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Leading the unwilling: Unilateral strategies to prevent arctic oil exploration☆

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ABSTRACT

Arctic oil extraction is inconsistent with the 2 °C target. We study unilateral strategies by climate-concerned Arctic countries to deter extraction by others. Contradicting common theoretical assumptions about climate-change mitigation, our setting is one where countries may fundamentally disagree about whether mitigation by others is beneficial. This is because Arctic oil extraction requires specific R&D, hence entry by one country expands the extraction-technology market, decreasing costs for others. This means that, on the one hand, countries that extract Arctic oil gain if others do so as well. On the other hand, as countries may disagree about how harmful climate change is, they may disagree whether an equilibrium where all enter is better or worse than an equilibrium where all stay out. Less environmentally-concerned countries (preferring maximum entry) have a first-mover advantage but, because they rely on entry by others, entry in equilibrium is determined by the preferences of those who are moderately concerned about the environment. Furthermore, using a pooling strategy, an environmentally-concerned country can deter entry by credibly "pretending" to be environmentally adamant, and thus be expected to not follow. A rough calibration suggests a country like Norway, or prospects of a green future U.S. administration, could be pivotal in determining whether the Arctic will be explored.

1. Introduction

In recent years, the Arctic areas have received increased attention. One of the main reasons for this is the estimation that around a quarter of all undiscovered oil and gas reserves are located in the Arctic (Brownfield et al., 2012).[1] This has a number of implications of great global importance. Firstly, should these resources be used, the effect on climate change is expected to be severe and it has been recognized that, as part of meeting the two-degree goal of the UN, leaving the Arctic oil untapped is key (McGlade and Ekins, 2015). Secondly, the race for oil has made the Arctic hot from a geopolitical perspective (see, for instance, reporting by The Guardian, 2011, and The Telegraph, 2009). Finally, the exploration and extraction of oil

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[1] The Arctic is estimated to contain 16% of undiscovered oil, 30% of undiscovered gas and 26% of natural gas liquids (Brownfield et al., 2012).

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in the Arctic also implies substantial local environmental risks as the activity itself and, not least, an oil spill would have a devastating effect on the wildlife and fragile ecosystems in these areas (see also Cole et al., 2014, for other challenges in the Arctic). This risk is sufficiently great to even be emphasized by one of the oil companies (see statements by Total in the Financial Times, 2012) and is also illustrated by the U.S. recently choosing to protect some of Alaska's coast from drilling and exploration due to environmental concerns (The Guardian, 2014).

Hence, leaving these resources untouched is key for the global environment. The purpose of this paper is to explore the possibility of unilateral action in doing so. In particular, we explore how the presence of technology spillovers may yield unilateral power to prevent Arctic oil extraction.

Extraction of oil in the Arctic requires tailored technologies due to the harsh weather and sea conditions (Wilson Center, 2014). These technologies do not exist today and developing them sufficiently to ensure that extraction costs are lower than the oil price requires large investments (Moe and Rottem, 2014; Lindholt and Glomsrød, 2012; Harsem et al., 2011). Thus, as for the development of any technology, market size is important in the Arctic.[2] More buyers of Arctic technologies implies that extraction per barrel will be cheaper (e.g., McDonald and Schrattenholzer, 2001) and the oil industry has expressed that bigger volumes of Arctic extraction will make extraction profitable under a lower oil price (see, e.g., Aftenposten, 2015).[3] What makes this interesting from a perspective of unilateral action is the fact that there is a limited number of countries that can extract in the Arctic. Russia, the U.S., Canada, Greenland and Norway each have jurisdiction over a certain area (see Fig. 1).[4] Hence, if any one of these countries chooses to stay out of the Arctic, it will imply a smaller market for Arctic exploration and drilling technologies, and higher costs of extraction for the remaining four. These higher costs may then imply that another one of the countries prefers to stay out, thus increasing the costs for the remaining three.[5] This way, there is potential for a chain reaction whereby all countries end up staying out. This is particularly true under conditions – which preside today and are expected to remain for the next decade or two – where the oil price is low.[6]

On the surface, this description resembles a classic coordination game whereby either all countries enter the Arctic or all countries stay out. The twist, however, is that in reality countries need not move simultaneously, which creates dynamic strategic interaction. This is particularly important since the countries in this game may perceive the environmental costs to be of varying importance. In particular, one country, say Russia, may prefer an equilibrium where all enter – to enjoy lower extraction costs – over one where all stay out. Another country, say Norway, may instead prefer the equilibrium where all stay out, due to pro-environmental preferences. The problem for Russia is that it may not want to enter alone and, vice versa, the problem for Norway is that it may not be able to commit to be the only one staying out. That is, even for Norway, the profits of entering may be greater than the perceived environmental costs in a scenario where all others have entered. We analyze this strategic interaction and characterize under what conditions all countries stay out and under what conditions all enter. Since, in reality, underlying preferences are not directly observable, only actions are, we further extend the model to one where countries are uncertain of how the others perceive the environmental costs. Our main results and insights are as follows.

Our first result (Proposition 1) is that those countries that are moderately concerned with environmental damage – say, the U.S. or Canada – hold the most decisive strategic role. To see why, note on the one hand that the most environmentally-conscious country's only strategic influence is achieved by staying inactive. On the other hand, the country that cares the least about the environment has a strategic advantage: by taking action (entering) first, it can lower the costs for others, potentially setting the wheels in motion for all others to enter as well. However, whether moving first is something that country wants to do depends on whether the moderately concerned countries will follow suit or not. Hence, a moderately concerned country can, by itself staying out, essentially determine that all other stay out as well.

The fact that the least environmentally-concerned country stays out if moderately concerned countries will not follow suit also motivates why uncertainty of other countries' preferences shifts the strategic advantage in favor of those countries that *do* care about the environment. Our second set of results pertains to how countries can use such uncertainty to their advantage. To help fix ideas, suppose there are two possible types of the most environmentally-conscious country (say, Norway) – a very green one, which stays out regardless of what others do, and a moderately green one that would prefer

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[2] It is widely documented that technological costs fall with market size across a broad range of industries, including electrical vehicles (Klier et al., 2016), coal power plants (Joskow and Rose, 1985), wind turbines (Kouvaritakis et al., 2000), gas pipelines (Zhao, 2000) and, most relevant to our study, North Sea oil extraction (McDonald and Schrattenholzer, 2001, Table 1). See also IEA (2000).

[3] As of today extraction in the more remote Arctic areas exceeds 100$/barrel. For instance, in the Russian Arctic areas it is estimated to be around 120$/barrel (see https://knoema.com/vyronoe/cost-of-oil-production-by-country#, accessed Dec. 9th 2016). These figures are in stark contrast with regular offshore technology, as made evident both by the previously mentioned references, and with costs for ultradeep offshore in, for instance, Nigeria and Angola being only around 30-40$/barrel (see, e.g., Reuters, 2009) and for the areas hard to access in the British North Sea being around 50$/barrel (see, e.g., Reuters, 2009).

[4] Ownership of some areas in the Arctic is disputed. We abstract from that here and in the modeling but discuss its implication in the concluding section. Strictly speaking, also Iceland should be on the list of Arctic countries. However, their assessed reserves are unknown but expected to be very small (USGS, 2008). See Cole et al. (2014) for a game-theoretic approach to other challenges in the Arctic.

[5] Our calibration in Section 5 suggests that the fall in extraction costs following entry in the Arctic may be sizeable enough to warrant strategic considerations.

[6] While the oil price is notoriously difficult to predict and the market often has biases in the predictions (Hamilton, 2009; Hart and Spiro, 2011; Spiro, 2014) the appearance of shale oil on the market has depressed the price. This factor is likely to be important over the next decades. See Andrade de Sá and Daubanes (2016) for a discussion.

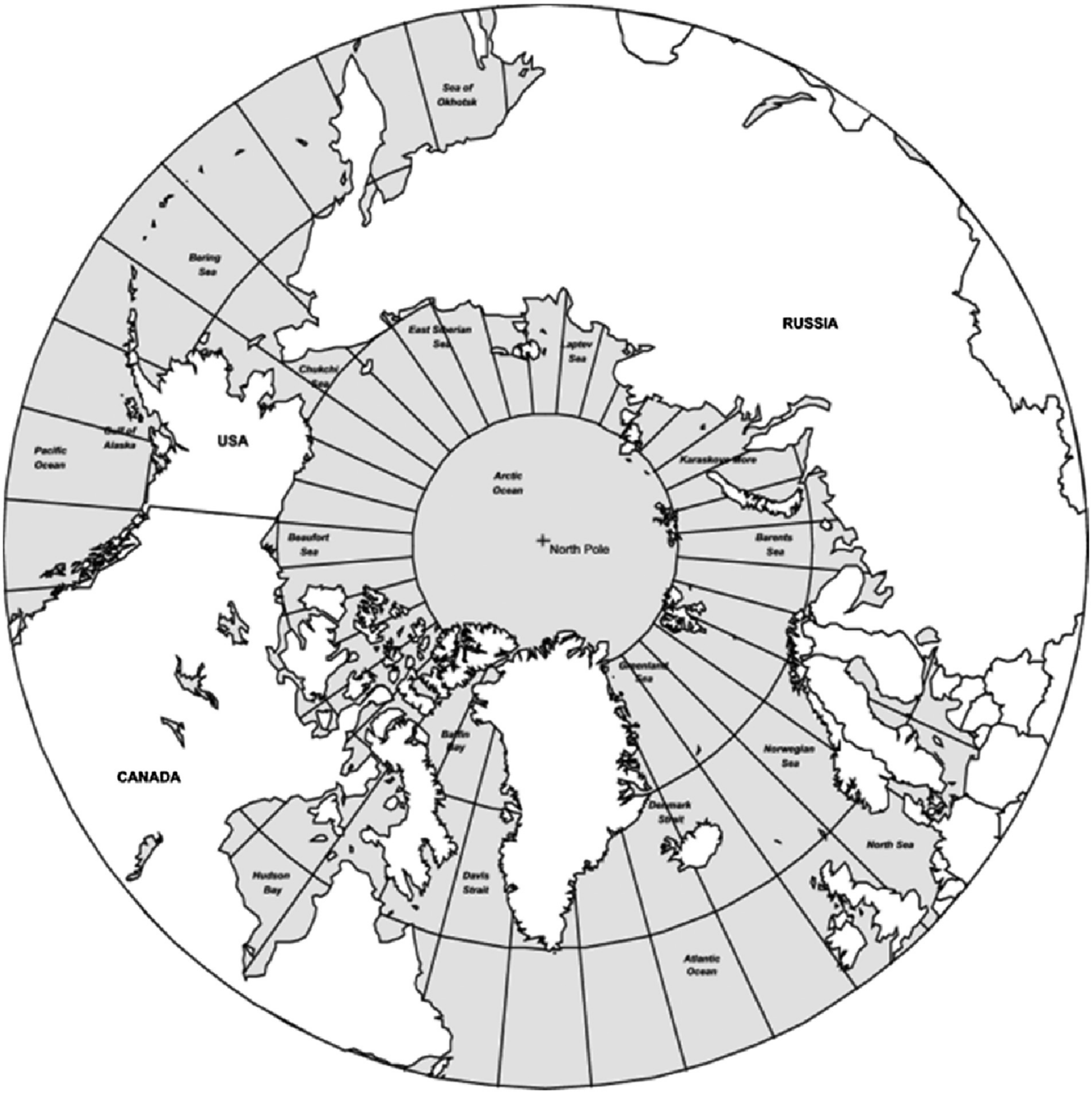

Fig. 1. Map of the Arctic region.

Source: https://www.abcteach.com/Maps/arctic.htm

if all stayed out but that enters if all others enter. The uncertainty that other countries may perceive about Norway's type gives it an advantage because by staying out it forces the other countries to consider the possibility that they may make a loss if they enter. If the other countries believe the very green type of Norway to be sufficiently likely, then they will not enter. This way, by being inactive, the less green Norway acts, without detection, like the very green Norway (a pooling strategy, see Proposition 2). A less formal interpretation of this result suggests that environmentally-conscious countries – as well as those who are only moderately concerned with the environment (see Proposition 3) – gain by convincing the other countries that they are very environmentally concerned. Finally, while there may exist preference uncertainty about all countries, it creates a strategic advantage only for environmentally-concerned countries and not for those who are not. The reason is that the uncertainty only exists as long as a country has not moved and therefore cannot be combined with the first-mover advantage of countries that do not care about the environment.

The model also reveals what forms of technological spillovers shift the strategic advantage in favor of environmentally-conscious countries. For instance, spillovers that are in the form of learning by doing – whereby one has to encounter a large variety of situations before extraction is profitable – gives environmentally-conscious countries the ability to deter entry. Conversely, if spillovers are in the form of shared fixed costs of R&D investment then countries that would like to see exploration in the Arctic have a strategic advantage.

Obviously, a country that prefers the equilibrium where all stay out should certainly not be the first to enter. This poses critique over the implemented policy in Norway, for instance. While Norway supposedly cares about the climate and hence should prefer all to refrain from Arctic oil extraction, in particular if considering the geopolitical heating, top politicians are acting as if their choices do not matter – the former Minister of Foreign Affairs has expressed that Arctic exploration is going to happen whether Norway wants it or not (Der Spiegel, 2012). While one can interpret this as Norway not truly caring for the climate, it may also be due to an underestimation of the technological spillovers. Indeed, if Norway stays out, others may do so as well; in particular because Norway, having the most accessible and least harsh Arctic areas, provides a testing ground for the technology.[7]

Section 5 offers an illustrative calibration of the model. Combining rough estimates of the environmental preferences of countries that have jurisdiction over the Arctic with estimates of technological spillovers (also taking into account that expected reserves differ between countries), we find it reasonable to believe that an allegedly environmentally-conscious country like Norway could induce others to leave the Arctic fields untouched at current oil prices. This conclusion hinges crucially on the price of oil not durably nearing the $90 mark, and on extraction costs in the Arctic not falling to $50/barrel (which is slightly above current African offshore costs, for instance). We find that Norway's role could become even more pivotal during a brown U.S. administration: Norway's refusal to enter the Arctic would make extraction by a brown U.S. and Russia only marginally profitable thus possibly deterring entry. Conversely, should Norway enter the Arctic, the profit margin increases, possibly leading to unrestrained exploitation from Arctic countries. Likewise, the prospects of a future green U.S. administration has an even more pivotal role as, absent U.S. entry, the costs for a single entrant would be very high which would greatly deter Russia.

