THE LONDON SCHOOL
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POLITICAL SCIENCE

A SUPPLY-SIDE STORY OF OIL AND GAS

HOW FEAR OF THE FUTURE DICTATES BEHAVIOR TODAY

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DECLARATION

I certify that the thesis I have presented for examination for the MPhil/PhD degree of the London School of Economics and Political Science is solely my own work other than where I have clearly indicated that it is the work of others (in which case the extent of any work carried out jointly by me and any other person is clearly identified in it).

I declare that my thesis consists of 38,239 words.

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ABSTRACT

The aim of this dissertation is to determine the spatial and dynamic mechanisms that govern the supply of oil and natural gas. Specifically, the research evaluates how fear of the future affects behavior today and thereby it tests whether non-renewable resource owners behave in the forward-looking manner described by Harold Hotelling in the 1930s. Understanding what governs the supply of oil and natural gas is vital, as these fuels have significant economic and environmental implications for the planet. Integrating original research papers, the dissertation unfolds in seven chapters. The first and second chapters provide the foundation for the following research, by introducing the existing literature on oil and gas management. The subsequent three chapters discuss common pool problems as a method of identifying forward-looking behavior. Retaining this focus on weak property rights, chapter six evaluates the short-term relationship between government stability and oil extraction in authoritarian petro-states. The final chapter summarizes the main findings and outlines key implications. Drawing on new datasets and novel methodological tools, this dissertation demonstrates how fear of common pool problems governs exploration and extraction in the oil and gas industry today. However, contrary to conventional theory, this dissertation does not find that political instability motivates authoritarian regimes to accelerate their extraction.

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TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

Chapter 1.

Introduction

The energy generated from oil and natural gas keeps the wheels of industry turning and thus functions as the driving force behind the global economy. At the same time, however, the greenhouse gases associated with the use of these fossil fuels pose a threat to the natural environment that civilization depends on. As a result of this dilemma, understanding the mechanisms governing the supply of oil and natural gas is more pressing than ever. Drawing on novel datasets and new methodological tools, this dissertation demonstrates how forward-looking behavior plays a key role in the exploration for and production of oil and gas. This finding has important implications for both the optimal management of hydrocarbon resources and the effectiveness of current climate regulation.

This dissertation unfolds in seven chapters that integrate original research papers. Following this introduction, the second chapter provides a brief outline of the oil and gas industry and reviews the wider literature on resource management to which this dissertation seeks to add. Both dynamic and spatial aspects of recovery are discussed. Drawing on the seminal work of Harold Hotelling (1931), forward-looking behavior is introduced as a key theoretical concept in the management of oil and gas resources. Based on inter-temporal optimization, Hotelling demonstrated that non-renewable resource owners should only keep reserves *in situ* if resource prices are expected to increase at a rate at least equal to the return on the next best asset. This theoretical description of forward-looking behavior underlines the importance of future conditions in determining current extraction. However, as the literature review in this dissertation demonstrates, the predictive power of this dominant theoretical paradigm is uncertain and findings have remained inconclusive to date. This is partly because existing studies have been vulnerable to statistical problems related to data availability and omitted variable bias. There is thus a discrepancy between what theory predicts and what empirical findings reveal. It is this shortcoming that this dissertation seeks to address, by studying how owners behave when exposed to the risk of losing access to their resources.

Following a discussion of the background literature in Chapter 2, the dissertation proceeds in four main research chapters, each of which constitutes a discrete piece of work. Chapter 3 develops a new theoretical model that demonstrates how spatial competition affects the deployment of exploration wells. Based on the Ising model, borrowed from the field of ferromagnetism, the setup realistically mimics the way in which information about the location of resources propagates across space as exploration is deployed. The analysis shows that forward-looking behavior in combination with common reservoirs results in inefficient clustering of exploration and aggregate profit losses. These results are empirically testable and form the theoretical foundation for the subsequent two chapters, which use common pool problems as a method of identifying forward-looking behavior.

Chapter 4 empirically analyzes the distribution of wells around national borders and evaluates the extent to which the predictions of Chapter 3 apply in international oil and natural gas exploration. Borders drawn prior to the discovery of hydrocarbons are the focus of this investigation. This ensures that property demarcations are independent of oil and gas deposits, which allows using national borders as an exogenous treatment of common pools. In line with the theoretical predictions of Chapter 3, the analysis finds strong evidence of forward-looking behavior, as a significant clustering of wells is observed in areas without unitization agreements. This general result is then further investigated, by evaluating the distribution of exploration in countries with unitization agreements. Such transnational aggrements of joint development are found to result in a relatively larger share of exploration being located away from borders. This suggests that agents, in line with theory, seek to internalize informational gains from exploration.

By zooming in on Colorado’s natural gas industry, Chapter 5 evaluates how spatial competition affects the extraction of existing wells. Using novel panel data, it assesses how the production of a well responds to the arrival of new neighbors who potentially threaten future extraction. In line with Hotelling’s predictions about forward-looking resource owners, the analysis shows that “rivals” located in close proximity motivate accelerated extraction, whereas distant neighbors do not affect behavior. Whether real or only perceived, resource leakage occurring in common pools is thus found to alter the relative time preference of extraction and thereby distort gas production in Colorado. In sum, the empirical results in Chapters 4 and 5 highlight that forward-looking behavior occurs both in the exploration and production phase of resource management.

Finally, Chapter 6 evaluates the short-term relationship between government stability and oil extraction using monthly production data from 32 authoritarian petro-states. *Prima facie*, focusing on the role of political risk may appear to be in contrast to the three previous research chapters that analyze common pools. However, what both problems have in common is that owners fear not having access to their resources in future periods, which theoretically should motivate changed extraction today. It is this prediction of forward-looking behavior that is tested throughout this dissertation. Based on panel data, Chapter 6 finds no evidence of Hotelling behavior when evaluating month-on-month fluctuations in the oil extraction of authoritarian petro-states. Resource extraction is thus found to slow when regimes become unstable. In contrast to past assumptions (Bohn & Deacon, 2000), this suggests that government stability is an enabling factor for oil recovery even in the very short run. The conventional Hotelling principle, in other words, does not explain the observed relationship between extraction and stability. This opens up promising avenues for future research to establish what mechanisms govern the short-term behavior of authoritarian petro-states.

Chapter 7 of the dissertation summarizes the main findings, discusses their implications and proposes avenues for future research. Policy options to improve the management of oil and gas resources and current climate regulation are also examined.

REFERENCES CHAPTER 1

Bohn, H., and R. T. Deacon. "Ownership Risk, Investment, and the Use of Natural Resources." *The American Economic Review* 90, no. 3 (June 2000): 526-549.

Hotelling, H. "The Economics of Exhaustible Resources." *Journal of Political Economy* 39, no. 2 (1931): 137-175.

Chapter 2.

Literature review

This chapter offers a brief introduction to the oil and gas industry and reviews the wider economic literature on resource management to which this dissertation seeks to add.[1] Prior to evaluating existing academic research, it is important to establish the context for this literature: the global oil and gas industry. This chapter therefore begins by discussing recent statistics on the location and ownership of reserves as well as major production and price trends. Against this industry background, the chapter then proceeds with the assessment of economic research on oil and gas management.

2.1. Industry background

The oil and gas resources studied in this dissertation play a dominant role in international energy markets. Over the past 25 years, global energy consumption has increased by almost 60 percent. In 2014, oil and gas accounted for a staggering 57 percent of this consumption (BP, 2015). Over the next 25 years, the International Energy Agency (IEA, 2015) in their central scenario forecasts global energy consumption to rise by nearly one-third and oil and gas are predicted to continue constituting a significant share. It is against this backdrop that this dissertation studies the economic mechanisms governing extraction behavior.

Global oil and gas reserves are extensive but deposits are spatially concentrated and ownership is therefore a privilege of the few. At current production levels, existing oil reserves[2] could last for another 52.5 years. In the case of natural gas,

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[1] As subsequent chapters form independent pieces of work, they include separate references to relevant literature that may not be discussed in this review.

[2] Reserves are here, and in general, understood as the proven quantity of a resource that is recoverable at today's prices with today's technology and which is legally mineable.

this reserves-to-production ratio is 54.1 years (BP, 2015). The substantial size of known reserves highlights that physical scarcity is unlikely to become a concern within the foreseeable future. Furthermore, current reserves are not necessarily the upper bound for the global stock of oil and gas. Examples such as the American shale gas revolution, examined later in this dissertation, show that technological development constantly makes new resources accessible. For example, horizontal drilling in conjunction with hydraulic fracturing have made previously inaccessible fields profitable (Deutsche Bank, 2011). A more immediate worry is that the global distribution of resources is highly asymmetric. Due to the lack of homogeneity of the Earth's geological structures, reserves are thus concentrated in only a few countries. As presented in Figure 2.1, the former Soviet Union and the twelve OPEC countries[3] control more than 75 percent of both oil and gas reserves. On a country level, the largest oil reserves exist in Venezuela (17 percent) and Saudi Arabia (16 percent). Iran (18 percent), Russia (17 percent) and Qatar (13 percent) dominate global gas reserves.

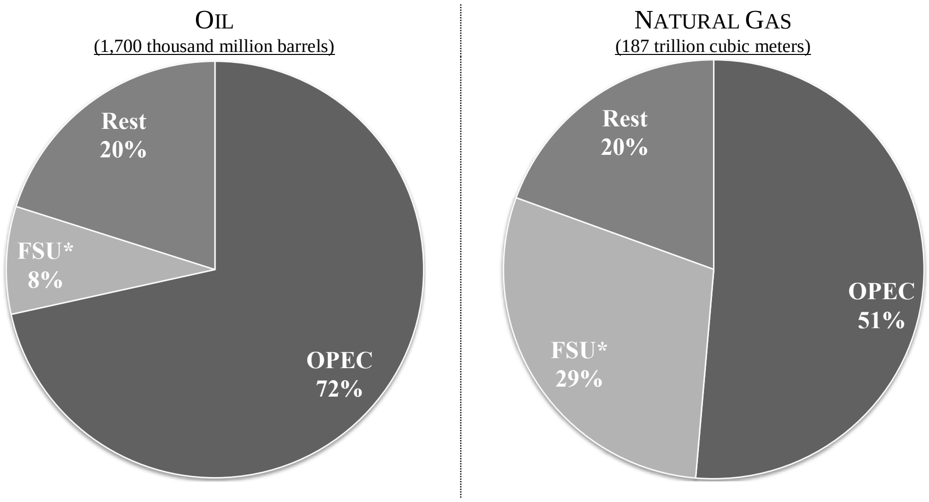

FIGURE 2.1. DISTRIBUTION OF GLOBAL RESERVES 2015

*Notes: *Former Soviet Union; Source:* BP, 2015; author.

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[3] Algeria, Angola, Ecuador, Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Saudi Arabia, UAE and Venezuela.

A common feature of the resource-rich countries in OPEC and the former Soviet Union is that their governments wield significant power over the extraction industry (Deutsche Bank, 2011). More broadly, it is estimated that governments and national oil companies (NOCs) own approximately 90 percent of all known oil reserves (IEA, 2012). The same pattern applies in natural gas where NOCs like Gazprom and Qatar Petroleum control significant reserves (Deutsche Bank, 2013). By comparison, international oil companies (IOCs) such as BP, Exxon Mobil and Shell only control a small share of resources. To understand general supply dynamics in the oil and gas market, it is thus important to identify the mechanisms governing the extraction behavior of governments.

Extraction predominantly occurs in reserve-rich areas. As Figure 2.2 illustrates, OPEC continues to dominate global oil production. At the end of 2014, the twelve member countries produced 41 percent of all oil in the world. The main producers outside OPEC are Russia and the US respectively, accounting for 13 and 12 percent of global production.

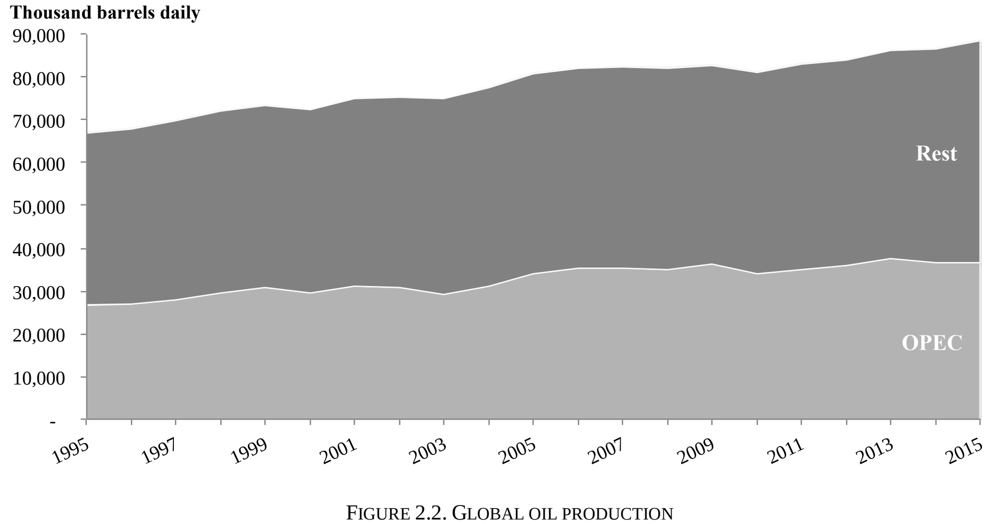

FIGURE 2.2. GLOBAL OIL PRODUCTION

Source: BP, 2015; author.

Figure 2.2 also shows that global oil extraction has been gradually rising with demand over the past 20 years. Despite this general trend, periods of economic downturn such as the 2007–08 financial crisis have temporarily dampened production. This highlights that growing oil and gas demand is dependent on continued economic growth. The principle underpinning this is that technological development, *ceteris paribus*, reduces the energy intensity of the global economy over time.

Production trends in natural gas markets have been less stable than in the oil industry. This is predominantly due to the introduction of new extraction technologies such as horizontal drilling and hydraulic fracturing. As illustrated by Figure 2.3, these technologies have enabled the USA to overtake Russia as the world's largest gas producer. In contrast to other big oil and gas producing countries, many small private companies dominate the American extraction industry (Deutsche Bank, 2013). As the US now accounts for 21 percent of global gas production, the behavior of relatively small producers has thus become increasingly important for global supply.

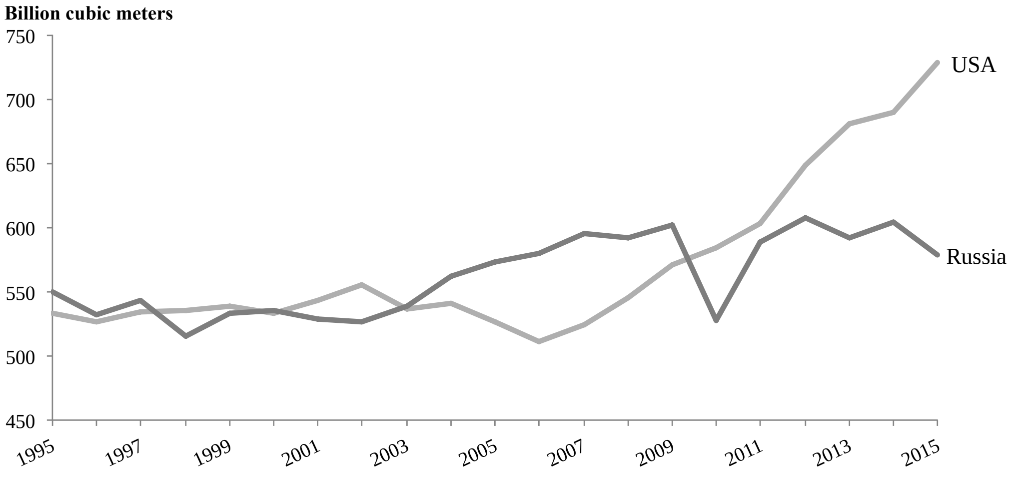

FIGURE 2.3. NATURAL GAS PRODUCTION

Source: BP 2015; author.

As illustrated by the discussion of production and reserves, OPEC plays a key role in the global management of hydrocarbon resources. Established in 1960, the official aim of this institution is:

> *"[T]o coordinate and unify the petroleum policies of its Member Countries and ensure the stabilization of oil markets in order to secure an efficient, economic and regular supply of petroleum to consumers, a steady income to producers and a fair return on capital for those investing in the petroleum industry".*
> (OPEC, 2015)

Functioning as an international oil cartel, OPEC seeks to achieve this aim by setting production targets for its member countries. However, history has shown that the members do not always follow these targets. This is because extraction reductions often conflict with the short-term economic needs of member states (Colgan, 2014). Despite this, the U.S. Energy Information Administration (EIA, 2015) concludes that OPEC continues to have significant market power even in current low price markets. When the organization reduces its production targets, oil prices thus tend to increase. Yet, it should be noted that this pattern is predominantly driven by the behavior of a single member, namely Saudi Arabia (EIA, 2015). Furthermore, the absence of a production cut in response to the recent lower oil prices suggests that OPEC's market power might be diminishing. Despite vague attempts by Russia and Iran (*The Wall Street Journal*, 2007) there remains no equivalent cartel institution in natural gas markets. OPEC is thus unique to the oil industry where, despite being weakened, it continues to act as a cartel producer (Lin, 2015).

In contrast to global production and reserve developments, oil and gas prices are notoriously volatile and therefore difficult to forecast even in the short run. As seen in Figure 2.4, the historical record shows substantial variability in spot prices for both oil and gas. This makes it complicated to forecast prices, which is illustrated by the recent collapse in oil markets. Almost nobody predicted that prices would fall from over $100 per barrel to less than $50 in the course of a few months. Despite this recent slump, IEA (2015), in their central scenario, predict that markets will rebalance at $80 per barrel in 2020 with prices increasing further thereafter. The financial crisis and the associated reductions in global demand for fuels explain the drop in prices observed in the middle of 2008. As oil and gas are partial substitutes, there is a certain degree of covariance between their prices. Modern technologies thus allow many users to switch between fuels meaning that if the price of one commodity rises too much they will change to the other. This effect of substitution ensures that oil and gas prices will not diverge completely.

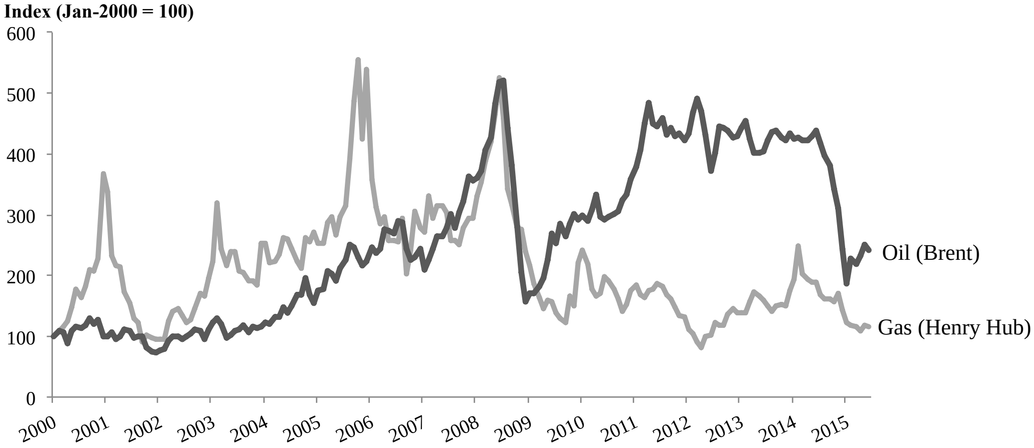

FIGURE 2.4. SPOT PRICE DEVELOPMENT

Source: EIA, 2015; author.

Allowing resources to move from wells to the end-users, transportation infrastructure is a key aspect of the oil and gas industry. As discussed earlier, hydrocarbons are mainly extracted in reserve-rich areas but these locations are rarely characterized by high economic activity. The majority of resources are therefore not consumed where extracted. Instead, there exists a significant trade of fuels between geographical areas. For both oil and gas, Asia Pacific, Europe and

North America are the big importers, whereas the Middle East, Africa and Russia are the big exporters. The European gas market illustrates these trade movements well. According to BP (2015), Russia exports 51 percent of its gas production to Europe via an extensive pipeline system. This has generated economic interdependencies between the two regions. Seaborne trade is an alternative and more flexible method of transporting oil and gas. However, tankers and LNG[4] ships are relatively expensive and therefore mostly used in situations where alternatives are not available. The imports of Japan, Taiwan and South Korea are a good example of this practice, as pipeline infrastructure does not exist in their region.

Another important step before raw resources can be sold to end-users is refining. This is especially true for oil, where crude is only marketable after having been refined into more useful products such as gasoline, diesel or asphalt. Refinery capacity is generally located in industrialized areas. The three most significant countries are the US, China and Russia which respectively account for 18, 15 and 7 percent of global capacity (BP, 2015). Although there has been excess global refinery capacity since the 2008 global financial crisis, significant regional differences persist in capacity utilization (Deutsche Bank, 2013). Older refineries can also not instantly alter the products emerging from the refining process. It is thus difficult to tailor regional production to meet market needs and it may be impossible for a refinery to satisfy local demands for a particular refined product even if spare capacity exists. As important links between the upstream production and end consumer markets, both refinery and transport capacity can thus make it challenging to adjust extraction rapidly. This is a key insight that will be discussed further in subsequent chapters.

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[4] Liquefied natural gas (LNG) is natural gas that has been converted to liquid form to ease storage or transport.

In sum, the above review highlights the economic importance of oil and gas and raises the question of what determines the extraction of these resources. The discussion of industry statistics clarifies that reserves are extensive but spatially concentrated, meaning that relatively few resource owners have significant power over global supply. Focusing on who these owners are, two main trends were identified. First, OPEC countries and their NOCs continue to dominate the industry and it is consequently vital to understand how governments make extraction decisions. Second, new technologies have changed global production patterns and made relatively small American companies increasingly important for supply. Despite the substantial differences between US companies and Arab oil sheikhs the economic literature has identified common mechanisms governing extraction behavior in general.

The remainder of this chapter will discuss existing academic research on resource management. Both oil and gas are non-renewable within any meaningful human time frame. Hydrocarbons are formed over thousands of years when layers of buried organic matter are exposed to intense heat and pressure. In contrast to timber or fisheries, hydrocarbons extracted today will, therefore, not be available within the foreseeable future. Recognizing this property, much economic research has been dedicated to determining at what rate resources should be extracted. Against this backdrop, the second section of this chapter introduces the existing literature on dynamic recovery. Another physical property that has guided economic research is that oil and gas are fluid. Unlike solid minerals, such as gold, hydrocarbons can migrate across space if underground conditions allow it. Accordingly, economists have studied the risk and consequences of spatially dependent common pool problems. Against this backdrop, the third section will review the literature on spatial aspects of recovery. The final section of this chapter situates the aims of this dissertation in the literature and maps out its core contributions.

2.2. Questions of timing

Current knowledge on when to extract oil and gas is dominated by the work of Harold Hotelling (1931). This original theoretical framework considers the problem of a non-renewable resource owner who seeks to maximize the present value of future profits stemming from extraction. Recognizing the finite nature of non-renewable resources, Hotelling stipulated that owners face a one-dimensional optimization problem, whereby the speed of extraction is the only decision parameter. The solution to this problem is known as the Hotelling rule and describes the time path of extraction that maximizes the present value of the resource stock:

$$(2.1) \qquad \underbrace{\frac{\dot{p}}{p}}_{Rate\ of\ return\ from\ resource\ in\ situ} = \underbrace{i}_{Rate\ of\ return\ from\ financial\ asset}$$

As an equilibrium condition, the Hotelling rule in Equation 2.1 states that non-renewable resource rents must increase at the rate of interest on financial assets. An optimizing resource owner will thus only keep reserves *in situ* if resource rents are expected to increase at a faster rate than the rate of interest on financial assets, the competing investment. If resources' rents increase at a rate less than the rate of interest, the owner should extract the entire remaining stock and sell it to invest in the best alternative asset. Arbitrage opportunities will thus temporarily arise if the Hotelling rule is not satisfied so, in equilibrium, Equation 2.1 must hold.

The Hotelling framework has been a profound contribution to the study of non-renewable resources as it outlines that owners should recognize that the opportunity cost of extraction today equals reduced recovery tomorrow. Another important insight of Hotelling's original research is that under perfect competition and appropriately set interest rates,[5] resource owners will engage in socially optimal extraction. Hotelling finds that resources will be extracted at a slower than optimal rate by monopolies. This follows from the monopolist’s trade-off between increased extraction and falling prices. Nonetheless, it is important to note that this result is dependent on the elasticity of demand (Stiglitz, 1975).

Despites its theoretical completeness, the original Hotelling model has been criticized for being overly simplistic in its description of non-renewable resource markets. The original model assumes that extraction is costless, independent of the remaining stock and that joint production[6] does not occur. Furthermore, it is assumed that both the stock and demand is known and fixed over time. Most of these assumptions do not apply in actual non-renewable resources markets. The original theoretical framework has therefore been expanded significantly since its inception. Important contributions include models that account for exploration dynamics (Pindyck, 1978; Pesaran, 1990), endogenous research and development (Kamien & Schwartz, 1978; Lin *et al*., 2009), uncertainty (Hoel, 1977; Pindyck, 1980; Reynolds, 2013), joint production of oil and natural gas (Pindyck, 1982), market imperfections (see Khalatbari, 1977; Polasky, 1992; Stiglitz, 1976; Sweeney, 1977), insecure property rights (Bohn & Deacon, 2000) and different stock effects in extraction costs (see Farzin, 1992; Hanson, 1980; Rouillon, 2013; Solow & Wan, 1976). Furthermore, the theory has been applied to timber prices despite forests not traditionally being considered non-renewable resources (Salant, 2013). All of these models have refined the original Hotelling framework and improved its applicability to real-life scenarios.

Economic research on optimal extraction has also had theoretical implications outside the narrow arena of oil and gas recovery. For example, German economist

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[5] Social and private interest rates must be aligned.

[6] Examples of by-products are air and soil pollution but also the joint production of oil and natural gas.

Hans-Werner Sinn draws on the Hotelling framework in his argument that the forward-looking behavior of resource owners might jeopardize the effectiveness of existing climate regulation (Sinn, 2008). In what he dubs the ‘Green Paradox’, Sinn outlines why a gradual expansion of demand-reducing regulation can exacerbate the problem of anthropogenic climate change: Existing climate policies induce expectations of falling future demand and prices, which incentivize resource owners to extract more of their fossil fuels today. The result is that emissions, and consequently climate change, are accelerated. Hotelling’s description of forward-looking non-renewable resources owners thus has significant theoretical implications for oil and gas market participants and climate change regulators alike. Yet the theoretical insights gained are only relevant if the Hotelling rule actually applies in real-life non-renewable resource markets.

A number of scholars have attempted to assess the empirical validity of the Hotelling framework but their findings have been inconclusive and vulnerable to criticism. Constant shocks and changing expectations in real non-renewable resource markets make it challenging to assess whether owners act as predicted by Hotelling theory. Disentangling a potential trend from the constant fluctuations observed in actual market data is thus difficult. For example, contrary to Hostelling’s classic description, resource prices have not uniformly increased over the past 125 years (see Pindyck, 1999; BP, 2015, p. 15). Slade (1982) explains this pattern as a combination of exogenous technical change and gradually increasing scarcity. Her model suggests that non-renewable resource prices should have a U-shaped time path. This is because technological advances, combined with economies of scale, initially reduce extraction costs and thereby prices. However in the long run, scarcity implies that extraction costs will eventually increase and this results in surging prices. An alternative explanation for the observed price volatility could be that resource owners simply re-evaluate their expectations and thus their Hotelling extraction behavior. New discoveries are an example of what might trigger such expectation adjustments (Livernois, 2009). The difficulty with testing this hypothesis is that data on resource owner expectations are not easily available. Empirical work is therefore largely forced to rely on indirect testing procedures, which complicates assessing the empirical validity of Hotelling theory (Withagen, 1998).

Most works within the empirical Hotelling literature are time series-based tests of the relationship between resource prices and interest rates (e.g. Heal & Barrow, 1980; Smith, 1981). The results of these tests have not been supportive of the Hotelling principle (Halvorson & Smith, 1991). Miller and Upton (1985) together with Krautkraemer (1998), however, argue that these tests suffer from limited data availability, which risks undermining the trustworthiness of their results. Their critique specifically concerns the use of market prices instead of net prices.[7] The predictions of the Hotelling framework are based on net prices. Yet, the lack of knowledge concerning marginal extraction costs means that these are often unobservable in practice. This problem of data availability has resulted in the reliance on market prices as a proxy for net prices, which can lead to systematic measurement errors. Alternatively, others have used estimated *in situ* resource prices[8] and found these follow the price trends predicted by Hotelling's rule (Miller & Upton, 1985). However, the approach of using *in situ* prices has its own statistical caveats. Adelman (1990) argues that this method overvalues the non-renewable resources, as the *in situ* prices used neglect development costs.

The restricted cost function approach used by Halvorson and Smith (1991) and later Chermak and Patrick (2001) offers an alternative method of testing Hotelling theory. Similar to that of Miller and Upton (1985), their approach utilizes the prediction that the value of underground resource deposits should increase at the

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[7] Net prices are market prices minus the marginal extraction costs.

[8] *In situ* prices are estimated prices on underground deposits based on the stock market price of extraction firms adjusted for their liabilities and non-resource assets.

rate of interest. The authors test this prediction of Hotelling theory by estimating the shadow prices of the resource stock using an indirect cost function. Whilst Halvorson and Smith (1991) rely on macro data from the Canadian metals industry, Chermak and Patrick (2001) use panel data from 29 natural gas wells. Neither study finds evidence in support of the Hotelling rule. However, their tests rely on relatively small samples, which limit the explanatory power of their analysis. Furthermore, both studies use *ex post* interest rates. This is problematic, since actual resource owners base their behavior on expectations. Consequently, *ex ante* interest rates would be more representative but corresponding data are not easily available.

