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Should the global community welcome new oil discoveries?

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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 with (endogenous) oil phase out 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.

Keywords Oil discovery · Windfall profit · Environmental cost · Herfindahl rule · Extraction cost · Endogenous phase-out

JEL Classification Q32 · Q35

1 Introduction

Oil usage is facing a barrage of criticism. While the exact external damages differ between the individual oil deposits (Coulomb et al. 2021), oil remains one of the drivers of climate change. Burning oil products leads also to emissions of sulfur

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dioxides and nitrogen oxides which decrease air quality and exacerbate respiratory problems for local population. At the same time, cheap energy is often considered a prerequisite for a thriving economy. With multiple new, often relatively small, oil discoveries made every year,[1] the question arises how new oil finds should be assessed by the global community. Are there scenarios in which oil discoveries can enhance global welfare or is more oil always worse? The latter verdict seems to be behind the recent call of the International Energy Agency to stop all new oil and gas exploration projects.[2] Against this background, this paper discusses the driving factors that decide on how global well-being is affected by a new, 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 (2001). As a consequence, a body of 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 (2011) and van der Ploeg (2019)). Attempts to quantify the effect of stock discovery on political regimes (Caselli and Tesei 2016), on the global oil production (Güntner 2019), and on the profits of resource owners, e.g. non-identical natural resource oligopolists (Benchekroun and van Long 2006), have also been undertaken. In addition, empirical literature has studied how news shocks in form of oil discoveries impact key macroeconomic variables, like current accounts (Arezki et al. 2017).

As for the welfare implications of the discoveries, to our knowledge, only one paper explicitly models the influence of oil windfall on general well-being. In this study, Benchekroun et al. (2010) 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 a few attempts to empirically estimate the local welfare effects of windfalls (Caselli and Michaels 2013; Postali and Nishijima 2013). Despite increasing environmental concerns the studies have not assessed the impact of oil finds controlling for the potential externalities created by such discoveries. We fill this gap by modelling the welfare channels through which an oil windfall affects welfare. As the country-level effects of the windfall have already been thoroughly investigated, we abstain from including them in our analysis, while putting particular emphasis on environmental effects that have been largely neglected in the windfall literature so far. Consequently, our study is motivated by a question complementary to the question of local welfare effects studied by Caselli and Michaels (2013): should the global community welcome or lament further discoveries of oil?

To answer this question we build a simple model that reflects three welfare channels through which a resource windfall operates: change in the extraction costs, utility from additional oil consumption, and the ensuing heightened pollution. To build up intuition, we first analyze the windfall in a static, one-period model, which

[1] 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). Global consumption during this period was estimated at 50 billion barrels, meaning that the discoveries were the equivalent of about 40% of annual consumption. Worldwide, there was no single discovery reaching or exceeding one billion barrels (Pedraza (2014), p. 66).

[2] Cf. Financial Times, 18 May 2021, https://www.ft.com/content/2bf04fff-5b2f-4d96-a4ea-ff55e029f18e.

can be interpreted as the last period before oil gets phased out. Second, we move to a dynamic framework with multiple periods before the pre-announced phase-out.

Finally, we endogenize the timing of the phase-out, making it dependent on the price development of oil, acknowledging that the end point of extraction can result from economic exhaustion rather than physical exhaustion. Following up on the proposition by Sinn (2008) that a carbon tax may not change the path of extraction as long as all carbon is extracted over time, endogenous phase-out has been studied by several papers discussing this green paradox. See, e.g., Gerlagh (2011).

The results of the study shed light on welfare effects of policies that target oil exploration: many governments encourage exploration using generous tax deductions,[3] while others, like New Zealand and state of Oregon, discourage it by designating areas in which extraction is forbidden or by stopping the issuance of oil exploration licenses. In an optimal setting, environmental policies related to exploration would be superfluous and an optimal emission tax applied to the externalities from the production and use of oil would induce optimal extraction. However, in settings, in which emission taxes set at the social cost of damages are not a viable option, one could wonder if policies targeting exploration can be part of the adequate climate policy toolkit.

Our findings suggest that, even on the eve of the renewables era, new oil findings have the potential to be welfare-enhancing. However, the conditions under which this is indeed the case may be rather narrow.

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 Sect. 3.2 and looks into possible qualification in the presence of market power. In Sect. 4 we briefly discuss our findings.

2 Modeling framework

Assume that oil producers face a (suboptimally low) tax on emissions associated with extraction and consumption of oil, whereby the tax t is set to cover a certain percent of the external damages.[4] Carbon intensities can differ between reservoirs of fossil fuel. For instance, oil sands can be more polluting than conventional oil extracted both onshore and offshore. Assume also that there exist an ordering of the resource units such that the private marginal extraction costs, $c(t, x)$, are a (weakly) increasing and continuous function of the unit numbers, such that $c(t,x) = c^p(x) + t \cdot \epsilon(x)$, where $c^p(x)$ is the cost associated with extraction

[3] For instance, in Australia exploration expenditure incurred in some designated areas is eligible to be deducted from the Petroleum Resource Rent Tax Act taxation liabilities at a rate of 150%.

[4] A report by the International Monetary Fund (2019) suggests, the average price on global CO_2 emissions is currently \$2 a ton.

operations[5] and $\epsilon(x)$ is the amount of emissions associated with extraction and consumption of unit x.

Environmental damages occur as a function of the cumulative amount of the emissions. When tax rate t does not cover all external damages per unit of emissions, i.e., when the tax is below the Pigouvian level, some damages remain uninternalized. The amount of uninternalized damages, e, is thus a function of the environmental tax and the number of extracted units, q, such that $e(q,t) = e(\int_0^q \epsilon(x)\mathrm{d}x, t)$. As the tax rate is chosen outside of our model and we are not interested in its effect on welfare *per se*, we suppress it in the formulas for extraction cost and uninternalized environmental costs, such that the notation simplifies to $c(x)$ and to $e(\int_0^q \epsilon(x)\mathrm{d}x)$. Note, however, that the tax, by defining the internalized portion of environmental damages, and thus the costs that oil suppliers face, will affect the outcomes and welfare channels. For instance, with an adequate Pigouvian tax rate schedule, there would be no effects that we label in Sect. 3.1. as "environmental."

We impose that there exist oil units that are prohibitively expensive to extract given the inverse demand schedule, $u(x)$, in particular given the choke price, $\bar{c}$, which may be interpreted as deriving from existence of a constant marginal cost alternative.[6] Consequently, some of the oil will always be left in the ground.

The main results are derived for a perfectly competitive oil market with the supply curve given by the marginal cost curve of a representative firm. That modeling choice follows the observation by MacAvoy (1982) that oil prices may be explained by a model focusing on demand or supply market fundamentals rather than cartel behavior. It also relates to the insight that potential monopoly power in extractive resource markets is reduced by the depletability of reserves Pindyck (1987). However, the assumption of a competitive oil sector may be a strong one given that the empirical evidence on oil market structure is rather mixed (Griffin 1985; Polasky 1992; Kisswani 2016; Asker et al. 2019). The assumption also generally does not hold when monopolist can strategically affect the amount of resource through exploration efforts (Gaudet and Lasserre (1988)). Therefore, we additionally introduce a monopolistic oil supplier in the static setting to understand how our findings can change for the polar opposite assumption on market power.[7]

[5] For the oil deposits not yet exploited, those costs will be 'full cycle' costs incorporating 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 a further discussion on the ordering of the extracted units, see Holland (2003). McGlade and Ekins (2015) provide information on the cost structure of worldwide known and unused fossil reserves.