Of course, our theory – being a toy model – abstracts from a number of real-world complications such as the fact that some regions are more natural to start exploration, that there are both gains and losses of moving first and that the property rights in some areas are not well defined. We discuss how such extensions would affect our results in the concluding section.

Related literature

This paper relates to thevery active literature on unilateral environmental policy. The starting point in this literature is that some countries *do* care about the environment and the analysis focuses on what tools they may use to reduce environmental harm globally. Most of this literature focuses on various forms of leakage where emission reductions in one country induces others to emit more as is nicely summarized by Meunier and Ponssard (2014) and Arroyo-Currás et al. (2015). Such leakage may be due to the pollution-haven effect – a displacement of activities to jurisdictions with lower environmental standards (Rock, 1996; Tobey, 1990; Markusen et al., 1993). It may also be due to the marginal damage of other countries' emissions falling when one country reduces its own emissions – the classic crowding-out effect (Varian, 1994). Alternatively, leakage may be the result of the policy affecting prices (Hoel, 1994; Markusen, 1975) through two possible channels: when demand for fossil fuels is reduced in one country this lowers the world price, which increases the consumption of fossil fuels in other countries (Copeland and Taylor, 1995; Stern et al., 1996; Arroyo-Currás et al., 2015); or, if a fossil-fuel exporter reduces its extraction, the world price increases, which raises extraction in other countries (Bohm, 1993; Harstad, 2012). These price channels have led to the focus on unilateral policies that do not create leakage, for instance the buying of high-cost reserves (Bohm, 1993; Harstad, 2012). While the price-leakage effect may exist in the Arctic as well – a lower extraction in the Arctic may increase the oil price in the long run – there also exist reversed externalities in the form of technological spillovers. These spillovers are the focus of this paper and imply that, not only may a policy of avoiding Arctic exploration cause no leakage, but it may in fact lead to a multiplier effect whereby the extraction is reduced in other countries. For this mechanism to be at work it is important that the technological leakage be stronger than the leakage through the price. Given how specific the technology for Arctic drilling is and given the many other factors that determine the price of oil (including shale-oil reserves, alternative energy sources etc.), this seems plausible. Industry representatives have expressed this possibility by saying that "the full potential in the Arctic can only be tapped through innovation and technological improvements and by getting costs down".[8]

Our paper also relates to the literature on climate leadership (e.g., Varian, 1994; Hermalin, 1998). Leadership (that is, moving first with ambitious abatement) may lead to crowding out of others' investments (Varian, 1994) but it may also crowd *in* investments if the mitigation of one country reduces the cost of others (Golombek and Hoel, 2004) or if leadership conveys information on the low costs of abatement (see Hermalin, 1998, for an early treatment and Mideksa, 2016, for a recent treatment of the interaction between crowding out, spillovers and signaling). The core premise in these works is that there is agreement between the players that abatement is desirable – all countries would like all others to abate more. In the Arctic, this may not be the case and hence our model contains heterogeneity – some countries want others to abate more (i.e., to not enter the Arctic) while some countries want the others to abate *less* (they prefer all to enter the Arctic). Hence, in our article, there is a fundamental disagreement about which equilibrium is the most desirable; we study the dynamic interaction and the ability to induce others to behave according to one's own preferred equilibrium. A second important

[7] See, for instance, reporting in Aftenposten (2016) and the discussion in the concluding Section 6.

[8] Expressed by Tom Dodson, director of exploration at Statoil (Aftenposten, 2012).

point of difference to existing works on environmental leadership is that they study signaling about the costs of abatement, where leaders have an incentive to make followers believe the costs are low (Hermalin, 1998; Mideksa, 2016). Because in the Arctic there is disagreement about the best equilibrium, we study a fundamentally different form of uncertainty – about others' environmental preferences. This difference is important because, unlike the previously mentioned research, we are interested in a situation where countries cannot commit to future actions of abatement (there are no binding promises of not entering the Arctic for good). Hence, by being perceived as having strong environmental preferences, a country can make others believe it is more committed to not entering. Consequently, the policy implications are vastly different. When uncertainty is about costs (like in Hermalin, 1998; and Mideksa, 2016) leaders may want to seize the first-mover advantage to spur others to abate whereas in the Arctic those that care the least about the environment have a first-mover advantage.

The rest of the paper is structured as follows. In the next section, we illustrate the mechanism in a static game. Section 3 extends the model to be dynamic. Section 4 adds uncertainty of other countries' preferences. Section 5 performs a rough but illustrative calibration. Section 6 concludes by discussing effects that attenuate and strengthen the mechanism. All proofs are in the appendix. The appendix also contains a number of model extensions to illustrate the robustness of the theoretical results.

2. Static model

We keep the modeling as simple as possible to highlight the main mechanism. The model consists of three countries. For each country $i \in \{A, B, C\}$ the monetary profits of exploring its own Arctic area ("entering") are:

$$\pi - c(n+1),$$

where π represents the oil revenues (assumed to be equal across countries), c is a function representing the cost of extraction, which depends on the number of *other* countries (n) that enter alongside itself. To capture the technological spillovers, c is a decreasing function in its argument. [9] We assume that

$$\pi < c(1), \tag{1}$$

so that no country wishes to enter the Arctic alone. This assumption is motivated by current extraction costs in the Arctic (see more in the calibration in Section 5).[10]

The total payoff of Country i is given by:

$$U_i(E_i, n) = [\pi - D_i - c(n+1)]E_i - nD_i, \tag{2}$$

where $E_i \in \{0, 1\}$ is the binary choice variable of Country i of whether to enter ($E_i = 1$) or not ($E_i = 0$). The term $D_i \geq 0$ represents the marginal environmental damage of one country entering as perceived by Country i. Hence, D_i is country specific. As manifested in the payoff function, Country i's perceived total damage depends both on whether Country i enters ($-D_i$) and how many of other countries enter ($-nD_i$, where $n = \sum_{j \neq i} E_j$).

Countries are ordered by their environmental consciousness:[11]

$$D_A > D_B > D_C = 0. \tag{3}$$

In the static version of the model, countries move simultaneously. The following lemma outlines the type of equilibria that exist under various conditions.

Lemma 1. *There exists a Nash equilibrium where no country enters ("all-out equilibrium"). In addition:*

- *A Nash equilibrium where all enter exists iff* $D_A \leq \pi - c(3)$.
- *A Nash equilibrium where only B and C enter exists iff* $D_A \geq \pi - c(3)$ *and* $D_B \leq \pi - c(2)$.
- *The all-out equilibrium is unique iff* $D_A > \pi - c(3)$ *and* $D_B > \pi - c(2)$.

[9] We assume in the model that the countries are of equal size (affecting costs and damages equally). We discuss later the effect of relaxing this assumption. In the calibration unequal size is taken into account. Furthermore, we assume that prices are not affected by the number of countries. This is without theoretical consequence as our model is isomorphic to one where there also exist price effects. Indeed, the spillovers with respect to costs can be viewed as net after also incorporating price effects. For our model to be relevant it is of course necessary that the cost spillovers are greater than the price spillovers (see discussion in the literature review). Quantitatively, adding price effects when a country enters would make the outcome where all stay out more likely compared to our current calibration in Section 5. Finally, in our setup the spillovers are symmetric – when one country enters it lowers the costs for all. Thus, we assume each country has access to the best technology and knowledge available globally when extracting nationally. This is the case, for instance, if there exists a private market for R&D (or more generally, extraction) selling the technology and where the R&D effort increase with market size.

[10] It is also meant to make the problem interesting. If $c(1) < \pi$ then, under the upcoming assumption that at least one country cares very little about climate change (Expression (3)), there would always be entry.

[11] Note that the results would not change if D_C was non-zero but small. Should D_C be large then the likelihood of an equilibrium where all stay out increases.

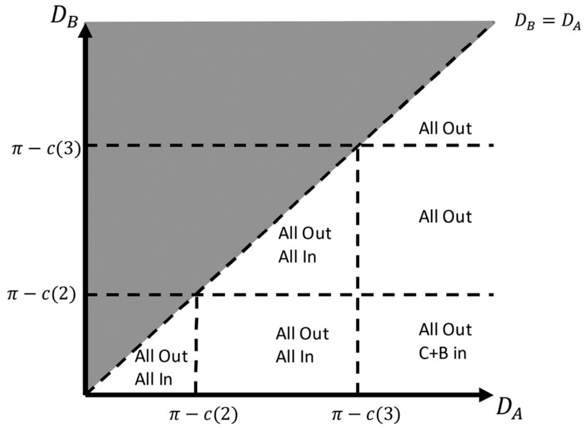

Fig. 2. Parameter space and existence of equilibria in the static model.

Proof. In the appendix

The results of the lemma are depicted in Fig. 2, which shows the space of possible combinations of damage parameters (D_A and D_B) and the existence of various types of equilibria (the grey area is not relevant since $D_B < D_A$ by construction). To see why the first sentence of the lemma is true, note that, since $\pi < c(1)$, no country would unilaterally want to deviate from a situation where each country is staying out – all out is always an equilibrium.

Next, if $D_A \leq \pi - c(3)$ (which implies $D_B < \pi - c(3)$) no country would deviate from a situation where all are entering. To see why, note that the payoff of Country A when it enters is $\pi - c(3)$–$3D_A$ while staying out yields $-2D_A$ (the two other countries are entering). Similarly for Country B. Hence, when $D_A \leq \pi - c(3)$, that is, when countries A and B are both sufficiently unconcerned with the environment, "all-in" is an equilibrium. Under these conditions we therefore get that the static game becomes a coordination game between all three countries – either all three enter or all three stay out.

Finally, if $D_A \geq \pi - c(3)$ (Country A is very concerned with the environment and would stay out even if the others enter) and if $D_B \leq \pi - c(2)$, then there exists an equilibrium where countries B and C enter. This is because Country B would, by deviating to "stay out", get payoff $-D_B \leq \pi - c(2)$–$2D_B$, where the right-hand side is the payoff it would get by entering. Hence, under these conditions, where Country A is very environmentally concerned but Country B is less so, the game is a coordination game between countries B and C – either both enter or neither does.

An implication of the lemma is that whether entry (full or partial) is an equilibrium largely depends on the preferences of Country B. To see this, note that independently of the preferences of Country A, a sufficient condition for entry in equilibrium is $D_B \leq \pi - c(2)$, that is, B is sufficiently unconcerned with the environment. However, if this condition does not hold then the preferences of countries A and B jointly determine the possibility of entry: both D_A and D_B need to be smaller than $\pi - c(3)$.

Fig. 2 can also be used to illustrate the comparative statics with respect to the extraction costs. For instance, if $c(2)$ increases sufficiently, so that $\pi < c(2)$, then extraction costs are so high that economically profitable entry can only be achieved if all three enter. In the figure this would imply that the leftmost vertical dashed line is to the left of the vertical axis and that the lowermost horizontal dashed line is below the horizontal axis. The total area where all-out is the unique equilibrium then becomes larger. Similarly, if $c(3)$ were to increase, then the rightmost vertical line moves to the left and the upper horizontal line moves down, again implying that there is a broader set of environmental preferences enabling uniqueness of the all-out equilibrium.

We now extend the model to a dynamic setting to capture that, in reality, the choice of entering the Arctic need not be simultaneous. This will help us distinguish the equilibria that are attainable in a dynamic setting, which will prove particularly useful since the countries may not agree on which equilibrium is the most desirable. Several alternative ways of modeling dynamic entry are available. For brevity, we analyze our preferred variant in the body of the paper – that is, the one that in our view strikes the best balance between realism and tractability – and treat some key alternatives in the appendix. The main issue when modeling the game dynamically is what actions countries can commit to. It should be noted that if countries can promise (i.e., commit) to never entering (should they not wish to enter) and at the same time commit to not exiting after they have entered, then the dynamic model would largely resemble the static model. We would then have the same set of equilibria under the same conditions as in the previous lemma (see further description in Appendix B3). Likewise, if countries cannot commit to anything – they can enter and exit the Arctic at any period back and forth as they wish – then the dynamic model is either silent or alternatively again boils down the static model (see discussion in Appendix B1). In what follows, we will assume 1) that countries cannot promise to never enter the Arctic but 2) that once they have entered they cannot exit. The first part can be motivated by that, in any country, it would be very hard to bind the hands of future governments with respect to oil extraction. The second part can be motivated by there existing costs of entry or exit – for instance fixed investment costs, costs of relocating labor, political or legislative costs or costs of breaking a contract after granting a concession for exploration – that would make exiting after an entry very costly or difficult. For simplicity we abstract from the precise reasons for this in the body of the paper but explore one such mechanism of endogenous commitment through sunk investments in Appendix B1.[12]

3. Dynamic model

To convey the dynamics at play, it is sufficient to have three periods.[13] We assume that a decision to enter is 'absorptive' in the sense that once a country enters, it cannot leave.