In sum, the above discussion clarifies that limited data availability undermines the effectiveness of existing empirical tests. The fact that findings remain inconclusive across existing studies suggests that some of the research suffers from statistical problems. Withagen (1998) even concludes that empirical tests of the Hotelling rule, in any of its current formulations, are bound to encounter difficulties. It thus remains unclear whether resource owners extract in a forward-looking manner as predicted by Hotelling theory. This poses a wider dilemma for economic research on resource extraction, as the validity of influential theories such as the Green Paradox remains ambiguous. To resolve this current impasse, further research is needed that uses new datasets and methods to explore the underlying mechanisms driving dynamic extraction behavior.

2.3. Questions of space

Despite playing an important role in actual oil and gas production, spatial considerations remain absent from the Hotelling framework of non-renewable resource extraction. Considering other strands of literature is therefore necessary in order to provide a nuanced understanding of the mechanisms governing the supply of hydrocarbons. A natural place to start this investigation is Hotelling's 1929 model of a spatial market. Originally developed to demonstrate the relationship between location and pricing behavior of firms, the model considers a market where consumers are distributed evenly along a straight line of unit length. However, the framework has diverse applications. Within the resource literature, the line model has been used to study product differentiation in exhaustable resource markets (Koldstad, 1994). Returning to questions of geographic space, there are two spatially-dependent externalities that might affect how owners manage their oil and gas resources. First, a so-called "extraction externality" is present as underground resources can leak between owners when production is spatially clustered. Second, an "information externality" can occur in exploration, as the shared geology of reservoirs makes it more likely to find resources in areas surrounding past discoveries. To grasp how spatial aspects affect oil and gas supply, this section reviews the existing literature on these two externalities.

The reservoirs studied as part of this dissertation can cover hundreds of square kilometers. This means that a deposit is rarely the sole property of a single owner and underground passageways can allow fluid resources to flow across property lines. Some oil and gas reserves are, as a result, non-excludable and share properties with resources such as fisheries. The literature on this type of mobile resource provides insights on how common pool problems might jeopardize the efficient management of oil and gas resources. For example, Gordon (1954) shows that an open access fishing ground would incentivize each individual fisherman to fish until the average product equals marginal costs. As a consequence, the profitability of the fishing ground would converge to zero. This inefficient outcome occurs because individual fishermen do not have a private incentive to account for the effect current extraction has on future yields through reduced stock. This insight is transferable to shared oil and gas reservoirs, where extraction externalities encourage inefficiently high recovery rates and excess investments in extraction capital (Khalatbari, 1977; Libecap & Wiggins, 1985). An associated effect of this rush for resources is that overly rapid extraction may damage the reservoir and reduce total physical recovery (Chermak & Patrick, 2001). The consequences of a spatial extraction externality are thus not limited to economic inefficiencies but can also include physical ones.

Models from the literature on groundwater management provide an improved description of common pool problems. The studies discussed so far have treated resources as static and uniform and thus do not explicitly model how fluids move across space. This simplification is problematic, as oil and gas resources do not travel unconstrained underground. To counter the shortcomings of existing one-dimensional models, Alley and Schefter (1987) build a multi-cell system to study groundwater resources. Their setup has the advantage that it explicitly models the horizontal flow of liquids across space. The authors thus provide a more sophisticated description of fluid resources such as water or oil and gas. Building on the idea of a multi-cell system, Brozović *et al*. (2010) explicitly model the spatial distribution of water wells and conclude that this design makes water resources less of a public good. Traditional one-dimensional models thus overestimate the risk and consequences of common pool problems. Drawing on the groundwater literature, it is clear that two-dimensional spatial models are necessary to decompose the implications of an extraction externality. This dissertation transfers these insights to the spatial deployment of oil and gas wells to compensate for the lack of research on this topic.

Despite the limitations of the existing literature, it is evident that the fluid nature of oil and gas can lead to economically inefficient outcomes and even armed conflicts. Spatial extraction externalities thus result in aggregate welfare losses, which could be avoided if reservoirs were managed as single entities. This raises the question of why common pools might remain. Drawing on the "Coase theorem”,[9] externalities, such as those present in common reservoirs, can be internalized if trade is possible and transaction costs are sufficiently low. However, a Coasian bargaining process does not always result in an efficient outcome in the oil and gas industry. One reason for this is that enforcement is often weak. An implicit assumption of the classic Coase Theorem is that property rights are respected. This might apply within sovereign states; however, oil and gas reservoirs often exceed national boundaries. This is problematic because there is no international governing body with the authority to enforce cross-border property rights and resources might therefore be contested by neighboring countries. Caselli *et al.* (2014) show that conflict is more likely when at least one country has natural resources; when the resources in the resource-endowed country are closer to the border; and, in the case where both countries have natural resources, when the resources are located asymmetrically vis-a-vis the border. However, national borders are not a necessity for resource wars. Morellia and Rohner (2015) thus find that civil wars are more likely when resource concentration and ethnic group concentration are high. However, even if conflict is avoided, the management of resources is complicated by the fact that underground oil and gas flows are difficult to monitor in practice. The challenge of cross-border externalities is, however, not unique to oil and gas extraction but has been discussed extensively in the context of international environmental problems (e.g Guruswamy *et al*., 2012).

The challenge of international enforcement is not the only reason why common pool problems might persist. An alternative explanation could be that the net benefits of unifying the management of reservoirs are too low (Demsetz, 1967). This argument has been challenged by examples of successful unification

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[9] The “Coase Theorem” is commonly accredited to Coase (1960). However, Ronald Coase himself attributed the theorem to George Stigler and criticized it for describing an unrealistic theoretical situation where transaction costs are zero.

agreements[10] in the American oil and gas industry (Libecap & Smith, 1999). Despite these positive cases, numerous examples remain where common pool problems do persist. By analyzing fields in Oklahoma and Texas, Libecap and Wiggins (1984) conclude that unification agreements are unlikely in areas with many producers. This can be attributed to high bargaining costs but may also be explained by land heterogeneities and producers having diverging views on how to share production (Wiggins & Libecap, 1985).

There are even some agents who might benefit from continued common pool problems. As argued earlier, the theoretical implication of spatial competition is that resource owners are incentivized to accelerate extraction. This is socially inefficient but some agents, such as drilling operators, petroleum engineers and geoscientists, stand to gain from the excess capital investment needed to accelerate production (Weitzman, 1974). These diverging interests might further complicate a contractual solution to existing common pool problems. If a unification agreement is not reached, Yuan (2002) shows that it is individually rational for landowners to subdivide their landholdings and delegate production to many competing firms. This behavior further increases the efficiency loss of common pools but, as highlighted by this section, it remains difficult to internalize extraction externalities.

Resource leakage is not the only spatial challenge facing the effective management of resources as information externalities have also been identified as playing an important role in applied oil and gas exploration. Knowledge about the exact location of underground deposits is incomplete and exploration therefore occurs under considerable uncertainty. The geology of hydrocarbons, however, entails that resources tend to be spatially correlated. This means that a resource owner is more likely to find oil and gas in areas of past discoveries than in

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[10] Unitization agreements are legal agreements whereby the leaseholders of a common reservoir merge their leases and operate the field as a single entity.

unexplored ones. The shared geology of the reservoir means that exploration outcomes are more highly correlated in the case of common pools (Porter, 1995). This has important implications for the deployment of exploration, as a well yields not only the oil and gas it can produce; it also generates valuable information about its surrounding geology. The exploration of neighbors thus provides owners with useful insights about the expected location of resources on their own lands. As drilling is costly, there can be a private incentive to postpone exploration until the respective neighbors have deployed. This can lead to a strategic waiting game, whereby common reservoirs are inefficiently explored (Isaac, 1987; Hendricks & Kovenock, 1989; Hendricks & Wilson, 1995). The empirical evidence of such slowed exploration, however, remains inconclusive. Hendricks and Porter (1996) find supportive evidence using data from the Gulf of Mexico. However, focusing on the same region but using a different measure of neighbors, Lin (2009) finds no evidence of inefficient petroleum exploration. These mixed findings might be attributed to the counteracting effect of the extraction externality. Engaging in a strategic waiting game can thus be too costly, as a neighbor in the meantime can extract oil and gas from underneath one's land. Although this clarifies the importance of understanding the interplay between spatial externalities, there are no theoretical models in the existing literature that capture these relationships. To make headway in this area, a new model design that accounts for both extraction and information externalities is introduced in this dissertation.

2.4. Conclusion and contributions

This chapter analyzed the literature on oil and gas management and identified a series of caveats that this dissertation seeks to address. Timing and space were introduced as the two key dimensions governing the recovery of oil and gas resources. Against this backdrop, Chapters 3 and 4 focus solely on spatial aspects, whereas Chapters 5 and 6 test the dominant theoretical paradigm on dynamic recovery of non-renewable resources.

The literature review identified extraction and information externalities as important spatial factors that influence the recovery of oil and gas. Despite this significance, most theoretical models have assumed that resources are uniform. This closes off the possibility of offering explicit depictions of spatial phenomena, which may explain why empirical findings remain unclear to date. As discussed, the groundwater literature offers notable examples of two-dimensional spatial models. Nonetheless, these only account for an extraction externality and thus ignore knowledge spillovers from exploration. To counter this shortcoming, Chapter 3 of this dissertation derives a novel model that incorporates both extraction and information externalities. Resting on principles of physics, this two-dimensional theoretical framework is unique in its ability to describe the deployment of exploration wells across space. To test the empirical relevance of this proposed framework, Chapter 4 evaluates the deployment of exploration around national borders. A shortcoming of the two-dimensional model introduced in Chapter 3 is its computational complexity. As a result, classic game theoretical solution concepts such as the sub-game perfect Nash equilibrium are not easily applied. To test the proposed framework, the model is therefore simplified to describe oil and gas exploration along a line. Consisting of two agents, this setup is a good representation of neighboring countries separated by a joint border. Using this insight, Chapter 4 tests the extent to which extraction and information externalities affect oil and gas recovery by comparing observed exploration development with that predicted by the theoretical model.

On the dynamic recovery of non-renewable resources, Hotelling theory was introduced as the dominant theoretical paradigm. Yet the literature review highlights that the empirical evidence supporting this framework remains limited.

To address this shortcoming, Chapters 5 and 6 test whether resource owners do indeed accelerate recovery when their future extraction is threatened. As becomes clear from the industry statistics discussed earlier, the increase in American shale production has significantly altered global supply dynamics. It was shown how many small private resource owners characterize this new and increasingly important industry. Against this backdrop, Chapter 5 analyzes how spatial competition affects the extraction of existing private gas wells in Colorado. The test is based on the hypothesis that new neighbors may jeopardize future extraction, which, drawing on the Hotelling framework, should lead to accelerated extraction. By testing this theoretical prediction in the context of Colorado, Chapter 5 assesses the empirical relevance of Hotelling theory in the new and growing American gas industry.

Focusing solely on the behavior of private extraction companies is, however, too limited. The discussion of industry statistics clarified that the majority of known oil and gas reserves remain government-owned. It is therefore crucial to understand what governs the extraction behavior of this type of agent. To do so, Chapter 6 analyzes how government stability affects oil extraction in authoritarian petro-states. Although this question has been investigated previously (see Bohn and Deacon, 2000), this dissertation is the first to employ relatively high frequency monthly data. This method improves existing research by bringing to bear its capability to identify responses to fast-developing political events.

In sum, this dissertation makes four important contributions to the existing literature. First, it introduces a new theoretical model that describes the spatial interplay between extraction and information externalities. Second, it tests the empirical validity of this framework, using global exploration data. Third, this dissertation evaluates the empirical validity of Hotelling theory in the growing American gas industry. Fourth, it is the first to use high frequency data in the analysis of how government stability affects oil extraction in authoritarian petro-states. Combined, these four dimensions offer a way forward to address key limitations that have obstructed economic research on oil and gas management in the past. In doing so, this dissertation seeks to advance our understanding of a recurring question among resource economists and practitioners: What mechanisms determine actual extraction decisions?

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Chapter 3.

Spatial rules of attraction in petroleum extraction

By THOMAS BLIGAARD NIELSEN AND THOMAS SCAFFIDI*

This chapter introduces a two-dimensional model that demonstrates how spatial competition can lead to a clustering of exploration wells and thereby the socially inefficient underprovision of geological information. The setup consists of two agents competing over access to a fluid resource such as an oil or gas reservoir. In line with real-life scenarios, knowledge about the location of resources is incomplete and propagates across space as exploration is conducted. To replicate this effect, the Ising model of ferromagnetism, commonly used in physics, is employed. Based on conditional probabilities generated by Bayesian inference, agents alternate in deciding whether and where to deploy wells. Using Monte Carlo simulations, two competing strategies of exploration are compared. The analysis shows that common reservoirs can cause inefficient clustering of exploration and aggregate profit losses. To avoid this adverse outcome and secure sufficient provision of geological information, practitioners are recommended to implement spacing regulation, unify the management of reservoirs or apply appropriate taxes.

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Maximizing the economic value of oil and gas resources requires addressing both dynamic and spatial considerations. Many studies have previously addressed the question of when to extract (e.g. Hotelling, 1931; Vousden, 1973; Pindyck, 1980) but the question of where to drill has received less theoretical attention. This is problematic because many oil and gas reservoirs have common pool characteristics, which makes spatial considerations key for their effective management. This chapter aims to address this analytical void by developing a novel two-dimensional model to study the question of where to deploy exploration. Integrating insights from the field of ferromagnetism, the model is unique in its ability to replicate the propagation of information across space, as wells are deployed. This makes it possible to show how non-cooperative interaction between resource owners adversely affects exploration. Common reservoirs are thus demonstrated to motivate clustering around property lines at the expense of a socially more efficient spacing of wells.

Harold Hotelling (1931) showed that non-renewable resources such as oil or gas reservoirs could be efficiently managed from a social perspective if resource owners act as price takers, private discount factors are in line with social ones and property rights are perfectly defined. However, property lines or even national borders do not confine hydrocarbon deposits and entire reservoirs are rarely the sole property of a single owner. This would not be problematic if oil and gas remained in place like gold or iron ore deposits do. Yet, the fluid nature of hydrocarbons means that extraction can cause resources to cross property lines. Such an extraction externality implies that owners cannot exclude their neighbors from accessing *in situ* resources. Insights from the literature on fisheries highlight why such a common pool situation is problematic. Gordon (1954) demonstrated how the open access of fisheries motivates the entrance of boats until profits are driven to zero. This insight is transferable to oil and gas, where competing rights to the common pool encourage inefficiently high extraction rates (Khalatbari, 1977; Libecap & Wiggins, 1985). Hotelling's prediction of efficient management thus collapses, as in practice agents do not have a private incentive to account for the effect current extraction has on future yields through reduced stock.

Imperfect property rights associated with resource leakage are not the only challenge facing the effective management of common reservoirs. Information externalities also play an important role in applied oil and gas exploration. Most countries require proprietary seismic data to be publicly disclosed after a certain confidentiality period (see Oil & Gas UK, 2011). Nonetheless, knowledge about the location of resources ("information" henceforth) remains incomplete and firms face considerable uncertainty when deploying exploration wells. Oil and gas deposits are, however, spatially correlated across property lines in the case of common pools (Porter, 1995). The shared geology of the reservoir thus renders it relatively more likely to find hydrocarbons in areas of past discoveries than in unknown ones. Figure 3.1 illustrates this empirical observation for the case of the Wattenberg field in Colorado, USA.

The spatial correlation of oil and gas has important implications for the social efficiency of exploration because a well yields not only the hydrocarbons it can produce; it also generates valuable information about its surrounding geology. Information has widely been considered a public good (see Samuelson, 1954; 1958). However, the value of geological information arises when it informs future drilling, which puts it in the realm of private goods. Many economists have thus argued that additional information about a market creates economic value through its use and this makes it rivalrous and excludable (see Boulding, 1966; Demsetz, 1967; Marshall, 1974; Stigler, 1983). However, unlike conventional private goods, such as chocolate bars and cars, information has unique features which can jeopadise the social efficiency of its supply (Arrow, 1962; Hall, 1981). In the context of oil and gas drilling, the exploration of neighbors provides owners with useful insights about the expected location of resources on their own lands. This spatial externality is uncompensated and because drilling is costly, the marginal cost of generating information is not equal to the private marginal benefit. As highlighted by Coase (1974) this can lead to a chronic underprovision of information. Furthermore, there is a private incentive to postpone exploration until the respective neighbors have deployed. In isolation, the information externality can thus lead to a strategic waiting game, whereby common reservoirs are inefficiently explored (Hendricks & Porter, 1996). However, one cannot study information and extraction externalities separately.

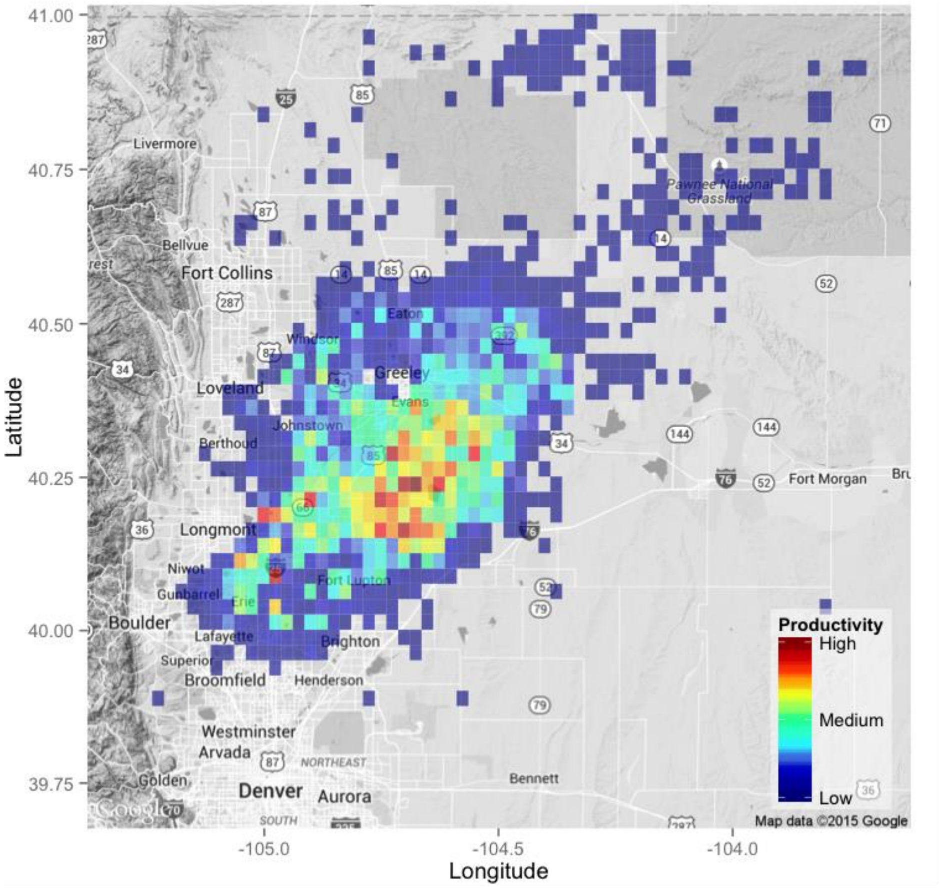

Figure 3.1. Gas output per land unit (Wattenberg Field, Colorado 2013)

Source: Based on gas production data from COGCC (2014) and mapping data from Google Maps (2015)

The literature on the strategic implications of extraction and information externalities is extensive, yet the empirical evidence remains inconclusive. For example, Lin (2009) finds no evidence of strategic interaction when studying exploration in the Gulf of Mexico. This could be because the effects of spatial externalities go in opposite directions. Waiting for information is thus costly, as leakage through the extraction externality can occur in the meantime. The failure to identify a net impact may hence be attributed to the two externalities canceling out. This suggests that the theoretical description of spatial interaction, on which the existing empirical work rests, is overly simplistic. Current studies have not explicitly accounted for the two-dimensional nature of space. Hendricks and Porter (1996) quantified the effect of neighbors using the area boundaries drawn by the US federal government. Similarly, Lin (2009) used simple distance measures. Yet, exploration is a spatial problem where reservoirs differ significantly. This affects the distance over which extraction and information externalities apply. Shale gas extraction, for example, tends to be relatively confined in spatial terms leading to short-distance extraction externalities (Davies *et al.*, 2012), whilst long-distance information externalities may remain.

To address limitations in the exiting literature, this chapter introduces a two-dimensional model capable of realistically describing the interplay between information and extraction externalities across space. The latter of these externalities is modeled by introducing incomplete property rights in a border area. To imitate the spatial correlation of resources found in reality, the Ising model (Ising, 1925) is deployed. The use of this well-studied model, drawn from statistical physics, allows replicating two-dimensional resource landscapes as illustrated by Norberg *et al.* (2002). Agents are modeled to correctly update their expectations concerning the likely location of resources by Bayesian inference using knowledge about the Ising model as input. Consequently, agents learn about the location of resources as exploration is deployed. The caveat of modeling the spatial propagation of information in this two-dimensional fashion is that no analytical solution exists. Deriving the exact optimal strategy of exploration therefore requires computationally complex numerical simulations that are beyond the scope of this chapter. Instead, two competing strategies that represent archetypal attitudes towards exploration are compared. Both strategies are chosen to account for the informational spillovers arising from exploration. They thus rest on the same fundamental principles and the only difference is that one gives preference to exploration of contested resources. Using Monte Carlo simulations these two archetypical strategies are then compared in different combinations and predictions about profitability and well clustering are deduced.

This chapter makes several important contributions. First, it offers an explicit physics-based method to model information and extraction externalities. In doing so, the chapter is the first to realistically replicate the propagation of information across a two-dimensional space thereby allowing better predictions. Second, the work illustrates how non-cooperative behavior affects profits through the spatial distribution of wells. As a result, this study provides new avenues for empirical analysis into the underprovision of geological information. Third, it allows the identification of how the range of resource leakage affects the aforementioned parameters and how policymakers should react. Despite the focus on a natural resource problem, the application of this cross-disciplinary framework is not limited to the oil and gas industry but relevant to a wide category of investment problems. On a broader scale, the model introduced in this chapter can thus be used to analyze other investment problems where information externalities and contest over assets apply.

The chapter unfolds in four sections. Section One introduces the theoretical model. Section Two presents the strategies of exploration. The numerical results obtained from the Monte Carlo simulations are presented in Section Three and Section Four provides policy recommendations and concluding remarks.

3.1. Model

The setup consists of two neighboring agents who share joint borders and sequentially decide whether and where to deploy their next well. These agents are identical apart from their exploration strategies. Both are risk-neutral, can access the same exploration technology and have no preference regarding the timing of revenue flows.[11] In every sequential move (‘turn’ henceforth), the agent chooses between different potential drilling sites. Exploring each of these so called “tiles” can either result in a successful discovery or finding it empty. To capture the cost of drilling, discovery is calibrated to yield one unit of profit, whereas unsuccessful exploration is set to result in a negative profit of one. The specific landscape used in this chapter consists of twelve-by-twelve tiles and is presented during different stages of exploration in Figure 3.2.

To replicate the extraction externality, the twelve-by-twelve grid is divided into resources which are governed by perfect property rights and resources which are accessible to both agents. As seen in Figure 3.2, there are thus resources which only agent A can extract ($\forall \in [A]$), resources that only agent B can extract ($\forall \in [B]$) and a contested pool of resources which both agents can access ($\forall \in [C]$). This allows for replicating that resources close to property lines are more likely to leak between neighbors than ones that are further away. The design also makes it possible to adjust the range of extraction externalities, by changing the relative size of the contested area. For technical reasons, the landscape is modeled on a torus. This means that the top and bottom borders, as well as the borders on the left and right sides of the twelve-by-twelve grid, are connected. To ease the understanding of this modeling method, it is useful to imagine the setup as a

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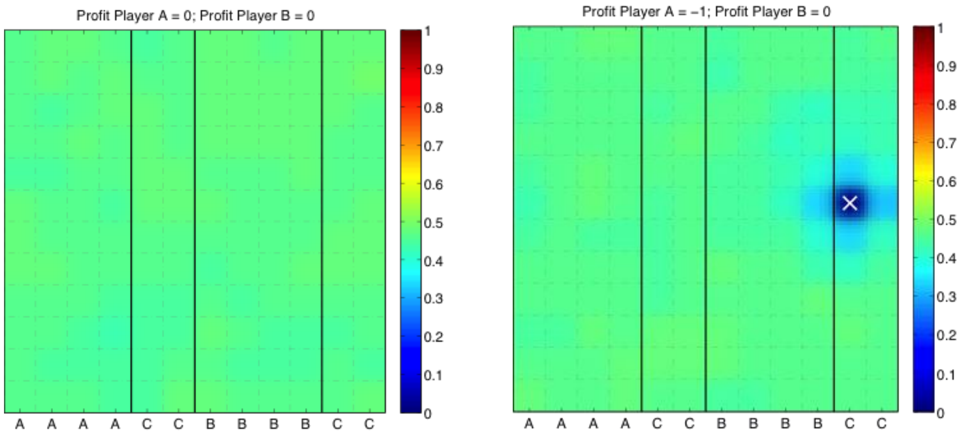
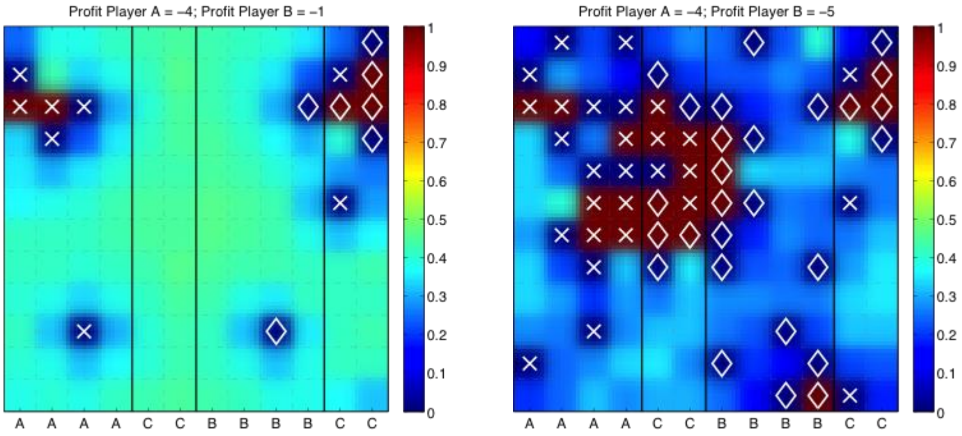
[11] A discount rate of zero allows the isolating of spatial effects from questions of timing, which have been extensively studied by Hotelling and others. Section 3.3.B discusses the implcations of incorporating more realistic temporal preferences.

scenario in which a resource owner has neighbors on each side. Using a torus allows replicating this setup but eliminates boundary problems and reduces computational requirements when conducting numerical simulations.



(STARTING POINT) (AFTER 1 TURN)



(AFTER 15 TURNS) (END OF EXPLORATION)

FIGURE 3.2. INFORMATION AT DIFFERENT STAGES OF EXPLORATION

Notes: The plots are based on both agents playing the “indifferent strategy” (introduced later). The tiles that have already been drilled are marked with a cross for agent A and a diamond for agent B. The color of these explored tiles is dark red in the case of a resource discovery and dark blue when the well is dry. All unmarked tiles correspond to sites that have not yet been drilled. Their color identifies the conditional probability of them containing resources according to the color scale presented to the right of the figures. These probabilities are generated through Bayesian inference, given all previous drillings. The letters at the bottom of the graphs signify the property rights governing that column of tiles. An “A” (resp. “B”) indicates that the resources in that column are only accessible to agent A (resp. B) whereas a “C” denotes contested resources, which both agents can access.

To imitate the spatial correlation of oil and gas resources, we employ the two-dimensional Ising model (Onsager, 1944). Borrowed from the field of ferromagnetism, this model was originally designed to capture the physics of magnetic moments (spins) with a binary set of possible states (up or down). Placed on a square lattice, these magnetic moments interact with their direct neighbors. This interaction makes it thermodynamically favorable to have clusters of magnetic moments with the same state. The specific phase of the Ising model used in this chapter is the so-called "paramagnetic phase", for which clusters are statistically distributed over space with an average cluster size determined by a "temperature" parameter. A magnetic field can be applied everywhere on the grid thereby statistically favoring one spin orientation (say up) over another (down). By altering a "magnetic field" parameter, one can thus adjust the unconditional probability of a given state.

Changing the terminology of the Ising framework allows for replicating the spatial distribution of resources found in reality. Each tile on the twelve-by-twelve grid, presented in Figure 3.2, can either contain hydrocarbons or not, corresponding to the magnetic moment being up or down in the Ising model. The fact that neighboring magnetic moments, on average, prefer to be parallel means that hydrocarbon resources tend to be spatially clustered, forming what could be understood as lakes in geological terms. The original "temperature variable" now governs how correlated resources are across space, or in other words the average size of reservoirs. Correspondently, the "magnetic field" variable controls the unconditional probability of successful discovery, meaning the uniform default probability of finding hydrocarbons on a given tile when no knowledge pre-exists. In practical terms, this would relate to the average resource concentration for the given region. Adjusting the "temperature" and the "magnetic field" variable in the original Ising framework thus allows for simulating different resource landscapes. The interested reader is refered to Appendix A for a detailed introduction to the

Ising model and the stochastic process that generates the spatially correlated resource landscapes.

We assume that agents know both the unconditional probability of discovery and the average size of hydrocarbon reservoirs. The values of both the “temperature” and the “magnetic field” parameters in the original Ising framework are thus assumed to be public knowledge. Initially, when no well has been drilled, the probability of finding hydrocarbons is the same on any tile and is equal to the unconditional probability. The fact that the occurrence of resources is correlated across space implies the following: If a well is drilled and a discovery is made, the surrounding tiles have a higher probability of containing hydrocarbons than tiles far away for which information is much poorer. Using the knowledge about the unconditional probability of discovery, the average size of hydrocarbon reservoirs and that resources are distributed according to the Ising model, agents are able to compute the conditional probability of finding hydrocarbons on any tile in the system given the success or failure of previous drillings. This calculation constitutes an example of Bayesian updating and, as illustrated in Figure 3.2, it results in a propagation of information across space as wells are deployed. To mimic common disclosure requirements, geological information is treated as a public good. This means that agents instantly and identically update their expectations about the distribution of resources following a new drilling.