[6] Note that the level of the choke price might be an outcome of an environmental policy, e.g. of generation subsidies paid to renewables. However, as the existence of such policies does not change the mechanisms through which the oil discovery affects welfare, we do not model how the choke price is formed but rather take it as given.

[7] Recently, several papers have modelled the oil market with OPEC exerting price setting power to limit the quantities for the competitive fringe countries with higher extraction costs or to optimally compete with a backstop technology. In such a framework, Andrade de Sa and Daubanes (2016) discuss the effectiveness of carbon taxes and subsidies for renewables. van der Meijden and Withagen (2019) generalize the model by Andrade de Sa and Daubanes (2016) with respect to the cost structures. Behar and Ritz (2017) discuss empirical evidence for limit pricing.

Since we assume away extraction capacity problems, impose homogeneous demand over time and pursue partial equilibrium analysis, we reason that the Herfindahl rule applies: resources will be extracted in strict sequence from lowest to highest marginal cost. This extraction order happens no matter whether the resources are owned by a representative firm or by many independent and competitive firms (Holland 2003).[8] Therefore, the price development is governed by a set of Hotelling conditions adjusted to our model. Within the above framework, oil discoveries permanently affect the market outcomes.[9]

The applied yardstick to measure optimality (welfare) is the sum of the consumer-producer surplus combined with a monetary measure of uninternalized environmental externality. To keep units comparable, we assume that the marginal utility of income is essentially constant around the equilibrium allocation before the discovery. A discussion of potential additional elements of welfare evaluation, such as exploration costs and the associated environmental externalities, is included in Sect. 4.

We assume a small oil find of size d, where all newly found units have the same extraction cost, c^d, and emissions, ϵ^d.[10] 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. Note that we focus on discoveries that are small relative to the known reserve and therefore we can rely on exploring welfare effects through marginal effects. This implies, however, that the welfare impacts of "giant" oil discoveries as studied in Arezki et al. (2017) cannot be fully captured in our framework.

3 Welfare evaluation of oil discoveries

3.1 One period model

To build up intuition, we start with a one-period model that can be thought of as representing the last period before the oil usage stops, be it because of development of a clean, low-cost alternative or because of a ban of fossil fuels becoming effective.

The new find changes the oil supply curve. Figure 1 shows an example of such a change. The old extraction cost is depicted here as a continuous curve; the windfall causes the shift of the cost curve to the new position, $cn(q)$, marked by the dashed

[8] Note, however, that alternative setups, such as in Daubanes and Lasserre (2019) where producers first choose when and how much reserves are developed, can lead to simultaneous extraction of resource with differing extraction costs.

[9] Some of the latest papers have been reformulating Hotelling's model, e.g. as a drilling problem where firms choose when to drill but production is constrained by available technology (Anderson et al. 2018), 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 (Venables 2014). However, we want to refrain from the technical side of the extraction and thus rely on the traditional modelling.

[10] Alternative cost structures of the windfall are conceivable and, with small modifications, compatible with our model.

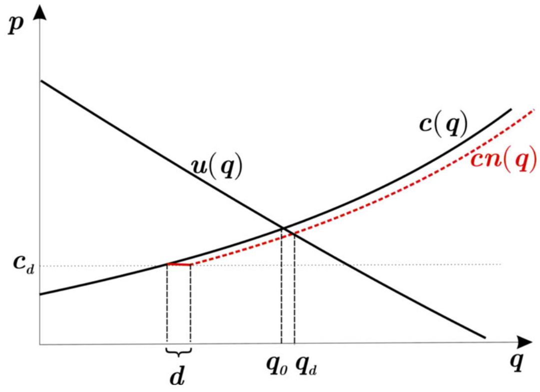

Fig. 1 The change in cost schedule after a marginal discovery of oil *Notes:* The graph assumes heterogeneous emission intensity of various reserves, such that $\epsilon(x) = 1\,\forall i$

line, shifting total consumption amount from q_0 to q_d and 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 costs for the initial equilibrium amount q_0 decrease, as the newly discovered units replace the most expensive ones.

When is the net welfare impact of the discovery positive? To address this question, we note that the total extraction cost of the new units is $C^d = dc^d$, with $c^d < c(q_0)$, and the total emissions from new units are $E^d = d\epsilon^d$. Denoting the total welfare with the discovery as W^d and without it as W^{nd}, we have that the welfare impact of oil discovery equals:

$$\begin{aligned}&\Delta W = W^d - W^{nd}\\&= \int_0^{q_d} u(x)\,\mathrm{d}x - \int_0^{(q_d-d)} c(x)\mathrm{d}x - C^d - e\Big(\int_0^{q_d-d} \epsilon(x)\mathrm{d}x + E^d\Big)\\&- \int_0^{q_0} [u(x) - c(x)]\,\mathrm{d}x - e\Big(\int_0^{q_0} \epsilon(x)\mathrm{d}x\Big),\end{aligned} \tag{1}$$

where $e(\cdot)$ reflects the uninternalized environmental damages and $c(x)$ the marginal extraction cost before the discovery of new oil (including the tax t paid on emissions). The formulation takes advantage of the fact that, for our purposes, the cost extraction curve under the discovery scenario is equivalent to the no discovery extraction cost shifted by the amount of discovery. Therefore, marginal extraction cost at amount x are $c(x-d)$ if we consider the new extraction cost curve to the right of the new find. Equivalently, for any total extraction x, unit $x+d$ has the old marginal cost, $c(x)$. Total extraction costs include the costs of the new units and are given by $\int_0^{q_d-d} c(x)\,\mathrm{d}x$ plus C^d. Note that the new extraction amount q_d is the same or higher than q_0 and that $q_d - d \leq q_0$.[11]

[11] The inequality 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.

To understand the impact of an oil discovery on welfare we can approximate Eq. (1) using the fact that q_d is a function of d. We also leverage the fact that the discovery is too small to change the marginal environmental damages, $e'(\cdot)$, such that the change in emissions resulting from the discovery can be approximated as:

$$EnvEff = d[\epsilon^d - \epsilon^o(1 - \frac{\partial q_0}{\partial d})]MD. \tag{2}$$

Here ϵ^o is the average emission intensity of the oil units that would be extracted without the discovery but get pushed out of the market if new oil gets found, $\frac{\partial q_0}{\partial d}$ is the change in the total amount extracted in response to an additional unit of discovered oil, and MD are marginal uninternalized damages from a unit of oil around the equilibrium, $MD = e'(\int_0^{q_0} \epsilon(x)\mathrm{d}x)$. We rearrange the terms from Eq. 1 to obtain:

$$\frac{\Delta W}{d} \approx (1 - \frac{\partial q_0}{\partial d})[c(q_0) + \epsilon^o MD] - c^d - \epsilon^d MD + \frac{\partial q_0}{\partial d} u(q_0),$$

where c^d and ϵ^d are the average unit extraction costs and average social damages. Rearranging the terms again, we see the three welfare channels through which oil discoveries operate in our model:

$$\frac{\Delta W}{d} \approx \underbrace{\frac{\partial q_0}{\partial d}[u(q_0) - c(q_0)]}_{\text{additional consumption}} \quad \overbrace{-\frac{\partial q_0}{\partial d}\epsilon^o MD}^{\text{environmental effect}} \quad \underbrace{+[c(q_0) + \epsilon^o MD - c^d - \epsilon^d MD]}_{\text{unit replacement effects}}.$$

The first two terms relate to the effects of increase in oil extraction resulting from the discovery: the rise in aggregate consumer and producer surplus and the growth in total pollution, respectively. The unit replacement effect relates to the fact that the marginal units extracted without the discovery remain in the ground under the oil find scenario as they get replaced by the discovered units.