In Period 1, all countries move simultaneously and decide individually whether to enter or not. These actions are observed before the second period. In the second period, those who did not enter previously may choose whether to enter or not. Period-2 actions are again observed before those who have not entered in previous periods decide, in Period 3, whether to enter or not. Payoffs are given at the end of the game according to Eq. (2) based on the status of the countries in Period 3. This way our model can be viewed as capturing the initial years during which entry decisions and initial investments are being made, there then follows a long period of extraction – which we do not model – at which costs and revenues arrive. The payoffs in the game can be viewed as the total of these costs and revenues.[14]

Note first that if $D_A < \frac{\pi - c(3)}{3}$, so that Country A (thus also Country B) prefers that all enter over all staying out, then it is immediate that there would exist no all-out equilibrium in the dynamic game. To see this, note that Country A can then enter in the first period, thus triggering Country C and then Country B to enter in later periods. For Country A this would dominate any subgame which ends with all staying out. To make the problem interesting we will therefore assume

$$D_A \geq \frac{\pi - c(3)}{3}. \tag{4}$$

We are interested in Subgame Perfect Nash Equilibria (SPNE) and proceed by analyzing the existence of such an equilibrium where all stay out.

Proposition 1. *There exists an all-out SPNE iff* $\pi - c(2) \leq D_B$ *and either*

1 $\pi - c(3) \leq D_A$, *or*
2 $\pi - c(3) > D_A$ *and* $\frac{\pi - c(3)}{2} \leq D_B$.

Proof. In the appendix

The proposition implies that it is the preferences of Country B that determine the existence of an equilibrium where all stay out. In particular, Country B has to be sufficiently environmentally concerned – independently of whether Country A is very environmentally concerned (first part) or less so (second part).

To see the intuition, consider the second point. The condition $\frac{\pi - c(3)}{2} \leq D_B$ implies Country B prefers an outcome where only one other country enters over an outcome where all enter. To see the role of this condition and the dynamics of the game, suppose the condition $\pi - c(2) < D_B$ holds and consider a subgame starting from Period 3 where Country C has entered but not the others. This situation – a simultaneous-move game between countries A and B – is depicted in Fig. 3. This subgame is essentially a coordination game, which has two Nash equilibria: one where both enter and one where both stay out.[15] However, although the subgame of Period 3 is a coordination game, the dynamic structure of the game implies that an outcome where countries A and B stay out may be unattainable under subgame perfection when instead starting from Period 2. This is the case precisely when $\frac{\pi - c(3)}{2} \leq D_B$ is violated. To see why, note that if countries B and C have entered before Period 3, then Country A will enter in Period 3. Hence, if Country B observes that Country C has entered in Period 1, it essentially has the choice of either entering in Period 2, thereby spurring a chain reaction where Country A enters as well, or staying out and stopping the chain reaction. Hence, and because the game is dynamic, Country B can ensure that both entering is achieved if it wants to; in other words, Country B can choose its preferred equilibrium from the normal form coordination game in Fig. 3. Country C is aware of this chain reaction. Hence, if $\frac{\pi - c(3)}{2} > D_B$ then Country C, by entering, can ensure its preferred outcome where all enter. Note that this is the outcome even if Country B really would prefer all to stay out. Alternatively, if D_B is so large that Country B prefers to stay out after only Country C has entered ($\frac{\pi - c(3)}{2} \leq D_B$ holds) then Country B gets its preferred outcome since the equilibrium will then be that all stay out, including Country C. This is so because staying out is a credible threat for Country B even after Country C has entered. Thus, having strong environmental preferences is a strategic advantage for B (if it prefers an equilibrium where *all* stay out) as it is then easier to endogenously commit to staying out.

[12] The opposite case – countries can commit to never enter but can exit after an entry – is briefly discussed in Appendix B4.
[13] See Appendix C for a rough description of a model and results with infinitely many periods.
[14] In reality some costs and revenues may also materialize during the investment periods. There are many ways to relax our assumption here: in Appendix B2 we consider a model extension where some costs are sunk upon entry; in Appendix C we illustrate how considering flow payoffs would affect the results; and in the concluding section we discuss the effect of having payoffs contingent on the date of entry.
[15] This is ensured in the generic case where inequalities are strict: $\pi - c(2) < D_B$ and $\pi - c(3) > D_A$.

Country A \ Country B	Enter	Do not enter
Enter	$\pi - c(3) - 3D_A$, $\pi - c(3) - 3D_B$	$\pi - c(2) - 2D_A$, $-2D_B$
Do not enter	$-2D_A$, $\pi - c(2) - 2D_B$	$-D_A$, $-D_B$

Fig. 3. Normal form of 2-country subgame in period 3 after Country C has entered.

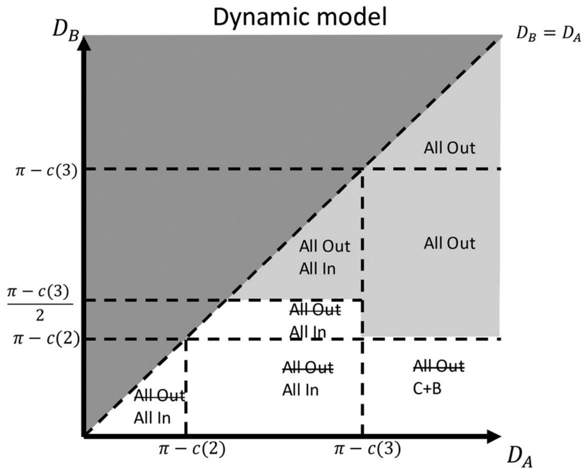

Fig. 4. Parameter space and existence of equilibria in the dynamic model. The existence and uniqueness of various equilibria follow from Proposition 1 and Appendix A3. The dark-grey zone is not permissible (since $\boldsymbol{D_B} < \boldsymbol{D_A}$). The light-grey zone is where an all-out equilibrium exists. The white zone is where the static model allowed an all-out equilibrium but the dynamic model does not.

The condition can also be interpreted in terms of technological spillovers. A low $c(3)$ (holding other parameters fixed) implies $\frac{\pi - c(3)}{2} \leq D_B$ is less likely to hold. A low $c(3)$ can thus be viewed as a form of temptation for Country B to enter after Country C, which prevents Country B from attaining its preferred outcome in case it would really want all countries to stay out. This means that strong technological spillovers (in the form of a low $c(3)$) give countries that do *not* care about the environment a strategic advantage.

A similar logic applies to the condition $\pi - c(2) < D_B$. When this condition is violated, the Period-3 normal form game between countries A and B in Fig. 3 contains no equilibrium where both stay out. Hence, by entering before Period 3, Country C can ensure that at least one country (possibly both) will follow. Again, the condition sets a lower bound on the environmental preferences of Country B or, equivalently, a bound on how extensive technological spillovers can be (i.e., on how low $c(2)$ can be).

One implication that follows from this logic is that the dynamic setting – under our assumption that a country that has entered the Arctic cannot easily reverse its decision (entry is absorptive) – implies that countries that are unconcerned with the environment (Country C) get a strategic advantage. By moving first, they can push for an equilibrium where the others are also entering. The ability to push for this is however contingent on the preferences of intermediately concerned countries (Country B).[16]

This also has the implication that equilibria that are attainable in the static setting may not be so when there are dynamics. This is shown in Fig. 4, which is the equivalent parameter space as in Fig. 2, but now depicting the equilibria that exist in the

[16] Had we assumed instead that countries could only commit to staying out of the Arctic, the balance of power would be reversed, with the more environmentally conscious countries having a strategic advantage (See Appendix B4). Our choice to make entry absorptive stacks the odds of achieving an all-out outcome against us, thus placing our analysis on the conservative side of the spectrum.

dynamic game.[17] The white space in Fig. 4 is where the static game would allow for an all-out equilibrium but the dynamic game does not.

4. Preference uncertainty

We now extend the dynamic model to include uncertainty of the environmental preferences of other countries. To highlight the strategic impact of this uncertainty we consider uncertainty only about one country at a time. That is, one country has private knowledge of her own type while the preferences of the two remaining countries are common knowledge. Since this extension makes for a more complex analysis we will restrict ourselves to illustrating the results for a more narrow set of parameters.

We start by analyzing uncertainty about Country A. Suppose there are two possible types of Country A: one *green* type, denoted by subscript *Ag*, which has preferences according to (4) – thus preferring all-out to all-in – and such that $\pi - c(3) > D_{Ag} \geq \pi - c(2)$; and one *very green* type, denoted by subscript *Agg*, for which

$$D_{Agg} > \pi - c(3). \tag{5}$$

That is, the very green type prefers to stay out regardless of whether the others enter.

We denote by p_A the exogenous probability that Country A is of the *Agg* -type. This probability is common knowledge. To stack the cards against an all-out equilibrium we will assume that Country B is not particularly environmentally conscious so that it prefers that all enter over one other country entering alone ($D_B < (\pi - c(3))/2$). It follows then from Proposition 1 that a full-information game played between countries B, C, and the *Ag* -type of Country A admits no all-out SPNE.[18] We are looking for a Perfect Bayesian Equilibrium (PBE), meaning that beliefs have to be consistent with the history of play.

Proposition 2. *All staying out is the unique PBE outcome iff p_A is sufficiently large* $\left(p_A > \frac{\pi - c(3) - 2D_B}{c(2) - c(3) - D_B}\right)$.

Proof. In the appendix

Country A can use the uncertainty others perceive about its preferences to its advantage. To see this, recall that the *Agg* -type will always stay out, independently of what the others do. This means that if Country B dislikes entering with only one other country ($D_B > \pi - c(2)$, which holds whenever $\frac{\pi - c(3) - 2D_B}{c(2) - c(3) - D_B} < 1$ and is therefore implied by the condition in the proposition), a known realization of the *Agg* -type would induce Country B to stay out, which in turn would induce Country C to stay out as well. Now, suppose the realization is that Country A is of the *Ag* -type. Had Country C known that Country A was of the *Ag* -type then it could have entered expecting Country B and then Country A to follow. However, by staying out, the *Ag* -type can mimic the behavior of the *Agg* -type, which leaves countries B and C with uncertainty about Country A's type. Whether the others enter then depends, again, on the preferences of Country B. Not knowing the type of Country A, Country B has to attach a sufficiently high probability to Country A being of type *Agg* in order to stay out, so that the risk of possibly entering with only Country C outweighs the possible gains from entering, even knowing that it would lead the *Ag* -type to follow suit. It may be interesting to note that the preferences of Country C do not play a role here. This is because Country C relies on the reaction of Country B: if Country B follows then Country C will enter and if Country B does not, then Country C will stay out.

A strategic interpretation of this result is that staying out is a way for Country A of hiding its type, which constitutes a strategic advantage. More loosely interpreted, the policy implication is that an environmentally-conscious country has a reason to try to influence the beliefs of the others (p_A). That is, it should try to get others to believe it is environmentally adamant and will never enter the Arctic—expressing environmental concerns is a form of cheap talk that is effective in this case. Finally, one interpretation of such a pooling strategy is that Country A can (should it be democratic) choose to wait and hold a referendum a few years down the line (in Period 3). In this case, the outcome of the referendum would depend on the economic activity that Arctic oil extraction would generate and therefore, indirectly, on extraction costs; these costs in turn depend on the actions of countries B and C. But the actions of countries B and C, as shown, depend on their expectations of the type of Country A which it effectively hides by holding a referendum later.

The extent of this strategic advantage is measured by the difference $c(2) - c(3)$, because the larger this difference, the lower p_A can be. Proposition 2 can thus be interpreted through the lens of the properties of technological spillovers. To make things simple, fix the value of $c(3)$ high enough that $\frac{\pi - c(3)}{2} > D_B$.[19] Recall also that it is not economically profitable to enter alone ($c(1) > \pi$). Then, Proposition 2 states that the likelihood of an all-out equilibrium outcome will depend on the magnitude of the difference $c(2)$–$c(3)$. More precisely, if $c(2)$–$c(3)$ is large, corresponding to a situation where the bulk of the spillovers kick in only after most countries enter, an all-out equilibrium outcome is more likely. For example, this could correspond to the case where spillovers are in the form of expertise acquired through 'learning-by-doing': one must

[17] The parameter space follows from Proposition 1 (showing existence and inexistence of "all-out" equilibria) and Appendix A3 (showing existence and inexistence of remaining equilibrium types in the dynamic model).

[18] This is due to the fact that Country C can start a chain reaction by entering, thereby inducing Country B to enter as well, which in turn induces the *Ag*-type to enter.

[19] Otherwise, an SPNE outcome where all stay out exists, as per Proposition 1, and the introduction of uncertainty is moot.

have been confronted with various adverse situations to be confident that the most significant setbacks can be avoided. In such a case, c will be a concavely falling function. Conversely, the smaller $c(2)$–$c(3)$, so that most of the spillovers are already exhausted with few entrants, the less likely an all-out equilibrium. This is the case if, for instance, drilling in the Arctic incurs a large fixed cost of developing a new design of drilling equipment to withstand the harsh sea and weather conditions whereas the marginal improvement, after this equipment has been developed, is small. In this case we would get a convexly falling cost function.

We move now to the case where there is uncertainty about the preferences of Country B. It is commonly known that Country B is less environmentally conscious than Country A, and more environmentally conscious than Country C, but uncertainty remains about its exact preferences. Formally, we have:

$$D_A > D_{Bg} > D_{Bb} > D_C = 0, \tag{6}$$

where Country B can either be of *green* or *brown* type. We restrict our attention to the following case. The *green* type – we use subscript Bg – has preferences such that it would want to enter if and only if the other two countries did: $\pi - c(2) < D_{Bg} < \pi - c(3)$ and $D_{Bg} > (\pi - c(3))/2$. The other type is *brown*, denoted by subscript Bb, with the following preferences:

$$0 > \pi - c(3) - 3D_{Bb} > \pi - c(2) - 2D_{Bb} > -D_{Bb} \tag{7}$$

This type prefers that all enter to entering with a single other country, which it prefers over staying out when one other country enters (that is, by Proposition 1, no SPNE where all stay out exists if this were a game between countries A, C, and the Bb -type of country B). The only element that makes Bb slightly environmentally conscious is that it prefers that all stay out to any other outcome.[20]

Denote by p_B the exogenous probability that Country B is of the green type. p_B is common knowledge. We are again looking for a Perfect Bayesian Equilibrium (PBE) in which the outcome is that all stay out.