Other studies have previously applied insights from statistical mechanics to understand social scientific problems, particularly in finance (see Weidlich, 1971; 2000; Weidlich & Huebner, 2008 for works on social interaction and Phan *et al*, 2005 for references on financial models based on the Ising framework). What is missing thus far is an approach that employs the Ising model to simulate geological conditions, which motivate information externalites in oil and gas exploration. This chapter fills this research gap.

3.2. Strategies

With the framework in place, it is now possible to outline the strategies that agents use when conducting exploration. A strategy is defined as a set of rules governing an agent's decision of whether and where to drill every turn, given the entire history of previous exploration. The range of possible strategies is naturally extensive. To be precise, there are $7.308 * 10^{70}$ possible candidates just for the twelve-by-twelve landscape evaluated in this chapter.[12] This enormous set of options makes it computationally challenging to solve the exploration problem using standard game theoretical solution concepts such as the sub-game perfect Nash equilibrium. Identifying the exact optimal sequence of exploration is consequently beyond the scope of this chapter. However, one might argue that the computational complexity of the problem also makes it de facto impossible for actual landowners to be strictly optimal. Instead of focusing on the exact optimal strategy, we therefore propose two nested strategies that represent archetypal attitudes towards information and extraction externalities. As will be shown later, both of these are consistent with good exploration behavior as they significantly improve on random deployment.

At any given time, the entire information set is encapsulated in the conditional probabilities of discovery (p_i) defined for each tile i. Building on these, and motivated by the spatial correlation of resources, a benefit function Ω_i is defined for each tile i. This takes into account the probability of discovery not only on the tile i, but also on its adjacent tiles. The benefit function is a weighted sum of two terms: First, the probability of discovery at a given tile i, and, second, the estimated value of the additional information about surrounding tiles i'_{1-4} that is

[12] The total number of options is the number of possible landscapes (3^{12^2}) times the number of tiles (12^2).

acquired when drilling at i.[13] The parameter β controls the relative importance given to this latter information component. The $\lambda_{i'}$ factor allows for differentiating between different types of information. It takes its full value of 1 when the neighboring tile is within the agent's perfect property area ($\in P$), a value of 0.5 when the neighboring tile is located in the contested area ($\in C$), and a value of 0 when the neighboring tile is already occupied by a well or belongs to another agent. Both strategies are based on this benefit function, defined in Equation 3.1.

$$\Omega_i = p_i + \beta\left(\lambda_{i'_1} p_{i'_1} + \lambda_{i'_2} p_{i'_2} + \lambda_{i'_3} p_{i'_3} + \lambda_{i'_4} p_{i'_4}\right) \tag{3.1}$$

$$\textit{where } {i'}_{1-4} \textit{ are the tiles neighboring tile } i \textit{ and where } \lambda_{i'} \textit{ is defined by}$$

$$\begin{gathered} \textit{if } i' \in P,\ \lambda_{i'} = 1, \\ \textit{if } i' \in C, \lambda_{i'} = 0.5, \\ \textit{otherwise } \lambda_{i'} = 0. \end{gathered}$$

Building on the benefit function, two competing strategies are considered: First, the *"indifferent strategy",* which does not factor potential resource leakage into the decision about well deployment. According to this strategy, the tile with the highest positive value of Ω_i should be drilled as long as this value is higher than 0.5. This applies regardless of whether the tile is located in P or C. The limit of 0.5 ensures that isolated tiles (for which the second term of Ω_i vanishes) are only explored when the expected profit is positive. The indifferent strategy is formally presented in Equation 3.2 below.

$$\textit{Let there be } i^* \in P \cup C \textit{ such that } \Omega_{i^*} = \max_{i \in P \cup C} \Omega_i \tag{3.2}$$

$$\begin{gathered} \textit{Drill at } i^* \textit{ if } \Omega_{i^*} > 0.5 \\ \textit{otherwise, do NOT drill.} \end{gathered}$$

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[13] Note that it is only possible to go from probabilities to benefits because we earlier defined discoveries to yield one unit of profit and empty wells to result in minus one unit of profit.

In contrast to the indifferent strategy, the *"rival strategy"* gives preference to exploring sites in the contested area C. Agents following the rival strategy thus deploy wells in the contested area first, as long as these sites are associated with positive expected profit. This strategy is based on the premise that agents realize contested recourses may be acquired by a rival neighbor if not explored today. Only when no such option is available does the rival strategy revert to the benefit function criteria used in the indifferent strategy. The formal representation is presented in Equation 3.3.

$$\begin{gathered}\textit{Let there be } \tilde{\imath} \in C \textit{ such that } p_{\tilde{\imath}} = \max_{i \in C} p_i \\ \textit{Drill at } \tilde{\imath} \textit{ if } p_{\tilde{\imath}} > 0.5 \\ \textit{otherwise,} \\ \textit{Let there be } i^* \in P \cup C \textit{ such that } \Omega_{i^*} = \max_{i \in P \cup C} \Omega_i \\ \textit{Drill at } i^* \textit{ if } \Omega_{i^*} > 0.5 \\ \textit{otherwise, do NOT drill.}\end{gathered} \tag{3.3}$$

It is noteworthy that, by design, agents are willing to drill on tiles for which the expected profit is negative (i.e. for which p_i is smaller than 0.5) as long as this yields sufficient information about the surrounding tiles. According to this reasoning, agents are thus willing to invest in information because it enables more efficient future exploration.

3.3. Results

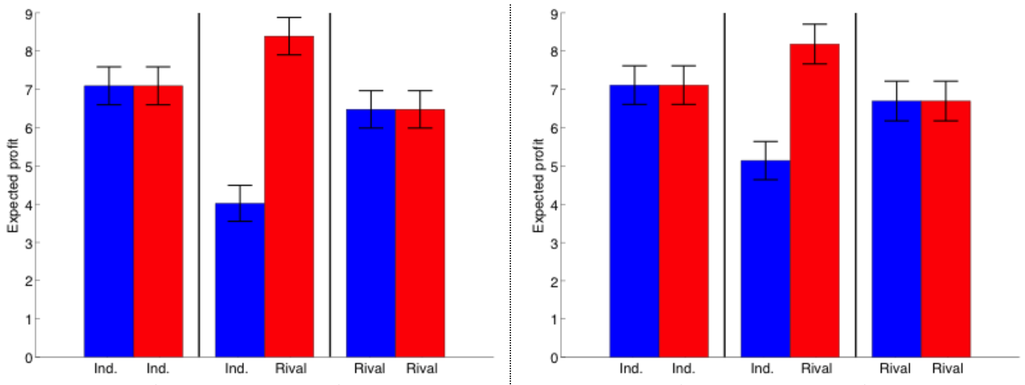
Using Monte Carlo methods, well deployment is repeatedly simulated according to the aforementioned strategies for a series of Ising-generated resource distributions. The data obtained is then used to conduct statistical inference comparing exploration outcomes, profitability and the clustering of wells for each possible strategy combination (i.e. indifferent vs. indifferent, indifferent vs. rival and rival vs. rival).

For the baseline estimations, 1,000 repetitions are conducted for each setup. A β of 0.125 is chosen in the benefit function to ensure that agents value information. The “temperature” parameter, which governs the clustering of resources, is set to 4. This ensures that the average cluster size is containable within the twelve-by-twelve system. If instead one had calibrated the model to have very high levels of spatial correlation (a high “temperature” parameter), a single discovery would indicate that the entire landscape contained oil. *Visa versa*, zero spatial correlation means that there are no informational spillovers from extraction. The unconditional probability of successful discovery is set by the “magnetic field” parameter to be 0.45 meaning that the unconditional probability of successful discovery is 45%. This implies that complete exploration (i.e. drilling wells on all tiles) would yield an expected net loss. Positive expected profits will thus verify that the proposed strategies succeed in using the knowledge about resource clustering. Figure 3.2 presents typical resource distributions optained when calibrating the model as described above. To eliminate any starting point effect, the agent who initiates the game is randomized as is the location of the first well deployed.

The following three subsections introduce the results of the Monte Carlo simulations. The first reviews profitability. The second shows how strategy combinations affect the timing of profit flows, and the third focuses on the spatial distribution of wells.

3.3.A. Profitability

Figure 3.3 presents the estimated profits for the three possible strategy combinations and for two different leakage setups. A situation of far-reaching extraction externalities is presented to the left, and a situation of spatially limited leakage is presented to the right. The bars represent the expected cumulative profit attained by each agent at the end of exploration. It becomes clear that all proposed strategies perform better than randomized exploration, which would yield an expected net loss of 0.05 for each tile explored. There are thus clear benefits to basing exploration decisions on the benefit function introduced earlier.



(LARGE CONTESTED AREA) (SMALL CONTESTED AREA)

FIGURE 3.3. EXPECTED TOTAL PROFITS

Notes: Error bars signify ninety-five percent confidence intervals. On each plot, from left to right, we show the expected profit for the following situations: Indifferent vs. indifferent, indifferent vs. rival, and rival vs. rival. "Ind." stands for the indifferent strategy. To mimic a situation of far-reaching extraction externalities, a "large contested" area is used covering a four-by-twelve area constituting one third of the entire region (as presented in Figure 3.2). To replicate cases with more limited extraction externalities, a "small contested" area is used covering a two-by-twelve area, which constitutes one sixth of the entire region.

The expected profit estimates show that common reservoirs result in a "prisoner's dilemma" type situation. Playing the rival strategy strictly dominates playing the indifferent strategy. The only possible Nash equilibrium[14] is therefore both agents playing the rival strategy. However, this is inefficient in terms of aggregate profits. Both agents would thus benefit if they could commit to playing the indifferent strategy. The only difference between the far-reaching and limited

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[14] The Nash equilibrium is a solution concept of multiplayer non-cooperative games where it is assumed that each player knows the equilibrium strategies of the other players. The Nash equilibrium exists when no player has anything to gain by changing only his or her own strategy.

extraction externality is that the increase in profits occurring when switching to the rival strategy is smaller in the latter case. As expected, the incentive to follow the rival strategy thus increases with the size of the contested area.

The counterproductive outcome associated with the prisoner’s dilemma occurs due to a combination of the information and extraction externalities. Knowledge about the expected location of resources is valuable because it enables more effective explorations in the future. Investing in information by spreading out exploration today is, however, costly as the respective neighbors can acquire contested resources in the meantime. This effect is further enhanced by information being a public good. Agents can thus ‘free ride’ on the information investments of their neighbors. From a social perspective, the rival strategy wastefully gives preference to exploring contested resources at the expense of more informative sites. Opting for the more exploratory indifferent strategy is, however, irrational from a private gains perspective.

3.3.B. Timing of profits

Figure 3.4 shows how expected cumulative profits evolve over time (turns) for different strategy combinations and thereby highlights the role of investment timing. It can be seen from the figure, that the expected profit from exploring the first tile is always negative (precisely -0.05). This originates from the model calibration, as the unconditional probability of discovery is set to 0.45. For random exploration, the curve in Figure 3.4 would be decreasing linearly with a negative slope of 0.05. Instead, we find that, for all strategy combinations, profits grow monotonically with time. Furthermore, the cumulative profits shown in Figure 3.4 exhibit two regimes: First, the curve is convex for approximately 15 turns, corresponding to an increasing marginal profit of deployment. This is due to the information gathered through exploration, which gradually allows for more efficient drilling. After this, the curve becomes concave corresponding to a decreasing marginal profit. This is the result of there being fewer and fewer tiles available and agents are thus forced to increasingly invest in less promising tiles.

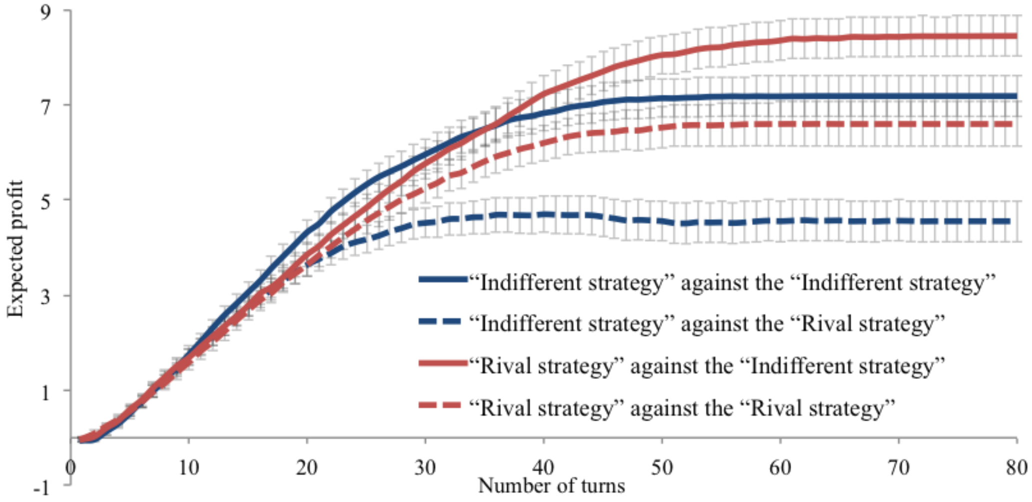


FIGURE 3.4. CUMULATIVE PROFITS OVER TIME

Notes: Error bars signify ninety-five percent confidence intervals.

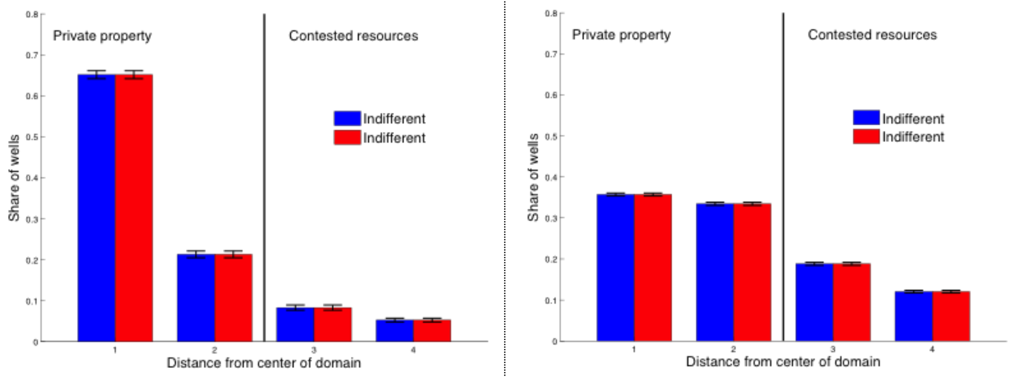
As we explained earlier, the expected profit at the end of exploration is larger for a rival, regardless of the strategy used by his or her neighbor. It is however noteworthy that this is not the case throughout the entire exploration period. Between turns 10 and 35 the expected cumulative profit of both agents following the indifferent strategy is higher than for any other strategy combination. This can be explained in the following way: The more agents adopt the indifferent strategy, the more exploration is initially spread out and the more information is acquired early on. This positive learning effect yields higher expected private profits in the intermediate term. However, following the rival strategy and letting one's respective neighbor follow the indifferent strategy dominates in the long run. This is because a rival firstly secures relatively uncertain tiles in the contested area and only secondly deploys wells in the interior. This leaves tiles in the perfect property domain, which can be accessed in later phases of exploration, leading to cumulative profits overtaking in the long run.

The model introduced in this chapter does not incorporate a discount factor and agents consequently do not have a preference regarding the timing of profit flows. In reality, however, firms might have an incentive to receive profits early. Combined with the insights from Figure 3.4 this suggests that a sufficiently high discount factor could tilt the relative expected profits associated with different strategies. The situation in which both agents follow the indifferent strategy could thus potentially become a Nash equilibrium if profits made at later stages of exploration were valued sufficiently less. This could help solve the prisoner's dilemma situation described in the previous subsection and thereby prevent the occurrence of a suboptimal aggregate profit.

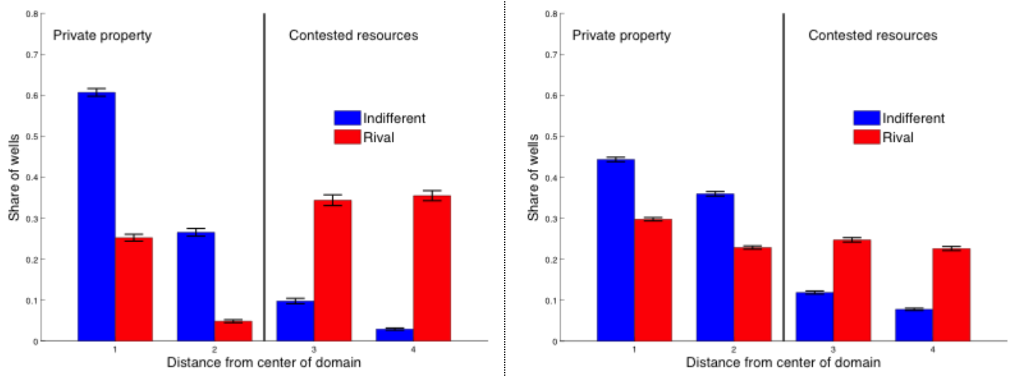
3.3.C. Spatial distribution

Analyzing the distribution of wells unravels the spatial consequence of strategic interaction. The well distributions at the end of turn 15 and at the end of exploration are plotted for the three different strategy combinations in Figure 3.5. Each diagram presents the share of wells located at different distances from the center of the agent's domain. The domain is here defined as the area where resources are accessible for exploration (including both perfect property and contested resources).

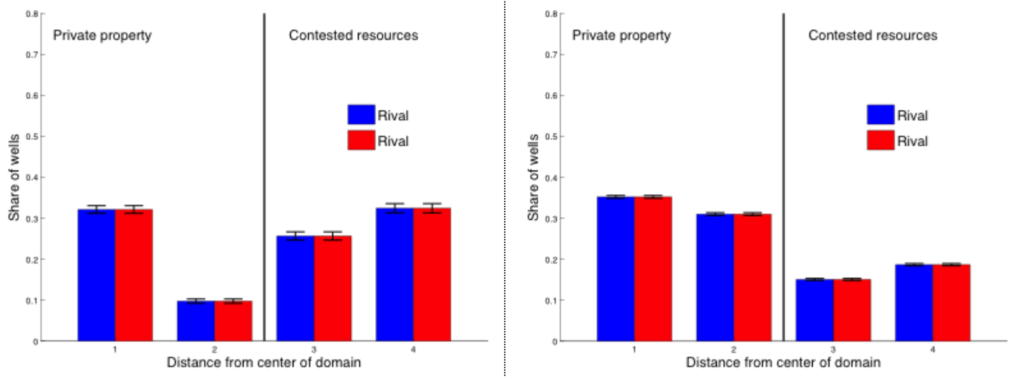
After 15 turns | End of exploration



(Indifferent strategy vs. Indifferent strategy)



(Indifferent strategy vs. Rival strategy)



(Rival strategy vs. Rival strategy)

Figure 3.5. Spatial distribution of wells

Notes: Error bars signify ninety-five percent confidence intervals.

There are two important things to note when interpreting Figure 3.5: First, contested resources are, by definition, accessible to both agents. This means that fewer tiles per agent tend to be available for exploration in this area. If strategies are identical, for instance, only half as many tiles are available in the contested area as in the comparable private property area. Second, the distribution of wells will naturally flatten as pre-deployed wells increasingly restrict the space of possible exploration investments.

As seen in Figure 3.5, different strategy combinations lead to different distributional outcomes. Agents following the indifferent strategy tend to deploy a higher proportion of wells in the center of their domain. This tendency can be directly attributed to the $\lambda_{i'}$ factor in the benefit function. Exploration close to a border is thus relatively less attractive as information about resources outside the perfect property domain is valued less or not at all. By construction, agents following the rival strategy tend to deploy a relatively greater share of their wells in the contested area. This is driven by the first criterion of the rival strategy.

Having a rival neighbor even induces agents following the indifferent strategy to shift investment focus closer to the contested area. This behavior is driven by a knowledge spillover as the extensive investment of a neighbor into the contested area provides superior information about the border region, which in turn makes investments here more likely.

Spatial competition over contested resources will thus motivate a clustering of exploration activity around property lines. This result remains true even when only one of the two neighboring parties gives preference to exploration of contested resources. This insight offers a new avenue for empirical research into the potential occurrence of common pool problems in the oil and gas industry. Assuming that capital and labor constraints limit the ability to instantaneously deploy wells, a symptom of common pool problems would be a significantly higher clustering of wells around property lines in early stages of exploration.

3.4. Conclusion

This chapter introduced a novel, physics-based and explicit method to model how information and extraction externalities influence oil and gas exploration across a two-dimensional common pool reservoir. Using the Ising model, knowledge about the location of resources was modeled to propagate across space as exploration is deployed. Extraction externalities were replicated by defining a subset of contested resources that are accessible to both agents. Using Monte Carlo simulations, two competing exploration strategies were compared.

Both strategies accounted for knowledge spillovers from exploration and thereby significantly improved on a randomized deployment of wells in terms of attained profit. Substantial differences in the relative profits associated with different strategy combinations were revealed. These differences result in a prisoner's dilemma type problem where the only possible Nash equilibrium is both agents following the socially inefficient rival strategy.

This inefficient outcome can be interpreted as a result of underinvestment in public information. Knowledge about the location of resources persists throughout the exploration period and acquiring it early is advantageous from an efficiency perspective. This, in isolation, should motivate information seeking behavior. Yet, extraction externalities incentivize the socially wasteful but privately rational clustering of wells around borders in the early phases of exploration. Such clustering was suggested as a signature of common pool problems, which offers promising avenues for future empirical analysis.

The economic inefficiencies revealed in this chapter suggest that there is room for policy intervention but implementing these successfully may be difficult. Broadly, three avenues are possible: command and control policies, taxes/subsidies and Coasian solutions. Most current regulation falls within the first category. Legal restrictions on the spacing of wells thus remain the preferred policy tool in most countries (Lowe, 2010). However, the model developed in this chapter implies that the effectiveness of such policies can be questioned. If large enough, implementing a legal “no man's land” between two resource owners might thus not only eliminate the extraction externality; it will also make some underground resources inaccessible. Regulating the spacing of wells may thus create new inefficiencies, which could be as large as the ones that it seeks to correct.

An alternative to current command and control policies could be implementing appropriate taxes or subsides. While this chapter showed that the rival strategy is strictly dominant in the long run this is not the case throughout exploration. The situation where both agents follow the indifferent strategy maximizes private profits in the intermediate run. This result originates from the rival forgoing higher immediate profits in order to secure contested resources. It is this behavior that is socially inefficient and it therefore also presents a potential avenue for corrective policies. Imposing a tax on profits, which increases sufficiently over time, could thus change the relative appeal of different exploration strategies. Introducing such a tax might thereby make the socially efficient outcome, where both agents follow the “indifferent strategy”, an alternative Nash equilibrium. The level of an efficient tax is dependent on the relative time preference of resource owners and the extent of extraction externalities. Alternatively, a government could provide subsidies to disincentivize clustering around borders. A problem with both taxes and subsidies is however, that a regulator might not know the exact extent of information and extraction externalities. Faced by this lack of knowledge, it is almost impossible to implement optimal taxes or subsidies and the regulator might thus end up exacerbating economic inefficiencies.

The classic ‘Coase Theorem’ (Coase, 1960) offers an alternative solution to the common pool problem described in this chapter. Assuming that transaction costs are sufficently low and property rights are assigned, bargaining could thus result in the economically efficent outcome where reservoirs are managed as one entity. In practice, this could be achieved through private acquisition of neighboring lands, joint development agreements[15] or unitization contracts.[16] All of these methods have the potential to internalize extraction and information externalities. However, land heterogeneities and producers having diverging views on how to share production can complicate such cooperation agreements (Wiggins & Libecap, 1985).

The model introduced in this chapter could easily be expanded to replicate more realistic situations but its core predictions should first be empirically tested. Some of the theoretical additions worth considering are: Moving beyond the sequential setup and accounting for asymmetric agents. The turn based setup presented in this paper assumes that landovners are identical in their capacity to drill. However exploration might occur in areas where neighboring agents have very different access to capital and technology. To mimic such setups one might alter the theoretical model allowing one agent relatively more turns then his or her neighbor. The potential implications of unequal drilling capacities are explored in more detail in Appendix C. Other theoretical addtions could be incorporating physical damages to the reservoir following overly rapid extraction and weakening the assumption of public information in order to capture the effect of temporary confidentiality periods. However, before expanding the framework one should first seek to identify the optimal search strategy and test the empirical validity of the model's predictions. A first step in this process would be to reduce computational complexity, by moving away from the large two-dimensional

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[15] A Joint Development Agreement is a deal between two states to jointly develop an oil or gas reservoir to which either or both of the participating parties may be entitled in international law. The financial split between parties is subject to negotiation and varies on a case-by-case basis. Examples include, but are not limited to: The 1974 Japan-Korean Joint Development Zone, the 1989 Timor Gap Treaty and the 2001 Nigeria-São Tomé and Príncipe Joint Development Zone.

[16] Unitization is an agreement between two or more parties by which a shared reservoir is managed as a single unit. The arrangement is made when multiple agents (states, firms or private individuals) hold exploration rights in a common oil or gas reservoir.

setting studied in this chapter. One could simplify the problem to describe hydrocarbon exploration along a line and solve this using backwards induction. Such a model setup would be a representative depiction of neighboring countries separated by a joint border. As a result, the predictions of the framework could be tested using international exploration data.

Despite currently describing a natural resource problem, the model used in this chapter fundamentally analyzes optimal investment in situations of information externalities and contest over assets. Consider the case of two or more national airline companies that are deciding on which new flight destinations to invest in. Each airline might have a de facto monopoly on their home market but face competition over international routes. Furthermore, adding a new destination is likely to yield insider information about the profitability of other destinations in the surrounding geographic area. This airline investment problem is comparable to that studied in this chapter and the proposed framework could thus be expanded to identify the optimal expansion of flight routes. The wider applicability of the model is, however, limited by the assumption that agents need to know the Ising parameters. This might not be realistic for most investment problems outside the oil and gas industry. The model can thus only be applied to strategic problems where agents know both the unconditional probability of success as well as the average clustering of outcomes.

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Chapter 4.

Borders and Resources: Evidence of strategic exploration

By JAMES CUST, TORFINN HARDING, THOMAS BLIGAARD NIELSEN AND THOMAS SCAFFIDI*

Divided into two main parts, this chapter show how the presence of information spillovers and potential contestability of deposits at property boundaries affect oil and gas exploration. Using data for more than 100,000 wells in over 120 countries, we first analyze the spatial distribution of wells. This empirical investigation finds evidence of excessive drilling close to national borders. However, this is not observed at borders with unitization agreements that are intended to solve the problem of cross-border resource leakage. Instead, states with unitization agreements have undertaken relatively more of their drilling in the interior of their countries. Recognizing that exploration and borders are correlated, the second part of the chapter applies techniques from statistical physics to model observed behavior. This analysis shows how a race to capture common pool resources can result in a peak of exploration near borders and how agents seeking to internalize informational spillovers can lead to an interior clustering of wells. As geology and not property lines should govern exploration, practitioners should aim to internalize spatial externalities. However, this chapter finds that existing unitization agreements remain unsuccessful in doing so as drilling activity remains dependent on borders.

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Subsoil natural resources such as oil and gas represent tremendous value globally. Even at current low oil prices, the global production of crude was worth more than 4.8 billion US dollars daily in 2015 (BP 2016). It is well known that the exploration for and extraction of these resources may not be socially efficient due to two spatial externalities. First, reservoirs can straddle property lines and the migratory nature of hydrocarbons gives rise to an "extraction externality": resources around property lines may be non-excludable, meaning that a neighbor's extraction can influence one's own extraction. This risk incentivizes landowners to accelerate extraction and drill inefficiently many wells in border areas (Khalatbari1977; Libecap and Wiggins 1985^{a}; 1985^{b}). Second, due to geology, oil and gas resources tend to be statistically clustered across space. This leads to an "information externality": The likelihood of discovering resources is greater in areas of past discoveries than in unexplored areas. A neighbor's exploration can thus provide useful information about the geology of one's own land. As drilling is costly, this might incentivize a strategic waiting game, whereby exploration of common reservoirs is inefficiently postponed (Hendricks and Kovenock 1989; Hendricks and Wilson 1985; Isaac 1987; Porter 1995).

In this chapter we show that drilling behavior in the global oil and gas industry is consistent with the presence of these two externalities. In the first part of the chapter, we study offshore oil and gas exploration, using data for more than 100,000 individual wells in over 120 countries. Close to national borders without a unitization agreement,[17] we find evidence of excessive exploration drilling. However, this pattern is not as present at borders with a unitization agreement, which is intended to internalize the extraction externality. Instead, countries with a unitization agreement have undertaken relatively more of their drilling close to

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[17] Unitization is an agreement between two or more parties by which a shared reservoir is managed as a single unit. The arrangement is made when multiple agents (states, firms or private individuals) hold exploration rights in a common oil or gas reservoir.

the interior of their countries. The previous literature studied the US exploration in Texas and the Gulf of Mexico. To the best of our knowledge, this is the first study of the global oil and gas industry, and hence the role of property lines in the form of country borders.

In the second part of the chapter, we model the dynamic game between two neighboring agents searching for a subsoil natural resource such as oil or gas. The focus is on where drilling takes place in relation to the property line between the two agents. To be able to solve the dynamic game of exploration and model the spread of geologic information as wells are drilled, we draw on insights from the field of ferromagnetism in statistical physics. The previous literature has shown that the two spatial externalities, the extraction externality and the information externality, are, separately, important to understanding drilling behavior. However, our model is, to the best of our knowledge, the first to incorporate them simultaneously.