With competitive markets, $c(q_0) = u(q_0)$ and $\frac{\partial q_0}{\partial d} = \frac{c'(q_o)}{c'(q_0) - u'(q_0)}$.

Consequently:

Finding 1 For competitive markets, in the last period before the oil extraction stops, an oil discovery is welfare increasing if:

$$c^d < c(q_0) - \frac{c'(q_0)}{c'(q_0) - u'(q_0)}\epsilon^o MD + (\epsilon^o - \epsilon^d)MD. \tag{3}$$

Accordingly, the difference between the extraction cost of the new unit and the previously most expensive unit (cost savings) must cover the additional uninternalized environmental externalities caused by increased consumption and by the unit replacement. The threshold unit cost, $\bar{c}^d = c(q_0) - \frac{\partial q_0}{\partial d}\epsilon^o MD + (\epsilon^o - \epsilon^d)MD$, 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 for the social desirability of the find.

We notice that when the marginal extraction costs are constant around q_0 and the oil units are homogeneous in their emission intensity, the right-hand side of (3) simplifies to $c(q_0)$. In such a 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. Consequently, if the marginal extraction cost around the old equilibrium point is constant, $c'(q_0) = 0$, the oil find has a weakly positive welfare impact resulting from decreased extraction costs. Similarly, if environmental taxes perfectly internalize pollution, such that $e(\cdot) = 0$, and thus also $MD = 0$, the oil discovery is weakly welfare-enhancing.

In the event 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 $u'(q_0) = -\infty$ (perfectly inelastic demand) the threshold unit cost of discoveries is reduced compared to the case of $c'(q_0) = 0$. The strength of this shift depends on the properties of demand. More elastic demand (values of $u'(q_0)$ closer to zero) leads to higher increases in total extraction and thus to relatively higher environmental costs and a lower threshold unit cost of discoveries, $\bar{c}^d$. Similarly, newly discovered units being more emission intensive than the ones they push out of the market will decrease the threshold unit cost.

Finding 2 In case of a perfectly inelastic demand and uniform emission intensity of oil units, any new oil find is (weakly) welfare increasing. The higher the demand elasticity, the lower the private cost of the discovered units needs to be for the find to be welfare-enhancing. In the limiting case of a perfectly elastic demand, the private cost needs to be lower than the difference between the marginal private cost absent the discovery and the marginal uninternalized environmental cost.

Figure 2 illustrates how the threshold unit cost $\bar{c}^d$ depends on the parameter values. It shows the relationship between demand slopes ($u'(q)$—on the x axis) and uniform marginal uninternalized environmental costs (MD - on the y axis, where t is assumed to be \$2 in accordance with International Monetary Fund (2019)), and the threshold discovery unit cost ($\bar{c}^d$ - on the z axis).[12]

The monotonicity in the variables is easily recognizable. For low marginal environmental damages, almost all oil finds with extraction costs lower than the equilibrium current extraction costs, are conducive to welfare. As uninternalized external costs increase, the threshold costs falls down. This drop is the quicker, the more elastic the demand: with more price-responsive consumption, the discovery increases the total amount of oil consumed, exacerbating the environmental effects.

In a next step, we want to understand how relaxing the assumption of competitive markets could affect our findings.

[12] A barrel of oil consumed leads to emissions of 0.43 metric tons CO_2 EPA (2017). Depending on the discount rate used for calculation of the social cost of carbon, an additionally consumed barrel of oil would lead to damages worth between \$16 and \$130 (see table 1 in Nordhaus Nordhaus (2017)).

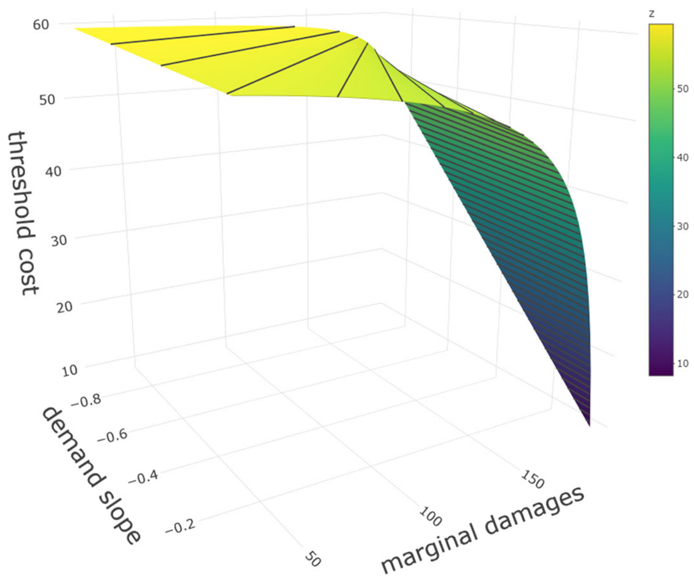

Fig. 2 Threshold discovery unit costs depending on uninternalized environmental costs and responsiveness of demand. *Notes:* The graph simulates the threshold value from Formula 3 using supply curve of the form $c(q) = \alpha_c + 0.017q$ and demand curve, $u(q) = \alpha_d + \beta q$. The slope of the supply function is based on Figure 1 in McGlade and Ekins (2015) and we simulate the threshold cost values for various demand slopes, β. We also allow the environmental costs per barrel to vary. Simulation assumes equilibrium extraction cost of \$60 and homogeneous pollution intensities of the reserves, i.e. $\epsilon(q) = 1 \, \forall q$.

Finding 3 With one period remaining until the stop in oil extraction, the welfare effects of an oil discovery are higher under the scenario of non-competitive oil extraction section sector than under the assumption of competitive supplier if:

$$\frac{\partial q_0^M}{\partial d} u(q_0^M) + (1 - \frac{\partial q_0^M}{\partial d})[c(q_0^M) + \epsilon^{o,M} MD^M] > (1 - \frac{\partial q_0^{PC}}{\partial d})\epsilon^{o,PC} MD^{PC} + c(q_0^{PC}), \tag{4}$$

where the index “^{PC}” refers to the competitive equilibrium outcomes and “^{M}” denotes the equilibrium results with market power. While the analysis in this papers focusses on a competitive framework, the above considerations may essentially preserve with market power. Under monopoly, the extraction quantities would be described by: $u'(q_o^M)q_0^M + u(q_0^M) = c(q_0^M)$ and $\frac{\partial q_0^M}{\partial d} = \frac{c'(q_0^M - d)}{c'(q_0^M - d) - 2u'(q_0^M) - u''(q_0^M) q_0^M}$.