Proposition 3. *All staying out is a PBE outcome iff p_B is sufficiently large: (i) $p_B \geq \frac{\pi - c(3)}{c(1) - c(3)} \in]0, 1[$ and (ii) $p_B \geq \frac{\pi - c(3) - D_A}{c(2) - c(3)} < 1$.*

Proof. In the appendix

The strategic intuition behind this proposition is similar but more straightforward than the intuition for the previous result. We will focus on condition (i).[21] Country A and the Bg -type of Country B, both being environmentally conscious, prefer to coordinate on staying out even if Country C entered in some earlier period. The Bb -type of Country B would follow an entry of Country C but, by staying out, the Bb -type can mimic the behavior of the Bg -type and thus force Country C to consider the risk that, if it enters, it might be entering alone. Hence, for Country C to stay out, p_B has to be sufficiently large so that the risk of entering alone (and earning $\pi - c(1) < 0$) is greater than the positive prospect of all entering (thus earning Country C $\pi - c(3) > 0$). The comparison for Country C is between entering alone and entering with two others because, if countries B and C enter, Country A will enter as well. The loose interpretation of this result is that a less green country (the brown type of Country B) that still prefers that the Arctic be left untouched has reason to pretend to be more environmentally conscious than it actually is.

The nature of the technological spillovers also plays a key role in Proposition 3, although this time it is the overall technological spillovers, $c(1) - c(3)$, that determine the likelihood of existence of an all-out equilibrium outcome, rather than the tail end of the cost function ($c(2) - c(3)$) as was the case in Proposition 2. This is because in Proposition 3 it is Country C that needs to be deterred from entry for there to exist an all-out equilibrium. This country compares the risk of entering alone with the prospect of getting the others to join. The magnitude of the spillovers, $c(1) - c(3)$, capture how reliant Country C is on others entering: a large difference implicitly means that entering alone is costly, which deters entry.

As a final step, we move now to discuss the case where Country C can be of two types. The first is very brown, denoted by *Cvb*, and has preferences according to (3). This type prefers entering as long as at least one other country does. The second is extremely brown, denoted by *Cvvb*, and would enter even on its own: D_{Cvvb} is sufficiently negative so that it is worthwhile for it to enter despite making an economic loss.[22]

The most interesting aspect of this case is that Country C *cannot* use uncertainty about its preferences in any strategic way. Since both types of Country C have greater incentives to enter than countries A and B, these latter countries have the option to wait and then enter only after Country C has. Country C of the *Cvvb*-type will enter independently of what the others do and the *Cvb*-type will enter if and only if Country B is expected to follow suit. So the uncertainty of Country C's

[20] To see that this preference set is non-empty note that the inequalities in (7) imply $D_{Bb} > \frac{\pi - c(3)}{3}$, $D_{Bb} < c(2) - c(3)$ and $D_{Bb} < \pi - c(2)$. That is, two upper bounds on D_{Bb} and one lower bound. The first upper bound is compatible with the lower bound iff $3c(2) - 2c(3) > \pi$ and the second upper bound is compatible with the lower bound iff $3c(2) - c(3) < 2\pi$. These two constraints are compatible as long as $c(2) > c(3)$, which holds by assumption.

[21] Condition (ii) is spelled out for completeness, but it is essentially an artefact of our limitation of the game to be over three, and not more, periods. Hence, it is of less economic interest. The condition says that, should Country C enter in period 2, then Country A needs to prefer the risk of being the only one staying out (should the Bb-type of Country B be the state of nature) over the risk of entering alone with Country C (should the Bg-type of Country B be the state of nature).

[22] Hence, we have $D_A \geq D_B \geq D_{Cvb} = 0 > D_{Cvvb}$. While difficult to frame in terms of environmental preference, a negative value of D_{Cvvb} can for instance be interpreted as Country C enjoying additional country-specific spillovers, for example, to increase employment or the population density in remote regions.

preferences does not play a role. An interpretation of this is that uncertainty of environmental preferences among those who do care about the environment is more important than of those that do not care about the environment. The strategic advantage of a country that does not care about the environment is that it can move first and thereby possibly initiate a process where more countries enter. However, the strategic advantage of an environmentally-conscious country is a result of the uncertainty about its preferences, which it can exploit by staying out (or announcing a later referendum, as mentioned above). This cannot be used by the country that does not care about the environment since it can only get the market rolling by moving first.

5. Illustrative calibration

We now propose a rough calibration to illustrate the model results and to get an idea about whether countries that do care about the environment can credibly commit to not entering. Naturally, being a highly stylized model, the results should be interpreted with caution. Our model requires information about oil production costs and technological spillovers, about the price of oil, and about the environmental harm as perceived by the players. To illustrate our results, we will simplify the Arctic map by considering the three-player game consisting of only Russia, the U.S. and Norway.

In this calibration we depart from the setup of the theoretical model in two ways. Firstly, to make the calibrated numbers more realistic, we will take into account that the prospective reserves differ between countries, and hence have heterogeneous effects on both environmental damage and technological spillovers. This is without consequence for the qualitative results but implies (to assess the possibility of different equilibria quantitatively) that we need to keep track of who it is that enters in various scenarios since not only the number of entrants but also their size plays a role. Had we included the possibility of heterogeneous reserves in the theoretical section, then we would have needed to deal with a number of subcases that are of little economic insight. To avoid dealing with these subcases here, our second departure from the theoretical setup is that we fix the order of actions so that the least environmentally-conscious country moves first and the most environmentally-conscious country moves last. This is without quantitative consequences as compared to our basic theoretical setup since it only presupposes that the least environmentally-conscious country enjoys a first-mover advantage, which is what arose endogenously in the theory section.

5.1. *Oil price*

For the oil price, we shall take $\pi = \$70$/bbl, the marginal cost of shale as a base scenario. This is motivated by the cost of shale extraction largely setting a maximum price for oil today.[23] This factor is likely to be important over the next decades. It is of course straightforward to adjust the results to other price scenarios and we discuss other price scenarios when presenting the results.

5.2. *Production costs and spillovers*

Calibrating the production costs and spillovers involves a great degree of uncertainty. For the purpose of this illustration, we will use the best available estimates of this but it is important to note that the estimates and results need to be interpreted with caution.

McDonald and Schrattenholzer (2001) estimate the learning spillovers in terms of reducing production costs in the energy sector. For North-Sea oil (the closest equivalent to Arctic off-shore oil) a doubling of the number of rigs lowers the average cost per rig by 25%. That is, for a current cost of production k_0, average production costs will be $k(s) = k_0 0.75^s$ where $s = \ln(m)/ln(2)$ and m is the number of multiplications of current market size.

To get a rough idea of the effect that entry of Russia, U.S. and Norway will have on the costs, we also need estimates of their expected Arctic reserves. Naturally, a large degree of uncertainty surrounds such estimates but, following USGS (2008), Russia and the U.S. have roughly equal-sized reserves and Norway's reserves are at around a quarter of each of them.[24]

Existing estimates of today's production costs of Arctic oil in Russia are around \$120/bbl, which gives an estimate for k_0.[25]

The most difficult value to estimate is the existing stock of knowledge of Arctic production. This determines how many doublings of market size, for instance, an entry of Russia to the Arctic would induce. This is determined partly by the current amount of offshore oil extraction in general, by the current amount of near-Arctic (e.g., Norwegian and Russian) oil extraction in particular but, importantly, by how much such extraction has in common with the more extreme Arctic extraction we are interested in here. Unfortunately, there are no reliable estimates for this implying that we have to make a guess about

[23] This assumption is motivated by OPEC's well-established strategy of limiting output so as to keep the oil price below the break-even point of competing fuels. We refer the reader to Andrade de Sá and Daubanes (2016) for a discussion.

[24] We focus here on off-shore oil technology hence exclude the predominantly on-shore regions WSB, YK, TPB, LA, LV and ZB (see USGS, 2008).

[25] Source: https://knoema.com/vyronoe/cost-of-oil-production-by-country#, accessed Dec. 9th 2016

it. [26] We will assume Russia alone would double the current market size so that $m = 2$ if Russia enters alone and (based on the relative reserve estimates) $m = 4$ if Russia and the U.S. enter and $m = 4.5$ if also Norway enters.

Put together, this yields $c(1) = 120 * 0.75^{\ln(2)/\ln(2)} \approx 90$, $c(2) = 120 * 0.75^{\ln(4)/\ln(2)} \approx 68$, $c(3) = 120 * 0.75^{\ln(4.5)/\ln(2)} \approx 64$.[27]

5.3. Perceived climate damage

We now calibrate the values that each country attaches to climate harm. We use each country's social cost of carbon (SCC) as an approximation. The SCC theoretically corresponds to the damage incurred worldwide as the result of GHG emissions, which is not the same thing as damage suffered in a given country. That being said, it is also apparent that the values declared – or revealed – by countries are in the lower range of estimates of the actual SCC (for example, Moore and Diaz, 2015, obtain a value of \$220/tCO2). Our view is that the stances taken by countries with regard to the SCC convey information about their concern for climate change nonetheless. While not perfect, we take these values to constitute reasonable approximations.

The US had, at least under the Obama administration, officially adopted an SCC for 2016 of \$37/tCO2 though we relax this later.[28] For comparison with the price and costs of oil extraction, we convert this based on the carbon content in a barrel of oil. Following the EPA, we use the conversion ratio 0.43 tCO2/bbl.[29] This means the adopted SCC in the US is about \$16/bbl of oil. For Norway, there is no official SCC to our knowledge, so as our main estimate we use a cost as implied by the CO2-tax it imposes on gasoline of 0.88 NOK/liter ≈ \$0.1/liter,[30] which translates into $0.1 * 425 = \$42.5/tCO2 \approx \$18$/bbl of oil.[31] We take Russia's SCC to be \$0/tCO2 since, although having signed the Kyoto Protocol and the Paris Agreement, it has shown no signs (to our knowledge) of putting a monetary value on CO2 emissions (neither by defining a SCC nor through taxation). Mapping these values to our model yields: $D_A = 18$, $D_B = 16$, and $D_C = 0$.

These damage values are measured in \$ per barrel of oil, hence are comparable to the extraction cost and price of oil. Note, however, that since countries differ in the size of their Arctic oil reserves, the damage as perceived by country i when country j enters may not be the same as that perceived by i when i itself enters. Because the effective order of entry, if at all, is Russia, then the U.S., then Norway, the only time this will play a role is for the damage perceived by the U.S. when Norway enters which, by Norway's reserves relative to the U.S., we consequently set to $\frac{1}{4}D_B = 4$.

An issue in obtaining a country's perceived damage is that damage occurring directly due to a country's own activities may not in practice be valued equally as damage occurring indirectly when a country's own actions affect others' actions. For instance, it may be that Norway does not feel equally responsible for damage that occurs when someone else burns oil that Norway has pumped as when Norway burns oil itself. Similarly, the emissions that are covered by the Kyoto Protocol, the Paris Agreement and the European ETS (like domestic transport that we used here when calibrating D_A using gasoline taxes) may be viewed differently than emissions not covered by these agreements (such as air travel). Hence, we will discuss how the calibrated model predictions change if the damage estimates change.

5.4. Predictions of the static model

We first note that indeed, as per our basic theoretical assumption, the calibrated numbers imply $\pi - c(1) = 70 - 90 < 0$. We further note that Norway, by the calibration, would not enter, independently of what the others do, because $D_A = 18 > \pi - c(3) = 70 - 64$. Hence, by Lemma 1, for there to exist an equilibrium where some enter, it is necessary that $D_B < \pi - c(2)$. This condition is violated, however: $D_B = 16 > \pi - c(2) = 70 - 68$. As an illustration, for the U.S. to enter without Norway given these extraction costs and the assumed oil price it would be necessary that the SCC in the U.S. be below 2\$ per barrel.

5.5. Predictions of the dynamic model

Before presenting the calibrated predictions of the dynamic model, a few conditions used in the theoretical section need to be changed to take into account the unequal size of the countries. First, the condition that at least Norway prefers an outcome where no one enters over one where all do (condition (4)) now will read[32] $(4 + 4 + 1)D_A > \pi - c(3)$ implying $D_A > \frac{\pi - c(3)}{9}$. Similarly, the condition for the U.S. to prefer that all stay out over all entering (where we note that the damages the U.S. perceives when Norway enters is a quarter of the damages it perceived when it itself enters) is $(1 + 1 + 0.25)D_B > \pi - c(3)$ implying $D_B > (\pi - c(3))/2.25$. For these two conditions to be fulfilled it must be that $D_A > \frac{70-64}{9} = 0.67$ \$/bbl

[26] One very basic reason for the lack of estimates is that there is uncertainty even around the current activity in the Russian Arctic (Oil and Gas Eurasia, 2007). A second reason is that it is hard to know how applicable the current technologies are to more remote Arctic areas.

[27] That is, as mentioned, here we assume that the entry order is always Russia first, then possibly US and then possibly Norway.

[28] Source: https://www.epa.gov/climatechange/social-cost-carbon, accessed Dec. 9th 2016.

[29] Source: https://www.epa.gov/energy/ghg-equivalencies-calculator-calculations-and-references, accessed Dec. 9th 2016.

[30] Source: http://www.statsbudsjettet.no/Statsbudsjettet-2011/English/?pid=48921#hopp. For the conversion, we use 1 NOK = 0.11764 USD, according to http://www.xe.com/currencyconverter/convert/?Amount=0.88&From=NOK&To=USD, accessed Dec. 9th 2016.

[31] 1 tonne of CO2 is equivalent to 425 liters of gasoline. See https://www.eia.gov/environment/emissions/co2_vol_mass.cfm, accessed Dec. 9th 2016.

[32] Due to asymmetric reserves, the damage Norway suffers from either the U.S. or Russia entering is four times the damage if it itself enters.

and $D_B > (\pi - c(3))/3 = (70 - 64)/3 = 2$ \$/bbl. The empirical values of D_A and D_B identified above clear these thresholds by a wide margin.