The empirical findings of this chapter are as follows: In countries without unitization agreements, an excess of drilling activity is observed close to national borders compared to a random distribution of exploration. In the sub-sample of country borders subject to a unitization agreement, we do not find significant over-exploration close to borders. Instead, such areas have a greater share of exploration situated away from neighbors towards the interior of the countries. To confirm that these patterns are independent of geology or other natural geographical features, we present suggestive evidence of no relation between country borders and discovery rates. Independence between country borders and geology is also found by Caselli et al. (2012) and Cust and Harding (2013). There is thus little evidence to suggest that our findings are explained by a systematic correlation between national border demarcations and the presence of oil and gas.

Our theoretical results show that the empirical findings of the chapter are consistent with the presence of both the extraction externality and the information externality. In isolation, the extraction externality creates a race for resources close to the property line, manifested as an over-exploration in border areas. In contrast, the information externality provides an incentive to explore away from neighbors and closer to the interior of countries, as this is where drilling yields the most information about the geology of one's own property domain. As the two externalities work in opposite directions, they are hard to isolate. However, a successful unitization agreement assigns property rights to common pool resources, removes the extraction externality and eliminates the incentive to over-explore border areas. This explains why excess exploration of border areas is observed in countries without unitization agreements but not in countries with them. However, a unitization agreement does not remove the information externality and exploration therefore remains dependent on borders even in countries with such arrangements. There is thus an over-representation of exploration away from borders in countries with unitization agreements.

Our results illustrate that both the extraction and information externalities affect where wells are located but the observed patterns are likely inefficient. From a social planning perspective, it is geology rather than property lines that should govern where exploration takes place and there is thus room for policy action. In terms of policies to reduce the strategic exploration, many countries have not reached unitization agreements with their neighbors. This is not surprising, given that even private firms often fail to make such a contract voluntarily due to heterogeneity and information asymmetries across parties (Libecap and Wiggins 1985[a]; 1985[b]). The information externality may be reduced by the mandatory provision of exploration data. This explains why some countries, such as the UK, Norway and Denmark, require seismic information to be made publicly available after a certain confidentiality period. However, the sharing of exploration data across country borders remains uncommon and there thus remains room for policy intervention to internalize the information externality.

This chapter builds on past research of strategic interaction in the oil and gas industry. Notably, Hendricks and Porter (1996) find that information externalities slow exploration in the Gulf of Mexico. However, focusing on the same region but using a different measure of neighbors, Lin (2009) finds no evidence of such a strategic waiting game. However, the counteracting effect of externalities is likely to explain these mixed findings. Waiting for information arising from additional drilling is thus made costly by the risk of cross-border leakage. Despite this, there remains no comprehensive theoretical framework that describes the interplay between information and extraction externalities across space. The existing description of behavior is thus incomplete. As this chapter serves to highlight, it is necessary to unravel strategic incentives and their impact on the spatial distribution of exploration in order to identify inefficiencies and improve outcomes.

The chapter proceeds in three main parts. Section One introduces the empirical analysis and is composed of subsections introducing the empirical strategy, data and results. Section Two is dedicated to the theoretical model and is composed of four subsections introducing the landscape, agents, solution concept and predictions. The final section summarizes the findings and discusses their implications.

4.1. Empirical distribution of wells

This section is dedicated to testing whether, and if so how, exploration activity is dependent on property demarcations. It does so by evaluating the distribution of wells around national borders and analyzing how these depend on institutional arrangements such as unitization agreements. We first discuss the data and empirical strategy and then move on to the results.

4.1.A. Empirical strategy and data

We use GIS (Geographic Information System) data on national borders and offshore exploration wells to test the relationship between property lines and drilling activity. Specifically, the PathFinder database owned by Wood Mackenzie (2011) is used. This provides the exact location of over 100,000 oil and gas exploration wells, together with information about when they were drilled and whether they contained oil and gas or not. To the best of our knowledge, this is the most comprehensive global database on exploration drilling in existence. The GADM database of Global Administrative Areas version 2.0 (Hijmans *et al*., 2010) is used to identify the location of onshore national borders and the EEZ Maritime Boundaries Geodatabase version 6.1 (Claus *et al*., 2013) is used for data on the location of offshore maritime borders.

A series of data restrictions are performed to ensure that the distribution of borders is independent of geology and thus the location of oil and gas resources. We exclude onshore wells and focus on offshore exploration to minimize the risk of capturing effects related to natural geography such as mountain chains or rivers that might be correlated with the location of borders. Furthermore, we follow Cust and Harding (2013) and only include borders with locations that have remained unchanged since 1965 and focus on wells drilled in the period after 1966. This ensures that borders are predetermined with respect to drilling. The location or outcome of exploration have thus not influenced the location of borders. To capture the full density of drilling we include all wells up to 2010. See Cust and Harding (2013) for further details on the data sources used. This yields a subset of 29, 285 ofshore wells.

The empirical analysis of this chapter rests on the assumption that the unconditional likelihood of discovering oil and gas is uniform across space. This is necessarily an assumption, as geology is unobservable in practice. The closest we get to observing the geology is the discovery rate; that is, the share of wells drilled that did have economically viable oil or gas. Figure 4.1 shows the discovery rate of offshore oil and gas wells across different distances from country borders.

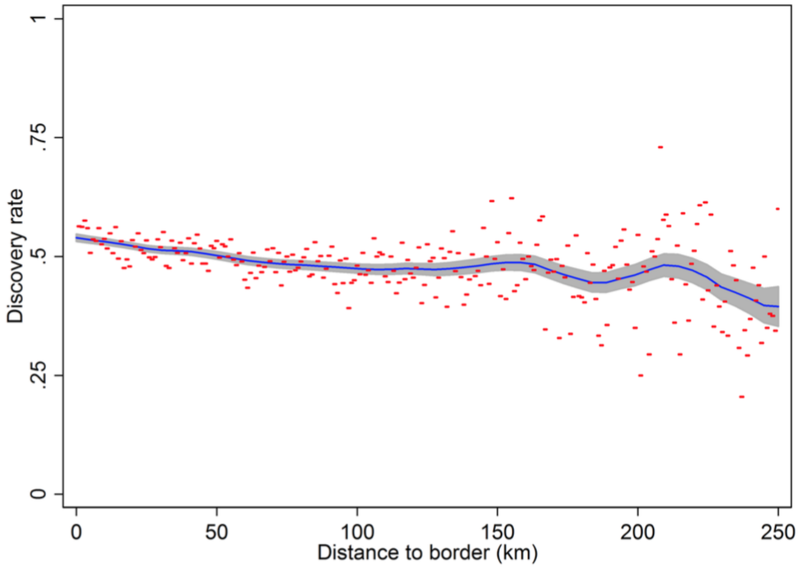


FIGURE 4.1. DISCOVERY RATES AT DIFFERENT DISTANCES FROM COUNTRY BORDERS

Notes: Based on all countries. Horizontal axis shows distance to nearest country border, vertical axis the share of non-dry wells. Red dots are estimated coefficients on dummies per one km. the blue line is local linear means estimation using a standard Epanechnikov kernel and a bandwidth of 5 km. Ninety-five percent confident intervals are marked in gray.

As seen from Figure 4.1, the discovery rate shows seemingly little variation according to the distance from the border. This supports the assumption that borders and geology are independently distributed and follows previous findings by Caselli et al. (2012) and Cust and Harding (2013). Given the validity of the assumption, we are able to analyze the distribution of wells around borders without worrying that geology rather than behavior drives the patterns.

Having defined the restricted sample, it is possible to plot the density of offshore wells at different distances from national borders, as is done in Figure

4.2. This figure presents the absolute density of exploration activity at different distances from country borders. It is clear that there is more drilling close to borders and there may be three reasons for this. First, the available area of any country is geometrically shrinking when approaching the center. This is because the radius is decreasing. Second, it is only large countries that contain areas far away from borders while all countries are represented at the border. To illustrate this insight, a small country like Singapore contains no point which is further then 50 kilometers from the nearest border. Third, there may be strategic drilling close to borders due to the extraction externality described in the introduction.

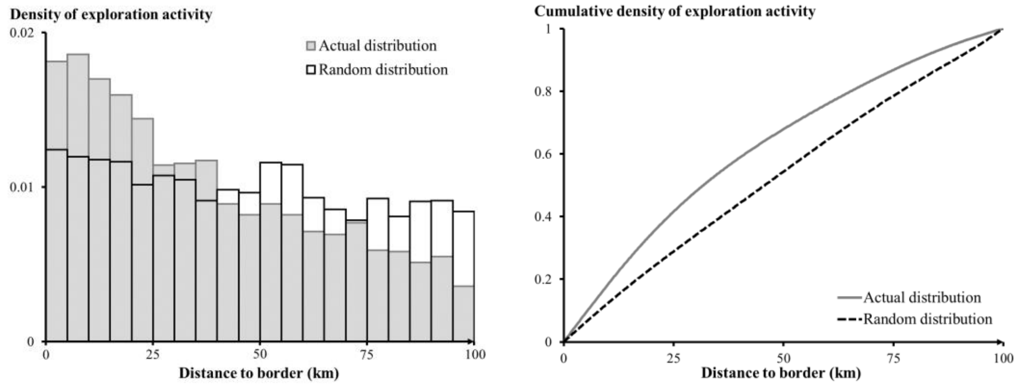


FIGURE 4.2. DENSITY OF EXPLORATION ACTIVITY AT DIFFERENT DISTANCES FROM COUNTRY BORDERS

Notes: Figures are based on all offshore oil and gas wells in the sample.

To isolate the effect of strategic drilling from questions related to the size and shape of countries, we identify the spatially dependent density of wells assuming random exploration. This is done by randomly assigning 100,000,000 points on the globe and recording the histogram of those points that are situated offshore. As seen in Figure 4.1, the distribution of these random points differ from that empirically observed distribution of wells. Specifically, a greater share of observed exploration appears to be located in border areas than a random distribution would suggest. To quantify this clustering, we calculate the following normalized density of exploration activity in bin b:

(4.1) $$Ndensity_b = \frac{\frac{\sum_b actual\ wells}{[\sum actual\ wells]/N}}{\frac{\sum_b random\ wells}{[\sum random\ wells]/N}}$$, where N is the number of bins

As evident from Equation 4.1, the normalized density of exploration will only equal one if the actual and random density of exploration is identical. If $Ndensity_b > 1$, it means that the density of exploration is higher than predicted by random exploration. *Visa versa*, $Ndensity_b < 1$ means that a smaller proportion of wells is located in the bin relative to a random allocation.

The areal extent of analysis has important implications for the normalized density of exploration. For the rest of this chapter, we focus on the first 100 kilometers from national borders as we have little support that extraction or information externalities apply beyond such vast distances. Furthermore, we seek to avoid oversampling big countries which have more areas far from borders. We therefore drop all wells that are further then 100 kilometers from a border. This reduces the sample from 29, 285 to 12,954 offshore wells. Following a trade-off between variance and precision, we use five kilometer bins in this chapter. Smaller bins would result in fewer observations within each distance band and the variance of estimates therefore increases. Larger bins reduce the variance but suffer from less precision, as estimates describe the average density across the entire zone.

To study the possible effect of a unitization agreement we split the sample into two subsamples. The first contains wells drilled close to borders with an active unitization agreement (6,853 wells) whereas the second contains wells drilled close to borders without such an agreement (6,101 wells). A border is defined as having an active unitization agreement if the neighboring countries have signed at least one transnational agreement relating to oil and gas development. Here we include any Joint Development Zones (JDZs), Memorandums of Understanding (MOUs) regarding unitization or the bilateral delimitation of maritime boundaries. The bilateral agreements signed between the United Kingdom and Norway on March 10, 1965 and between the United Kingdom and the Netherlands on October 6, 1965 constitute good examples of active unitization agreements (see Bastida *et al.*, 2007). In contrast, the South Pars/North Dome natural gas field, located between Iran and Qatar, lack such an an agreement of joint development. The data on unitization agreements was collected manually by reviewing publicly disclosed documents from national governments, the Wood Mackenzie PathFinder database and the records of oil and gas companies.

4.1.B. Results

This subsection introduces the findings of the empirical analysis outlined above. Figure 4.3 presents the normalized density of exploration for wells respectively located in areas with and without unitization agreements.

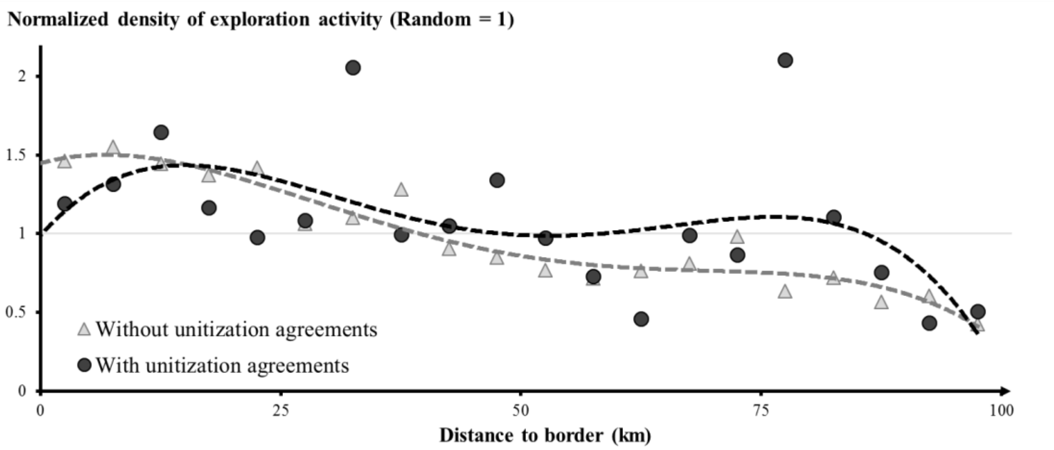


FIGURE 4.3. NORMALIZED DENSITY OF EXPLORATION ACTIVITY

Notes: Figure is based on all offshore oil and gas wells in the sample. Dotted lines are fourth-order polynomial approximations.

Focusing on the first 100 kilometers from borders, Figure 4.3 suggests that exploration activity is not independently distributed with respect to property lines. Specifically, drilling activity appears to be more concentrated around borders in areas without an active unitization agreement then the random allocation of wells would suggest. For areas with a unitization agreement, exploration activity appears to peak further away from borders.

To test whether observed patterns are statistically significant, it is useful to apply fourth-order polynomial approximations as presented by the dotted lines in Figure 4.3. Comparing the functional form of these approximations with a constant function equal to one, it is possible to deduce whether and how the distribution of exploration is significantly different from the random allocation. Table 4.1 presents the output obtained when estimating the fourth-order polynomial approximations and statistically comparing them to the constant function of random allocation. It should be noted that all significance tests presented in the table are two-sided tests for a sample mean of 0 except for the test of the constant (intercept), which is a two-sided test for a sample mean of 1. This equates to testing whether the distribution is significantly different from random allocation and whether there is excessive drilling close to borders.

TABLE 4.1. TESTING IF DISTRIBUTIONS ARE SIGNIFICANTLY DIFFERENT FROM RANDOM

Normalized density of exploration activity	*Without unitization agreements*	*With unitization agreements*
Constant (intercept)	1.448*** [0.063]	0.989 [0.228]
Distance to border (km)	0.017 [0.012]	0.070 [0.050]
[Distance to border (km)]^2	-0.002*** [0.000]	-0.003 [0.002]
[Distance to border (km)]^3	0.000*** [0.000]	0.000 [0.000]
[Distance to border (km)]^4	-0.000*** [0.000]	0.000 [0.000]
F-test *[H_0: Cons=1; Dist=0; Dist^2=0; Dist^3=0; Dist^4= 0]*	Rejected at a < 1 percent level	Rejected at a 5 percent level
R^2	0.914	0.289
Number of observations	20 bins based on 6,101 wells	20 bins based on 6,853 wells
Number of countries	41	30

Notes: Bootstrapped standard errors in brackets (clustered at 5 km intervals). All significance tests are two-sided tests for a sample mean of 0 except for the test of the constant (intercept), which is a two-sided test for a sample mean of 1. This equates to testing whether the distribution is significantly different from random and whether there is excessive drilling close to borders.

*** Significant at 1 percent level

** Significant at 5 percent level

* Significant at 10 percent level

Reviewing Table 4.1, the estimated role of borders differs greatly between wells located in areas with a unitization agreement and wells located in areas without such arrangements. However, the F-test reveals that the distribution of exploration is statistically different from random for both subsamples (at a five percent level). Furthermore, there is statistically significant evidence of exploration clustering in border areas without a unitization agreement. The constant is thus significantly larger than one at the 1 percent level. More precisely, the density of exploration is expected to be 45 percent higher at borders without unitization agreements then predicted by the random distribution.

Focusing on areas with a unitization agreement, there is no statistically significant evidence that exploration is clustered around borders. Furthermore, a one-sided test confirms that the intercept in areas of unitization is significantly smaller then that observed for wells in areas without a unitization agreement. This suggests that unitization shifts the distribution of drilling activity away from borders and towards the interior of countries.

In sum, the empirical analysis has revealed three main insights:

(i) Exploration activity is dependent on borders both in cases with and without unitization agreements.

(ii) There is a clustering of exploration near borders without unitization agreements.

(iii) Unitization agreements are associated with a greater share of exploration being located away from borders than is observed in areas without a unitization agreement.

The next section is focused on introducing a theoretical model that explains how the two spatial externalities, the extraction externality and the information externality, might explain the observed patterns.

4.2. Theoretical model of exploration

This section develops an original theoretical model that integrates insights from theoretical physics in order to analyze the deployment of exploration wells across space. The framework is based on two neighboring agents who explore a one-dimensional landscape for underground oil and gas resources. The section begins by outlining the landscape and agent characteristics upon which the framework rests. A solution concept is then developed in order to determine the optimal deployment strategy for the agents. The section concludes with a discussion of the model's predictions with respect to the expected spatial distribution of wells.

4.2.A. Landscape

Figure 4.4 graphically illustrates the landscape explored in the theoretical model. Land rights are evenly split and perfectly assigned to the two neighboring agents. However, property lines do not necessarily confine underground resources. This, results in two categories of potential resource discoveries. The first category is private resources ($\forall \in [A]$ for agent "A" and $\forall \in [B]$ for agent "B"). This resource type is fully contained within a single landowner's property. As a result, it is only accessible to one agent and its rents are therefore excludable. The second category is contested resources ($\forall \in [C]$) that can flow across property lines. Located in cross-border reservoirs, these resources are accessible to both landowners and therefore non-excludable (i.e. a common pool resource).

Agents search for oil and gas by deciding on whether and where to deploy exploration wells on the landscape. These wells can be drilled on a fixed set of potential drilling sites. As illustrated in Figure 4.4, the sites are spaced evenly across the landscape. Those sites that are located close to the property line access contested deposits whereas interior sites access private resources. The exploration of each site can either result in striking oil and gas or finding a dry hole. To capture the cost of drilling, discovery is calibrated to yield one unit of instant profit, whereas unsuccessful exploration is set to result in a negative profit of one.

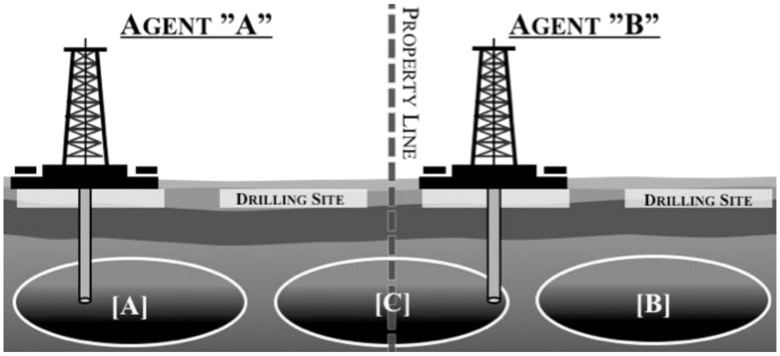


FIGURE 4.4. THE LANDSCAPE

As discussed in the introduction, the shared geology of underground rock formations mean that oil and gas deposits tend to be statistically clustered across space. *Ceteris paribus*, this implies that an agent is more likely to find hydrocarbons in areas of past discoveries than in areas surrounding unsuccessful exploration wells. To mirror this key feature of oil and gas exploration, the one-dimensional Ising model (Onsager, 1944) is employed. Borrowed from the field of ferromagnetism, this model was originally designed to capture the physics of magnetic moments (spins) with a binary set of possible states (up or down). Placed on a line, magnetic moments interact with their direct neighbors, making it more likely to find clusters of spins with the same state. The Ising model describes how these clusters are statistically distributed over space. In its original form, a "temperature" parameter governs the average size of the clusters, whilst the unconditional probability of a given state (up or down) is determined by a "magnetic field" parameter.

The relevance of ferromagnetism to solve a problem of oil and gas exploration may not be obvious. Yet, a slight alteration in terminology highlights the Ising model's usefulness. As described, each drilling site on the landscape can either contain hydrocarbons or not. This corresponds to the magnetic moment either being up or down in the Ising model. As neighboring magnetic moments, on average, tend to be parallel, regions with hydrocarbons will statistically be clustered across space. In geological terms, these clusters can be understood as reservoir formations. Ising's original "temperature" variable now controls how correlated resources are across space, that is, the average size of hydrocarbon reservoirs ("resource clustering"). The magnetic field variable controls the unconditional probability of discovering hydrocarbons ("resource richness"). This refers to the general probability of finding oil and gas when no wells have previously been drilled. In practical terms, this would relate to the average resource concentration for the region in question. By adjusting the "resource clustering” and the “resource richness” parameters, the framework developed in this chapter is thus capable of simulating different exploration settings. The interested reader is referred to Appendix A for a detailed introduction to the Ising model and the stochastic process that generates the spatially-correlated resource landscapes.

4.2.B. Agents

The two neighboring agents in the model are assumed to be identical and profit maximizing. Both are risk neutral and have no time preference regarding the flow of profits. Furthermore, the agents know the unconditional probability of discovery and the average size of hydrocarbon reservoirs. Translated into the Ising framework, this implies that both the “resource clustering” and the “resource richness” parameter are publicly known. Knowing the statistical process governing the distribution of resources, agents can compute the conditional probability of finding hydrocarbons anywhere in the landscape, based on the outcome of previous drillings. This calculation constitutes an example of Bayesian updating and rests on the assumption that agents know the “resource clustering” and “resource richness” parameters in the underlying Ising model. The result is a learning effect whereby geological information spreads across space as wells are deployed. In the model, such geological knowledge is assumed to be a public good. Agents therefore instantly and identically update their expectations about the likely distribution of resources after a new drilling. A graphical representation of this process is presented in Appendix A.

As agents are assumed to have identical investment capabilities, the option to drill is designed to occur sequentially. Agents thus alternate on deciding whether and where to deploy their next well. This turn-based design captures situations where both agents have access to the same capital and technology. However, sequential deployment does not represent setups where neighbors have different exploration capabilities. The interested reader is referred to Appendix C for an example where the assumption of sequential deployment is relaxed.

4.2.C. Solution concept

Following the above model outline, it is now possible to determine where wells will likely be drilled across the landscape. A first step towards making this distributional prediction is to identify the exploration strategy that maximizes the expected profit of the respective agent. Determining this privately optimal strategy is, however, complicated by the fact that exploration is a dynamic problem in which the strategic interaction of agents is key. Any optimal behavior should thus account for both the outcome of past exploration as well as the expected location and outcome of future wells. To solve this dynamic game, it is useful to draw on the idea of the sub-game perfect Nash equilibrium borrowed from game theory. The aim is to identify the strategy profiles in which neither of the two agents can increase their expected profits by unilaterally changing their exploration strategy.

These sub-game perfect Nash equilibria are found using backward induction. Specifically, one first considers the last time an exploration decision might be made and what decision would be made in that given situation. Using this result, one then determines how to proceed at the second-to-last time a well is deployed. This process of reasoning backwards is repeated until the best exploration decision for every possible situation has been identified. The result is a strategy vector, which classifies the optimal exploration behavior for every conceivable landscape of wells. As each of the n drilling sites can either contain no well, a dry well or a successful discovery there are n^3 possible landscapes. Deducing this substantial strategy vector is computationally cumbersome, as it requires identifying the Nash equilibria of every sub-game in the extensive form game. To ease this procedure, the game is programed using recursive equations in the standard mathematical software package MATLAB. The interested reader is referred to Appendix B for a formal derivation of the optimal exploration strategy.

Before making predictions regarding the distribution of wells, it is necessary to simulate optimal deployment for every conceivable landscape of resources. The strategy vector provides the optimal exploration decision for all possible situations. However, it does not describe how likely those situations are. To make predictions about the expected location of wells, it is therefore necessary to solve the exploration game for every conceivable landscape. In practice, this is achieved by letting the agents apply the optimal strategy to all possible resource distributions and then sum over the probabilities for each landscape. The result is a distribution function that describes the exact probability of observing exploration on every given site in the system.

4.2.D. Predictions

This section analyzes the spatial consequences of strategic interaction, by evaluating the distribution of wells predicted by the model. The specific setup consists of 22 drilling sites, of which each agent initially has eleven to pick from. To avoid starting point bias, the first exploration site is chosen randomly and the game is initiated if a discovery is made. As a consequence, none of the agents have a systematic first-mover advantage. With respect to the Ising-parameters, the core estimations are based on a “resource clustering” parameter set to 0.5 and a “resource richness” parameter set to 0. This specific calibration corresponds to a 50 percent unconditional probability of discovery and an expected size of hydrocarbon deposits that is containable within the 22-site system.

The effect of common pool reservoirs is best illustrated by estimating the model for two different resource setups. In the first scenario, all potential oil and gas discoveries are modeled as private resources. This setup serves as a baseline and represents a situation of perfect property rights where resource leakage is not possible. One can think of this setup as a situation where a successful unitization agreement has internalized the extraction externality. In the second scenario, the two drilling sites directly adjacent to the property line are modeled to access the same contested resource pool. This represents a situation of imperfect property rights equivalent to a situation without a unitization agreement.

Figure 4.5 illustrates the probability of exploration and the normalized density of exploration activity predicted under the two distinct resource setups. As agents are identical and the first exploration site is chosen randomly, the solution is symmetrical for both agents and the figure therefore focuses only on the expected distribution of agent A’s exploration.

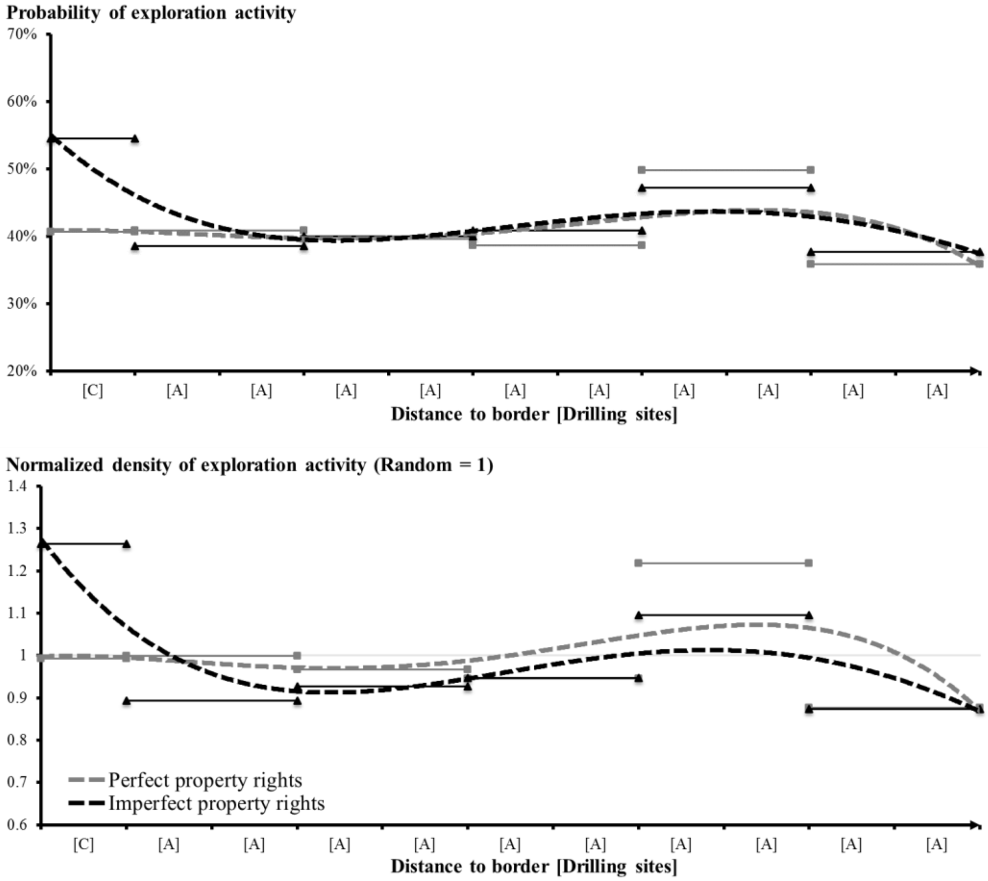


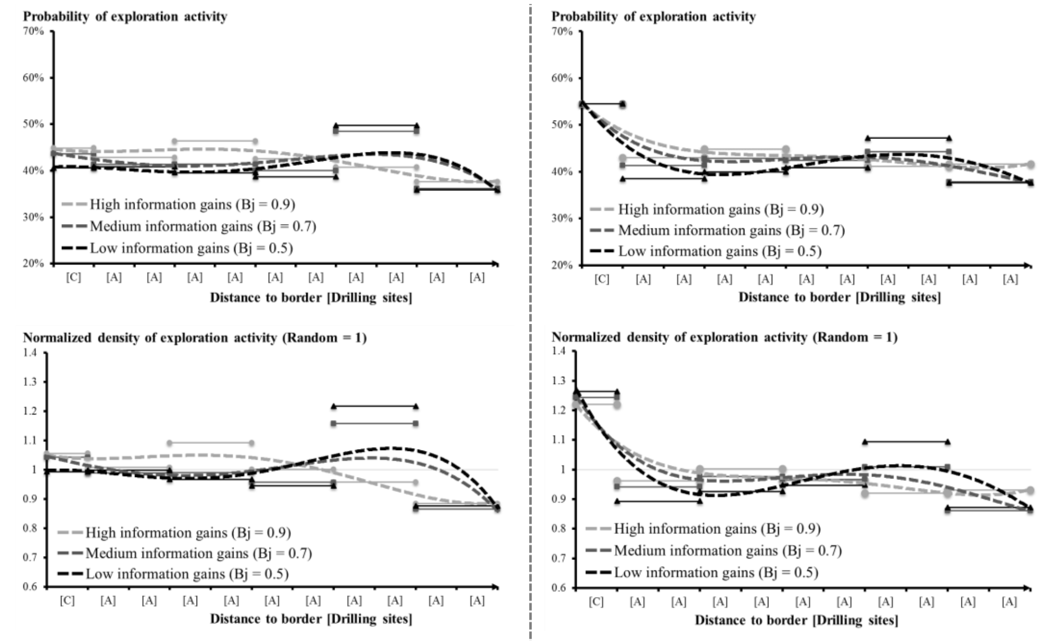
FIGURE 4.5. THE EFFECT OF COMMON POOLS

Notes: The top figure presents the expected probability of exploration identified by the model and the bottom figure presents the normalized density of exploration. Dotted lines are fourth-order polynomial approximations. The drilling sites are categorized as follows: $\forall \in [A]$ access resources private to agent A and $\forall \in [C]$ access-contested resources. Resources are perfectly assigned in the perfect property rights setup and all sites thus access private resources.