To understand the configurations under which oil finds could be welfare-enhancing under one but not the other market power regime, it is useful to recall the three discovery welfare channels that operate in our model. The above result can be interpreted using the three welfare channels discussed above. The additional consumption effect will work towards oil finds having better welfare effects for monopolists—as monopolists withhold production, marginal utility from increased consumption will be higher than the associated marginal extraction cost. The replacement effect, on the other hand, will be generally more positive for competitive markets: since they produce more, the marginal units is more expensive to extract, hence the savings from replacing it with a discovered unit are higher. Which of the regimes will have more negative environmental effects will depend on the shape of the marginal environmental damages curve.

We should emphasize that in some cases, market power can lead to a deviation from the Herfindahl rule, creating further welfare channels. Among others, this might be the case for a dominant firm with small fringe like in Benchekroun and van Long (2006). Market power may thus reduce the net welfare from low cost finds if these finds do not fully substitute for preexisting high cost resources. Conversely, in a situation of market power, high cost finds could crowd out preexisting low cost resources. These effects would tend to reduce the benefit from new finds.[13]

3.2 Dynamic model with predetermined timing of oil phase-out

Market outcomes

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

$$\max_{q_1,q_2} p_1q_1 - \int_0^{q_1} c(q)dq + (1+r)^{-1}[p_2q_2 - \int_0^{q_2} c(q_1+q)dq].$$

Here, q_1 and q_2 are the amounts extracted in the first and second periods. While the maximum extraction is confined to total initial reserves at time 0, at the end of the second period, some of the oil units will be too expensive to extract given the choke price. Therefore the extraction quantity constraint is not binding and does not enter the maximization problem. Conditions that assure that a competitive oil producer sells in both periods (interior solution) read:

$$p_2 = c(q_1+q_2) \text{ and } p_2 = (1+r)p_1 - rc(q_1). \tag{5}$$

Combining them with market clearing conditions yields the equilibrium condition:

$$(1+r)u(q_1) - rc(q_1) = c(q_1 + q((1+r)u(q_1) - rc(q_1))), \tag{6}$$

where $q(\cdot)$ denotes the demand schedule and $u(\cdot)$ the inverse demand schedule. With strictly monotonic demand and decreasing cost function and a satiation level of demand, a unique solution to the problem exists.[14] Notice that we always have that $q_1 > q_2$ as the profitability of the firm requires $u(q_1) > c(q_1)$ in condition (5).

[13] We are grateful to a referee for drawing our attention to this.

[14] 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, whereas the right-hand side is an increasing function of q_1.

Now, assume a discovery is made of additional d units of oil[15] with extraction costs c^d, giving rise to the new extraction cost schedule $cn(\cdot)$:

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

where $\widehat{q^c} = c^{-1}(c^d)$ denotes the extraction unit which, under the old cost schedule, had the marginal extraction cost of c^d. The windfall moves the consumption in both periods, q_1 and q_2, to new levels, q_1^d and q_2^d, driving the marginal cost of the most expensively extracted unit in the second period to $c(q_1^d + q_2^d - d)$.

First assume a discovery d_l with the newly found units cheaper to extract than the marginal unit consumed in the first period under no discovery scenario. For now assume that c^d is very close to zero. In this case it is clear that the new oil is consumed already in the first period and, in order to find $\frac{\partial q_1}{\partial d}$and $\frac{\partial q_2}{\partial d}$, we use the relevant version of the Hotelling rule given by: $(1+r)p_1 - rc(q_1 - d_l) = p_2 = c(q_1 + q_2 - d_l)$. The associated adjustments in the extraction path are derived in the appendix and can be written as:

$$\begin{aligned} \frac{\partial q_1}{\partial d_l} &= \frac{rc'(q_1) + (1 - rq'(p_2)c'(q_1))c'(q_1+q_2)}{\varpi}, \\ \frac{\partial q_2}{\partial d_l} &= q'(p_2)\frac{\partial q_1}{\partial d_l}[(1+r)u'(q_1) - rc'(q_1)] + rq'(p_2)c'(q_1) \end{aligned} \tag{7}$$

where $\varpi = rc'(q_1) - (1+r)u'(q_1) + c'(q_1+q_2)[1 + q'(p_2)(u'(q_1)(1+r) - rc'(q_1))]$ and $q'(\cdot)$ is the slope of the demand curve. Notice that new deposits' quality, c^d, does not enter the expressions.

Assume now an oil find that is of relatively poor quality, d_h. Let its extraction cost be close to that of the marginal unit under the no-windfall scenario, $c(q_1+q_2)$. Given its high cost, the newly found unit is physically extracted only in the second period. With the Hotelling rule now taking the form $(1+r)p_1 - rc(q_1) = c(q_1 + q_2 - d_h)$ we get the following quality adjustments (derivations presented in the appendix):

$$\begin{aligned} \frac{\partial q_1}{\partial d_h} &= \frac{c'(q_1+q_2)}{\varpi}, \\ \frac{\partial q_2}{\partial d_h} &= q'(p_2)\frac{\partial q_1}{\partial d_h}[(1+r)u'(q_1) - rc'(q_1)]. \end{aligned} \tag{8}$$

Again, the adjustments are independent of the costs of the new deposit, c^d. However, for the new extraction path it is relevant whether the units get extracted in the first or the second period. The unit costs of the new deposit, c^d, do not influence the decision of the oil producers other than through the timing of the physical extraction.

15 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.

Finding 4 The quality of a new oil find, c^d, affects the market outcomes only indirectly, through determining in which period the find is physically extracted.

In our case there are thus two ranges for costs of new deposit, with costs within one range having the same effects on prices and quantities. How to determine those ranges? In Eq. (7) we derived the change in the equilibrium amount consumed in the first period with an almost zero-cost discovery. As the expression is independent of the discovery's quality, it can be shown that any find with cost c^d less than the marginal extraction cost of q_1^d, is extracted in the first period. Consequently, we will refer to an oil find with $c^d < c(q_1 + \frac{\partial q_1}{\partial d_l} - 1)$ as "high quality" discovery and to an oil find with costs above that threshold as "low quality" discovery.

It may appear surprising that the size of production adjustment 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[16]— conditional on being above or below the threshold $c(q_1 + \partial q_1/\partial d_l - 1)$— does not influence the production decision, as it has no effect on marginal cost. It changes the point where the extraction curve is shifted out, but not its steepness. Therefore, it affects the average costs only (and, consequently, the profit levels) in the two periods but not the incentives on the margin.