Next, the very last condition in Proposition 1 (which says that B should not want to enter if A will follow) now needs to be reformulated taking into account that the damages as perceived by the U.S. when Norway enters are only $D_B/4$ implying

$$D_B > \frac{\pi - c(3)}{1.25}. \tag{8}$$

It is easy to see that, under the calibrated values, "all out" is an equilibrium and in fact is unique. To see this, note that Russia does not make economic profits unless at least the U.S. enters ($c(1) > \pi > c(2)$). Then note that Norway's and the U.S.'s damage estimates are such that none of them would want to enter even if the other two did which means none of them would follow Russia.

Looking at this more in detail, the first necessary condition for there to exist an all-out SPNE in Proposition 1 requires: $D_B > \pi - c(2)$. This means $D_B >$ \$2/bbl, which is satisfied.

The next condition pertaining to Country B is the one now expressed by (8). This condition is fulfilled if $D_B >$ \$4.8/bbl, which corresponds to the threshold value for the U.S. to credibly not enter after Russia. This is also clearly satisfied.

For Norway and the U.S. to enter after enough other countries enter, we need $D_A, D_B < \pi - c(3) =$ \$6/bbl. This condition is not satisfied by any country but Russia. Hence, Norway and the U.S. would not enter following Russia.

The conclusion of this numerical illustration is that an all-out outcome seems credible should the U.S. and Norway really want it. Enough countries are sufficiently climate conscious to prevent a chain reaction of entry from unraveling and, by doing so, to discourage Russia from initiating it in the first place. Russia is also reliant on the entry of others given that its cost when entering alone far exceeds the price of oil.

Given that the values adopted in our base scenario are broad approximations, we now perform a sensitivity analysis of sorts. Namely, we investigate how robust our prediction is to these values differing from the base scenario. We perform this analysis along three dimensions: the approximated perceived damages by the U.S. and Norway, the price of oil (π) and the magnitude of technological spillovers.

In the previous calibration there are two obstacles preventing the "all-in" outcome. Firstly, D_B is so high that the U.S. would not follow Russia even if it knew that Norway would join. The estimate of damage for the U.S. is $D_B =$ \$16/bbl. For the U.S. to join after Russia (given that Norway will not follow) it is necessary that $D_B < \pi - c(2) = 2$. Hence, the U.S.'s perceived SCC has to be reduced to nearly zero. Given that President Trump denies climate change, perhaps D_B close to zero is realistic today. Whether it will be so also in the future is more uncertain.

As for Norway's perceived climate damage, it is not necessarily written in stone either. For Norway to enter after the U.S. it is necessary that its SCC be $D_A < \pi - c(3) = 6$. If this were the case, then using Eq. (8) the U.S. would enter iff $D_B < (\pi - c(3))/1.25 =$ \$4.8/bbl. Hence, if both Norway and the U.S. lower their perceived climate costs to be below \$6/bbl and \$4.8/bbl respectively, then all-enter is the equilibrium. Is it plausible that Norway perceives damages to be so low? That is hard to say since, looking at a broader set of estimates gives a very inconclusive picture. For instance, one indication of Norway's willingness to pay for emission reductions abroad is given by its involvement in the REDD+ program where it has agreed to pay the equivalent of \$2/bbl.[33] This is of course below \$6/bbl and would suggest entry in the Arctic is likely. On the other hand, an indication can also be given by Norway's air-travel taxes, since air travel is (or at least was) mostly not covered by the European emission-trading system. Norway recently instituted a fee of roughly \$9 per passenger. Depending on the distance of the flight this is equivalent to between \$4/bbl (for the longest-distance flights) to \$70/bbl (for domestic flights).[34] Finally, Norway has a tax on air fuel of around \$22/bbl[35] and estimates of individual willingness to pay for emission reductions in air travel have been estimated for Europe at around \$19/bbl (Brouwer et al., 2008).[36] This range is of course very broad and encompasses scenarios where Norway should want to stay out of the Arctic and scenarios where it would enter.

Holding the D's fixed as in the base scenario, we can investigate what oil price would be needed to get an equilibrium where some or all countries enter. Firstly, and quite directly, if the price exceeds \$90/bbl for a durable period of time, Russia would enter independently of the other countries' strategies since $c(1) = 90 < \pi$. Next, for Norway to enter after the U.S., it is necessary that $D_A < \pi - c(3)$ hence that the oil price exceeds \$82/bbl. If this is the case then using Eq. (8), for the U.S. to enter, the oil price would have to durably exceed $\pi > 1.25D_B + c(3) =$ \$84/bbl. Hence, in total, an oil price above \$84/bbl would lead to entry of all.[37] While such a high oil price seems unlikely as long as shale oil is an important source, the International Energy Agency (2016) uses in its outlook scenarios where the oil price is \$80/bbl or above (some scenarios have

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[33] The Joint Concept Note (2009) between Norway and Guyana establishes that Norway will pay the equivalent of 5 \$/tonne of CO2 for reductions in deforestation in Guyana.

[34] See Naturverneforbundet (2016) which estimates around 0.054 tonnes/CO2 per passenger for domestic flights to almost 1 tonne/CO2 per passenger for the longest international flights (which would be subject to the tax going only one way).

[35] 1.08 NOK/liter of fuel. For transformation to CO2, see previous calculations of the fuel tax in Norway.

[36] The equivalent number for the US willingness to pay was around 8 \$/bbl of CO2 in their study.

[37] The other possibility for inexistence of an all-out equilibrium from Proposition 1 is if Norway would not follow the US (first numbered part of the proposition) but the US would enter nevertheless. For this to apply it is necessary that $D_A > \pi - c(3)$ which is violated when the price of oil is \$84/bbl.

an oil price of \$90-\$150 per barrel in the medium and long term). Should such a scenario indeed materialize (and perhaps equally importantly are they considered likely by the Arctic oil countries) then all-enter would be the only equilibrium by our calibration.

Finally, supposing the price of oil hovers around π = \$70/bbl, technological spillovers will have to be so large as to reduce $c(2) < \pi - D_B = \$54/bbl$ for the U.S. to enter if Norway does not follow (first constraint of Proposition 1); or $c(3)$ down to costs of \$52/bbl for Norway to follow the U.S. and to reduce $c(3) < \pi - 1.25D_B$ = \$50/bbl (by (8)) for the U.S. to follow Russia. Alternatively, if $c(1) < 70$ then Russia would enter also alone.

Given the uncertainty surrounding these values, and that the model is not a full account of the forces shaping Arctic extraction, the ambition of the calibration is of course not to provide a forecast of what will actually happen. Rather, the main conclusion following the calibration values is that Arctic oil extraction is likely to be only marginally profitable if at all. Furthermore, it seems that the costs of extraction and the oil price are at such levels as to make the forces of our model relevant and that profitable entry by one player is contingent on the actions of other players. Hence it is possible that countries such as Norway would be able to deter entry, should they want to. This illustration was of course done under the assumption that the preferences (SCC) of all countries are known. As illustrated by the case of the U.S. where the current and previous administration differ greatly in the view on climate change, we turn now to illustrate the results on preference uncertainty quantitatively.

5.6. Predictions of the dynamic model with preference uncertainty

Of course, in reality the indicated SCC for Norway and the U.S. may not be entirely representative of long-run preferences as they can be changed by future governments and, in particular and as discussed earlier, they may not represent how these countries view climate damage arising from their own selling of oil. For instance, there is a heated discussion in Norway over whether exploration should be allowed in its Northern territories. Several political parties are in favor of essentially stopping new exploration while others are in favor of continued exploration. As an illustration of the uncertainty of preferences in our model, suppose these pro-environment parties indeed have an SCC of \$18/bbl, making these parties of the *Agg* -type. Suppose further that the current U.S. administration will have long-term consequences, lowering the SCC of the U.S.. If the U.S. uses a value between \$2 and \$4.8/bbl in the future, then it fulfills the assumptions of Country B in Proposition 2.[38] Hence, as a first example, suppose $D_B = \$4$/bbl. Then, according to the requirement of Proposition 2, the U.S. would not follow Russia (and hence Russia would not enter) if $p_A > \frac{\pi - c(3) - 1.25D_B}{c(2) - c(3) - 0.25D_B} = \frac{70-64-5}{68-64-0.25} \approx 27\%$.[39] That is, if a green coalition is more likely than this to set the long-run policy of Norway then that discourages entry by others.

Turning now to the uncertainty of the preferences of the U.S., we can first note that if the U.S. administration values the SCC at zero then, under the assumed oil price and spillovers they would simply enter since they would then face an oil price above their costs of extraction ($\pi - c(2) = 70 - 68 > 0$) as Russia would then enter as well. Under a slightly lower price scenario or a slightly higher cost scenario, a brown U.S. would be more reliant on Norway's entry.

However, it is not certain that the current U.S. administration will be able to alter the long-run Arctic policy of the U.S. and, given that future election results are uncertain, there is uncertainty about the long-run preferences of the U.S.. Suppose that with probability p_B a relatively environmentally friendly U.S. administration will determine the long-run preferences of the U.S., with an SCC at $D_B = 16$ as per the Obama administration.[40] With probability $1-p_B$ a brown administration will set the long-run policy of the U.S. at $D_B = 0$. Clearly, with $D_A = 18$, Norway would not enter under any circumstances since $D_A > \pi - c(3)$ and similarly a green U.S. administration would not enter under any circumstances. Likewise, as concluded above, a U.S. administration with $D_B = 0$ would enter provided that Russia does. Hence, Russia, if it wants to enter today, faces with probability p_B costs at $c(1) = 90$ with profits of -20 and with probability $1-p_B$ faces costs at $c(2) = 68$ with profits of 2. For Russia to enter today under such a scenario, expected profits have to be positive ($p_B(-20) + (1 - p_B)2 > 0$) implying the probability of $p_B < 0.09$. That is, for Russia to enter today, it must believe that a brown administration will set the long-run policy with a greater chance than 91%. Hence, the environmental preferences of Norway or a green U.S. administration could play a pivotal role in deterring entry by Russia.

6. Conclusion and policy implications

We have shown that market size for Arctic technology creates strategic interaction between countries that may want to induce others to enter the Arctic or may want to induce others not to do so. A rough calibration suggests that, indeed, the cost of extraction and price of oil are such that countries that do not care about the environment are reliant on environmentally-conscious countries joining also. In turn, this gives a country like Norway a pivotal role in letting the Arctic fields remain

[38] The condition $D_B > \$2$ is for $U_B(0,1) > U_B(1,1)$ to hold and the condition $D_B < \$4.8$ is for $U_B(1,2) > U_B(0,1)$. In our context, where the perceived damages by the U.S. when Norway enters are $0.25D_B$, the latter translates to $D_B < (\pi - c(3))/1.25 = 4.8$.

[39] From the proof of Proposition 2 the condition in Proposition 2 stems from the requirement $U_B(0,1) > p_A U_B(1,1) + (1 - p_A) U_B(1,2)$. When the damages perceived damages of the US when Norway enters are $0.25D_B$ this requirement translates to $p_A > \frac{\pi - c(3) - 1.25D_B}{c(2) - c(3) - 0.25D_B}$.

[40] A survey of attitudes towards climate change in the U.S. population shows that a majority thinks that the US government should do “A great deal” or “A lot” to fight climate change and a vast majority are in favor of unilateral action (Resources For the Future, 2015).

untouched, if it wishes. This pivotal role seems to be particularly central in light of the uncertainty surrounding the long-run policy of the U.S..

We have kept the modeling as simple and sparse as possible to highlight this strategic interaction and the main results. A few factors attenuating or strengthening the results are, however, worth mentioning. The first is that size is unevenly distributed among the five countries with jurisdiction over the Arctic. Russia has the largest piece of the pie. This was abstracted from in the theoretical analysis but was incorporated in the numerical illustration. To the extent that Russia has the weakest environmental preferences, this size gives them an advantage to be partly able to push the technology by themselves. However, as the numerical illustration suggests, they are reliant on a less environmentally-friendly U.S. administration setting the long-run policy.

On the other hand, Russia partly has the least accessible areas while Norway is sometimes called "the gateway to the Arctic" because it can start extraction in rather mild Arctic areas thus providing a testing ground for the technology. Hence, to the extent that Norway has strong environmental preferences, it may largely halt the development of the necessary technology, since a stepwise testing of this technology is hard to perform if firms only have access to Russia's Arctic region. Russia may also face problems with the willingness to invest by firms possessing these technologies (Harsem et al., 2011). In terms of our model, this would mean Norway has the first-mover advantage.

We have assumed in the model that the payoffs arrive at the end of the game and only depend on the final status of the countries – the sequence of decisions to enter has no effect. In practice there are probably both gains of waiting and benefits of being first to enter. If one enters early, one faces the risk of sinking large costs whereas the others decide to stay out in the event of, say, a drop in the oil price. In addition, one may need to cover the costs of various failed technological attempts and extract at high costs while the others have not yet entered (see Appendix C for an extension where flow payoffs depend on the number of countries currently in the Arctic). On the other hand, the benefit of being first is that one provides a testing ground for domestic firms that may be able to patent and then sell this technology to other countries. Extending the model so that the first entrant would incur a higher cost of extraction (at least initially) than later entrants would not substantially change the theoretical results. The early entrant would still need to consider whether the others will enter at some point and whether in total, over the decades of Arctic extraction, entry would yield net profits. In fact, such an extension would create an endogenous commitment to stay in after entering (in the same flavor as we have modeled in Appendix B2). This is due to the fact that once the early entrant has sunk some investments and performed some extraction, the learning-by-doing mechanism would lower its own future costs thus making it profitable to stay in even without the others. Thus, we would get a situation where single-country entry is ex ante unprofitable but ex post profitable.