As can be seen from Figure 4.5, common pool problems significantly increase the likelihood of observing wells in border areas. This is because the opportunity cost of postponing the exploration of contested deposits ($\forall \in [C]$) is significant. The reason for this is that a neighbor might access these resources and make them inaccessible in the future. In turn, this incentivizes agents to initiate their exploration close to the property line even in situations where the probability of discovery here is smaller than on alternative interior drilling sites. The theoretical model is thus capable of replicating the exploration distributions observed in areas without unitization agreements.

The predicted exploration behavior in situations of imperfect property rights is in stark contrast to that identified when all resources are treated as private. In such situations of perfect property rights, agents have no risk of forfeiting access to underground resources. This eliminates the race for contested deposits and allows agents to focus solely on identifying the most likely location(s) of oil and gas deposits on their own lands. If agents operated alone, the best strategy to achieve this would be to initiate exploration in the center of one's own property domain. Such a strategy would provide the best understanding of the private resource landscape and therefore allow for the optimal deployment of wells in subsequent stages of exploration. According to the theoretical model, the majority of exploration would thus be found in and around the center of the private property domain. However, as agents are not alone, they expect some informational spillover from the exploration of neighbors. This alters optimal behavior, as it incentivizes exploration to be skewed slightly away from the property line. As a consequence, we see the skewed interior spikes in exploration observed in Figure 4.5. These findings are in accordance with the empirical results, which highlighted that exploration is not independent of borders even in areas where unitization agreements are in place.

Having established the implications of information and extraction externalities, it is now possible to analyze the relationships between the predicted distribution of wells and reservoir characteristics. The proposed model allows for altering both the unconditional probability of discovery and the statistical clustering of resources. Focusing on the latter of these two, Figure 4.6 plots the expected distribution of exploration wells when the "resource clustering" parameter (B_j) is altered.



(PERFECT PROPERTY RIGHTS) (IMPERFECT PROPERTY RIGHTS)

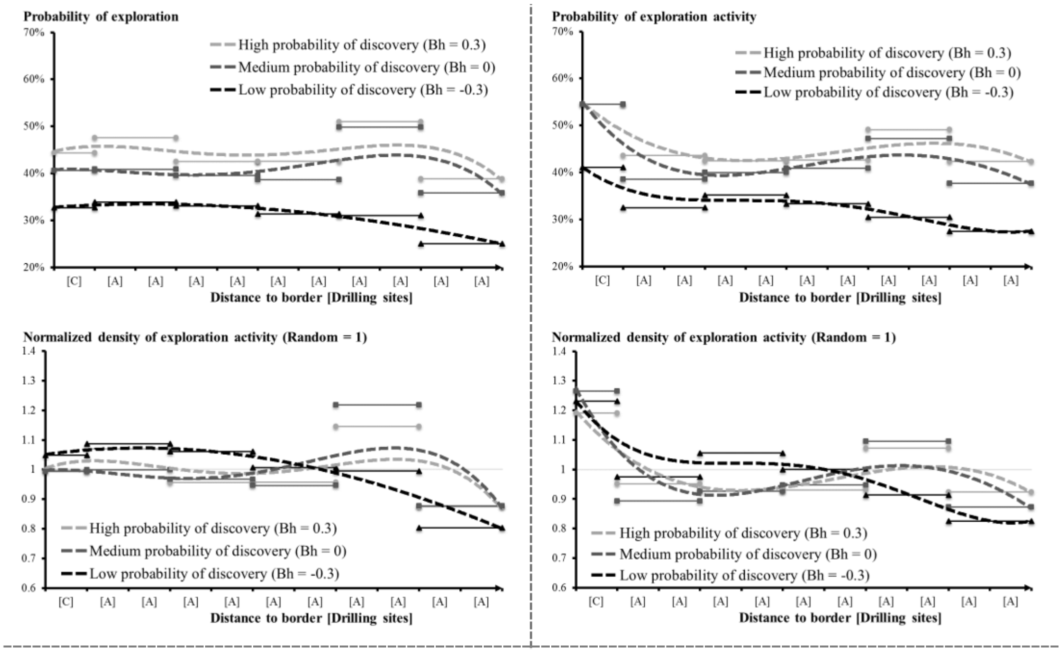
FIGURE 4.6. CHANGING THE SIZE OF RESOURCE CLUSTERS

Notes: The top figures present the expected probability of exploration identified by the model and the bottom figures present the normalized density of exploration. Dotted lines are fourth-order polynomial approximations. The drilling sites are categorized as follows: $\forall \in [A]$ access resources private to agent A and $\forall \in [C]$ access-contested resources. Resources are perfectly assigned in the perfect property rights setup and all sites thus access private resources.

Calibrating the model with a high value of the "resource clustering" parameter (B_j) corresponds to oil and gas being strongly correlated across space. A discovery thus significantly increases the probability of finding hydrocarbons on surrounding sites, whereas a dry well greatly decreases the likelihood. This means that drilling yields substantial information about the likely location of surrounding resources. In contrast, a low value of the "resource clustering" parameter entails that the information gains from exploration are limited.

As shown in Figure 4.6, the spatial correlation of resources affects the theoretically predicted distribution of exploration. The general trend is that a higher "resource clustering" parameter (B_j) motivates a more even distribution of wells further away from the property line. Agents terminating their exploration when faced by dry wells explain this pattern. The insight that resource leakage induces clustered exploration around property lines remains, nonetheless, robust to different levels of spatial resource correlation.

Governing the unconditional probability of discovery, the "resource richness" (B_h) controls how resource-rich a region is. Keeping the "resource clustering" parameter constant at 0.5, Figure 4.7 illustrates the expected distribution of exploration for three "resource richness" values.



(PERFECT PROPERTY RIGHTS) (IMPERFECT PROPERTY RIGHTS)

FIGURE 4.7. CHANGING THE UNCONDITIONAL PROBABILITY OF DISCOVERY

Notes: The top figures present the expected probability of exploration identified by the model and the bottom figures present the normalized density of exploration. Dotted lines are fourth-order polynomial approximations. The drilling sites are categorized as follows: $\forall \in [A]$ access resources private to agent A and $\forall \in [C]$ access-contested resources. Resources are perfectly assigned in the perfect property rights setup and all sites thus access private resources.

As shown by Figure 4.7, a smaller unconditional probability of discovery reduces the general likelihood of observing exploration. Calibrating the "resource richness" parameter (B_h) to a value of -0.3, 0 and 0.3 thus corresponds to a 35, 50 and 65 percent unconditional probability of discovery, respectively. The insight that resource-rich regions are associated with a relatively higher number of wells is intuitive, as the expected gains from exploration increase with the probability of discovery. For sufficiently resource-rich environments, the distribution of wells will converge toward uniformity, as complete exploration becomes rational. Following the model's design, the predicted probability of observing exploration on every site would thus be constant at 100 percent. Conversely, a sufficiently resource-poor environment eliminates the benefits from exploration. This means that the probability of observing wells would be zero across all sites. On their own, however, these two extreme scenarios are not insightful, since most exploration occurs under uncertainty. In uncertain environments, the distribution of exploration is predicted to be non-uniform as illustrated by Figure 4.7. Previous conclusions regarding the concentration of exploration in border areas are thus theoretically robust as long as some uncertainty about exploration outcomes remains.

However, as illustrated by Figures 4.6 and 4.7, the location of interior peaks in exploration activity relative to the border depends on reservoir characteristics. One can therefore not expect to find empirically significant evidence of interior peaks when averaging over many different types of reservoirs. This might explain why we do not identify a single point of interior clustering when evaluating exploration behavior under unitization agreements in Section 4.1 of this chapter. Instead, we thus find suggestive evidence of a series of interior peaks at different distances from the border.

4.3. Conclusion

Based on a global dataset of offshore oil and gas wells, this chapter showed that the distribution of exploration activity depends on national demarcations. It documented over-exploration in areas close to borders which are not covered by a unitization agreement. This pattern is not identified in areas of unitization, where exploration instead is concentrated away from borders towards the interior of countries. To explain these patterns, a new theoretical framework was introduced. Deploying the Ising model, borrowed from the field of ferromagnetism, this spatial setup was capable of mimicking empirically-observed exploration patterns by accounting for both information and extraction externalities. It showed how a clustering of exploration around borders without a unitization agreement can be rationally explained by agents responding to the risk of an extraction externality. Furthermore, the theoretical model highlighted that the presence of informational spillovers would result in a non-uniform distribution of exploration even in cases where the extraction externality is internalized. This was explained by agents seeking to internalize as much of the information externality as possible and supported by the empirical evidence which suggested a clustering of exploration away from borders in the case of unitization.

The patterns identified in this chapter are socially inefficient but persist because agents optimize exploration across their private lands. From a social planning perspective, it is geology rather than property lines that should govern where wells are drilled. However, as oil and gas deposits are not constrained by legal boundaries, information and extraction externalities remain. The presence of these uncompensated cross-border effects implies that the first welfare theorem breaks down and that strategic exploration, as identified in this chapter, is thus not Pareto efficient. It is important to note that not all clustering is wasteful. The information externality must be factored into the optimal deployment of wells. To maximize the learning effect of drilling, exploration should thus be initiated in the center of the resource landscape. The caveat is that the geological and political centers are not necessarily identical. From an efficiency perspective, there should not be peaks in the distribution of exploration relative to borders.

Drawing on the "Coase theorem", the management of underground oil and gas resources could be improved if trade in externalities was possible and bargaining costs were zero. Practically, this could be achieved through private acquisition of neighboring lands, joint development agreements[18] or unitization contracts as studied in this paper. In theory, this would eliminate at least the extraction externality and thus the clustering of exploration around borders. However, in reality bargaining costs are not zero and enforcement of international agreements is complicated. This explains why all countries have not implanted unitization agreements. Furthermore, as highlighted by the empirical evidence presented in this paper, the information externality continues to influence exploration even in cases of successful unitization. There thus remains room for unifying the management of underground reservoirs both through the spread of unitization agreements and ensuring that the informational spillovers from exploration are internalized through appropriate compensation systems or public disclosure programs.

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[18] A Joint Development Agreement is a deal between two states to jointly develop an oil or gas reservoir to which either or both of the participating parties may be entitled in international law. The financial split between parties is subject to negotiation and varies on a case-by-case basis.

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Chapter 5.

The curse of neighbors in Colorado’s gas industry

By THOMAS BLIGAARD NIELSEN*

A fragmented property landscape and the “ad coelum” doctrine in American mineral law motivate common pool problems when wells are spatially clustered and gas can, or is perceived to, flow between resource owners. Drawing on the Hotelling framework on non-renewable resources, such situations of potential leakage should induce owners to accelerate extraction. Using original spatial panel data, this chapter evaluates how the owners of existing wells respond to the threat posed by new neighbors. In line with the theoretical predictions, rivals located in close proximity are found to motivate accelerated extraction, whereas distant neighbors do not affect behavior. From a social perspective, the prospect of resource leakage thus distorts extraction. As a consequence, practitioners are recommended to internalize externalities by unifying the management of resources.

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The decision to extract non-renewable resources such as natural gas is irreversible, as their stock cannot be increased through investments or conservation. Recognizing this property, Harold Hotelling (1931) identified the optimal extraction path that maximizes the value of the resource stock. His original use of inter-temporal optimization and the idea of the forward-looking owner became the dominant theoretical paradigm in the field of non-renewable resource management. Yet, its empirical validity remains questionable (see

Krautkraemer, 1998; Withagen, 1998). To make headway in the field, this chapter investigates whether the Hotelling framework is consistent with observed extraction behavior in Colorado’s gas industry. Weak property rights and underground passageways sometimes allow subterranean gas to flow between landowners. This risk of leakage increases the opportunity cost of postponing extraction, as current reserves may be unattainable in the future. A forward-looking resource owner should then respond by accelerating extraction. This implication of Hotelling theory is tested in this chapter by analyzing how the owners of existing wells respond to the arrival of new neighbors who might threaten underground reserves.

Home to seven percent of all American gas wells (EIA, 2014), Colorado is at the heart of modern fossil fuel extraction and therefore a good testing ground for assessing the wider relevance of the Hotelling framework. The wells in Colorado primarily extract unconventional gas made accessible by the pioneering work of George P. Mitchell (Yergin, 2012). Including shale gas, coal-bed methane and tight gas, unconventional gas refers to natural gas trapped within fine-grained sedimentary rocks (EIA, 2011, pp. 4-5). Unlike traditional reservoirs (Setup C, Figure 5.1), these resources require hydraulic fracturing (commonly known as ‘fracking’) in order to become productive. A mixture of water and chemicals is pumped into the source rock creating a network of fractures, which allow trapped gas to flow to the well (Setup A and B, Figure 5.1). These cracks do not spread uniformly and the areal extent of production varies according to the permeability[19] of the source rock (Reynolds *et al*., 1961). Natural passageways sometimes link up with hydraulically stimulated fractures leading to a larger than expected area of extraction (Cipolla *et al*., 2008). Despite generally being geographically confined (Davies *et al*., 2012), production networks reaching up to

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[19] Permeability is a measure of the ability of a porous rock to allow fluids to pass through it.

460 meters away from the wellbore have been identified using microseismic maps (Warpinski *et al*., 2005). There are even examples of unintended frac hits where one well pushes water into a neighboring well (see Figure 5.1). This highlights that uncertainty surrounds the extent of production. In turn, this is likely to motivate common pool concerns, as leakage between competing owners may occur when wells are spatially clustered.

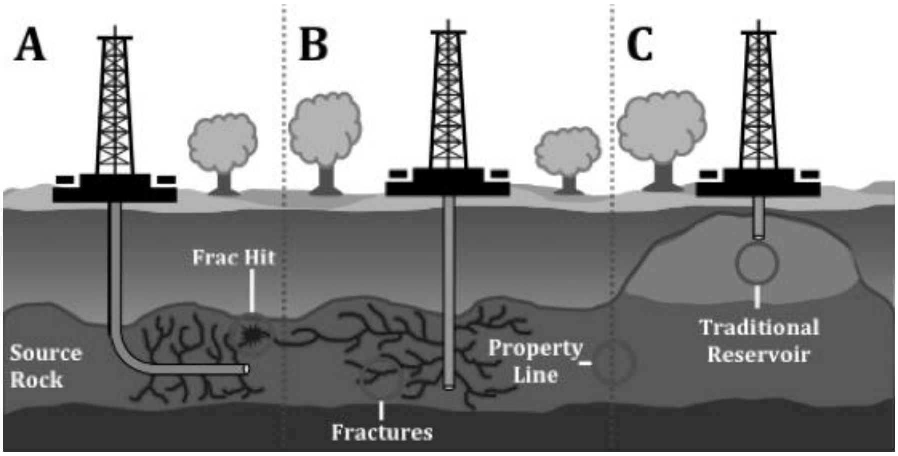

FIGURE 5.1. FUNDAMENTALS OF GAS EXTRACTION

A fragmented property landscape and American mineral law further enhance the risk of common pool problems. Previously undeveloped areas in Colorado are now filled with hundreds of wells, as unconventional gas has become accessible. Yet, the property demarcations of this new landscape are not drawn based on the location of hydrocarbon deposits. In contrast to most other countries, American natural gas reserves are generally governed by the "*ad coelum*" doctrine (Lowe, 2010, p. 9), which states that landowners have the legal right to everything from the heavens above the surface to the core of the earth. Some mineral rights have since been severed from surface rights but the original borders still largely apply. Operators (oil and gas companies) typically lease plots from landowners who, in exchange, are paid an up-front lease bonus payment plus a royalty percentage of the value of any production. De facto, this makes the operator the acting resource owner. However, original property structures continue to shine through and single operators rarely have the sole right to an entire deposit. The implication is that gas can migrate between neighboring operators if natural or stimulated passageways allow for it. To counter this problem, Colorado courts generally apply the "ownership-in-place" principle, which terminates the ownership claim to a unit of natural gas if it migrates to the property of another operator (Lowe, 2010, p. 30). This clarifies that resources cannot be considered truly private until extracted, which should give rise to common pool problems when wells are clustered.

The research design introduced in this chapter exploits this potential scenario of common pool problems to test the theoretical premises of forward-looking resource owners. The chapter unfolds in six sections. First, a Hotelling model with incomplete property rights is introduced to derive testable theoretical predictions. Second, common pool problems are quantified using new spatial data from Colorado. Third, a two-stage statistical model is deduced. Fourth, the results are presented. Fifth, the robustness of the findings is tested. The sixth and final section summarizes the main findings. In line with the theoretical predictions, this chapter finds that operators accelerate their extraction when "rival" neighbors threaten their reserves. Practitioners are therefore recommended to internalize externalities by unifying the management of gas deposits

5.1. Theory

The first step in testing whether resource owners are forward-looking when faced by common pool problems is to identify how the risk of leakage affects the optimal extraction path identified by Hotelling. In the original 1931 model, resources were defined as private goods, meaning that owners had perfect property rights over current and future extraction. However, as described earlier, natural gas deposits are often better characterized as common pool resources. It is thus costly, but not impossible, for resource owners to exclude others from obtaining benefits from their reserves. To illustrate how this affects the Hotelling extraction path, a simple theoretical model similar to that used by Khalatbari (1977) is introduced. This consists of n identical resource owners who operate under perfect competition and therefore take the resource royalty P_t as given.[20] Each owner j decides on a time-dependent extraction level $R_{j,t}$ seeking to maximize their individual discounted profit as presented in Equation 5.1 below.

$$\max_{R_{j,t}} \int_{t=0}^{t=\infty} P_t * R_{j,t} * e^{-it}\, dt \tag{5.1}$$

The total resource stock $\bar{S}$ is fixed[21] but, in contrast to the original Hotelling model, subterranean gas reserves can leak between neighbors. Leakage flows, l, are assumed to be identical in both directions and only extraction ensures excludability. The framework consists of a fixed and finite number of extractors who can access the reservoir. This design rests on the insight that land rights are required in order to engage in extraction and thus the trivial open-access case is eliminated. If agents could enter freely and there is no extraction cost, the resource would thus be depleted instantly (Khalatbari, 1977). Given the assumptions presented above, profit maximization must be subject to the following resource constraint:

$$\int_0^\infty R_t\, dt = \bar{S} = 1 \tag{5.2}$$

$$\dot{S}_{j,t} = \underbrace{-R_{j,t} - l * S_{j,t} + \frac{l}{n-1} * \left(S_{1,t} + \ldots + S_{j-1,t} + S_{j+1,t} + \ldots + S_{n,t}\right)}_{g(S_{j,t},\, R_{j,t},\, t)} \tag{5.3}$$

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[20] By defining “P_t” as the market royalty, this model abstracts from marginal extraction cost.

[21] $\bar{S}$ is set to 1 to ease mathematical derivation but this does not jeopardize the main conclusions.

Assuming gas markets are regional, due to high transport costs, and specifying a demand function for this market ($P_t = R_t^{-v}$ where $0 < v < 1$) allows the maximization problem to be solved and the Hotelling extraction path presented in Equation 5.4 to be identified.[22]

$$R_{j,t} = \left(\frac{(l+i)}{v} * \frac{1}{n} * S_t\right) \tag{5.4}$$

Drawing on Equation 5.4, the theoretical implications of resource leakage can be illustrated. Consider a situation in which two agents operate on the same field but no leakage occurs (i.e. $l = 0$). Now assume that suddenly, in period $t = \varsigma$, an unintended fracture joins the drainage area of the two producers (i.e. $l > 0$). This risk of leakage would, according to Hotelling theory, motivate an instant acceleration of extraction. This scenario is graphically illustrated in Figure 5.2.

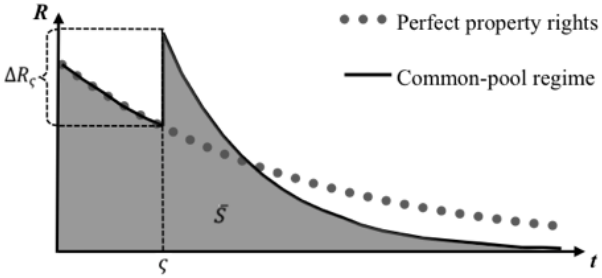

FIGURE 5.2. BEHAVIORAL RESPONSE TO INCREASED LEAKAGE RISK

The accelerated extraction and faster depletion presented in Figure 5.2 can be understood as the consequence of a rise in the opportunity costs associated with preserving reserves. Postponing extraction is thus more expensive when the reservoir is common, since gas can leak to a “rival” neighbor before it has been

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[22] The interested reader is referred to Appendix D for a comprehensive derivation of the model as well as a discussion of optimal behavior assuming prices are internationally determined and exogeonous to extraction in Colorado.

exploited. As a result, accelerated extraction is incentivized. The effect is further enhanced by an agent's ability to attract neighboring reserves. In other words, the risk of leakage in conjunction with neighbors alters the relative time preference of extraction, which is what governs behavior according to Hotelling.

Despite clear theoretical predictions, the literature remains inconclusive about the empirical relevance of Hotelling theory (Withagen, 1998). On the one hand, this may be the result of inadequate statistical tests. On the other hand, it is possible that owners do not consider the examined resources scarce. The theoretical predictions identified in this section hinge on the assumption that future scarcity rents justify forward-looking extraction behavior. Drawing on the analysis of oil and coal, it has, however, been argued that scarcity rents play only a marginal or even nonexistent role in modern fossil fuel markets (Hart & Spiro, 2011). If this holds true, Hotelling offers no explanation for why resource owners should postpone extraction. A price-taking owner who does not expect rising royalties has no incentive to wait and should thus simply determine extraction based on his or her marginal extraction costs. Analyzing whether operators accelerate their extraction when faced with "rival" neighbors thus offers a method of both determining the scarcity of natural gas and the extent to which agents engage in inter-temporal optimization, as predicted by Hotelling.

5.2. Data

The degree to which a resource owner faces a common pool problem can be quantified, by evaluating his or her surroundings. As mentioned earlier, it is the clustering of extraction that enables leakage of gas between owners. The extent of leakage risk faced by a given resource owner can thus be quantified by the proximity and number of neighbors surrounding his or her well. The Colorado Oil and Gas Conservation Commission (COGCC) have compiled the coordinates and production characteristics of every well operating in the state since 1999 (COGCC, 2014). These spatial data make it possible to map production and identify the number of neighbors surrounding each well at different distance bands (Figure 5.3). Repeating this exercise for every year and merging the annual datasets by well, one can construct a panel. These novel longitudinal data describe how the surroundings of a well change over time and thereby the variation in leakage risk faced by a given operator. Distinguishing between neighbors is key, as common pool problems only arise when somebody else threatens future extraction. Wells managed by the same operator are therefore here defined as being “friendly” and wells managed by any other operator as being “rival”. This abstracts from potential within-firm conflicts of interest, cross-company cartels and different operators extracting under the same overarching landowner. However, if such effects are present they will only increase the difficulty of identifying a potential behavioral response to “rival” neighbors and later conclusions are thus not vulnerable to this design.

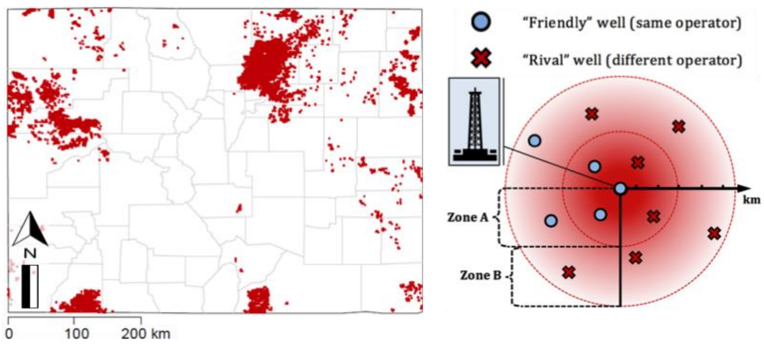

FIGURE 5.3. MAPPING COLORADO’S GAS WELLS AND QUANTIFYING COMMON POOL PROBLEMS

The areal extent of the investigation has important implications for the results of the study. In this chapter, distance bands of 100-meter intervals around each well are used (i.e. 0-100 meters, 100-200 meters and so on). The size of these zones is a trade-off between precision and variance. Smaller zones result in fewer observations within each distance band and the variance of estimates therefore increases. Larger zones reduce the variance but suffer from less precision as estimates describe the average effect across the entire zone. Using 100-meter intervals offer the maximum degree of precision while maintaining a sufficient number of wells within each individual zone.[23] Furthermore, empirical data suggests that fractures rarely extend beyond 600 meters from the wellbore (Davies *et al.*, 2012). The first few zones should thus be able to capture the theoretically predicted effect of “rival” neighbors. To account for all possible effects associated with clustering of exploration, the investigation covers a one-kilometer radius around each well. This means that every well in the dataset has ten 100-meter zone variables that describe its surrounding landscape of neighbors.

To ensure the reliability of the sample, the constructed panel has to be restricted. First, wells within one kilometer of the state border are omitted from the analysis. This omission is necessary, as it is impossible to identify any potential neighbors outside Colorado’s state border. Second, boreholes commissioned before 1999 are excluded. For the purpose of this analysis, knowing the entire history of a well is necessary in order to account for the natural decline in reservoir pressure. Both data restrictions are made after the number of neighbors has been identified for all wells in the sample. This ensures that any well located closer than one kilometer from the state border will appear as a neighbor to wells that are located further away from the border. However, the data point itself will be excluded from the sample. Finally, it should be noted that non-producing exploration wells are excluded from the analysis. The rationale for this data restriction is that, in isolation, these wells do not pose a risk to underground reserves. Table 5.1 describes the restricted panel used in this chapter.

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[23] 50-, 200- and 300-meter intervals were assessed as alternative intervals but 100-meter intervals were identified as offering the maximum precision while still including sufficient wells in each interval to ensure a meaningful analysis.

TABLE 5.1. DATA SUMMARY

Variables:	*Description*
Well coordinates	Exact coordinates of each boring to extract hydrocarbons (2,130 active wells in the sample)
Operator identifier	Code for the legal entity operating the well (179 unique legal entities in the sample)
County identifier	Code for the county in which the well is located (26 active counties in the sample)
Formation identifier	Code for the geological formation on which the well is located (55 active formations in the sample)
Field identifier	Code for the oil or gas reservoir on which the well is operating (111 active fields in the sample)

Numerical variables:	*Min*	*Mean*	*Max*	*Std. Dev*
Annual extraction (Btu)	1	106,688.51	1,551,121	121,382.91
Annual extraction days	1	302.21	365	100.24
<u>Number of wells:</u>				
- Within: 0-100 m	0	1.84	29	2.91
- Within: 100-200 m	0	0.37	33	1.66
- Within: 200-300 m	0	1.21	28	2.22
…	…	…	…	…
- Within: 900-1,000 m	0	5.18	67	6.03
<u>Number of “rival” wells:</u>				
- Within: 0-100 m	0	0.03	3	0.19
- Within: 100-200 m	0	0.03	9	0.25
- Within: 200-300 m	0	0.06	9	0.42
…	…	…	…	…
- Within: 900-1,000 m	0	0.41	16	1.18
		- General -		
Unbalanced Panel	N = 10,890	n = 2,130	T = 14	

5.3. Empirical strategy

A two-stage statistical model is proposed to test the theoretical prediction that operators accelerate their extraction when faced by “rival” neighbors. The reserve expectations of resource owners are first estimated using historical data and these predicted expectations are then included as a control in the second stage, where the impact of neighbors is ultimately tested. This two-stage setup is necessary because of data limitations and the way behavior is described in the Hotelling framework. Returning to Equation 5.4, “rival” neighbors introduce the potential for leakage (l) but the optimal extraction path is also governed by the size of remaining reserves. Separating the causes of a change in extraction behavior consequently requires knowledge about both the flow and stock of resources. The gas reserves of a well are, however, largely unobserved in practice. Consequently, a necessary first stage in determining the role of neighbors is to estimate stocks.

An implicit assumption of the theoretical model introduced earlier is complete information about the resource stock. In reality, however, information is incomplete and operators have to rely on their expectations when making extraction decisions (Krautkraemer, 1998). Rather than being determined by the actual stock ($\frac{1}{n} * S_t$), extraction is thus governed by the expected sum of future production ($E\left[\int_{k=t}^{\tau} R_{j,k}\, dk\right]_t$). This value is unobserved but can be reconstructed using knowledge about how operators form their expectations. Applied in both conventional and unconventional extraction (see Valko & Lee, 2010), decline curve analysis (DCA) is currently the industry’s preferred reserve estimation technique (Khanamiri, 2010; Bahadori, 2012). Building on Arp’s (1945) seminal work, the method fits the observed production rates of individual wells by a mathematical function in order to predict future extraction potential. Drawing on the widespread use of DCA, it is possible to reconstruct the reserve expectations of resource owners by replicating their statistical estimation technique.