With a finding of low quality (denoted as d_h) that is physically extracted in the second period, the extraction cost savings are deferred, as opposed to the case of high quality discovery, d_l, where the cost savings are encountered directly. However, for any type of discovery the equilibrium production will need to be increased in both periods. For a representative firm that experiences a windfall of d_h type, the costs of additionally extracted units in the first period, together with a slight decrease in the oil price compared to the counterfactual scenario of no discovery, curb the relative profitability of period one. For the d_l discovery, on the other hand, the profitability of the second period is negatively affected. Those intertemporal differences are the reason why low and high quality findings result in distinct extraction paths.[17]

Importantly, all the quantity adjustments are non-negative but smaller than unity. The high quality discovery induces stronger adjustments in the first period, $\frac{\partial q_1}{\partial d_l} > \frac{\partial q_1}{\partial d_h}$,[18] while low quality discovery leads to stronger adaptation in the final period, $\frac{\partial q_2}{\partial d_h} > \frac{\partial q_2}{\partial d_l}$. Clearly, with the d_l discovery leading to greater discounted cost savings, it can be shown that it also leads to stronger total adjustments, $\frac{\partial q_1}{\partial d_l} + \frac{\partial q_2}{\partial d_l} > \frac{\partial q_1}{\partial d_h} + \frac{\partial q_2}{\partial d_h}$.

The steepness of the supply curve, $c'(q_1)$, also affects the quantity adjustment differently for d_l and d_h. For the case of cheap windfall, the company extracts a

[16] The higher the extraction costs, c^d, the lower the quality of discovery.

[17] Obviously, in the case of zero interest rates, only the sum, and not the distribution of profits between the periods, matters. Consequently, with $r = 0$ any discovery will have the same impact on the extraction paths. This is visible when comparing solutions (7) and (8).

[18] This is true as $1 - rq'(p_2)c'(q_1) > 1$.

relatively large fraction of the expanded production, $\frac{\partial q_1}{\partial d_l} + \frac{\partial q_2}{\partial d_l}$, 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 the "savings" in marginal costs are greater, the steeper the supply curve around q_1. The equilibrium conditions thus require that $\partial \frac{\partial q_1}{\partial d_l} / \partial c'(q_1) \geq 0$. 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 and it can be shown that $\partial \frac{\partial q_1}{\partial d_h} / \partial c'(q_1) \leq 0$.

Welfare outcomes

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 global welfare for a high quality find is given by the expression:

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

where δ is the parameter of linear decay of pollutants which 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.[19] The perfectly competitive solution is the same as when maximizing the sum of consumer and producer surpluses, while disregarding the uninternalized externalities. Therefore, as producers are maximizing their profit, we can apply the envelope theorem to some parts of the welfare function when investigating the effects of a cost schedule change.

Similarly to the static model, we find the windfall to be welfare-enhancing when savings in the extraction costs exceed the negative non-internalized environmental effects (*env_eff*) caused by extra consumption and unit substitution. The savings are to be understood as the difference between the cost of the marginal unit extracted before and the cost of the unit from the new deposit replacing that marginal unit (adjusted for intertemporal changes).

Finding 5 In a competitive setting, the condition for an oil find being welfare-increasing reads:

[19] While the CO_2 is considered to be relatively persistent, latest publications suggest that, because of the climate system's intertia, the temperature consequences of additional carbon dioxide are delayed, allowing for more decay over time Lemoine and Rudik (2017).

$$\frac{r}{1+r}c(q_1) + \frac{1}{1+r}c(q_1+q_2) - c^d > EnvEff_l \qquad \text{(high quality find)}$$
$$\frac{c(q_1+q_2)-c^d}{1+r} > EnvEff_h, \qquad \text{(low quality find)}$$

where high quality finds are characterized by $c^d < c(q_1 + \frac{\partial q_1}{\partial d_l} - 1)$. The environmental effects of the change in pollution path is given by:

$$\begin{aligned} EnvEff_i = & - MD_1 \frac{\partial q_1}{\partial d^i}\epsilon_1^o - \frac{MD_2}{1+r}(\frac{\partial q_1}{\partial d_i} + \frac{\partial q_2}{\partial d_i})\epsilon_2^o \\ & + \frac{MD_2}{1+r}(1-\delta)\frac{\partial q_1}{\partial d_i}\epsilon_1^0 + \frac{MD_2}{1+r}[\epsilon_2^o - \epsilon^d] \\ & + \mathbb{1}_{i=h}\left(\epsilon_1^o - \epsilon^d\right)\left[MD_1 - MD_2\frac{1-\delta}{1+r}\right] \quad \text{for } i = \{h, l\}. \end{aligned} \tag{9}$$

In general, a windfall find ensures that the most expensive of the previously extracted units are not used anymore and, for the high quality discovery, it shifts some of the costs that were previously borne in the first period to the second one. As consumption increases in both periods, the associated damages from emissions increase (terms 1 and 2 in *EnvEff*). For some of the units, the extraction gets shifted from period 1 to period 2, so there are intertemporal effects related to their decay (term 3). Discovery permanently substitutes (and thus replaces emissions) associated with units which are marginal in the second period under the "no discovery" scenario (term 4) but high quality discovery has additional intertemporal adjustment effects as it gets extracted already in the first period (term 5).

Extraction costs of the newly discovered units need to be low enough to balance out the change in the resulting uninternalized environmental damages. A higher environmental tax t increases the chance that the discovered oil, if it gets extracted, increases welfare. On the other hand, the more persistent the pollutant (the higher the δ), the harder it is for the windfall 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. Because 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.

When all oil units have the same carbon intensity, i.e. $\epsilon = \epsilon^d = \epsilon_1^o = \epsilon_2^o$, and when the marginal damages are constant across periods, i.e. $MD = MD_1 = MD_2$, the emission effects are unequivocally negative and independent of the quality of the find:

$$EnvEff_i = -\epsilon MD\left[\frac{\partial q_1}{\partial d^i}(1 + \frac{\delta}{1+r}) + \frac{\partial q_2}{\partial d^i}\frac{1}{1+r}\right] \text{ for } i = \{h, l\}. \tag{10}$$

As discussed in Sect. 3.1, if the marginal costs around the old equilibrium points are constant, $c'(q_1) = c'(q_1+q_2) = 0$, the effect of oil find depends on the emission intensities of the find and the units pushed out of the market, whereby newly discovered oil being weakly less emission intensive guarantees an unambiguously positive welfare effect due to decreased extraction costs.[20] The demand elasticity moderates the impact of the windfall on welfare in a way analog to Finding 2.

The formulas in Finding 5 show that, depending on the functional forms chosen, low quality discovery might be welfare-enhancing, while a high quality discovery would detract from welfare.

Finding 6 Welfare effects of an oil find may be non-monotonic in the marginal extraction costs of the oil find.

To verify this, assume two possible discoveries, one of d_h type (with costs c_h^d), the other of d_l type (costs c_l^d), but with both costs being close to threshold $c(q_1 + \partial q_1/\partial d_l - 1)$. Should the externalities associated with resource consumption be substantial and persistent, the additional environmental burden can outweigh the cost savings made for d_l. For the d_h discovery, the extraction costs savings are lower by $\frac{r}{1+r}[c(q_1) + c_h^d - c_{low}^d]$, which, however, may be compensated by lower environmental costs.[21] To what extent the environmental effects differ for the two types of finds depends to a large extent on the rate of decay of the pollutants, δ, and the curvature of the environmental burden curve.

Our framework could easily be transformed to accommodate multi-period analysis. The intuition from findings concerning the elasticities of demand and supply extends to the model. However, the welfare superiority condition with T periods quickly grows in complexity as it needs to encompass T different cases (differing in the quality of the discovery and thus the period in which the newly found unit gets physically extracted).