Another simplification of the model is that entry is binary – countries cannot choose how much of their own Arctic areas to explore. This simplifies the analysis substantially. One interpretation is that, for whatever share of their own Arctic area that is optimal to explore, each country decides whether to do it or not.

A final factor is the partial uncertainty of property rights in the Arctic. There is, for instance, a dispute over which country owns the North Pole and, by international law, the one whose continental shelf goes under it is the rightful owner (UNCLOS, 1982). This means that keeping one's own territory free of oil drilling may imply that a country with stronger military muscles may partially explore that area instead. Now, this uncertainty over the rights does not cover the entire Arctic region – no one would argue that the U.S. does not have sole jurisdiction of the waters of the Alaskan coast or that Norway does not have jurisdiction over the Lofoten Islands. Therefore, the model results apply to such areas where there is less of a dispute. Furthermore, the fact that there is a dispute is a reason by itself to avoid making such areas more economically appealing which can be achieved by not drilling in the undisputed areas hence cooling down the geostrategic tensions in the Arctic.

Finally, while this paper has been applied to oil extraction in the Arctic, the analysis and insights may be applicable also to other domains. For instance, within environmental economics, similar interaction may exist when it comes to fisheries in remote or deep locations or other oil resources that require specific technologies. Outside of environmental economics, it may have bearing on investments in weapon systems or surveillance technologies.

Appendix A. Proofs

A1 Proof of Lemma 1

Some notation will be useful. Being a 3×2-game (three players, two strategies), there are 9 relevant inequalities to worry about. For Country A, and focusing on strict inequalities, they take the form:

$$\pi - D_A - c(1) >< 0$$

$$\pi - D_A - c(2) >< 0$$

$$\pi - D_A - c(3) >< 0$$

Let us denote by A1, A2, and A3 these three inequalities, respectively. Furthermore, we shall write A1+ if $\pi - D_A - c(1) \geq 0$, and write A1- if $\pi - D_A - c(1) \leq 0$. Similarly, we shall write A2+ if $\pi - D_A - c(2) \geq 0$, and write A2- if $\pi - D_A - c(2) \leq 0$. Similar notation applies to the inequality with $c(3)$ and to the other countries' inequalities. The notation "++" and "–" denotes strict inequalities.

First, notice that the fact that c is a decreasing function implies that A1+ $\rightarrow$ A2++ $\rightarrow$ A3++, and that A2+ $\rightarrow$ A3++. Also, A3- $\rightarrow$A2– $\rightarrow$A1–, and A2- $\rightarrow$A1–. Similarly for B and C.

Next, the fact that $D_A > D_B > D_C$ implies that A1+ $\rightarrow$B1++ $\rightarrow$C1++, and that C1- $\rightarrow$B1– $\rightarrow$A1–. Similarly for "2″ and "3″.

Recall that we assume $\pi < c(1)$ (Assumption 1), which implies that C1-, B1- and A1- hold. This immediately implies that no country wishes to enter alone, so that an "all-out equilibrium" exists. Hence follows the first statement of the lemma.

The remaining four possible equilibrium outcomes are "entry by countries B and C only", entry by all countries ("all-in equilibrium"), "entry by countries A and B only" and "entry by countries A and C only". We examine them in turn.

"Entry by countries B and C only" is an equilibrium outcome (no entering country gains by deviating to staying out and no non-entrant gains by deviating to entering) if and only if B2+, C2+ and A3- hold. Because B2+ $\rightarrow$ C2+, this combination is equivalent to A3- and B2+ holding simultaneously. Hence follows the sentence about the existence of an equilibrium involving only the entry of countries B and C.

An "all-in equilibrium" exists if and only if A3+, B3+ and C3+. Because A3+ $\rightarrow$ B3+ $\rightarrow$ C3+, this combination is equivalent to A3+. Hence follows the statement about the existence of an all-in equilibrium.

"Entry by countries A and B only" is an equilibrium outcome if and only if A2+, B2+ and C3- hold. However, this combination is impossible because C3- $\rightarrow$ B3– $\rightarrow$ B2–, by the above observations.

"Entry by countries A and C only" is an equilibrium outcome if and only if A2+, C2+ and B3- hold. However, this combination is impossible because B3- $\rightarrow$ A3– $\rightarrow$ A2–, by the above observations.

Since we just showed that there cannot exist an equilibrium where only A and B or where only A and C enter, it follows that if the conditions for entry of B and C and for entry of A, B and C are all violated then "all out" is the unique equilibrium. Hence follows the last statement about uniqueness.

END OF PROOF

A2 Proof of Proposition 1

To prove the proposition it is necessary and sufficient to show that the following 4 statements are true:

1 There exists an all-out SPNE if $\pi - c(2) \leq D_B$ and $\pi - c(3) \leq D_A$.
2 There exists an all-out SPNE if $\pi - c(2) \leq D_B$, $\pi - c(3) > D_A$ and $\frac{\pi - c(3)}{2} \leq D_B$.
3 There does not exist an all-out SPNE if $\pi - c(2) > D_B$.
4 Assuming $\pi - c(2) \leq D_B$, there does not exist an all-out SPNE if $\pi - c(3) > D_A$ and $\frac{\pi - c(3)}{2} > D_B$.

PART 1

Note that an all-out equilibrium always exists if $\pi - c(3) < 0$ (simply set all countries' strategies to "never enter"). Therefore, we shall assume $\pi - c(3) \geq 0$ in what follows.

Suppose $\pi - c(2) \leq D_B$ and $\pi - c(3) \leq D_A$, where we note that this also implies $\pi - c(2) < D_A$, $(\pi - c(3))/2 < D_A$, $(\pi - c(3))/3 < D_A$, and $(\pi - c(2))/2 < D_A$. This means that A will not enter under any circumstances. Recall finally that $\pi - c(1) < 0$.

There are two cases: 1) $\frac{\pi - c(3)}{2} \leq D_B$ and 2) $\frac{\pi - c(3)}{2} > D_B$. In case (1) we claim the following strategies constitute an SPNE:

- A: Do not enter in any period independently of history.
- B: Do not enter in Period 1. In later periods enter iff A has entered in a previous period (if $\pi - c(3) < D_B$, augment this strategy to "do not enter independently of history").
- C: Enter iff at least one other country has entered in a previous period (if $\pi - c(2) < 0 < \pi - c(3)$ augment this strategy to "enter iff both other countries have entered").

We check that no country would unilaterally deviate from these strategies. A's strategy is trivially a best response. On the equilibrium path B's payoff is zero. B's strategy is a best response because entering in the first or second period would imply C following, thus leading to a payoff of $\pi - c(2) - 2D_B < \pi - c(2) - D_B \leq 0$ for B; entering in the third period would give $\pi - c(1) - D_B < 0$; entering after only C has entered (off the equilibrium path) yields payoff $\pi - c(2) - 2D_B < -D_B < 0$; entering after A has entered (off the equilibrium path) yields B a payoff of $\pi - c(3) - 3D_B$ (since C's strategy prescribes entering after A) which is smaller than the payoff of not entering ($-2D_B$) because $\pi - c(3) - 2D_B < 0$, as was the assumption of case (1).

Given that B does not enter after only C has entered, and that A never enters, C's best response is to not enter (and C has a best response to enter if either A or B or both have entered). The augmented statements are trivial cases where either B never enters, regardless of history; and/or C relies on entry of both A and B to enter, hence does not enter on the equilibrium path).

The above strategies imply that all stay out in equilibrium, hence there exists such an SPNE in case (1).

In case (2) we use the same strategies as in case (1) (short of the augmented cases where $\pi - c(3) < D_B$, which is not possible here) and note that B's best response is to not enter following entry by only C since that would (given that A never enters) give a payoff $\pi - c(2) - 2D_B \leq -D_B$ by the initial supposition on B's preferences. These strategies imply all stay out in equilibrium, hence there exists such an SPNE in case (2).

PART 2

Suppose that $D_B \geq \pi - c(2)$. Suppose also that $\pi - c(3) > D_A$, and note that this also implies $\pi - c(3) > 0$. Suppose finally that $D_B \geq \frac{\pi - c(3)}{2}$.[41] Recall also that, by (1) $\pi - c(1) < 0$.

We claim that the following profile of strategies constitutes an SPNE:

- A: Do not enter in Period 1, and enter in subsequent periods if and only if B has entered already.
- B: Do not enter in Period 1, and enter in subsequent periods if and only if A has entered already.
- C: Do not enter in Period 1, and enter in subsequent periods if and only if at least one other country has already entered.

The outcome of these strategies is that all stay out and each obtains a payoff of zero. We check that the strategies indeed constitute an SPNE. Given the strategies of countries A and B, C cannot gain by entering alone because $\pi - c(1) < 0$ but it is optimal for it to enter (off the equilibrium path) if someone else did since, by the strategies of A and B, the one that has not yet entered would also enter, giving C a payoff of $\pi - c(3) > 0$. Likewise, B cannot gain by entering alone in periods 1 or 2, as this would spark a chain reaction in which A and C end up entering. B loses by such a move because $D_B \geq \frac{\pi - c(3)}{2} > \frac{\pi - c(3)}{3}$, implying that B prefers an all-out outcome to an all-in outcome. B's best response is to not enter in Period 3 after no one else has, since that would yield a payoff of $\pi - c(1) - D_B < 0$. B's best response is to not enter after only C has entered in Period 1 (off the equilibrium path) since $-D_B > \pi - c(3) - 3D_B$, which are the only payoffs it could get by entering after C given A's strategy to follow entry by B. Country B's best response is to not enter after only C has entered in Period 2 (off the equilibrium path) since, given the strategy of A, B would get payoff $\pi - c(2) - 2D_B \leq -D_B < 0$ since $D_B \geq \pi - c(2)$. Finally (off the equilibrium path), upon observing entry by A, B does best by entering since by C's strategy, B would otherwise end up staying out alone which would give payoff $-2D_B < \pi - c(3) - 3D_B$ since $\pi - c(3) > D_A > D_B$. A similar argument holds for A.

PART 3

Suppose $\pi - c(2) > D_B$. Note first that this implies $\pi - c(2) > 0$, that is, C will prefer to enter with one more country than no entry (recall that $D_C = 0$). We make the following observation. The normal-form game described by Fig. 3 pertains to a subgame starting in period 3 after C, but no other country, has entered. This subgame admits [Do not enter, Do not enter] as an NE if and only if $\pi - c(2) \leq D_B$ holds. If this condition is violated, which is the case we are considering here, any NE in this subgame must involve entry by at least one of the two countries A and B. Hence, by entering no later than in Period 2, C can ensure at least one more will enter, which it C prefers over no entry. It follows that any SPNE of the game must have entry by at least two as the outcome as otherwise Country C would profitably deviate to entering before Period 3. That is, no all-out equilibrium exists.

PART 4

Suppose $\pi - c(2) \leq D_B$; $\pi - c(3) > D_A$; and $\frac{\pi - c(3)}{2} > D_B$, which implies $\pi - c(3) > 0$, meaning that C earns a positive payoff if all enter. Consider a strategy where C enters in the first period. Then, in the subgame played between countries A and B in periods 2 and 3, B can ensure getting $\pi - c(3) - 3D_B > -D_B$ by entering in Period 2, so that A may observe that it is the only one out and thus enter in Period 3 (because $\pi - c(3) - 3D_A > -2D_A$). Hence, the outcome of this subgame is that all enter. Because C anticipates this, and because "all in" is the best outcome for C, it follows that any SPNE of the game must have all enter as the outcome because C can guarantee this outcome by entering in Period 1. Hence, there exists no all-out equilibrium.

END OF PROOF

A3 Equilibria in the dynamic game

We here outline and prove the existence and uniqueness of the equilibria outlined in Fig. 4.

Note first that the existence and inexistence of "all-out" SPNEs are covered by Proposition 1. Note next that, by the same logic used in the proof of Lemma 1, no equilibrium exists where only A and B enter (C would deviate) or where only A or C enter (B or A would deviate). Hence the following remains to be shown (we ignore weak inequalities, that is the borders between regions, here):

[41] Note that it follows from $D_A > D_B$ that we also have $D_A > \frac{\pi - c(3)}{2}$.

Case 1: $D_B < D_A < \pi - c(3)$
An all in SPNE exists.
The reader can verify that the following strategy profile is an SPNE: All countries enter in Period 3 but not earlier. The outcome is that all enter.

No B+C SPNE exists.
For entry of only B and C to be an equilibrium it is necessary that A stays out in the last period. But since $D_A < \pi - c(3)$, A would profitably deviate from such a strategy either in Period 3 or before.

Case 2: $D_B < \pi - c(2) < \pi - c(3) < D_A$
No all-in SPNE exists.
A would deviate from a strategy profile where all enter at some point since $D_A > \pi - c(3)$.

A B + C SPNE exists.
The reader can verify that the following strategy profile is an SPNE: A stays out independent of history; B and C enter in the last period but not earlier. The outcome is that only B and C enter.

Case 3: $D_A > \pi - c(3)$ and $D_B > \pi - c(2)$
No all-in SPNE exist.
A would deviate from a strategy profile where all enter at some point since $D_A > \pi - c(3)$.

No B + C SPNE exist.
For entry of only B and C to be an equilibrium outcome it is necessary that A stays out independently of history (which it indeed must, due to $D_A > \pi - c(3)$) and that B and C enter at some point. Given the strategies of A and C, B would deviate from any such strategy profile since $D_B > \pi - c(2)$ and entering gives $\pi - c(2) - 2D_B < -D_B$ which is B's payoff when staying out.

END OF PROOF

A4 Proof of Proposition 2

In the proof we simply write A when referring to Country A, same for B and C. Likewise, *Ag* and A*gg* will stand for the green and very green type of Country A, respectively.