As a purely statistical exercise, DCA rests on the extrapolation of relationships between variables known today and future production outcomes. Identifying these empirical relationships requires a sample of wells for which the entire production history is known. Returning to the dataset introduced earlier, this information is only available for wells decommissioned in the period between 1999 and 2013

(1,953 wells). Focusing on this subgroup, it is possible to mimic the reserve estimation conducted by resource owners. The most popular types of DCA predict future production potential using the time a well has been active in combination with past flow rates (production per day). Another common technique plots future extraction against cumulative past production. To allow for flexibility, the DCA performed in the first stage used in this chapter relies on a combination of flow rate, time and cumulative production together with a series of field and time controls. Specifically, a pooled ordinary least squares (OLS) model such as that presented in Equation 5.5 is performed where R is gas extraction, D is the number of production days, F is a set of field controls, C controls for when the well was commissioned and T is a set of time controls.

$$(5.5) \qquad E\left[ln\left(\sum_{k=t}^{\tau} R_{j,k}\right)\right]_t = \boldsymbol{\beta}\begin{bmatrix} \ln(R_{j,t-1}) \\ \ln(D_{j,t-1}) \\ \ln(\sum_{k=0}^{t-1} D_{j,k}) \\ \ln(\sum_{k=0}^{t-1} R_{j,k}) \\ F_j \\ C_j \\ T_t \end{bmatrix}, \text{ where } t \text{ is annual}$$

Resource owners are assumed to be rational and their expectations about reserves should therefore be non-biased. In order to replicate real expectations, the DCA used in the first stage must consequently have significant out-of-sample predictive power. Cross-validation can be used to validate this property (Stone, 1974; Geisser, 1975) and the original data is therefore divided into two equally sized samples. The model from Equation 5.5 is then fitted to one of these two subsamples (the training set), and its predictive accuracy is assessed using the other (the validation set). Evaluating the coefficient of determination from the validation set illustrates the model’s out-of-sample predictive performance. To reduce variability, 5,000 random partitions are performed, and the validation results are averaged over the rounds. The findings from this cross-validation procedure support the choice of model used in the first stage. By extrapolating the relationships identified using the test set, the DCA model can thus explain 85.04 percent of the variation observed in the validation set. The first stage is thus highly efficient in predicting out-of-sample reserves. This supports the specific choice of DCA and underlines its ability to replicate expectations.

Having established a method of reconstructing reserve expectation, attention returns to the core problem of identifying the impact of neighbors. To motivate the statistical design of this second stage, it is useful to revisit and modify the optimal extraction path that was presented in Equation 5.4. First, the reserve term ($\frac{1}{n} * S_t$) is substituted by the well-specific expectations ($E\left[\int_{k=t}^{\tau} R_{j,k}\, dk\right]_t$) deduced using the first-stage model. Second, the natural logarithm is taken to both sides in order to turn multiplications into additions and account for positive skewness. Performing these two alterations to the optimal extraction path results in the second-stage estimation presented in Equation 5.6.

$$(5.6) \qquad \ln\left(R_{j,t}\right) = \beta_1 \ln\left(l_{j,t} + i_t\right) - \beta_2 \ln(v_t) + \beta_3 \ln\left(E\left[\int_{k=t}^{\tau} R_{j,k}\, dk\right]_t\right) + u_j + \varepsilon_{j,t}$$

With the core two-stage statistical model outlined, it is now possible to formulate a test of whether Colorado’s gas extractors operate as predicted by theory. Drawing on previous sections, the risk of leakage increases with the number of nearby “rivals”. Given that resource owners realize this risk, Hotelling theory predicts accelerated extraction. Evidence of a positive relationship between gas extraction and the number of nearby “rival” neighbors would thus support the empirical relevance of the Hotelling framework. Returning to the two-stage statistical model, this can be translated into a formal test with the following two hypotheses: H_1, operators accelerate their extraction when faced by nearby “rival” neighbors (i.e. $\beta_1 > 0$ in Equation 5.6). H_0, operators do not accelerate extraction when faced by nearby “rival” neighbors (i.e. $\beta_1 \leq 0$ in Equation 5.6). It is noteworthy that the response to “rivals” is expected to decrease with distance, as subsurface interaction becomes less likely. Effects should thus converge towards zero when evaluating the role of sufficiently distant neighbors. This insight later becomes useful as it offers a good first step in verifying the validity of results.

5.4. Results

Table 5.2 presents the results obtained from deploying the two-stage statistical model. Focusing on the coefficients obtained from the second stage, the table outlines four distinct model specifications, each of which constitutes a stepwise implementation of controls. The presented standard errors are bootstrapped (5,000 repetitions) and clustered on a field level (111 fields). These standard errors are chosen because residuals are likely correlated across years within each field and conventional OLS standard errors are therefore unreliable. The first three models presented are pooled OLS estimations and the final one is a fixed effects (within) model.

OLS-1 is the first and most streamlined of the models presented in Table 5.2. It pools the data and regresses annual gas extraction against the number of “rival” neighbors at different distances. This basic setup is, however, vulnerable to omitted variable bias, as it ignores factors that may be correlated with both the extraction and clustering of wells. To mitigate this potential problem, the following three models gradually incorporate a series of control measures.

OLS-2 accounts for the number of annual extraction days as well as operator changes. The dataset used in this chapter is based on an annual frequency. This means that wells might be commissioned or acquired by other operators within a single data point. To reduce variation and approximate actual productivity, it is therefore useful to control for annual extraction days. Takeovers may, however, be correlated with both the clustering and the productivity of wells. To account for this latter effect, a dummy is included for years in which wells change operators, together with an interaction term allowing for differences in well productivity throughout periods of ownership change.

OLS-3 builds on the previous model by including a vector accounting for the influence of neighboring wells in general (both “friendly” and “rival”). This controls for any non-behavioral effects associated with a high degree of well clustering. One example of such an effect are the frac hits discussed earlier, where extensive fractures result in unintended well-to-well interaction. Little work has been done on the impact of frac hits, but existing knowledge suggests that fracture interference typically reduces the performance of wells (Jackson *et al*., 2013). As well-to-well interaction is more likely when extraction is spatially clustered, ignoring frac hits can offset the behavioral effect that this chapter seeks to test. However, given that these and other non-behavioral effects of clustering are independent of ownership structures, it is possible to avoid bias by using neighboring wells in general (both “friendly” and “rival”) as a control.

FE-1 is, in contrast to the three previous models, a fixed effects (within) model. It utilizes the panel dimension of the dataset to account for both entity and time fixed effects (Stock & Watson, 2011, p. 396). Geology is an example of an entity fixed effect that varies across wells but not across time, and gas demand (v in Equation 5.6) is an example of a time fixed effect that varies across time but not across wells. To understand the necessity of using fixed effects, consider a region with gas reservoirs that are difficult to access. Such an area will need multi-well-fracturing meaning that wells will be highly clustered but, on an individual level, relatively unproductive. The pooled OLS estimator mistakenly attributes such a geological effect to the presence of neighbors and thereby underestimates the potential behavioral response. By evaluating the “within well” effect of additional “rival” neighbors, the fixed effects model counters this problem.

TABLE 5.2. MODEL SELECTION

ln(Annual extraction)	*OLS-1 (Pooled)*	*OLS-2 (Pooled)*	*OLS-3 (Pooled)*	*FE-1 (Within)*
Number of “rival” wells:				
- Within: 0-100 m	-0.031	0.056	0.089	0.452***
	[0.159]	[0.127]	[0.100]	[0.078]
- Within: 100-200 m	-0.078	-0.022	0.001	0.224**
	[0.110]	[0.160]	[0.164]	[0.091]
- Within: 200-300 m	0.036	0.030	0.038	0.033
	[0.064]	[0.071]	[0.073]	[0.068]
…	…	…	…	…
- Within: 900-1,000 m	-0.003	-0.008	-0.004	0.003
	[0.025]	[0.020]	[0.022]	[0.019]
ln(Expected reserves)	0.834***	0.730***	0.730***	0.452***
	[0.028]	[0.021]	[0.022]	[0.072]
Other control variables:				
ln(Annual extraction days)		0.935***	0.933***	1.100***
		[0.076]	[0.081]	[0.056]
Controls for operator change		✓	✓	✓
Number of wells:				
- Within: 0-100 m			0.053**	0.024***
			[0.020]	[0.008]
- Within: 100-200 m			0.000	-0.040
			[0.037]	[0.032]
- Within: 200-300 m			-0.008	-0.007
			[0.026]	[0.019]
…			…	…
- Within: 900-1,000 m			0.003	-0.005
			[0.011]	[0.007]
Entity fixed effects (well)				✓
Time fixed effects (annual)				✓
Number of observations	8,758	8,758	8,758	8,758
Number of clusters	111	111	111	111
R-sq: Within	N/A	N/A	0.695	0.704
Between	N/A	N/A	0.802	0.837
Overall	0.851	0.862	0.757	0.802

Notes: The first stage DCA analysis is based on a subset of the complete sample as it rests on data about already decommissioned wells.

Bootstrapped standard errors in brackets (clustered at field-level).

*** Significant at 1 percent level

** Significant at 5 percent level

* Significant at 10 percent level

Reviewing Table 5.2, the estimated effect of “rival” neighbors differs greatly between the four different setups. The three OLS models find no significant extraction effect associated with close “rival” neighbors and the estimates do not converge as expected towards zero when evaluating the role of distant neighbors. However, these findings are unreliable if factors such as geology and gas demand are correlated with both extraction and the clustering of extraction. By exploiting fixed effects, the FE-1 model eliminates this problem and finds strong support for the Hotelling framework. “Rival” neighbors within the first 200-meters are thus found to significantly (at a five percent level) increase extraction. As the dependent variable is the natural logarithm of gas extraction, the coefficients in Table 5.2 are so-called semi-elasticities. This means that the expected effect of an additional “rival” neighbor within the first 100 meters is to multiply gas extraction by exp(0.452) = 1.571. Each additional “rival” is thus, *ceteris paribus*, associated with a 57.1 percent acceleration in extraction. To illustrate graphically how the response to neighbors diminishes as distance increases, Figure 5.4 plots the expected change in extraction associated with “rivals” at different distance bands.

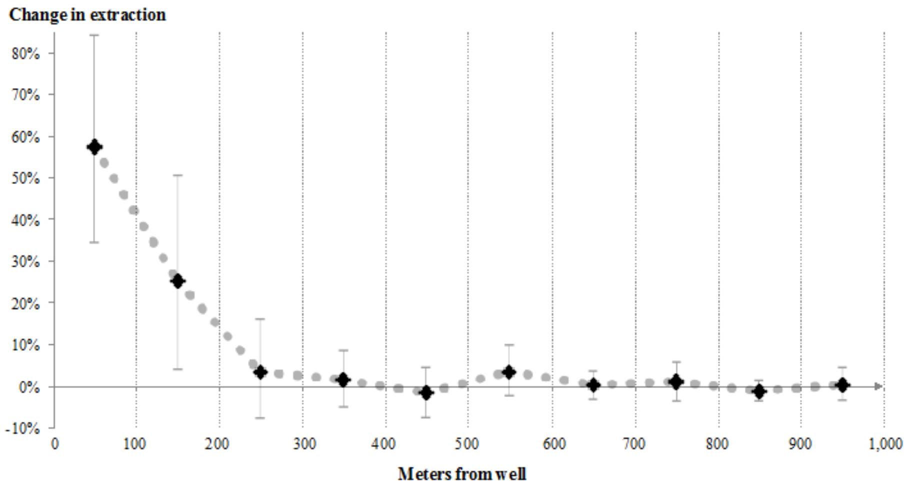

FIGURE 5.4. EXTRACTION RESPONSE TO A “RIVAL” NEIGHBOR DEPENDING ON DISTANCE

Notes: Error bars signify ninety-five percent confidence intervals.

Having established that close “rival” neighbors motivate a statistically significant change in extraction, attention turns to evaluating whether the effect is economically significant. In Colorado, the average number of “rival” neighbors is 0.03 within the first 100 meters and 0.03 in the span between 100 and 200 meters (see Table 5.1). Combining this knowledge with the results of the two-stage fixed effect model, adjacent “rivals” thus motivate an average 2.47 percent acceleration in extraction. As a share of Colorado’s annual production, this equates to about 39.7 trillion British thermal units (BTU) of natural gas. To put this number into perspective, the average American annually consumes 312 million BTU of energy (EIA, 2011). Leakage risk in Colorado thus motivates an acceleration in annual gas extraction sufficient to satisfy the energy demand of approximately 127,300 Americans. This significant number stands testimony to the substantial distorting effects common pool problems can and are inflicting on modern-day gas extraction.

5.5. Robustness and model specification

Any empirical investigation is vulnerable to potential flaws in its design and this makes the study of robustness crucial. To ensure the validity of the findings introduced earlier, this section therefore carries out four tests that examine the predictions of the research design when variables and assumptions are altered.

5.5.A. Accounting for reserves

The results of this chapter rest on the validity of the two-stage estimation procedure and specifically its ability to correctly account for reserve expectations. An implicit assumption of the analysis is thus that actual resource owners use a similar DCA method to that deployed in the first stage. To test whether the findings remain robust if this assumption is relaxed, it is useful to alter the method of controlling for reserves. Building on the FE-1 framework, two alternative setups are proposed and the results obtained when estimating these models are presented in Table 5.3.

TABLE 5.3. THREE APPROACHES TO CONTROLLING FOR RESERVES

Second stage coefficients: *- ln(Annual extraction)*	*R-1* *(Within)*	*R-2* *(Within)*	*FE-1* *(Within)*
Number of "rival" wells:			
- Within: 0-100 m	0.477***	0.267***	0.452***
	[0.087]	[0.068]	[0.078]
- Within: 100-200 m	0.071	0.098	0.224**
	[0.137]	[0.063]	[0.091]
- Within: 200-300 m	0.078	0.045	0.033
	[0.112]	[0.028]	[0.068]
…	…	…	…
- Within: 900-1,000 m	0.001	0.002	0.003
	[0.028]	[0.012]	[0.019]
Other control variables	✓	✓	✓
ln("True" reserves or Expected reserves)		0.794***	0.452***
		[0.025]	[0.072]
First stage coefficients: *- ln(Sum of future extraction)*	*Not applicable*	*"True" reserves*	*DCA (Pooled)*
ln(Gas extraction last year)			0.441***
			[0.023]
ln(Days of activity last year)			-0.257***
			[0.039]
ln(Sum of past extraction days)			0.302***
			[0.026]
ln(Sum of past extraction)			-0419***
			[0.040]
Field dummies			✓
Well commission dummies (annual)			✓
Time dummies (annual)			✓
Number of observations	10,886	6,578	8,758

Notes: The first stage DCA analysis is based on a subset of the complete sample as it rests on data about already decommissioned wells. "Other control variables" includes controls for extraction days, operator changes, neighbors in general, and fixed effects.

Bootstrapped standard errors in brackets (clustered at field-level)

*** Significant at 1 percent level

** Significant at 5 percent level

* Significant at 10 percent level

The first model in Table 5.3, R-1, excludes reserves completely from the analysis. It thus rests on the simplistic assumption that operators do not base their extraction decisions on reserve predictions. The second model, R-2, controls for reserve expectations using true reserves (i.e. the actual sum of future production). In doing so, this model assumes a situation where resource owners have complete knowledge about future extraction potential and base their extraction decisions on this. R-1 (complete ignorance) and R-2 (complete information) thus represent two respective extremes on the spectrum of operator information. When reviewing the predicted effect of "rivals" presented in Table 5.3, both simplified models reveal a statistically significant effect of neighbors within the first 100 meters. These results are in line with the findings of the main FE-1 model and underline the model's robustness to alternative reserve formulations.

5.5.B. Binary behavior

So far, the analysis has built on the principle that the number of neighboring "rivals" governs the risk of resource leakage and thus determines operator behavior. However, if resource owners only distinguish between having and not having "rival" neighbors, then this assumption is too restrictive. To counter this potential problem, a binary response model is tested. This uses a statistical setup similar to that employed in the FE-1 model but replaces the number of neighbors with a series of dummies. These are coded '1' if there are any "rival" wells located within the zone and '0' otherwise. Drawing on the empirical observation that effects are limited to the first 200 meters, the binary analysis focuses on this confined area. A graphical comparison of the coefficient obtained from estimating the binary model and the original FE-1 model is presented in Figure 5.5.

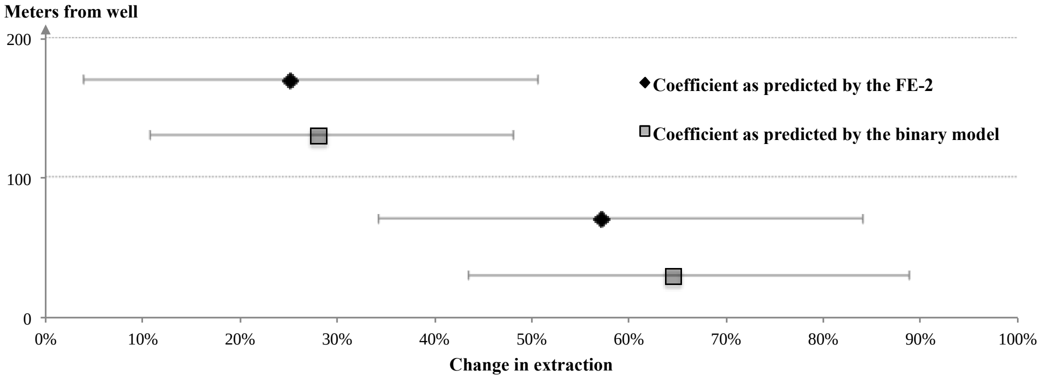

FIGURE 5.5. A SIMPLE COMPARISON OF ESTIMATED COEFFICIENTS

Notes: Error bars signify ninety-five percent confidence intervals.

As Figure 5.5 illustrates, the coefficients obtained from the two models appear similar. Yet, one should note that they describe two separate issues. The FE-1 model identifies the expected change in extraction per “rival”. In contrast, the binary setup describes the predicted impact of having “rival” neighbors at all. This difference in interpretation can help explain why the binary coefficients appear generally larger than those obtained from the FE-1 model. The binary response model treats a well identically regardless of whether it has one or more “rival” neighbors. If numbers govern behavior, the FE-1 coefficients, by design, will be smaller than those obtained from the binary setup.

Moving beyond coefficient interpretation, it is useful to confirm that the FE-1 model and the binary setup reach similar conclusions regarding the general impact of common pool problems. If the two setups identify significantly different impacts it suggests that at least one of the descriptions of behavior is inaccurate. To compare the predicted impacts, it is helpful to normalize the coefficients, by using the average number of “rival” neighbors and the number of wells with “rivals”, respectively. Figure 5.6 shows the results obtained from this exercise.

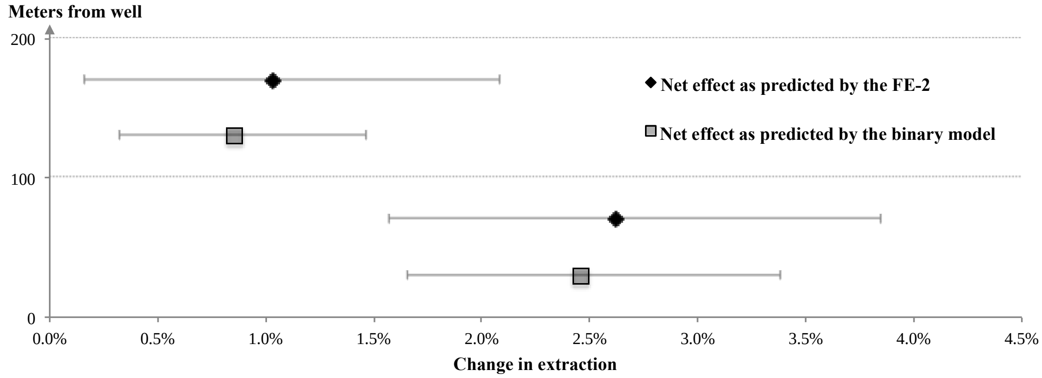

FIGURE 5.6. A COMPARISON OF THE NORMALIZED EFFECT OF "RIVALS"

Notes: Error bars signify ninety-five percent confidence intervals.

The comparison of the normalized effect of "rivals" shows that there is no statistically significant difference in the predictions of the two models. This clarifies that there is no reason to choose the binary setup over the FE-1 specification. The choice of FE-1 as the main model is further supported by the findings presented in Figure 5.5. These indicated that the number of neighbors does affect behavior. Comparing a binary setup with the FE-1 model has, in sum, confirmed the robustness of the main results presented in this chapter.

5.5.C. Reverse causality

Thus far, the analysis has been based on the principle that neighbors drive extraction behavior rather than *visa versa*. This, however, is a simplification of reality if operators respond to the information provided by the extraction outcomes of others. An unforeseen increase in a well's production is likely to give rise to expectations that resources are abundant. In turn, this might induce the well's neighbors to pursue additional drilling around it. If such an information externality is strongly present within annual observations, the main model specification will suffer from problems of reverse causality. However, the panel structure of the data combined with the fact that wells are not built instantly allows for determining the role of information. If reverse causality were important, one would expect current extraction to be strongly correlated with the number of neighbors observed in the following year. One can thus identify the role of information by estimating the FE-1 model using the one-year lead of neighbors, as is done in Table 5.4. If the two model specifications portray similar patterns, it shows that extraction shocks drive the number of neighbors and, by implication, the findings of this chapter would be biased.

TABLE 5.4. USING THE LEAD OF NEIGHBOURS

- ln(Annual extraction)	*Lead-1 (Within)*	*FE-1 (Within)*
Number of "rival" wells:		
- Within: 0-100 m	-0.045 [0.124]	0.452*** [0.078]
- Within: 100-200 m	-0.067 [0.179]	0.224** [0.091]
- Within: 200-300 m	0.049 [0.134]	0.033 [0.068]
…	…	…
- Within: 900-1,000 m	0.004 [0.031]	0.003 [0.019]
Number of wells:		
- Within: 0-100 m	0.016 [0.022]	0.024*** [0.008]
- Within: 100-200 m	-0.033 [0.051]	-0.040 [0.032]
- Within: 200-300 m	-0.026 [0.041]	-0.007 [0.019]
…	…	…
- Within: 900-1,000 m	-0.020 [0.014]	-0.005 [0.007]
Other control variables	✓	✓

Notes: The first stage DCA analysis is based on a subset of the complete sample as it rests on data about already decommissioned wells. Lead-1 substitutes current neighbors with the one-year lead of neighbors. "Other control variables" includes all controls used in the FE-1 model.

Bootstrapped standard errors in brackets (clustered at field-level)

*** Significant at 1 percent level

** Significant at 5 percent level

* Significant at 10 percent level

The results presented in Table 5.4 underline that reverse causality does not jeopardize the main findings. Current extraction shocks are not found to be associated with a statistically significant increase in surrounding neighbors in the following year. This applies independent of the type of neighbor. There is thus no evidence that an information externality plays a major role in the case of Colorado. The findings presented above also highlight the fact that future neighbors do not yet pose a leakage risk and therefore do not affect behavior. A likely explanation for why information externalities do not play a significant role in the case of Colorado is that the majority of fields in the state are already well developed. This means that the geology is largely known and in such a setting information must be assumed to play only a minor role in the deployment of wells. Consequently, problems of reverse causality are more likely in the initial exploration phase of field development.

5.5.D. Accounting for spatial correlation

The statistical inference presented in this chapter rests on the validity of the standard errors used and specifically their ability to correctly account for spatial correlation. In the main section, it was argued that residuals are likely correlated within fields and the standard errors were therefore clustered at this level. However, these standard erors would be biased if residuals are correlated on a broader spatial level. Therefore, this section explores whether clustering at the field level sufficiently accounts for spatial correlation, or whether one needs to cluster on a larger level.

In the context of this chapter, there are three levels on which one might cluster the standard errors. First, the field level which is used in the main section of this chapter. Clustering on this level rests on the assumption that regressors and errors are correlated within single oil depostits but not beyond these. Second, the formation level which is a superset of fields. Clustering on this level assumes that residuals are correlated within rock formations rather then single fields. Third, the county level which assumes spatial correlations are politically rather then geologically determined. Building on the FE-1 framework, the results obtained when clustering on these three levels are presented in Table 5.5.

TABLE 5.5. CLUSTERING OF STANDARD ERRORS

Second stage coefficients: *- ln(Annual extraction)*	*Clustering by field* *FE-1 (Within)*	*Clustering by formation* *FE-1 (Within)*	*Clustering by county* *FE-1 (Within)*
Number of "rival" wells:			
- Within: 0-100 m	0.452*** [0.078]	0.452*** [0.079]	0.452*** [0.091]
- Within: 100-200 m	0.224** [0.091]	0.224** [0.095]	0.224 [0.153]
- Within: 200-300 m	0.033 [0.068]	0.033 [0.036]	0.033 [0.141]
…	…	…	…
- Within: 900-1,000 m	0.003 [0.019]	0.003 [0.016]	0.003 [0.034]
ln(Expected reserves)	0.452*** [0.072]	0.452*** [0.088]	0.452*** [0.064]
Other control variables	✓	✓	✓
Number of clusters	111	55	26

Notes: The first stage DCA analysis is based on a subset of the complete sample as it rests on data about already decommissioned wells. "Other control variables" includes controls for extraction days, operator changes, neighbors in general, and fixed effects.

Bootstrapped standard errors in brackets (clustered at field-level)

*** Significant at 1 percent level

** Significant at 5 percent level

* Significant at 10 percent level

There is no formal test of the level at which to cluster but to avoid bias there is a consensus to use bigger and more aggregated clusters when possible. However, there is a trade-off between bias and variance. When using large clusters, such as the 26 counties, there are very few clusters to average over and the resulting variance matrix can therefore be a poor estimate. This could explain why there is relatively little change in the standard errors when clustering on a formation rather then a field level whereas errors grow significantly when clustering on a county level. Despite this, the results in Table 5.5 highlight that findings remain robust notwithstanding clustering errors at broader levels. Even when clustering at the very restrictive county level, the closest of “rival” neighbors are thus found to motivate a statistically significant change in extraction.

5.6. Conclusion

Focusing on Colorado’s gas industry, the aim of this chapter was to test the empirical validity of the Hotelling framework, and specifically its assumption on forward-looking behavior. For this purpose, the chapter set out to assess how operators respond to potential resource leakage enabled by close “rival” neighbors. The chapter began by deducing testable predictions based on existing theory. Using these predictions, common pool problems in Colorado were quantified and a two-stage statistical model was introduced that isolates the impact of “rival” neighbors. The chapter then evaluated the predicted extraction response to leakage risk and assessed the robustness of the findings.

In line with the theoretical predictions of the Hotelling framework, operators were found to significantly accelerate their extraction when faced with “rivals” located in close proximity. The response faded as distance increased and disappeared fully once the distance exceeded 200 meters. This declining pattern supports the prediction that operators respond to leakage risk, which falls as the likelihood of subsurface interaction decreases. Despite being geographically confined, the consequences of common pool problems across Colorado were identified to be economically significant. Spatial competition thus, *ceteris paribus,* motivates an average acceleration in extraction of 2.47 percent across wells in the state. The validity of this substantial result was evaluated by four robustness checks. First, different reserve estimation techniques were used as control measures. These did not alter the insight that close “rival” neighbors motivate accelerated extraction. Second, a binary setup was tested and compared with the main statistical model employed in this chapter. This comparison indicated that the number of “rival” neighbors is influential for extraction behavior. More importantly, however, the binary setup confirmed the robustness of the findings even if the nature of agent behavior differed. Third, the findings were tested for reverse causality. This analysis highlighted that information externalities do not play a major role in the case of Colorado, and consequently the main findings were found to be robust. Fourth, it was explored whether clustered standard errors at the field level sufficiently account for spatial correlation. This investigation underscored that the findings remain robust when clustering at higher political or geological levels.

The robust evidence presented in this chapter demonstrates that operators make strategic extraction decisions even after the completion of their wells. This strongly supports the empirical relevance of the Hotelling framework. The observation that existing wells change their extraction when faced with “rival” neighbors is, however, not sufficient to prove that Colorado’s gas deposits are indeed common pools. As discussed earlier, it is practically impossible to determine the exact areal extent of production and thus whether gas actually migrates between owners. However, behavior is governed by perceptions, so the mere suspicion of resource leakage suffices to explain the behavioral patterns observed in this chapter. Irrespective of whether leakage is real or only perceived, spatial competition and the prospect of an extraction externality distort extraction in Colorado today.

To foster non-rival extraction behavior, government intervention is required. Yet solving common pool problems in isolation might not lead to better global extraction outcomes. The evidence presented in this chapter highlights that there is scope for regulators to ensure the enforcement of property rights in Colorado's gas industry. Examples of intervention could include stricter regulation concerning the spacing of wells or the unification of resource deposits. Both of these policies would establish local monopolies on the management of underground natural gas. In turn, this eliminates the distorting risk of leakage and therefore motivates a deceleration in extraction. Pre-existing problems of market power may, however, jeopardize the efficiency of such policies. One of Hotelling's main original findings was that, from a social perspective, monopolies extract their resources in an inefficiently slow manner. This behavior is motivated by the trade-off between increased extraction and falling prices. In an ideal world, there would be perfect price competition at the global scale but monopolies on extraction at the local level. This would ensure that owners act as price-takers but conduct their extraction under perfect property rights. Such a scenario of no market failures is, however, largely unfeasible in practice, as pre-existing problems of market power are likely. As an example, Russia accounts for almost 18 percent of global gas production today (BP, 2015). Such a substantial share is likely to provide the country's largely state-owned gas industry with substantial price setting ability. In this context, a second-best solution could be to allow local common pool problems as, *ceteris paribus*, these would counter the slower extraction associated with dominant market participants.