3.3 Dynamic model with endogenous timing of oil phase-out

The previous subsections have assumed that the date of a phase-out is fixed and known in advance by market participants. Such an assumption describes particularly well a case of a ban on oil usage that comes into effect a couple of years after its announcement. It also represents the situation in which a clean energy source with marginal cost below those of oil is developed and the expected time for technology behind it to become mature is public knowledge.

To learn about the interactions between oil discoveries and a relatively expensive backstop, e.g. electric vehicles, we turn to a model where the phase-out happens after the oil price climbs to the marginal cost of the backstop $\bar{c}$. In such a setting, all oil units with extraction cost below $\bar{c}$ get consumed. The maximization problem that the representative oil producer faces is given by:

[20] Having $c'(q_1) = c'(q_1 + q_2) = 0$ would imply that the discovery does not affect the amount of extracted units ($\frac{\partial q_1}{\partial d} = \frac{\partial q_1}{\partial d} = 0$). with the only change being which units are extracted. As the most expensive units are exchanged with the cheaper ones, welfare increases.

[21] Both the amount of oil extracted in the first period and the total oil consumption are lower for the d_h find.

$$\max_{\{q_t\}_{t=0}^{T}} \sum_t (1+r)^{-t}[p_t q_t - \int_0^{q_t} c(\sum_{i=0}^{t-1} q_i + q)dq].$$

where T denotes the last period in which the oil is used. Consequently, an oil windfall of size d with $c^d < \bar{c}$ leads to an increase d in the cumulative oil consumption, affecting both the amounts consumed in each period and, potentially, the number of periods before which the backstop technology takes over the market.

Within the model, the Hotelling conditions governing the price development are analogous to conditions (5):

$$p_i = (1+r)p_{i-1} - rc(\sum_{j=1}^{i-1} q_j) \; \forall i \leq T \tag{11}$$

$$p_T = c(\sum_{j=1}^{T} q_j), \tag{12}$$

As we know that in the last period, the price will hit the choke price, the condition $c(\sum_{j=1}^{T} q_j) = \bar{c}$ helps pin down the timing of the phase-out.[22] While there are no closed-form solutions for the equilibrium extraction path, we can still make some inference on the impacts of a windfall.

First, note that an oil windfall can delay the switch to backstop. As all price levels (weakly) fall it might take longer for the Hotelling price path to climb to level $\bar{c}$. Note also that, while the aggregate consumption of oil is known and equal to the pre-discovery consumption plus the discovery size, the exact consumption path needs to be determined.

As in the case of an exogenous phase-out, the impact of the quality of discovery is important for the consumption path only insofar that it defines the period in which the find is physically extracted. Therefore, an oil discovery with extraction costs of c^d that would get extracted in period t will have the same effect on the markets as a discovery with extraction costs of $c^d + x$ as long as $c^d + x < c(\sum_{i=1}^{t} q_i)$.

The larger the discovery, the more probable an increase in T is, which causes a major perturbation in the price path. *Ceteris paribus*, the discoveries with higher extraction costs are the ones that tend to delay the switch. The underlying intuition relates to the price adjustments for low quality discoveries being stronger in later extraction periods. The effect of the windfall quality on T is also confirmed by simulation results. Figure 3 illustrates a case where a low quality discovery leads to later phase-out of oil than a high quality discovery of the same size.

How can the change in T affect the environmental outcomes? Given a total amount of oil to be consumed (as in our case of a backstop technology), the more stretched out the extraction phase, the less damage happens from pollution for decaying pollutants, i.e. pollutants with $\delta > 0$.

[22] Note that the amount of oil consumption in period T has to be less that $q(\bar{c})$ and is determined by the condition: $\sum_{j=1}^{T} q_j = c^{-1}(\bar{c})$.

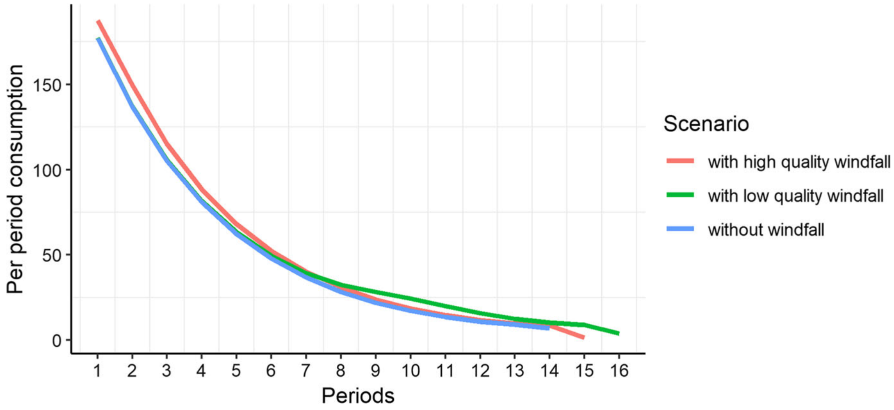

Fig. 3 Response in oil consumption to oil discoveries. *Notes:* The graph was generated using the following assumptions: choke price $\bar{c}$ =390, demand $q = 379 - 0.95p$, r=0.2, cost $c = 0.4q + 0.2q^{1.2}$. Low quality discovery has marginal extraction costs of $c_l^d = 340$ and high quality is characterized by $c_h^d = 1$. Discovery size is given by $d = 45$. In the phase-out time both oil and its clean substitute are consumed. Note that the high quality discovery delays the phase-out from period $T = 14$ to $T = 15$, while low quality discovery postpones the phase-out to time $T = 16$

This positive environmental effect of increased *T*, combined with the finding that lower quality windfalls are more prone to shift out *T*, constitutes a second reason for why the welfare might not be monotonically increasing in oil find quality, pointing into the same direction as Finding 6 presented in Subsection 3.2.

4 Discussion

In a world, in which CO2 emissions were subject to an efficient Pigouvian tax, the discussion of whether a new oil find is good or bad would be easy to address. The individual rational and the social rational would be congruent. Given suboptimally low Pigouvian taxes in reality, the question of whether new finds may still be welcomed by the international community is a more difficult one. In this paper we derive conditions for an oil find to be welfare-enhancing when looking at the sum of 'global' effects: the change in utility, total extraction costs and environmental externalities.

We show that several factors feed into the change in welfare, which may be negative or positive, in sometimes nontrivial ways. The size of the environmental externality tends to reduce the welfare effect of a new find. In addition, we identified the importance of the slope of supply and demand around the preexisting equilibrium. With constant marginal cost, for example, it is easy to construct cases in which welfare increases despite high environmental costs of oil use. At the same time, the intertemporal nature of the problem allows for cases in which a low cost find is worse for aggregate welfare than a high cost find.

Our analysis points out that the impact of monopoly power on the welfare effects of oil finds will be case-specific and cannot be signed without the knowledge of functional and parameter specification. In so far, as more complex forms of market power may lead to a deviation from the Herfindahl rule additional effects could come to play, potentially reducing the benefit of new finds.

A worthwhile future extension of our study would be to incorporate investments into oil field search in order to better understand the circumstances under which oil exploration should be incentivized or discouraged. Such framework would allow an evaluation of exploration subsidy policies.[23] Additionally, parameterizing our functions would give policy-makers some guidance on what oil discoveries can be socially valuable despite the nearing switch to clean energy sources.