First, note that the condition $p_A > \frac{\pi - c(3) - 2D_B}{c(2) - c(3) - D_B}$ is equivalent to $-D_B > p_A(\pi - c(2) - 2D_B) + (1 - p_A)(\pi - c(3) - 3D_B)$. The numerator of $\frac{\pi - c(3) - 2D_B}{c(2) - c(3) - D_B}$ is strictly positive because we assumed $D_B < \frac{\pi - c(3)}{2}$. The denominator is strictly positive if and only if $D_B < c(2) - c(3)$, which may or may not hold, but this is of little consequence.[42]

If.

Suppose $p_A > \frac{\pi - c(3) - 2D_B}{c(2) - c(3) - D_B}$. Note that this implies that:

$$\frac{\pi - c(3) - 2D_B}{c(2) - c(3) - D_B} < 1, \text{ i.e., that } D_B > \pi - c(2). \tag{9}$$

Existence.
Denote $\mu_j(h(T))$ Country *j*'s belief in period *T* along history *h* that A is of type *Agg* (*j* = B,C, *T* = 2,3). Consider the following belief system:

- $\mu_B(h(2))=\mu_C(h(2))= p_A$ if A did not enter in Period 1.
- $\mu_B(h(3))=\mu_C(h(3))= p_A$ if A has entered in neither periods 1 nor 2 and B had not entered in Period 1.
- $\mu_B(h(3))=\mu_C(h(3))=0$ if A has entered in Period 2 after B has entered in Period 1 (with or without C).
- $\mu_B(h(3))=\mu_C(h(3))=1$ if A has not entered in Period 2 after B has entered in Period 1 (with or without C).
- $\mu_B(h(2))=\mu_C(h(2))=p'$ for any $p' \in [0, 1]$, if A entered in Period 1.
- $\mu_B(h(3))=\mu_C(h(3))=p''$ for any $p'' \in [0, 1]$, if A entered in Period 2 and no one had entered in Period 1.
- $\mu_B(h(3))=\mu_C(h(3))=p'''$ for any $p''' \in [0, 1]$, if A entered in Period 2 after C (but not B) entered in Period 1.

Now consider the following strategy profile:

[42] Because the numerator is positive, a negative denominator simply means that the equilibrium condition is satisfied for all values of p_A.

- Country A, type *Agg*: "Never enter".
- Country A, type *Ag*: "Do not enter in Period 1, and enter in subsequent periods if and only if B has entered already."
- Country B: "Do not enter in Period 1, and enter in subsequent periods if and only if A has entered already."
- Country C: "Do not enter in Period 1, and enter in subsequent periods if and only if at least one other country has already entered."

The reader can check that the belief system and strategy profile just described constitute a PBE. In particular, one can verify that, given the condition on p_A, B would not follow an entry by C in Period 1 and hence C will not enter in Period 1.

Uniqueness.
We show uniqueness by showing in turn that all outcomes where at least one country has entered are *not* part of a PBE.

A number of outcomes involving entry by only B and C can easily be refuted: C enters alone → C deviates. Only B and C enter → B deviates by Expression (9). B enters alone → B deviates.

Now note that no PBE exists in which *Agg* enters. Hence, all outcomes involving entry by *Agg* can be refuted.

It remains to be shown that no PBE exists with an outcome involving entry by *Ag*.

Note that C will enter if it expects or observes B's or *Ag*'s entry, so no PBE exists where the outcome is that only *Ag* and B enter.

Consider player strategies that involve *Ag* entering in Period 3 but not before (and *Agg* not entering, naturally). Then B and C need to decide whether to enter without having learnt anything about A's type; hence, going into Period 3 their beliefs must be p_A. The condition on p_A implies that B will not enter even if it observed or expected C to enter (since it is unsure of A's type, and hence of whether A will enter, and since $p_A > \frac{\pi - c(3) - 2D_B}{c(2) - c(3) - D_B}$). Therefore, B will not enter. Given this, there exist two possible subcases depending on C's preferences that have not been eliminated. 1) Under the condition that C has sufficient expected profits of entering only with *Ag*, C will enter: *Ag* gets payoff $\pi - c(2) - 2D_{Ag} \leq -D_{Ag}$, hence *Ag* gains by deviating to staying out in Period 3. 2) Alternatively, if C does not have sufficient expected profits to enter with *Ag* alone, C will stay out and *Ag* will enter alone and get payoff $\pi - c(1) - D_{Ag} < 0$, hence *Ag* will deviate to not entering in Period 3.

Consider all strategy profiles involving a strategy for *Ag* that says "enter iff B has been observed to previously enter". The best response for B is to not enter before it has observed entry by A by the same argument as in the case just described above. The best response of C is thus not to enter since it will get $\pi - c(1) < 0$. Hence, under this strategy *Ag* gets 0.

Compare this to all strategy profiles involving a strategy where *Ag* enters (in Period 1 or Period 2) without having observed a previous entry of B. It is a best response for C to enter after *Ag* and so it is a best response for B to enter as well. This yields *Ag* a payoff of $\pi - c(3) - 3D_{Ag}$, which is less than what it obtains by using "enter iff B has been observed to previously enter" (in which case it obtains $0 > \pi - c(3) - 3D_{Ag}$, as we just saw). Hence, "enter iff B has been observed to previously enter" is a strictly better strategy for *Ag* and hence B and C will not enter either on the equilibrium path. It follows from the previous arguments that entry by *Ag* is not part of a PBE.

Only if.

Suppose $p_A \leq \frac{\pi - c(3) - 2D_B}{c(2) - c(3) - D_B}$. Note that this means that B wishes to enter after C if it expects *Ag* to enter and *Agg* not to. Then, the following strategy profiles and beliefs are part of a PBE:

- *Agg*: "Never enter."
- *Ag*: "Enter in Period 3 (but not earlier)."
- B: "Do not enter in period 1. In Period 2, enter if and only if at least one country has entered. In Period 3, enter if not yet in."
- C: "Enter in Period 1 (and, off the equilibrium path, enter if not already entered)."
- $\mu_B(h(T)) = \mu_C(h(T)) = p_A$ for $T = 2,3$, if A has not entered in a previous period.
- $\mu_B(h(3)) = \mu_C(h(3)) = p'$ for any $p' \in [0, 1]$ and $T = 2,3$ if A has entered in period 1 or 2.

The outcome of this PBE is that all enter. Hence, $p_A > \frac{\pi - c(3) - 2D_B}{c(2) - c(3) - D_B}$ is a necessary condition for an all-out equilibrium.

END OF PROOF

A5 Proof of Proposition 3

As in the proof of Proposition 2, we write A when referring to Country A, same for B and C. Here, *Bg* and *Bb* will stand for the green and brown types of Country B, respectively.

Note first that (i) $p_B \geq \frac{\pi - c(3)}{c(1) - c(3)}$ is equivalent to $0 \geq p_B(\pi - c(1)) + (1 - p_B)(\pi - c(3))$; and (ii) $p_B \geq \frac{\pi - c(3) - D_A}{c(2) - c(3)}$ is equivalent to $p_B(-D_A) + (1 - p_B)(-2D_A) \geq p_B(\pi - c(2) - 2D_A) + (1 - p_B)(\pi - c(3) - 3D_A)$.

Note also that it follows from $D_A > D_{Bg}$ and the assumption that $D_{Bg} > \pi - c(2)$ that:

$$\pi - c(2) < \boldsymbol{D_A} \tag{10}$$

Furthermore, $\frac{\pi-c(3)}{c(1)-c(3)} \in]0,1[$ since by assumption $c(3) < \pi < c(1)$. Finally, $\frac{\pi-c(3)-D_A}{c(2)-c(3)} < 1$ by inequality (10). Note that the numerator could be negative; in that case, condition (ii) is trivially satisfied. It corresponds to the situation where A would not enter even if it knew for sure that B would enter along with C.

If.

Suppose the conditions hold. Denote $\mu_j(h(T))$ Country *j*'s belief in Period *T* along history *h* that B is of type *Bg* (*j* = A,C, *T* = 2,3). Consider the following belief system:

- $\mu_A(h(T))=\mu_C(h(T))=p_B$, $T=2,3$, if no country has yet entered.
- $\mu_A(h(3))=\mu_C(h(3))=p_B$ if B entered in Period 2 after A (or A and C) had entered in Period 1.
- $\mu_A(h(3))=\mu_C(h(3))=0$ if B entered in Period 2 after C had entered alone in Period 1.
- $\mu_A(h(3))=\mu_C(h(3))=1$ if B did not enter in Period 2 after C had entered alone in Period 1.
- $\mu_A(h(T))=\mu_C(h(T))=p'$, $T=2,3$, for any $p' \in [0,1]$, if B entered in Period 1.
- $\mu_A(h(3))=\mu_C(h(3)=p''$, for any $p'' \in [0,1]$ if B entered in Period 2 after no one had entered in Period 1.
- $\mu_A(h(3))=\mu_C(h(3))=p'''$, for any $p''' \in [0,1]$, if B did not enter in Period 2 after A had entered alone in Period 1.
- $\mu_A(h(3))=\mu_C(h(3))=p''''$, for any $p'''' \in [0,1]$, if B did not enter in Period 2 after A and C entered together in Period 1.

We will show that these beliefs are part of a PBE with the following strategies:

- A does not enter in Period 1 and stays out unless B has entered in an earlier period, after which it enters immediately;
- *Bg* does not enter in Period 1 and stays out unless A (or A and C) has entered in an earlier period; and *Bb* stays out unless either A or C have entered in an earlier period, after which it enters immediately;
- C does not enter in Period 1 and stays out unless at least one of the other countries has entered in an earlier period, after which it enters immediately.

Note that the above belief system is consistent with these strategies.

Proof that Country B is playing a best-response strategy.
Possible subgames for B depending on the behaviors of A and C:

- Period-1 subgame (i.e., the whole game): Given the others' strategies, B's best response is to not enter.
- Period-2 subgame where A has entered alone in Period 1. C will enter in Period 2 by its postulated strategy. Both types of B do best by entering in Period 2. This is because $\pi - c(3) - 3D_{Bi} > -2$ for $i = g, b$.
- Period-3 subgame where A has entered in period 2 (and C has not entered in period 1 or 2). Similar argument as previous point.
- Period-2 subgame where C enters alone in Period 1. By its postulated strategy, A does not enter in Period 2. If *Bb* enters in Period 2, A will enter in Period 3 given its postulated strategy. Then *Bb*'s payoff is better than that of not entering ($\pi - c(3) - 3D_{Bb} > -D_{Bb}$) or than that of entering in Period 3 ($\pi - c(3) - 3D_{Bb} > \pi - c(2) - 2D_{Bb}$). If *Bg* does not enter in Period 2, A will not enter in Period 3, yielding a payoff of $-D_{Bg}$ to *Bg*. If *Bg* does enter in Period 2, A will enter in Period 3, yielding a payoff of $\pi - c(3) - 3D_{Bg}$ to *Bg*. Since, by assumption, $D_{Bg} > (\pi - c(3))/2$, *Bg*' s best response is to not enter.
- Period-3 subgame where C enters in Period 2 (and A has not entered in period 1 or 2). Similar argument as previous point.
- Period-2 subgame where A and C have entered in Period 1. Both types of B have as a best response to enter in Period 2.
- Period-2 subgame where no one has entered in Period 1 (equilibrium path). By their postulated strategies, neither A nor C enter in Period 2. From the assumptions on *Bb*'s preferences, and because $D_{Bg} > D_{Bb}$, both types have a preference for an all-out outcome— $\pi - c(3) - 3D_{Bi} < 0$ and $\pi - c(2) - 2D_{Bi} < 0$ for $i = g, br$ —so neither type will choose to enter *before* the others. Furthermore, neither type wishes to enter alone in Period 3.
- Period-3 subgame where no one has entered in period 1 or 2. Similar argument as previous point.
- Period-3 subgame where A and C have both entered (in any order) before Period 3. The best response for both *Bg* and *Bb* is to enter in Period 3.

Proof that Country C is playing a best-response strategy.
If either A or B or both have entered in period 1 or 2, C will prefer to enter immediately. The remaining cases are the ones where C compares the equilibrium path with entering first (no one else has previously entered) in Period 1, in Period 2, or in Period 3.

Suppose C enters in Period 1. Then, if the *Bb* type is realized, B enters, which induces A to enter in Period 3. Hence, if C enters in Period 1 and the *Bb* type is realized, it gets payoff $\pi - c(3)$. Otherwise, if the *Bg* type is realized, B does not enter in Period 2; and neither does A, by its postulated strategy. In addition, neither country enters in Period 3 by their postulated strategies. Hence, if C enters in Period 1 and the *Bg* -type is realized, it gets payoff $\pi - c(1)$. Given condition (i), C's expected payoff of entering in Period 1 is less than that of not entering in Period 1.

Now suppose C enters in Period 2. Then, if the *Bb* type is realized, it enters and does so in Period 3. However, by its postulated strategy, A does not enter in Period 3. Hence, if C enters in Period 2 and the *Bb* -type is realized, C gets payoff $\pi - c(2)$. Otherwise, if the *Bg* type is realized, B does not enter in Period 2, nor does it enter in Period 3. Hence, if C enters in Period 2 and the *Bg* type is realized, C gets payoff $\pi - c(1)$. Because $\pi - c(2) < \pi - c(3)$, condition (i) implies that C's expected payoff of entering in Period 2 would be less than that of not entering in period 2.

Finally, given the strategies of the other countries, C would never enter in Period 3 if no other country has entered since $\pi - c(1) < 0$.

Proof that Country A is using a best-response strategy.
On the equilibrium path, A will not enter because "all out" is its preferred outcome.

After a history of B entering in Period 1 or Period 2 (with or without C) it is a best response for A to enter immediately since C will eventually enter by its postulated strategy and $\pi - c(3) - 3D_A > -2D_A$.

After a history of only C having entered by the end of Period 2, A is better off not entering if and only if $p_B(-D_A) + (1 - p_B)(-2D_A) \geq p_B(\pi - c(2) - 2D_A) + (1 - p_B)(\pi - c(3) - 3D_A)$, which is true by condition (ii).