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Chapter 6.

Short-term oil extraction: A matter of regime stability

By THOMAS BLIGAARD NIELSEN*

This chapter evaluates the short-term relationship between government stability and oil extraction, using monthly production data from 32 authoritarian and oil-producing countries. Conventional Hotelling theory on non-renewable resources suggests that an unexpected surge in ownership risk should induce faster extraction. In the context of authoritarian petro-states, this implies that an unexpected fall in government stability should motivate accelerated oil production. This chapter tests this theoretical proposition, by using modern panel data techniques. Relying on monthly data, the analysis is unique in its ability to identify extraction responses to fast-developing political events, while controlling for endogeneity. The findings of the chapter challenge the empirical validity of the existing theoretical paradigm. Contrary to conventional Hotelling theory, it is concluded that a sudden fall in government stability is associated with slowed oil extraction in the most authoritarian of petro-states.

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The oil production of authoritarian petro-states plays a key role in international energy markets and understanding what governs extraction decisions in these countries is therefore critical. Countries ruled by governments ranked among the 25 percent least accountable regimes, according to the World Bank’s Worldwide Governance Indicators (WGI), account for about 60 percent of global oil (BP, 2015; Kaufmann *et al*., 2014). Equatorial Guinea, Kazakhstan and Saudi Arabia are notable examples of such oil producing nations that largely deny their citizens the right to participate in selecting their own governments. This highlights that globally important extraction decisions are essentially determined by a handful of authoritarian rulers. The aim of this chapter is to identify what economic mechanisms drive these decisions and specifically whether the dominant theoretical paradigm holds in this context.

The literature on non-renewable resources such as oil is grounded in Hotelling's theoretical model developed in 1931. Featuring forward-looking agents, this framework holds that resource owners maximize their wealth by trading off extraction today versus extraction in the future. According to this intuition, an unexpected surge in ownership risk should induce accelerated extraction, as it becomes more unlikely that one will have the ability to extract in the future. In the context of petro-states, it is the authoritarian ruler who acts as the custodian of underground hydrocarbon resources. This means that the ownership risk they face is directly linked to the stability of their regimes. Following the Hotelling principle, a threatened ruler should thus accelerate extraction.

Despite the clear theoretical implications of the Hotelling framework, the question of how exactly government stability affects oil extraction remains unanswered. The tensions between short- and long-term effects help explain this. As described above, the Hotelling principle suggests that increased ownership risk motivates accelerated extraction. However, this effect will likely only apply in the short run. In the long run, ownership risk reduces the incentive to invest in capital expenditure such as drilling rigs or pipelines. Eventually, government instability would thus lead to slowed oil production. This leaves the empirical question of when the short run ends and the long run begins. Or in other words, on what timescale, if any, does government instability motivate accelerated extraction?

To empirically assess the role of political risk, Bohn and Deacon (2000) use ordinary-least-squares (OLS) estimation on cross-country data. When deploying this method, they find that the net long-run effect of political risk is slowed extraction. This supports the principle that prolonged ownership risk reduces extraction capabilities. Using within-country models, Bohn and Deacon also attempt to estimate short-run effects. In contrast to what might be expected, they find no consistent positive relationship between government instability and oil extraction. However, their estimation suffers from two problems that could explain why Hotelling behavior is not clearly identified in the short run. First, one can question whether Bohn and Deacon actually study short run effects, as they rely on annual data. It is thus likely that the long run effect of reduced capital investment might apply even within single observations. In other words, a year might not be short enough to identify the hypothesized Hotelling behavior. Second, Bohn and Deacon's estimator presumably suffers from problems of endogeneity. The reason is that an extraction shock today is likely to affect political risk in the future. One mechanism could be that an increase in oil production provides additional funds to equip the army, which in turn might strengthen the regime's stability in the future. If this is the case, Bohn and Deacon's results would be biased and their conclusions questionable.

Recognizing the limitations of the existing literature, this chapter improves empirical estimation in a twofold manner. First, it relies on monthly and not annual data. The use of relatively high frequency statistics makes it possible to study effects across shorter intervals than previous studies. This has the advantage that long-run effects, such as reduced capital investment, are less likely to apply within single observations. Second, this chapter improves on existing OLS models by applying a generalized method of moments (GMM) system estimator, which eliminates past problems of endogeneity. In sum, these improvements make it possible to determine whether government instability ever motivates accelerated extraction as suggested by Hotelling theory. Or alternatively, if other intervening factors, such as reduced capital investment, mean that government instability is associated with reduced extraction even in the very short run.

The chapter unfolds in six sections. First, a simple Hotelling model incorporating ownership risk is introduced in order to identify testable theoretical predictions. Second, the relevant variables are quantified and the panel dataset is outlined. Third, the empirical model is deduced. Fourth, results are discussed. Fifth, robustness is assessed and areas of future research are identified. The final section summarizes the main findings. Contrary to conventional Hotelling theory, this chapter finds that government instability is associated with slowed oil extraction even on a month-by-month basis. This pattern is found to be stronger for more authoritarian regimes. The result indicates that government stability functions as an enabling mechanism for oil extraction in petro-states, which calls for rethinking the dominant paradigm on extraction behavior.

6.1. Predictions of Hotelling

Capital theory is at the core of the Hotelling framework. It is therefore useful to begin by considering an agent who is faced with a conventional investment decision. Imagine a factory owner who has to decide how many machines to acquire. To further simplify the analysis, assume that this owner has perfect information about future conditions and that the demand function is well-behaved. Conventional capital theory holds that, in equilibrium, this profit-maximizing factory owner should be indifferent between investing in an additional machine and placing the money in the alternative interest-yielding asset (henceforth the financial asset). The condition in Equation 6.1 must thus apply in equilibrium:

$$(6.1) \qquad \underbrace{\frac{v_t+p_{t+1}}{p_t}}_{Return\ from\ machine} = \underbrace{1+i}_{Return\ from\ financial\ asset}$$

The left side of Equation 6.1 gives the return obtained from investing in the machine and the right hand side the alternative return acquired from the financial asset. The return of the machine can be divided into two subcomponents: the yield that the machine generates (v_t) and its future sales price (p_{t+1}), which includes deductions for depreciation and wear. Both of these components are divided by the initial price of the machine to identify the percentage return. Unlike man-made assets such as the evaluated machine, the stock of a non-renewable resource is unproductive *in situ* ($v_t = 0$) and cannot be increased through investments. As a result, resource owners face a one-dimensional decision-making problem, whereby the speed of extraction is the only parameter that can be influenced. Realizing this, Hotelling concluded that the owner of a non-renewable resource should only keep reserves *in situ* if prices increase with at least the alternative cost, which is the interest rate of the financial asset. Presented in Equation 6.2, this condition is called the Hotelling rule.

$$(6.2) \qquad \underbrace{\frac{p_{t+1}}{p_t}}_{Return\ from\ resource\ in\ situ} = \underbrace{1+i}_{Return\ from\ financial\ asset}$$

In its simplicity, the Hotelling rule governs both resource prices and extraction behavior, as its violation results in arbitrage possibilities on the part of the resource owner. Consider a situation in which the return from investing in the financial asset is greater than the potential yield from future price increases on *in situ* resources. This would provide the owner with incentives to extract today and place the potential sales revenue in the financial asset. All agents should realize this arbitrage potential. Their collective behavior will then lead to increased supply of the resource today. The expanded supply, coupled with an assumption of a well-behaved demand function will, *ceteris paribus,* result in falling resource prices today ($p_t \downarrow$). This effect continues until all arbitrage possibilities are eroded and the Hotelling rule is restored. The same mechanisms apply in the reverse out-of-equilibrium situation ($p_{t+1} > (1+i)p_t$): Relatively high future resource prices would provide an incentive to keep resources *in situ*, leading to falling supply and rising prices ($p_t \uparrow$). Drawing on information about the size of resource stock, the structure of demand and the alternative interest rate, the Hotelling rule thus governs optimal extraction behavior.

The introduction of Hotelling theory has so far relied on an assumption of perfect information. In reality, resource owners must rely on their expectations when making extraction decisions (Krautkraemer, 1998). Rulers such as Syrian president Bashar al-Assad are, at the time of writing, uncertain about their future power and continued custodianship of national resource reserves. To understand how this affects the Hotelling rule, consider a petro-state ruler who faces a revolution threat. Assume this ruler expects a successful revolt with a probability "z" and that a completely safe investment alternative is available with a return of "i". Figure 6.1 illustrates this decision-making process graphically.

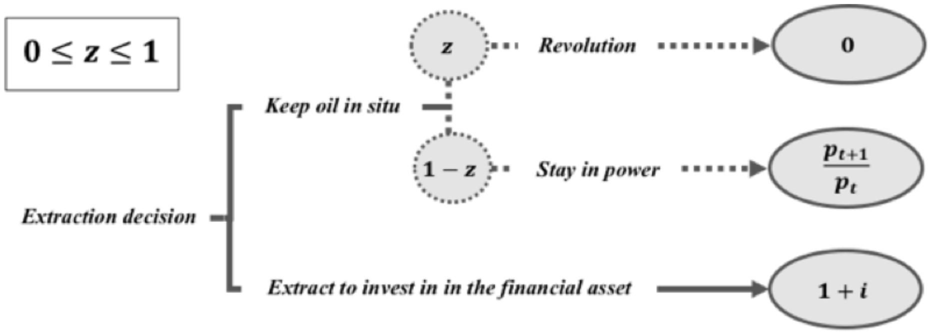

FIGURE 6.1. ACCOUNTING FOR THE RISK OF REVOLUTION

Drawing on insights from Konrad *et al*. (1994), the rational agent will base behavior on a relative comparison of the expected returns. In turn, the presence of revolution risk alters the Hotelling rule to that presented in Equation 6.3.

$$(6.3) \qquad \underbrace{(1-z) * \frac{p_{t+1}}{p_t}}_{E[Return\ from\ resource\ in\ situ]} = \underbrace{1+i}_{Return\ from\ financial\ asset}$$

As seen, an increased risk of revolution ($z \uparrow$) reduces the expected return from the resource *in situ* and raises the opportunity costs of preservation. This means that the conventional Hotelling rule is no longer privately rational. Instead, a risk premium is required for the resource owner to remain indifferent between extracting today and preserving reserves. Keeping the interest rate and oil prices constant, the Hotelling principle thus entails that an unexpected rise in ownership risks should induce the authoritarian ruler to accelerate extraction. It is this theoretical proposition that is tested throughout the rest of this chapter.

6.2. Empirical strategy

This section develops the empirical model used to assess the empirical validity of the Hotelling framework in explaining short-run extraction patterns observed in authoritarian petro-states. The analysis rests on the assumption that the ruling government wields the ultimate power over oil resources *in situ*. This assumption is supported by the fact that National Oil Companies (NOCs) are major extractors in most petro-states and control about 75 percent of global production (Deutsche Bank, 2011). However, even in cases where a ruler does not directly control resources, the literature suggests that government stability and ownership risk are directly linked. Deacon and Bohn (2000) postulate that ownership risk is dependent on government stability and Olson (1993) argues that a change in government often is associated with shifts in property structures. By assuming that the incumbent government wields the ultimate power over resources, it is possible to assess the relationship between oil extraction and perceived ownership risk across countries. Expectations regarding a government's stability can thus be used as a proxy for ownership risk and it is therefore unnecessary to identify the risk faced by potential individual resource owners within countries. Accordingly, the empirical model of this chapter focuses on the relationship between oil extraction and government stability and can be summarized as follows:

$$R_{j,t} = \beta_1 R_{j,t-1} + \beta_2 Gov_{j,t} + \boldsymbol{X'_{j,t}\beta_3} + v_j + \varepsilon_{j,t} \tag{6.4}$$
$$where\ j = 1, \dots, N\ and\ t = 1, \dots, T$$

The core model presented above consists of five explanatory elements. First, past oil extraction ($R_{j,t-1}$) as the non-renewable nature of oil deposits entails that this month's extraction ($R_{j,t}$) is conditional on past production levels. Second, the main variable of interest, $Gov_{j,t}$, which stands for the expected government stability of country j at time t. Third, a vector of potentially endogenous covariates ($\boldsymbol{X'_{j,t}}$). This includes the option value of *in situ* resources (i.e. the oil price multiplied by remaining reserves) and the interest rate, which, according to the Hotelling framework, both govern extraction. The fourth type of explanatory variable, v_j, refers to country-specific factors. Geology is an example of such an effect that varies across countries but not across time. The fifth element is the country-specific error term, $\varepsilon_{j,t}$.

Estimating the model as presented in Equation 6.4 is made challenging by the fact that most country-specific effects (v_j) are unobservable. For example, there is no good account of extraction costs at the country level. Omitting country-specific factors from the analysis can, however, result in bias, as these effects are likely correlated with both government stability and extraction. One solution is to take first differences, as demonstrated in Equation 6.5. This allows the removal of any factors that vary across entities but not across time. Consequently, it is possible to omit the unobservable country-specific effects without causing bias.

$$\Delta R_{j,t} = \beta_1 \Delta R_{j,t-1} + \beta_2 \Delta Gov_{j,t} + \Delta \boldsymbol{X'_{j,t}} \boldsymbol{\beta_3} + \Delta \varepsilon_{j,t} \tag{6.5}$$

Using conventional statistical techniques to estimate Equation 6.5 is problematic, as the lagged dependent variable is, by design, correlated with the error term. For example, OLS estimates will be biased even if the errors themselves are not autocorrelated. To address these issues, Arellano and Bond (1991) developed a dynamic panel data estimator. Their method uses the levels of the dependent variable lagged two and more periods and the levels of the endogenous independent variables lagged two and more periods as instruments. This eliminates the problem of technical endogeneity. But since both the dependent and independent variables in Equation 6.5 are very persistent, the lagged levels would be weak instruments (Blundell & Bond, 1998). However, by assuming that the first-differences of the independent variables are uncorrelated with any individual effects, lagged values of the first-differences can be used as additional instruments, thereby increasing efficiency (Arellano & Bover, 1995). Faced by the potentially persistent nature of oil extraction and government stability, this chapter therefore relies on the Arellano and Bover GMM estimator when estimating Equation 6.5.

Choosing the GMM moment conditions carefully allows the elimination of the endogeneity problems associated with previous studies. As an estimation technique, the GMM estimator relies on a set of moment conditions formed by assuming that particular lagged levels of the dependent variable are orthogonal to the differenced disturbances. Commonly, it is assumed that $E[x_{is}\varepsilon_{it}] = 0$ for all s and t. However, as discussed earlier, an extraction shock today is likely to affect government stability tomorrow. This means, that the explanatory variables are not strictly exogenous and the whole vector of possible instruments can therefore not be used. To counter this problem, the explanatory variables are treated as predetermined. The GMM estimator used in this chapter thus relies on a less restrictive assumption, namely that $E[x_{is}\varepsilon_{it}] = 0$ for $s \leq t$. If this holds and the restricted lagged levels are correlated with the endogenous explanatory variables, then the estimator will be unbiased.

Following the outline of the empirical model, it is now possible to identify the null hypothesis for testing the empirical applicability of the Hotelling framework in the short run. Assuming ultimate power, low government stability (i.e. a low value of $Gov_{j,t}$) is expected to be associated with high ownership risk. As outlined earlier, high levels of ownership risk should lead to accelerated extraction, according to theory. This means that the empirical analysis will support the validity of the Hotelling framework if a negative relationship between oil extraction and ownership risk is identified (i.e. $\beta_2 < 0$). This can be used to infer the formal statistical null hypothesis (H_0) and alternative hypothesis (H_1) presented below:

(H_0) $\beta_2 < 0$: Support for the Hotelling framework
(H_1) $\beta_2 \geq 0$: Reject the Hotelling framework

6.3. Data

This section quantifies the relevant factors in Equation 6.5 and outlines the dataset on which the analysis in this chapter is based. To make inferences about how government stability affects short-run oil extraction in authoritarian petro-states, it is necessary to draw a representative sample of relevant countries. This requires, first and foremost, a definition of what constitutes an authoritarian petro-state. In the context of this chapter, a country is defined as a petro-state if it satisfies two specific criteria: First, the country needs to produce a minimum of ten thousand barrels of oil per day. Second, the country's government must be consistently ranked among the 50 percent least accountable regimes in the world according to the WGI index (Kaufmann *et al.*, 2014). The exact threshold at which a government is categorized as being authoritarian will later be investigated in more detail. Globally, there are 35 countries that satisfy the two criteria and these are all included in the initial sample. For a complete list of countries, the interested reader is referred to Appendix D. The panel consists of monthly data spanning a period of twelve years, that is, the beginning of 2003 to the end of 2014. A detailed discussion of how the individual components of Equation 6.5 are quantified is presented in the following four subsections.

6.3.A. Oil extraction

The U.S. Energy Information Administration (EIA, 2015) provides accounts on the monthly oil supply at the country level. These figures are used as approximations of a country's total oil extraction and comprise the production of crude oil, natural gas fluids and other liquids including lease condensate. To account for positive skewness, the natural log of oil supply is used in the statistical model. This log-transformation furthermore ensures that the model does not overemphasize the behavior of big producers such as Saudi Arabia. The chapter thus focuses on identifying relative alterations in extraction (percentage changes) rather than absolute ones.

6.3.B. Government stability

Quantifying government stability is complicated by its non-numerical nature. Drawing on the methodology of Dietz *et al*. (2007) and Tusalem (2010), this chapter relies on assessments presented in the International Country Risk Guide (henceforth ICRG). This data catalogue is a product of the PRS Group (PRS, 2015) and it consists of index scores that experts allocate to nation-states reflecting the prevailing political conditions. As a proxy for the ruling government's ability to stay in power, this chapter specifically relies on the ICRG index of government stability. Reported at the beginning of each month, this index runs from 0 to 12, where low values indicate a significant risk of government collapse. Representing predictions about future outcomes, this index thus serves as a good proxy of the expectations, which are hypothesized to govern behavior according to the Hotelling framework.

6.3.C. Option value of in situ resources and interest rates

Interest rates on alternative investments and the option value of remaining reserves are important factors for extraction behavior according to the Hotelling framework. Therefore, both variables are included in the analysis. The value of *in situ* resources is approximated by multiplying known reserves with the crude oil price. Reserve estimates are acquired from BP (2015) and oil prices are obtained from the World Bank (2015). The exact prices used are the equally weighted average spot of the three major oil benchmarks Brent, Dubai and West Texas Intermediate (WTI). The analysis uses the U.S. Treasury bill rate as a proxy for capturing international interest rates. The selection of this proxy is justified by the dollar’s de facto status as the global reserve currency, whilst its validity depends on the access of authoritarian rulers to international financial markets. Data on U.S. Treasury rates was gathered from the International Monetary Fund (IMF, 2015).

6.3.D. Ability to extract

So far, the empirical model incorporates all variables that, according to theory, govern extraction behavior. However, there are factors outside the theoretical Hotelling model that might limit (or alter) behavior. These factors must be controlled for in order to ensure an unbiased estimation of the relationship between oil extraction and government stability.

The potential capability of an authoritarian ruler to act in accordance with the Hotelling framework is dependent on his or her ability to extract. Military conflicts between nation-states and/or civil war can forcibly make extraction impossible. The case of the Libyan revolt in 2011 illustrates this point. The combination of internal unrest and foreign airstrikes eliminated oil export opportunities and blocked the Libyan government's access to oil deposits in the eastern part of the country (Darbauche & Fattouh, 2011). This case demonstrates that civil war and foreign pressure can be correlated with both oil extraction and government stability, thus highlighting the need to control for both factors.

To account for incidents of internal armed conflict, this chapter relies on the ICRG index of "Civil War" (PRS, 2015). This index describes the actual or potential risk of situations where a domestic rebel force (that holds territory) is in armed conflict with the security forces of the ruling government. Based on expert assessments, the civil war index runs on a scale from 0 to 4, whereby low values indicate high levels of internal conflict. To account for incidents of armed conflict with other nations, this chapter again relies on estimates provided by the PRS group (2015). Specifically, the "War" index is used. This runs on a scale from 0 to 4 where low values indicate a high level of armed conflict with another nation state. Table 6.1 below describes the complete panel used in this chapter.

TABLE 6.1. DATA SUMMARY

Variable:	*Min*	*Mean*	*Max*	*Std. Dev*
Oil production (thousand barrels per day)	13	1,784.67	12,248	2,548.17
Government stability index	2	8.86	11.5	1.83
War index	0	3.79	4	0.42
Civil war index	0.5	3.47	4	0.74
U.S. treasury bill rate	0.5	2.25	6.25	1.98
Oil price ($US avg. spot WTI, Brent and Dubai)	25.56	73.46	132.83	27.78
Oil reserves (thousand million barrels)	0.43	39.15	298.35	66.30
Balanced Panel	*4,608 observations*	*n = 32 countries*	*T = 144 (12 years)*	

Sources: EIA 2015; IMF 2015; PRS 2015 and World Bank 2015

6.4. Results

With the building blocks of the empirical analysis in place, it can now be assessed whether the effect of government instability is indeed accelerated extraction in the short run. Table 6.2 presents the results obtained from estimating the empirical model using Arellano and Bover's system GMM estimator. The four columns represent the estimates obtained from gradually more restricted samples. The first column of estimates is based on the entire sample. It therefore includes all petro-states that continuously ranked among the 50 percent least accountable regimes in the world in the period between 2003 and 2014, according to the WGI. Respectively, the second, third and fourth column restrict this sample to include only countries that are ranked among the 40, 30 and 20 percent least accountable regimes.

TABLE 6.2. ESTIMATES CORE MODEL

Δ ln(Oil production)	*Top 50 pct. (GMM)*	*Top 40 pct. (GMM)*	*Top 30 pct. (GMM)*	*Top 20 pct. (GMM)*
Δ ln(Oil production):				
- lag 1	-0.053	-0.009	-0.013	-0.038
	[0.075]	[0.061]	[0.064]	[0.029]
Δ Government stability index	0.070	0.108**	0.124**	0.155**
	[0.043]	[0.053]	[0.055]	[0.066]
Δ ln(U.S. treasury bill rate)	0.008	0.005	0.005	0.008
	[0.005]	[0.004]	[0.005]	[0.007]
*Δ ln(Oil price * reserves)*	0.011	0.018	0.023	0.041
	[0.016]	[0.018]	[0.022]	[0.035]
Number of observations	4,544	3,266	2,840	1,420
Number of countries	32	23	20	10

Notes: "Δ" signifies the first difference. All explanatory variables were treated as endogenous and predetermined (i.e. $E[x_{is}\varepsilon_{it}] = 0$ for $s \leq t$ but $E[x_{is}\varepsilon_{it}] \neq 0$ for $s > t$). The Arellano-Bond test for zero autocorrelation did not present evidence that the model is mis-specified (i.e. the null hypothesis of no serial correlation was rejected at order one but not at higher orders)

Robust standard errors corrected for finite samples (Windmeijer, 2005) in brackets.

*** Significant at 1 percent level

** Significant at 5 percent level

* Significant at 10 percent level

Before interpreting the results, there are two important things to note about the estimation. First, we use robust standard errors as the Breusch-Pagan test suggests heteroskedasticity in the data-generating process. The lack of homoskedasticity also means that the conventional Sargan test of over-identifying conditions cannot be performed.[24] If one wrongly attempts to estimate the Sargan test using normal standard errors, the null hypothesis is rejected at the five percent level. Under assumptions of homoskedasticity, this would suggest problems of over-identification. However, as shown by Arellano and Bond (1991), the Sargan test overrejects in the presence of heteroskedasticity and a test using normal standard errors can thus not be trusted. However, to limit any potential problems of over-identification, the maximum number of lags used as instruments is limited to twelve.[25] Second, it is important to recall the functional form of the variables in the model. Since the natural log of oil production is the dependent variable, a one-unit increase in any of the depending variables, controlling for other explanatory variables, is expected to lead to a $\hat{\beta}$-unit change in $ln(R)$. The estimated coefficients for government stability are thus semi-elasticities.

Returning to the results presented in Table 6.2, none of the estimates are statistically significant for the entire sample. However, for all of the restricted samples, government stability is significantly positive at the 5 percent level. The expected effect of a one-unit increase in the ICRG-index of government stability is thus, *ceteris paribus*, an expected increase in extraction of 11, 13 and 17 percent respectively. Contrary to the predictions of the Hotelling framework, these results suggest that an increase in government stability is associated with accelerated extraction in petro-states even on a month-by-month basis.

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[24] Following Arellano and Bond (1991), only for a homoskedastic error term does the Sargan test have an asymptotic chi-squared distribution.

[25] Six and 18 were assessed as alternative maximum lag limits but estimates were not found to be sensitive to this and 12 lags were thus chosen as this limit represents the span of a year.

Furthermore, this relationship is found to be statistically and economically more significant, the more authoritarian the evaluated countries are. The results in Table 6.2, however, do not account for incidents of military conflict. To address this, Table 6.3 presents the estimates obtained when controlling for incidents of civil war and cross-border conflicts.

TABLE 6.3. ESTIMATES ACCOUNTING FOR MILITARY CONFLICTS

Δ ln(Oil production)	*Top 50 pct. (GMM)*	*Top 40 pct. (GMM)*	*Top 30 pct. (GMM)*	*Top 20 pct. (GMM)*
Δ ln(Oil production):				
- lag 1	0.018	0.109	0.124	0.178
	[0.105]	[0.099]	[0.112]	[0.168]
Δ Government stability index	0.057*	0.080***	0.089***	0.110***
	[0.029]	[0.031]	[0.030]	[0.035]
Δ War index	0.221	0.318**	0.362**	0.372**
	[0.138]	[0.143]	[0.143]	[0.181]
Δ Civil war index	0.090	0.098	0.098	0.047
	[0.069]	[0.072]	[0.071]	[0.031]
Δ ln(U.S. treasury bill rate)	0.009*	0.009*	0.007	0.011
	[0.005]	[0.005]	[0.005]	[0.009]
*Δ ln(Oil price * reserves)*	0.014	0.018	0.025	0.039*
	[0.015]	[0.018]	[0.015]	[0.021]
Number of observations	4,544	3,266	2,840	1,420
Number of countries	32	23	20	10

Notes: "Δ" signifies the first difference. All explanatory variables were treated as endogenous and predetermined (i.e. $E[x_{is}\varepsilon_{it}] = 0$ for $s \leq t$ but $E[x_{is}\varepsilon_{it}] \neq 0$ for $s > t$). The Arellano-Bond test for zero autocorrelation did not present evidence that the model is mis-specified (i.e. the null hypothesis of no serial correlation was rejected at order one but not at higher orders)

*** Significant at 1 percent level

** Significant at 5 percent level

* Significant at 10 percent level

Comparing the results from Tables 6.3 and Table 6.2, it becomes clear that accounting for armed conflicts generally reduces the expected effect of government stability. For example, the effect of a one-unit change in government stability falls from 17 percent to about 12 percent when evaluating the most restricted sample, that is, petro-states ranked among the world's 20 percent least accountable regimes. This pattern is explained by armed conflicts decreasing both government stability and the ability to extract oil. Incidents of civil war are not found to have a statistically significant effect on oil extraction. In contrast, military conflicts with other nations significantly reduce domestic oil production. In sum, the core model used earlier suffered from omitted variable bias, as it did not account for armed conflicts reducing extraction ability. As a consequence, the role of government stability was overestimated.

However, even when controlling for conflicts, the testing procedure employed in this chapter offers no empirical support for the Hotelling framework. From Table 6.3, it is thus clear that $\hat{\beta}_2$ is significantly positive on a 1 percent level for all three restricted samples. The null hypothesis identified earlier can therefore be statistically rejected for petro-states ranked among the 40 percent least accountable regimes in the world. Contrary to the principles of Hotelling, growing government instability is thus found to result in decelerated extraction across the world's least accountable petro-states. When evaluating the estimates for the full sample, government stability is only significantly positive at the six percent level. This matches the general pattern that stability plays a bigger role for oil extraction in more authoritarian societies. One explanation for this could be that the instability of a government only affects extraction if the threatened regime has substantial powers over the wider society. Neither the interest rate nor the proxy value of *in situ* resources is found to be statistically significant on a 5 percent level. This further supports the conclusion that the Hotelling principal does not explain monthly variations in the extraction of authoritarian petro-states.

Another important observation is that monthly changes in extraction are not persistent over time. For all samples presented in Table 6.3, the lagged dependent variable is thus statistically insignificant. This means that, *ceteris paribus*, changes in extraction are not correlated across months. However, it does not mean that extraction itself cannot be persistent. Analyzing month-on-month changes in extraction, this chapter thus only concludes that extraction is first-differencestationary on a monthly basis. In other words, in the very short run it is only instability, in the form of armed conflicts or government weakness, which systematically influence changes in extraction.

6.5. Robustness

The conclusions of this chapter are vulnerable to the statistical design used. There are three broad areas of concern: data reliability, unaccounted constraints on extraction and sampling period bias. This section is dedicated to highlighting these potential caveats, assessing robustness and suggesting future research to improve our understanding of the empirical results.

6.5.A. Data reliability

The conclusions reached in this chapter fundamentally rest on the quality of the chosen dataset. The statistical results cannot be trusted if the underlying data is inaccurate. In the context of this chapter, there are two potential reasons for concern. First, the chosen variables might not be good representatives of the factors described by theory. Second, the reliability of the data itself might be questionable. This subsection introduces these potential concerns and discusses the pre-emptive measures taken to avoid bias.

The fact that the ICRG-index of government stability is not a perfect proxy for perceived ownership risk should motivate concerns. As argued earlier, it is the expectations of resource owners that determine extraction within the Hotelling framework. Ideally, one should thus use psychological assessments to identify the degree to which individual authoritarian rulers or entire regimes feel that their status as custodians of national resources is threatened. Yet, in practice, such an assessment is impossible hence this chapter’s reliance on the ICRG-index as a proxy. Relying on proxies is, both in the context of this chapter and more generally, a source of fundamental concern for data reliability. However as argued earlier, the use of government stability indexes finds support in the wider literature and this limits the risk associated with using them. Furthermore, there is no clear reason to believe that the government stability index, used systematically, mismeasures the perceived ownership risk of authoritarian rulers. In this case, a potential measurement error would only result in attenuation bias meaning that estimates would converge towards zero. However, this chapter found a significantly positive effect of government stability and potential attenuation bias will thus only make it more unlikely to reject the Hotelling framework.