Derivation of Equations (7) and (8)

In order to find $\frac{\partial q_1}{\partial d}and\frac{\partial q_2}{\partial d}$, we use the relevant version of the Hotelling rule. In case of low cost discovery, d_l, the shift in the extraction cost curve directly affects the marginal costs in both periods. Consequently, the Hotelling rule is given by: $(1+r)p_1 - rc(q_1 - d_l) = p_2 = c(q_1 + q_2 - d_l)$. It can be rewritten as an equilibrium condition as:

$$(1+r)u(q_1) - rc(q_1 - d_l) - c(q_1 + q((1+r)u(q_1) - rc(q_1 - d_l)) - d_l) = 0,$$

where $q(.)$denotes the demand function and $u(.)$ is the inverse demand function. Furthermore, 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 and evaluate at $d_l = 0$ to obtain:

$$\begin{aligned}&(1+r)u'(q_1) - rc'(q_1)\\&- c'(q_1 + q(p(q_1)(1+r) - rc(q_1)))[q'(p(q_1)(1+r) - rc(q))(u'(q)(1+r) - rc'(q)) + 1].\end{aligned}$$

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

$$rc'(q) + [1 - rq'(p(q_1)(1+r) - rc(q_1))c'(q_1)]c'(q_1 + q(u(q_1)(1+r) - rc(q_1))).$$

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

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

Analyzing the terms, we notice that $\frac{\partial q_1}{\partial d_l} = \frac{a}{a + (1+r)u_1' q'(p_2)c'(q_1+q_2) - (1+r)u'(q_1)} \leq 1$, where a is the numerator of the previous expression.

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

[23] At the present, considerable schemes for incentivization exist in Australia, the United States, and Norway.

$$\frac{\partial q_2}{\partial d_l} = q'(p_2)[(1+r)u'(q_1) - rc'(q_1)]\frac{\partial q_1}{\partial d_l} + q'(p_2)rc'(q_1). \tag{13}$$

After some transformations, it can be shown that $\frac{\partial q_2}{\partial d_l} \geq 0$ which is plausible because a decrease in q_2 would cause the price p_2^d to increase compared to the equilibrium price p_2 before. Given that $\frac{\partial q_1}{\partial d_l}$ was found to be less than 1, the new cost $c\left(q_1^d + q_2^d - d_l\right)$ 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 a low quality deposit, d_h. As the newly discovered units are physically extracted in the final period and thus do not directly affect the marginal costs in the first period, the Hotelling rule now takes the form of: $(1+r)u(q_1) - rc(q_1) - c(q_1 + q((1+r)u(q_1) - rc(q_1)) - d_h) = 0$. As previously done, we apply the IFT to find:

$$\frac{\partial q_1}{\partial d_h} = \frac{c'(q_1+q_2)}{rc'(q_1) + c'(q_1+q_2)(1 + q'(p_2)((1+r)u'(q_1) - rc'(q_1))) - (1+r)u'(q_1)} > 0. \tag{14}$$

We know that q_2 in equilibrium is determined by the demand at the prevailing price $p_2 : q(p_2) = q((1+r)p(q_1) - rc(q_1))$, we therefore have that:

$$\frac{\partial q_2}{\partial d_h} = q'(p_2)\frac{\partial q_1}{\partial d_h}((1+r)u'(q_1) - rc'(q_1)) > 0.$$

Derivation of $W^{nd} < W^d$

To investigate how the social outcome is influenced by the windfall (Eq. (9)), we compare welfare with and without the discovery, W^d and W^{nd}. First, we examine the situation of **high quality discovery**, i.e., when the extraction cost of the newly discovered units is lower than $c(q_1 + \partial q_1/\partial d_l - 1)$. This condition is decisive for the windfall to be be extracted in the first period.

$$\begin{aligned}
&W^{nd} < W^d \iff \\
&\int_0^{q_1} [u(x) - c(x)] \;\; \mathrm{d}x - e\Big(\int_0^{q_1} \epsilon(x)\mathrm{d}x\Big) + (1+r)^{-1}\Big[\int_0^{q_2} u(x) \;\; \mathrm{d}x - e\Big(\delta \int_0^{q_1} \epsilon(x)\mathrm{d}x \\
&+ \int_{q_1}^{q_1+q_2} \epsilon(x)\mathrm{d}x\Big) - \int_{q_1}^{q_1+q_2} c(x) \;\; \mathrm{d}x\Big] \\
&< \int_0^{q_1^d} u(x) \;\; \mathrm{d}x - \int_0^{q_1^d - d} c(x) \;\; \mathrm{d}x - e\Big(\int_0^{q_1^d - d} \epsilon(x)\mathrm{d}x + E^d\Big) - C^d \\
&+ (1+r)^{-1}\Big[\int_0^{q_2^d} u(x) \;\; \mathrm{d}x - e\Big(\delta \int_0^{q_1 - d} \epsilon(x)\mathrm{d}x + \delta E^d + \int_{q_1-d}^{q_1+q_2-d} \epsilon(x)\mathrm{d}x\Big) - \int_{q_1^d - d}^{q_1^d + q_2^d - d} c(x) \;\; \mathrm{d}x\Big]
\end{aligned}$$

By rearranging and simplifying we get:

$$C^d - \frac{r}{1+r}\int_{q_1^d-d}^{q_1} c(x)\ \mathrm{d}x - \frac{1}{1+r}\int_{q_1^d+q_2^d-d}^{q_1+q_2} c(x)\ \mathrm{d}x$$
$$-\int_{q_1}^{q_1^d} u(x)\ \mathrm{d}x - (1+r)^{-1}\int_{q_2}^{q_2^d} u(x)\ \mathrm{d}x < TEnvEff_h,.$$

where $TEnvEff_h$ summarizes the total environmental effects of a high quality discovery. When we approximate the integrals around q_1 and q_2 and divide both sides by d, the size of discovery[24], we arrive at:

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

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:

$$c^d - \frac{r}{1+r}[1-\frac{\partial q_1}{\partial d}]c(q_1) - \frac{c(q_1+q_2)}{1+r}[1-\frac{\partial q_1}{\partial d}] - \frac{\partial q_1}{\partial d}u(q_1) < EnvEff^h.$$

Let's look in more details at the environmental effects, splitting them into the effects occurring in the first and second period.

$$\begin{aligned} TEnvEff_h =& \overbrace{e\Big(\int_0^{q_1}\epsilon(x)\mathrm{d}x\Big) - e\Big(\int_0^{q_1^d-d}\epsilon(x)\mathrm{d}x + E^d\Big)}^{\text{first period changes (''M'')}} \\ & \underbrace{+(1+r)^{-1}\Big[e\Big(\delta\int_0^{q_1}\epsilon(x)\mathrm{d}x + \int_{q_1}^{q_1+q_2}\epsilon(x)\mathrm{d}x\Big) - e\Big(\delta\int_0^{q_1^d-d}\epsilon(x)\mathrm{d}x + \delta E^d + \int_{q_1^d-d}^{q_1^d+q_2^d-d}\epsilon(x)\mathrm{d}x\Big)\Big]}_{\text{second period changes (''N'')}} \end{aligned} \tag{15}$$