Suppose only C entered in Period 1. Then, A is better off not entering in Period 2. To see why, note that the strategy being played by B is a separating one in this subgame: the *Bb* type enters in Period 2 whereas the *Bg* type does not. By entering in Period 2, A induces also the *Bg* type to enter in Period 3, thus earning the certain payoff $\pi - c(3) - 3D_A$. By staying out in Period 2, A gets an expected payoff of $p_B(-D_A) + (1 - p_B)(\pi - c(3) - 3D_A) \geq \pi - c(3) - 3D_A$; hence, staying out in Period 2 is a best response.

Only if.
Suppose condition (i) does not hold. Then C is strictly better off entering in Period 1 compared to using any alternative strategy that leads to all staying out at the end. To see this, note that C knows that at least the *Bb* type will follow in period 2 or 3. Hence, by entering in Period 1, C ensures a payoff of at least $p_B(\pi - c(1)) + (1 - p_B)(\pi - c(3))$ (and possibly more if the *Bg* type follows as well), which we know to be greater than zero whenever condition (i) is violated. Hence, condition (i) is necessary.

Suppose condition (ii) does not hold. Then C is strictly better off entering in Period 2 compared to any strategy that leads to all staying out at the end. To see this, note that the *Bb* type will follow in Period 3. Furthermore, A, having preferences (by the violated condition (ii)) where $p_B(-D_A) + (1 - p_B)(\pi - c(3) - 3D_A) < p_B(\pi - c(2) - 2D_A) + (1 - p_B)(\pi - c(3) - 3D_A)$ will prefer to enter in Period 3 as well even if the *Bg* type would stay out in Period 3. Hence, C, by entering in Period 2, can ensure at least one other country entering in Period 3, which we know it prefers over all staying out. Hence, condition (ii) is necessary.

END OF PROOF

Appendix B. Commitment extensions

B1 Extension 1: Non-binding entry

Suppose a country that has entered can exit without a cost. Since any action taken by a country can be reversed in Period 3 where a one-shot simultaneous move game is played, this extension boils down to the static game analyzed in Lemma 1. The equilibria and the conditions for their existence are thus those outlined there. In particular the importance of countries that are intermediately concerned about the environment remains. A first-mover advantage of course disappears in a static setting.

B2 Extension 2: Fixed cost of entry but all decisions are non-binding

Suppose a country that has entered can exit without cost. Suppose furthermore that there are fixed costs of entry, denoted F, independent of when the country entered and how many others enter. Suppose finally that there are variable costs, $v(x)$, which depend on the number of entrants at the end of the game. This extension essentially separates the total cost of extraction used in the base model, $c(x)$, into a fixed component and a variable component: $c(x) = F + v(x)$. The fixed costs can be interpreted as political costs (e.g., analyzing where and how to enter, setting up legislation, etc.), or as exploration activities, the building of pipelines or transportation routes, moving labor to port towns, or other costs that must be incurred before any extraction can start. The variable costs can be interpreted as the average cost of building and operating rigs over a longer period of operation in the Arctic; these costs depend on the technological advancements over the whole period of operation in the Arctic and thus on market size.[43] We maintain the (only) parameter assumption that the total costs when being the sole final entrant are larger than the revenues: $F + v(1) > \pi$. We will analyze this game heuristically here. Since the addition of fixed costs and the possibility of exit increases the number of subgames to consider we will make a slight

[43] In reality the division between costs that depend on market size and costs that do not is not so clear cut. The idea here is to represent, in a reduced form, that a country has to take some costs already at the entry stage.

simplification of the base model, that helps us abstract from irrelevant combinations of actions. We will assume that Country A can only take an action in Period 3 (countries B and C can take actions in all periods). All other aspects of the dynamic game are as in the base dynamic model.

Since any previous action by a country can be reversed in any later period, the first step in analyzing the existence of various equilibria is done by considering the "static" game of Period 3. Once the equilibria in the Period-3 subgames have been identified we use backward induction to analyze which subgames will be "chosen" by various players.

A first case to consider is when $v(1) > \pi$. Then, independently on other parameter assumptions, there always exists an SPNE where "all out" is the final state. Indeed, if all play "out" in Period 3, no country will have an incentive to deviate, regardless of whether it has already incurred the fixed cost F (by entering in a previous period).

Now consider the case where $v(1) < \pi$. One way to interpret this condition is that a large share of the total costs of Arctic extraction consist of the market-independent costs of extraction. This implies that Country C can, endogenously, commit to staying in the Arctic once it has entered – the revenues cover the marginal cost of actually extracting. The question of course is whether it will have an interest in making such a commitment. If this were the case then there would exist no "all-out" equilibrium. To analyze this question, we need to know how many others need to enter in order for C to make a profit. Since, by assumption, $F + v(1) > \pi$, at least one other country is needed.

There are three cases to analyze: 1) $F + v(3) > \pi$; 2) $F + v(2) < \pi$, that is, one more entrant would make total profits positive for C; and 3) $F + v(2) > \pi > F + v(3)$, that is, C makes positive profits iff there are two more entrants.

Case 1 is trivial. The profits do not cover the total costs for C (hence, neither for any other country) independently of how many enter, implying the only equilibrium is one where all stay out.

We move now to case (2). Consider a group (1a) of period-3 subgames where C has entered in some earlier period but A and B have not. Country C will want to avoid such a subgame if both A and B playing "out" is the only NE. Such a subgame is depicted in normal form below.

Country A \ Country B	IN	OUT
IN	$\pi - F - v(3) - 3D_A, \pi - F - v(3) - 3D_B$	$\pi - F - v(2) - 2D_A, -2D_B$
OUT	$-2D_A, \pi - F - v(2) - 2D_B$	$-D_A, -D_B$

As can be seen, OUT/OUT is the only NE iff $\pi - F - v(2) - 2D_B < -D_B$, that is, iff B has sufficiently strong environmental preferences (because $D_B < D_A$, A's preferences are non-binding).

A second group (1b) of subgames to consider are those where both B and C have entered prior to Period 3 (though not necessarily simultaneously). We know C will stay in, but the question is whether B stays in or exits in Period 3. This static game between A and B is depicted below where we have subtracted F, being a sunk cost, from all payoffs of B. OUT/OUT is an NE here iff $\pi - v(2) - 2D_B < -D_B$ (again, since $D_B < D_A$, A's preferences are non-binding). In this case, Country 2′s overall payoff is $-F$, so that it will choose not to enter prior to Period 3. Suppose instead that $\pi - v(2) - 2D_B > -D_B$, then an entry by B prior to Period 3 is endogenously binding. Going backwards in time, we hence need to ask whether B will choose such a commitment. It will do so if either 1) B prefers to enter alongside C over letting C enter alone ($\pi - F - v(2) - 2D_B > -D_B$) and A does not follow a committed entry by B and C ($\pi - F - v(3) - 3D_A < -2D_A$); or 2) B prefers that all enter ($\pi - F - v(2) - 3D_B > -D_B$) and A does follow a committed entry by B and C ($\pi - F - v(3) - 3D_A > -2D_A$). That is, if B has sufficiently weak environmental preferences, then C can and will endogenously commit to enter, and B will follow and endogenously commit to entry as well.

Country A \ Country B	IN	OUT
IN	$\pi - F - v(3) - 3D_A, \pi - v(3) - 3D_B$	$\pi - F - v(2) - 2D_A, -2D_B$
OUT	$-2D_A, \pi - v(2) - 2D_B$	$-D_A, -D_B$

Subgames 1a and 1b cover the full set of possible subgames, hence this means that, in total under case (1) strong environmental preferences by B is "necessary and sufficient" for the existence of an all-out equilibrium.[44]

We move now to case (3), where C makes positive profits iff there are two more entrants ($F + v(2) > \pi > F + v(3)$). Here, there exists no all-out equilibrium iff C, after committing to entry, can count on the entry of both B and A. The conditions for this are the same as under (1b) above. This means that, again, strong environmental preferences of B are a prerequisite for the existence of an all-out equilibrium.

B3 Extension 3: Two-sided commitment

Suppose countries can commit to both actions (i.e., staying out and entering). Then no player has a first-mover advantage and the game boils down to the static game which could then be played in the first period. The possible equilibria and their conditions are outlined in Lemma 1. For any given final outcome for which there exists an equilibrium, there are of course other possibilities to reach that equilibrium than by committing in the first period. But there is no reason for any country to not commit in the first period if that would imply a worse equilibrium from its own point of view. Hence, as follows from Lemma 1, under such commitment assumptions the importance of countries that are intermediately concerned about the environment remains. A first-mover advantage of course disappears in a static setting.

B4 Extension 4: Only commitment to not enter

We finally consider the case where "out" is absorptive but not "in". To do this consider a game where countries can either enter (while retaining the right to later exit), stay out initially (while retaining the right to later enter) or commit to always stay out. Then the roles of A and C are reversed: A has a first-mover advantage by (sometimes) being able to push the final outcome to be in line with her preferences. Hence, the existence of various equilibria is also reversed. Unlike in the base case where "all in" is essentially always an equilibrium while "all out" is not, here "all out" would always be an equilibrium while "all in" would generally not be. However, the prominent role of B in being decisive for the existence of various equilibria remains: if B is sufficiently environmentally conscious, then an "all-in" equilibrium does not exist since A can start by committing to staying out for good on account that B would commit as well, thus finally discouraging C from entering. If B is not sufficiently environmentally friendly then A cannot count on this snowball effect. Thus the results, about the importance of B, resemble those of the base model.

Appendix C. Infinite time model with flow payoffs

Consider a model which goes over an infinite number of discrete time periods. Choices are simultaneous within each period, entry is absorptive and the payoffs of the main model ($\pi - c(1)$, etc.) are now per-period payoffs discounted by a per-period factor of $\rho < 1$.

We illustrate the workings of such a model (and its similarity and discrepancy with the main model) by solving it heuristically for a subset of parameter combinations. The basic parameter assumptions are as in the dynamic model: $\pi < c(1)$ and $D_A > \frac{\pi - c(3)}{3}$.

Consider first the case where $\boldsymbol{\pi} - \boldsymbol{c}(2) > \boldsymbol{D_B}$ and $\boldsymbol{\pi} - \boldsymbol{c}(3) < \boldsymbol{D_A}$ so that, in the main dynamic model the unique outcome is that B and C enter while A stays out (see Fig. 4). We will now show heuristically the additional conditions necessary so that entry at some point by B and C is the unique outcome.

Note first that there indeed exists an SPNE where B and C enter. For instance, the following strategies are an SPNE: A never enters; B enters in Period 1; C enters in Period 1. A's marginal payoff of deviating (given that B and C enter) is negative by the parameter assumptions made. Likewise B has a higher payoff of entering (given that C does) than staying out, thus does not deviate. Similarly for C.

To see whether entry (at some point) by B and C is unique we now check if an all-out equilibrium exists. First note that, by the assumption made on D_B, B would always follow if it observed an entry by C. Hence, any SPNE strategy has to include that B will enter upon observing C's entry.[45] Now consider the following strategies (where we ignore A, since it never enters anyway). B starts by staying out in period 1 and, in later periods, enters iff it has observed C or A to enter previously; C starts by staying out in period 1 and, in later periods, enters iff it has observed B or A to enter previously. The outcome of these strategies is that all stay out. Is it an SPNE? Consider C's strategy. By entering (that is, deviating) in the first period it knows B will follow. Hence C would by entering get payoff $\pi - c(1) < 0$ from the first period when it enters alone and then

[44] Strictly speaking, as can be seen, also the preferences of A matter here. However, for each possible environmental preference of A, it is necessary that B has strong environmental preferences for the existence of an all-out equilibrium. Furthermore, while the preferences of B always work in the same "direction" – the more it cares about the environment the more likely there exists an all-out equilibrium – the conditions on A are in different directions. Under case (1b) depending on the preferences of B, the existence of an all-out equilibrium sometimes requires that A is sufficiently clean (it would not follow entry by the others) and sometimes that it is sufficiently dirty (it would follow an entry by others). This can be seen by the analyzing the two groups of conditions under (1b).

[45] Unless B enters already in the first period.

a discounted stream of payoffs amounting to $\frac{\rho}{1-\rho} * (\pi - c(2)) > 0$. C would hence enter iff $\frac{\rho}{1-\rho} * (\pi - c(2)) > c(1) - \pi$, that is, iff $\rho > \frac{c(1)-\pi}{c(1)-c(2)}$. This condition is therefore necessary and sufficient for there *not* to exist an all-out equilibrium.[46]

The condition is interesting since it captures the nuance, not present in the main model, that C's first-mover advantage (that enables it to push for the equilibrium that it prefers) depends on its willingness to suffer an initial loss while waiting for the other(s) to enter as well. If it is willing to take that loss then entry is guaranteed (under the parameter restrictions in this example) as in the main model.

Now consider the case where $\pi - c(2) < D_B < \pi - c(3)$ and $\pi - c(3) < D_A$ so that, in the main dynamic model, the unique outcome is that all stay out. Note first that A's preferences are the same as in the previous example – it never enters. Note next that B would only enter if A and C did. Hence, since A stays out, so does B. In turn this implies that C stays out as well and that we have a unique all-out equilibrium as in the main game.

Comparing these two examples, where A's preferences are the same in both, we can note that the existence of an equilibrium with entry depends on B being sufficiently unconcerned with the environment. This echoes the result from the main model. The twist here is that, whether entry is the only equilibrium, also depends on C's willingness to take the initial costs of entering alone as discussed above. A similar logic applies for other parameter combinations thus maintaining our main conclusions of the paper.

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[46] Sufficiency was shown in the text. To see why the condition is necessary note that the condition is necessary and sufficient for C to deviate from all-out. For B to deviate it would need to get a positive payoff by doing so, which boils down to $\frac{\rho}{1-\rho} * (\pi - c(2) - 2D_B) > c(1) - \pi + D_B$ which clearly would require an even larger ρ. Thus the binding constraint is for C to not deviate.

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