p(\cdot)$  is the inverse demand function and we use the observation that the firm will choose quantity  $q_2$  such that:  $c(q_1+q_2) = p_2$ . To use the implicit function theorem (IFT) take first the derivative with respect to  $q_1$  (below denoted as  $q$ ) and evaluate at  $d_l = 0$  to obtain:

$$\begin{aligned}
& (1+r)p'(q) - rc'(q) \\
& - c'(q + m(p(q)(1+r) - rc(q))) [m'(p(q)(1+r) - rc(q)) (p'(q)(1+r) - rc'(q)) + 1].
\end{aligned}$$

Secondly, the derivative with respect to  $d$  is given as:

$$rc'(q) + [1 - rm'(p(q)(1+r) - rc(q))] c'(q) c'(q + m(p(q)(1+r) - rc(q))).$$

<sup>13</sup>We bear in mind that  $q_1^d = q_1 + d \frac{\partial q_1}{\partial d}$ ,  $q_2^d = q_2 + d \frac{\partial q_2}{\partial d}$  and consequently  $q_1 - (q_1^d - d) = d - d \frac{\partial q_1}{\partial d} = d(1 - \frac{\partial q_1}{\partial d})$ .

Plugging in we get the effect of low-cost discovery on the amount extracted in the first period:

$$\frac{\partial q_1}{\partial d_l} = \frac{rc'(q_1) + [1 - rm'(p_2)]c'(q_1)c'(q_1 + q_2)}{rc'(q_1) + c'(q_1 + q_2)[1 + m'(p_2)(1 + r)p'(q_1) - rc'(q_1)] - (1 + r)p'(q_1)} > 0.$$

Analyzing the terms we notice that  $\frac{\partial q_1}{\partial d_l} = \frac{a}{a + (1+r)p'_1 m'(p_2)c'(q_1+q_2) - (1+r)p'(q_1)} \leq 1$ , where  $a$  is the numerator of the previous expression.

Now we analyze how  $q_2$  is influenced by the discovery. We know that  $q_2$  in equilibrium is determined by the demand at the prevailing price  $p_2$ :  $q_2^d = m(p_2) = m((1+r)p(q_1^d) - rc(q_1^d - d_l))$ . Therefore,  $\frac{\partial q_2}{\partial d_l}$  is given by:

$$\frac{\partial q_2}{\partial d_l} = m'(p_2)[(1+r)p'(q_1) - rc'(q_1)]\frac{\partial q_1}{\partial d_l} + m'(p_2)rc'(q_1). \quad (11)$$

After some transformations one finds that  $\frac{\partial q_2}{\partial d_l} \geq 0$  which is plausible as a decrease in  $q_2$  would cause the price  $p_2^d$  to increase compared to the equilibrium price  $p_d$  before. Given that  $\frac{\partial q_1}{\partial d_l}$  was found to be less than 1, the new cost  $c(q_1^d + q_2^d - d_l)$  would be smaller than  $c(q_1 + q_2)$ . However, since the firm obeys  $c(q_1 + q_2) = p_2$  this would not be an equilibrium outcome.

Now assume a discovery of  $d_h$  units such that  $c^d > \bar{c}$ . In this case, the welfare condition can be rewritten as:

$$c^d < \frac{1}{1+r}c(q_1 + q_2) - \frac{\partial q_1}{\partial d}((1+r)e(q_1) - e(\delta q_1 + q_2))[\delta \frac{\partial q_1}{\partial d} + \frac{\partial q_2}{\partial d}] + \delta \frac{\partial q_1}{\partial d} e(\delta q_1)$$

and the Hotelling rule takes now the form of:  $(1+r)p(q_1) - rc(q_1) - c(q_1 + m((1+r)p(q_1) - rc(q_1)) - d_h) = 0$ . As previously, apply IFT to find:

$$\frac{\partial q_1}{\partial d_h} = \frac{c'(q_1 + q_2)}{rc'(q_1) + c'(q_1 + q_2)(1 + m'(p_2)((1+r)p'(q_1) - rc'(q_1))) - (1+r)p'(q_1)} > 0. \quad (12)$$

We know that  $q_2$  in equilibrium is determined by the demand at the prevailing price  $p_2$ :  $q_2 = m(p_2) = m((1+r)p(q_1) - rc(q_1))$  so  $\frac{\partial q_2}{\partial d_h} = m'(p_2)((1+r)p'(q_1) - rc'(q_1))\frac{\partial q_1}{\partial d_h} > 0$ .