Call $\eta(q)$ the total amount of emissions associated with using all oil units up to q. Note that, while the aggregated damage curve is generally non-linear, with continuous marginal cost functions the marginal extraction quantity changes have a negligible impact at the marginal damages within individual periods, MD_1 and MD_2. Consequently, we have that

$$\begin{aligned} M^h =& e\big(\eta(q_1)\big) - e\big(\eta(q_1^d-d)+E^d\big) = e\big(\eta(q_1)\big) - e\big(\eta(q_1)\big) - MD_1\Big[\eta(q_1^d-d)+E^d-\eta(q_1)\Big] \\ =& -MD_1[\eta(q_1+\frac{\partial q_1}{\partial d}d-d)+E^d-\eta(q_1)] \end{aligned} \tag{16}$$

Total emissions associated with extraction of q_A units of oil as compared to q_B

[24] 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 $q_1 - (q_1^d - d) = d - d\frac{\partial q_1}{\partial d} = d(1-\frac{\partial q_1}{\partial d})$.

amount is the emissions associated with q_B plus the difference between the two extraction quantities, $q_A - q_B$, weighted by the emission intensity of these additional units. With ϵ_1^o being the average emissions intensity of these units that would be extracted in period $t = 1$ under no discovery scenario but stay in the ground if discovery is made, we have that:

$$\begin{aligned} M^h &= -MD_1[\eta(q_1) + [q_1 + \frac{\partial q_1}{\partial d}d - d - q_1]\epsilon_1^o + \epsilon^d d - \eta(q_1)] = MD_1 d[(1 - \frac{\partial q_1}{\partial d})\epsilon_1^o - \epsilon^d] \\ &= MD_1 d\Big[(\epsilon_1^0 - \epsilon^d) - \frac{\partial q_1}{\partial d}\epsilon_1^o\Big]. \end{aligned} \tag{17}$$

We can perform similar calculations for second period effects:

$$\begin{aligned} N^h(1+r) &= e\Big(\delta\eta(q_1) + \eta(q_1+q_2) - \eta(q_1)\Big) \\ &\quad - e\Big(\delta\eta(q_1^d - d) + \delta E^d + \eta(q_1^d + q_2^d - d) - \eta(q_1^d - d)\Big) \\ &= e\Big(\underbrace{\eta(q_1+q_2) - (1-\delta)\eta(q_1)}_{\substack{\text{amountofpollutantsinperiod2} \\ \text{withoutthediscovery, } E_2^o}}\Big) - e\Big(\delta\eta(q_1^d - d) + \delta E^d + \eta(q_1^d + q_2^d - d) - \eta(q_1^d - d)\Big) \\ &= e(E_2^o) - e\Big(E_2^o + (1-\delta)d(1 - \frac{\partial q_1}{\partial d})\epsilon_1^0 + \delta d\epsilon^d - d(1 - \frac{\partial q_1}{\partial d} - \frac{\partial q_2}{\partial d})\epsilon_2^o)\Big) \\ &= e(E_2^o) - e(E_2^o) - MD_2\Big[(1-\delta)d(1 - \frac{\partial q_1}{\partial d})\epsilon_1^0 + \delta d\epsilon^d - d(1 - \frac{\partial q_1}{\partial d} - \frac{\partial q_2}{\partial d})\epsilon_2^o\Big], \end{aligned} \tag{18}$$

where ϵ_2^o and are the average emissions intensities of these units that would be extracted in period $t = 2$ under no discovery scenario but stay in the ground if discovery is made.

Consequently, we have that per unit of discovery, the emission effects in period 2 equal:

$$N^h = \frac{dMD_2}{1+r}\Big[\underbrace{\epsilon_2^o}_{\substack{\text{damagesavoidedthrough} \\ \text{unitsubstitution}}} \underbrace{-(\frac{\partial q_1}{\partial d} + \frac{\partial q_2}{\partial d})\epsilon_2^o}_{\substack{\text{damagesfrom} \\ \text{increasedconsumption}}} \overbrace{-(1-\delta)(1 - \frac{\partial q_1}{\partial d})\epsilon_1^0}^{\substack{\text{decayofpollutants} - \text{unitsextracted} \\ \text{withoutdiscoveryint} = 1 \\ \text{butextractedint} = 2\text{withdiscovery}}} \underbrace{-\delta\epsilon^d}_{\substack{\text{remainingemissionsfrom} \\ \text{thediscoveredunits}}}\Big]. \tag{19}$$

Total welfare change associated with changes in emission (per unit of discovery) equals:

$$\begin{aligned} EnvEff_h = MD_1\Big[(\epsilon_1^0 - \epsilon^d) - \frac{\partial q_1}{\partial d}\epsilon_1^o\Big] \\ + \frac{MD_2}{1+r}\Big[(1 - \frac{\partial q_1}{\partial d} - \frac{\partial q_2}{\partial d})\epsilon_2^o - (1-\delta)(1 - \frac{\partial q_1}{\partial d})\epsilon_1^0 - \delta\epsilon^d\Big]. \end{aligned} \tag{20}$$

From (6) 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 to obtain the final condition for the supremacy of windfall:

$$(1+r)c^d - rc(q_1) - c(q_1+q_2) < EnvEff_h. \tag{21}$$

For the **low quality find**, d_h, we compare the following welfare expressions:

$$\begin{aligned} &\int_0^{q_1}[u(x)-c(x)]\,\mathrm{d}x - e\Big(\int_0^{q_1}\epsilon(x)\,\mathrm{d}x\Big) + (1+r)^{-1}\Big[\int_0^{q_2}u(x)\,\mathrm{d}x - \int_{q_1}^{q_1+q_2}c(x)\,\mathrm{d}x \\ &- e\Big(\delta\int_0^{q_1}\epsilon(x)\,\mathrm{d}x + \int_{q_1}^{q_1+q_2}\epsilon(x)\,\mathrm{d}x\Big)\Big] \\ &< \int_0^{q_1^d}u(x)\,\mathrm{d}x - \int_0^{q_1^d}c(x)\,\mathrm{d}x - C^d - e\Big(\int_0^{q_1^d}\epsilon(x)\,\mathrm{d}x\Big) + (1+r)^{-1}\Big[\int_0^{q_2^d}u(x)\,\mathrm{d}x \\ &- \int_{q_1^d}^{q_1^d+q_2^d-d}c(x)\,\mathrm{d}x - e\Big(\delta\int_0^{q_1}\epsilon(x)\,\mathrm{d}x + \int_{q_1}^{q_1+q_2-d}\epsilon(x)\,\mathrm{d}x + E^d\Big)\Big] \end{aligned}$$

In this case, the welfare condition can be rewritten as:

$$\frac{1}{1+r}c^d < \frac{1}{1+r}c(q_1+q_2) + EnvEff_l,$$

where

$$EnvEff_l = -MD_1\frac{\partial q_1}{\partial d}\epsilon_1^o + \frac{MD_2}{1+r}\left[(1 - \frac{\partial q_1}{\partial d} - \frac{\partial q_2}{\partial d})\epsilon_2^o + (1-\delta)\frac{\partial q_1}{\partial d}\epsilon_1^0 - \epsilon^d\right]. \tag{22}$$

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