Another concern is that weak monitoring capability and potentially skewed incentives jeopardize the reliability of self-reported data. The analysis relies on reserve and extraction data from BP (2015) and the EIA (2015), which originates from figures supplied by national statistical agencies and governments. A problem with this is that some countries might consider extraction and reserves data a state secret and therefore can have skewed incentives to misreport. A second challenge facing the self-reported data is that certain countries lack the institutions needed to keep a statistical record of monthly oil production levels. Weak monitoring capability, coupled with potentially skewed incentives, should motivate concerns about the reliability of the oil production data used in this chapter. If the data is inaccurate in a non-random manner, then the statistical model will estimate biased results. To counter this problem, countries that displayed persistently stable production levels or limited precision in reported data were temporarily removed and the analysis was repeated. Venezuela constitutes a case in point of this practice; it was temporarily omitted because it had reported the same production levels over a period of four consecutive months. However, this did not significantly affect results. Consequently, all countries were included in the final analysis to ensure that the sample did not suffer from the researcher imposing arbitrary selection bias.

6.5.B. Constraints on extraction

The performance of the empirical model is dependent on the implicit assumption that resource owners are capable of altering their extraction. Hotelling theory describes the voluntary behavior of resource owners. Therefore, it is important to statistically distinguish between forced and voluntary changes in behavior. This was the reason why incidents of armed conflict were controlled for earlier. However, it remains uncertain whether the employed method fully succeeds in identifying purely voluntary extraction patterns.

One reason the statistical model fails to identify Hotelling behavior may be that the chosen strategy overemphasizes the power of governments and neglects capital constraints. The oil industry is capital-intensive, and considerable investments are needed to expand extraction capacities (Krautkraemer, 1998). This technical feature puts constraints on governments seeking to adjust extraction quickly. Also, many petro-states rely on international oil companies to operate their fields and the government might therefore not control production on a daily basis. As a consequence, this chapter might mistakenly denounce the Hotelling framework simply because constraints outside the theory prevent extraction adjustments within the short intervals assessed.

To test whether the results of this study are driven by an intervening effect of technical constraints, it is helpful to use OPEC countries[26] as a robustness check. This is because the governments of OPEC countries wield more power than others over their monthly oil extraction levels. There are two reasons for this. First, industry experts widely consider OPEC members to have excess production capacity (Deutsche Bank, 2013, p. 28). This means that the problem of capital constraints is less of a concern for this subset of twelve countries. Second,

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[26] Algeria, Angola, Ecuador, Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Saudi Arabia, UAE and Venezuela.

government-controlled NOCs manage a significant share of the daily extraction made in OPEC countries. As an example, Saudi Aramco controls almost all oil production in Saudi Arabia.[27] This ensures that the ruling governments of OPEC members are relatively less dependent on international oil companies and that they therefore have actual ability to change monthly extraction levels. To ensure robustness, it is thus useful to compare the results introduced earlier with those obtained when estimating the empirical model for the restricted sample of twelve OPEC countries. The estimates obtained from performing this exercise are presented in Table 6.4.

TABLE 6.4. ESTIMATES FOR OPEC COUNTRIES

Δ ln(Oil production)	*Top 40 pct. (GMM)*	*Top 30 pct. (GMM)*	*Top 20 pct. (GMM)*	*OPEC (GMM)*
Δ ln(Oil production):				
- lag 1	0.109	0.124	0.178	0.175
	[0.099]	[0.112]	[0.168]	[0.119]
Δ Government stability index	0.080***	0.089***	0.110***	0.089**
	[0.031]	[0.030]	[0.035]	[0.035]
Δ War index	0.318**	0.362**	0.372**	0.310
	[0.143]	[0.143]	[0.181]	[0.207]
Δ Civil war index	0.098	0.098	0.047	0.225*
	[0.072]	[0.071]	[0.031]	[0.129]
Δ ln(U.S. treasury bill rate)	0.009*	0.007	0.011	0.007
	[0.005]	[0.005]	[0.009]	[0.006]
*Δ ln(Oil price * reserves)*	0.018	0.025	0.039*	0.034
	[0.018]	[0.015]	[0.021]	[0.029]
Number of observations	3,266	2,840	1,420	1,704
Number of countries	23	20	10	12

Notes: "Δ" signifies the first difference. All explanatory variables were treated as endogenous and predetermined (i.e. $E[x_{is}\varepsilon_{it}] = 0$ for $s \leq t$ but $E[x_{is}\varepsilon_{it}] \neq 0$ for $s > t$). The Arellano-Bond test for zero autocorrelation did not present evidence that the model is mis-specified (i.e. the null hypothesis of no serial correlation was rejected at order one but not at higher orders)

*** Significant at 1 percent level

** Significant at 5 percent level

* Significant at 10 percent level

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[27] A complete list of the main NOCs of the petro-states evaluated in this chapter is presented in Appendix E. It should, however, be noted that many of the companies included in this list do not function as actual operators.

As can be seen from Table 6.4, the estimated effect of government stability identified for the subset of OPEC countries is similar to that found for the three restricted samples. This underlines the robustness of the result that increased government stability in the short run is associated with accelerated extraction in petro-states. The main findings of this chapter can thus not be attributed to a lack of spare capacity or limited direct influence of governments.

6.5.C. Sample period concerns

Apart from concerns regarding technical capability, one might worry that the findings of this chapter are dependent on the specific period of assessment. As discussed, the original sample covers the time span between 2003 and 2014. These years were characterized by a series of major events, which have affected the oil industry. Notably, these include the Iraq war (2003), the global financial crisis (2007) and the Arab Spring (2010). One should be concerned that these specific events are driving results. The findings of this chapter might thus not be robust outside the specific period of assessment. To test this, it is useful to split the sample by date and estimate the model separately. One can then compare whether the conclusions differ significantly depending on the sample period chosen. In the context of this chapter, the original sample is split into two equal halves. The first of these covers the years 2003 to 2008 and the second covers the period 2009 to 2014. Using these subsamples, the original empirical model is then estimated separately. Drawing on earlier insights, this exercise is only performed for the 30 percent least accountable regimes. However, performing the same exercise for other subsets of countries does not affect overall conclusions. Table 6.5 presents the results obtained when estimating the Arellano and Bover GMM model for the subsamples as described above. Furthermore, the third column includes the original estimates for the full sample (i.e. 2003-2014).

TABLE 6.5. ESTIMATES FOR DIFFERENT PERIODS

Δ ln(Oil production)	*2003-2008*	*2009-2014*	*Full period*
	Top 30 pct. (GMM)	*Top 30 pct. (GMM)*	*Top 30 pct. (GMM)*
Δ <u>ln(Oil production):</u>			
- lag 1	0.255	0.098	0.124
	[0.246]	[0.061]	[0.112]
Δ Government stability index	0.119***	0.043*	0.089***
	[0.034]	[0.023]	[0.030]
Δ War index	0.474**	0.132	0.362**
	[0.224]	[0.112]	[0.143]
Δ Civil war index	0.005	0.211*	0.098
	[0.018]	[0.126]	[0.071]
Δ ln(U.S. treasury bill rate)	0.011*	-0.011	0.007
	[0.006]	[0.029]	[0.005]
*Δ ln(Oil price * reserves)*	0.024	0.018	0.025
	[0.026]	[0.019]	[0.015]
Number of observations	1,400	1,420	2,840
Number of countries	20	20	20

Notes: "Δ" signifies the first difference. All explanatory variables were treated as endogenous and predetermined (i.e. $E[x_{is}\varepsilon_{it}] = 0$ for $s \leq t$ but $E[x_{is}\varepsilon_{it}] \neq 0$ for $s > t$). The Arellano-Bond test for zero autocorrelation did not present evidence that the model is mis-specified (i.e. the null hypothesis of no serial correlation was rejected at order one but not at higher orders)

*** Significant at 1 percent level

** Significant at 5 percent level

* Significant at 10 percent level

As seen from Table 6.5, the effect of government stability remains significantly positive on at least a 10 percent level when evaluating the subsamples separately. Furthermore, the estimates of the three samples are not statistically different from one another. This suggests that the conclusions of this chapter are robust across periods. Earlier findings can thus not be attributed to single events such as the Arab Spring but represent general patterns in the data. However, the above robustness check only confirms within-sample validity. External validity outside the sample period can thus not be determined.

6.5.D. Further research

As the three previous subsections showed, a combination of due diligence and robustness checks allows for ensuring both the validity and reliability of the chapter's empirical conclusions. Despite these verifications, there remains room for further research to confirm that the findings carry external validity beyond the narrow arena of short-term oil extraction in authoritarian petro-states.

As a commodity, oil has unique features that distinguish it from many other non-renewable resources. These differences might be what jeopardize the Hotelling framework's explanatory power in this setting. A significant share of global oil is traded on long-term forward contracts (Fattouh, 2011). This is largely because refinery capacity is required before the raw material can be sold to end-users. A consequence of this market structure is that, even if extraction capacity exists, it can be challenging to accelerate or decelerate oil exports in the short run. A related problem is the potential constraint imposed by transportation infrastructure. In 2014, 17,073,000 barrels of oil were exported daily from the Middle East (BP, 2015). These significant physical flows require infrastructure such as harbors, shipping lanes and tanker capacity. The consequence is that transport bottlenecks can reduce a ruler's incentive and ability to rapidly accelerate extraction in times of government instability. However, other non-renewable resource types, such as secondary diamonds, have a more unconstrained way from mine to market (Lujala *et al*., 2005). The limitations on rapid extraction adjustment thus vary across different types of non-renewable resources. It might, therefore, be that Hotelling theory is better suited to explain the extraction of resources other than oil. To ensure the external validity of the findings, one should thus apply the high frequency empirical model used in this chapter to a wider category of non-renewable resources.

The discussion above highlights the potential limits to short-term extraction responses. However, it does not explain the finding that oil production is accelerated in times of high government stability. To explain this empirical pattern, it is necessary to study the incentives of domestic actors as well as those of international trade partners. A promising avenue for future research could thus be to analyze the role of retrospective punishment. Domestic agents such as a country’s bureaucracy or the employees of state oil companies might not desire to assist a weakened ruler in accelerating extraction because they fear that a future leader might punish this action retrospectively upon gaining power. Also, international trade partners might not wish to be overly affiliated with a “sunset” government, as this is likely to weaken relations with a potential future leader. The consequence of these intertemporal incentives could, as identified in this chapter, be that extraction falls as a ruler is weakened. Likewise, a government that carries momentum in terms of stability might have an easier time convincing international and domestic actors to help them accelerate extraction. There is thus room for further research into the underlying mechanisms driving the observed patterns in order to explain the empirical relationships identified in this chapter.

6.6. Conclusion

With the aim of testing the empirical relevance of Hotelling theory, this chapter assesses the short-run relationship between government stability and oil extraction in authoritarian petro-states. The focus on undemocratic societies was grounded on the observation that a significant share of global oil originates from nations where the citizens are unable to participate in selecting their own governments. As a consequence, it was argued that vital extraction decisions rest with a few authoritarian rulers and understanding their behavior was therefore deemed to be crucial. The Hotelling principle was outlined as the dominant theoretical paradigm on the economics of non-renewable resource management. It was argued that an implication of this framework is that authoritarian rulers, as the custodians of oil resources, should accelerate their extraction when threatened. This relationship should mainly apply in the short-run, as political instability has not yet limited production capabilities. To test the empirical validity of this theoretical description, a panel dataset comprising 32 countries was used. Unlike the existing experimental literature on Hotelling, this chapter relied on monthly data that uniquely allowed for identifying responses to sudden political events. Furthermore, the analysis improved on existing studies by applying a dynamic panel data system GMM estimator that eliminated the risk of endogeneity. Contrary to conventional theory, the empirical analysis found that government instability, *ceteris paribus*, is associated with reduced oil extraction in the most authoritarian of petro-states. The Hotelling framework can thus not explain the short-run monthly variations in oil extraction observed in the data.

However, one cannot denounce the wider relevance of the Hotelling principle purely on the basis of this chapter. As argued, oil as a commodity has characteristics that distinguish it from other non-renewable resources. An analysis similar to the one introduced here is thus needed to establish whether the conclusions apply outside the realm of oil production in authoritarian petro-states. More broadly, a theory is always a simplification of a complex world. This very simplification may thus mean that parts of the theory fall short in its description of reality. This does not change the fact that a theoretical framework such as Hotelling's may generate deeper insights, by simplifying the complexity of reality. Nonetheless, this chapter has found no empirical support for Hotelling’s description of extraction. It is thus not evident that the existing theoretical paradigm offers any insight into the short-run relationship between government stability and oil production in authoritarian petro-states. As a consequence, there remains room for future research to map and understand the underlying mechanisms driving the patterns identified in this chapter.

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Chapter 7.

Concluding remarks

Oil and gas resources continue to dominate international energy markets and serve as a major engine for economic growth. Grasping what drives extraction decisions of these resources is thus essential if we are to understand the development of the wider global economy. Harold Hotelling's description of forward-looking agents continues to be the dominant theoretical paradigm in the field of non-renewable resource management. However, the empirical validity of this theoretical framework remains questionable to date. In addition, spatial considerations are neglected in the classic Hotelling model. This is problematic, since spatially-dependent extraction and information externalities are important during exploration and production. As discussed, previous studies have sought to address this limitation. Yet none have modeled oil and gas recovery as the two-dimensional spatial problem it is. Set against this lack of comprehensive modeling and limited empirical evidence, the main objective of this research project was to identify the mechanisms that govern the behavior of resource owners. To make headway, this dissertation deduced a new theoretical framework and analyzed original data, using modern methodological tools. This chapter summarizes the main findings, their implications and avenues for future research.

7.1. Summary of findings

This dissertation unfolded in four main chapters, each of which constitutes a discrete piece of research. What unites them is their shared focus on how fear of losing access to future extraction affects the behavior of owners today.

Chapter 3 deduced a novel interdisciplinary model capable of realistically describing the deployment of exploration wells. This theoretical framework is unique in its ability to model extraction and information externalities across a two-dimensional space. Knowledge about the location of resources was thus designed to propagate across space, as exploration was deployed. This realistic property was achieved by using the Ising model, borrowed from the field of statistical physics. Based on this interdisciplinary environment, Monte Carlo simulations were used to compare two competing exploration strategies. Both of these accounted for knowledge spillovers from exploration and thereby significantly improved on a strategy of random deployment. However, substantial differences in the relative profits associated with different strategy combinations were revealed. These resulted in a 'prisoner's dilemma' type problem, where the only possible Nash equilibrium is for both neighboring landowners to cluster their exploration near the property line during early stages of exploration. This behavior was motivated by the fear of losing access to common pool resources in border areas. Yet, it occurred at the expense of a socially more efficient spacing of wells. Forward-looking strategic behavior in combination with common reservoirs was thus theoretically identified as the cause of efficiency losses, as information externalities were not internalized.

A limitation of the complete two-dimensional model introduced in Chapter 3 was its computational complexity. This complicated the testing of the empirical relevance of its predictions. To address this shortcoming, Chapter 4 relied on a simplified version of the original model that described oil and gas exploration along a line. This setup could be understood as a situation of two neighboring countries and made it possible to identify the sub-game perfect Nash equilibrium strategies, using backwards induction. In turn, this allowed for deducing the expected spatial distribution of wells around borders under different scenarios of resource leakage and information spillover. These simulated distributions were compared to those observed in international oil and gas exploration data covering more than 100,000 individual wells in over 120 countries. The findings of this analysis confirmed the empirical validity of the theoretical framework deduced in this dissertation. In line with the predictions of the model, a general clustering of offshore exploration was found around borders without unitization agreements. Furthermore, unitization agreements were found to shift the peak in exploration away from borders and towards the interior of countries. This finding was in line with the theoretical insight that agents seek to internalize the informational spillover from exporation. Combined, Chapters 3 and 4 deduced and tested how fear of losing access to common pool resources affects exploration.

Maintaining the focus on common pools, Chapter 5 tested how spatial competition affects the extraction of existing wells. Focusing on Colorado's gas industry, the empirical analysis was rooted in the principle that spatially close neighbors can jeopardize a well's future extraction. Drawing on the Hotelling framework, it was argued that such a risk of resource leakage should motivate owners to accelerate extraction. This theoretical prediction was tested by analyzing how the entrance of a "rival" neighbor affects extraction. In line with Hotelling theory, rivals located in close proximity were found to motivate accelerated extraction, whereas distant neighbors did not affect behavior. As predicted, fear of losing access to future extraction thus induces the owners of already installed wells to change extraction behavior.

Departing from the focus of the three previous chapters, Chapter 6 examined how political risk influences extraction behavior in the short run. Specifically, it assessed the month-on-month relationship between government stability and oil extraction, using production data from 32 authoritarian petro-states. Drawing on the Hotelling principle, it was argued that a regime should accelerate extraction when its future custodianship over national resources becomes more uncertain. However, as discussed by Bohn and Deacon (2000), political unrest in the long run reduces extraction capabilities due to lack of capital investments. This left the empirical question of whether government instability in the very short run leads to accelerated extraction as predicted by Hotelling theory. To test this, Chapter 6 refined existing empirical studies in a twofold manner. First, the use of monthly data allowed for identifying short run extraction responses to sudden political events. Second, the analysis applied a dynamic panel data system GMM estimator to eliminate the risk of endogeneity (e.g. that a current fall in oil extraction drives future government instability). In contrast to conventional theory, Chapter 6 found that oil extraction slows as instability in authoritarian regimes increases. Classic Hotelling theory can thus not explain the short-run variations observed in the data. This result suggests that government stability is an enabling factor rather than a cause of oil extraction even in the very short run.

The four main research chapters of this dissertation have all studied how fear of the future influences the behavior of resource owners in the oil and gas industry. Of these, Chapters 3, 4 and 5 demonstrated that the theoretical description of forward-looking behavior applies both during exploration and extraction of common pool deposits. The mere prospect of resource leakage thus motivates socially inefficient clustering of exploration around property lines and overly rapid extraction. In contrast, government instability, which was argued to constitute a different form of ownership risk, was not found to motivate the changes in behavior predicted by theory. The fear that a dictator whose political power is in decline will accelerate extraction is thus unfounded.

7.2. Implications

The findings of this dissertation have important implications for both the optimal management of oil and gas resources and the effectiveness of current climate regulation. Focusing on questions of resource management, Chapters 3, 4 and 5 examined how common pool problems result in economic inefficiencies both during the exploration for and the extraction of hydrocarbons. Recognizing this problem, regulators should consider intervention to internalize externalities.

As discussed, there are three main avenues for alleviating problems of spatial competition. These are command and control policies, taxes/subsidies and Coasian solutions. However, as discussed in Chapter 3, implementing any of these in practice poses difficulties. For example, whilst existing spacing regulation might eliminate extraction externalities, it does so by leaving some underground resources inaccessible. Similarly, a Pigouvian solution (Pigou, 2002) was deemed impractical, as regulators needed unrealistic levels of information to identify the optimal level of tax/subsidy. Coasian bargaining, such as the acquisition of neighboring lands, joint development agreements or unitization contracts, presented the most promising solutions to achieving the efficient management of resources. Nonetheless, problems of bargaining and enforcement were highlighted as limitations. For example, no international body exists to ensure that property rights are respected. Consequently, it will be difficult to solve the cross-border common pool problems identified in Chapter 4 using Coasian bargaining. Furthermore, as discussed in Chapter 5, it remains unclear whether solving local common pool problems in isolation results in improved global extraction outcomes from a social planner perspective. This is because problems of market power may persist in international oil and gas markets. However, from an operator perspective, this dissertation has shown that there are clear profit losses associated with spatial competition. To improve profitability, private companies should thus seek to internalize spatial externalities, by buying up neighbors or engaging in joint production agreements.

Apart from questions of resource management, the findings of this dissertation suggest that the effectiveness of existing climate regulation may be questionable. As outlined by Sinn (2008), the gradual expansion of demand-reducing regulation can exacerbate the problem of anthropogenic climate change. The core thesis guiding this logic is that existing climate policies induce expectations of falling future demand and resource prices. Drawing on the Hotelling framework, this should incentivize owners to extract more of their fossil fuels today. Consequently, the flow of greenhouse gases (GHG), and thereby the process of climate change, is accelerated. By implication, forward-looking behavior, as identified in this dissertation, can render existing demand-reducing climate policies counterproductive.

Faced by resource owners who act according to the Hotelling principle, regulators should refrain from implementing sharply increasing fossil fuel taxes as this could, counterproductively, motivate accelerated extraction (Hoel, 2010). Instead, as argued by Kalkuhl and Edenhofer (2010), climate policies should be focused on binding quantitative targets such as carbon quotas. There are, however, at least two developments that will likely constrain the ability of policymakers to execute this course of action. First, the damage caused by climate change will become more apparent to the public over time, which in turn, will probably increase political pressure to adopt gradually more stringent regulation. Second, climate damage is likely to be convex with respect to the stock of GHG in the atmosphere (IPCC, 2007). Damages would thus increase with extraction. In isolation, this implies that an economically efficient fossil fuel tax should rise over time. This argument is supported by Stern:

> *"The social cost of carbon is likely to increase steadily over time because marginal damages increase with the stock of GHGs in the atmosphere, and that stock rises over time. Policy should therefore ensure that abatement efforts at the margin also intensify over time"* (2007:17).

In sum, the above discussion underlines that regulators have to understand the inter-temporal mechanisms governing the supply of oil and gas when designing effective climate and resource management regulation. As shown by Chapter 6, the extent to which resource owners act as described by the Hotelling principle, however, depends very much on the circumstances. Consequently, other behavioral models are needed to describe the range of possible mechanisms in the oil and gas industry.

7.3. Future research

Despite the advances made by this dissertation, there remains room for further research to improve understanding of the mechanism governing the supply-side of oil and gas. Various suggestions for future work have been discussed in earlier chapters. The remainder of this section draws these together.

As current computational constraints diminish, future research should seek to identify the optimal extraction strategy for the two-dimensional framework developed in Chapter 3. This ought to be done numerically, employing the same backward induction reasoning used for the simpler line model deduced in Chapter 4. The difficulty with performing such an exercise is that it requires computational capacity that is currently unavailable to most researchers. High-performance cluster computers at the Physics Department at the University of Oxford were used to perform the simulations needed for Chapters 3 and 4 of this dissertation. However, even when relying upon such extensive capacity, that equates to approximately 150 home computers. The calculations took almost two weeks of uninterrupted computational activity. Such practical limitations are, however, likely to diminish over time, as technological innovation improves computing capacity (see Brock, 2006).

Once the exact optimal strategy is determined, the model developed in Chapter 3 could easily be expanded to account for aspects such as realistic fluid dynamics, asymmetric agents, potential physical damage to the reservoir, and non-public seismic information. All of these additions would make the framework capable of replicating more realistic exploration problems in the oil and gas industry.

Empirically testing the predictions of the full two-dimensional model is a natural next step after having determined the optimal strategy. Chapter 4 of this dissertation tested whether neighboring nations portrayed the strategic behavior predicted by the theoretical framework. However, it did so based on a simplified line version of the complete framework developed in Chapter 3. Whilst this simplification is unproblematic in the case of neighboring nations, most exploration does not occur in such simplified two-player setups. As discussed in this dissertation, the American extraction landscape is a patchwork of many small resource owners. This means that a single owner can have many “rival” neighbors to whom he needs to respond. The complete two-dimensional model is thus a better representation of American hydrocarbon exploration and its predictions should therefore be tested in such settings. This would not only test the empirical validity of the framework; it would also allow for assessing how small private companies engage in exploration as opposed to the country-level focus adopted in Chapter 4.

Finally, there remains room for determining the underlying mechanisms driving the observed relationship between short-term government stability and oil extraction. As described in Chapter 6, oil production is found to decelerate in times of government instability. In the context of authoritarian petro-states, the direct predictive power of the dominant theoretical paradigm is thus limited. This is problematic because these regimes control the majority of global oil and gas production, which makes it necessary to understand their behavior. Consequently, there remains room for future research to determine what explains the empirical relationships observed in petro-states. As discussed in Chapter 6, this investigation should focus on the inter-temporal incentive structures of domestic agents as well as those of international trade partners. Specifically, the fear of retrospective punishment by a potential future leader provides interesting avenues for further research.

Overall, any theory is a simplification of a complex reality. Harold Hotelling's description of forward-looking extraction might thus not explain *all* behavior observed in the multifaceted oil and gas industry. There is thus a need for further research improvements in the literature on resource management, by developing more realistic theoretical models and offering refined empirical investigations. The work presented in this dissertation makes an important step in this direction.

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Appendixes

A. Ising and the resource generating process

This appendix introduces the stochastic process that generates the spatially-correlated resource landscapes of the underlying Ising model used in Chapters 3 and 4. By doing so, it is illustrated how the expected probability of discovery changes when a well is drilled. To ease understanding, this appendix focuses on a one-dimensional line setup. However, results are easily transferable to a two-dimensional space such as that used in Chapter 3.

Assume we have L unopened drilling sites, which are located between a left and a right site as presented in Figure A.1.

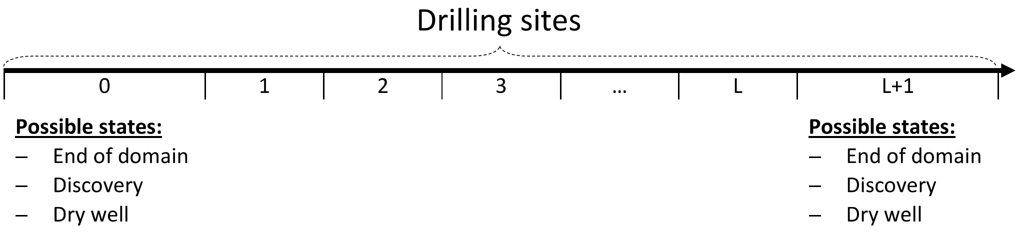


FIGURE A.1. ILLUSTRATION OF DRILLING LANDSCAPE

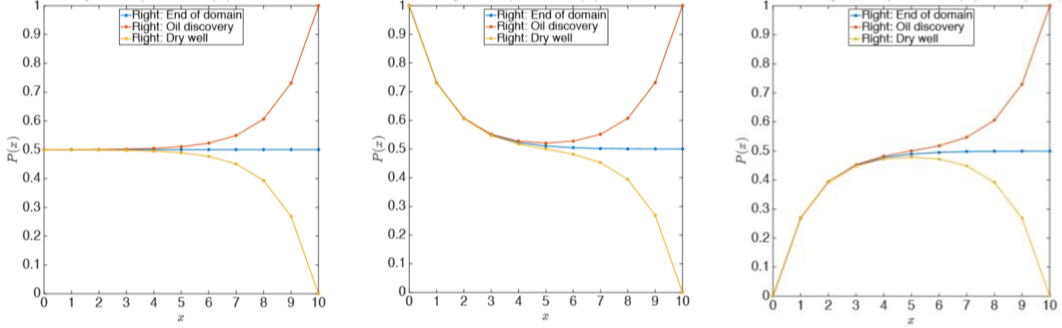
In this setup, the probability of finding oil at $x \in [1, L]$ is given by:

$$\text{(A1)} \qquad P_{\sigma_0,\sigma_{L+1}}(x) = \frac{1}{Z} \sum_{\{\sigma_i\}, i \in [1,L]} \left(\frac{1+\sigma_x}{2}\right) exp\left[J \sum_{i \in [0,L]} \sigma_i \sigma_{i+1} + h \sum_{i \in [1,L]} \sigma_i\right]$$

Here, $\sigma_0 = -1, 0, +1$ is the state of the Left drilling site and $\sigma_{L+1} = -1, 0, +1$ is the state of the Right site. In both cases $+1$ means that the site is a discovery, -1 means that the site is a dry well and 0 means that the site is outside the domain. The normalization is given by:

$$Z = \sum_{\{\sigma_i\}, i\in[1,L]} exp\left[J \sum_{i\in[0,L]} \sigma_i\sigma_{i+1} + h \sum_{i\in[1,L]} \sigma_i\right] \tag{A2}$$

In the equations above, J governs the clustering of resources (the temperature in the original Ising model) and h governs the unconditional probability of discovery (the magnetic field in the original Ising model). Figure A.2 plots the conditional probability of discovery for different resource landscapes using the model calibration $h = 0.5$ and $J = 0.5$.



(Left site: End of domain) (Left site: Oil discovery) (Left site: Dry well)

Figure A.2. Conditional probability of discovery for different landcapes

B. Deriving the optimal strategy

This appendix is dedicated to deriving the optimal exploration strategy introduced in Chapter 4. The market consists of two identical and neighboring resource owners who sequentially explore a one-dimensional landscape. It is assumed that a discovery yields one unit of profit whereas a non-discovery (dry well) yields a negative profit of one. Each agent decides his or her exploration strategy, S, seeking to maximize their expected profit:

(B1) $$max_S E[\pi] = max_S(E[No.discoveries] - E[No.dry\,wells])$$

The domain of exploration is given by a fixed number of potential drilling sites, N. As information about the likely location of resources evolves with exploration, we define the dynamic exploration "landscape" as a function $B(x)$ with $x \in [1, N]$ and $B = -1, 0, +1$ for a dry well, an unexplored site and a discovery, respectively. Every time a player has to make an exploration decision, all information is contained in $B(x)$. Hence, a strategy is defined as a conditional decision function $S[B(x)]$, where S can either be the choice of deploying a well at a given unexplored drilling site y, or the decision to not explore (STOP). As described in the main text, each player has a subset of drilling sites on which they can drill. Given that the one-dimensional landscape is evenly split, we can define the strategy for player $1, 2$, respectively as:

(B2) $$S_1[B] = \begin{cases} STOP \\ Explore \;\; x \in \left[1, \dfrac{N+1}{2}\right] \; such\; that\; B(x) = 0 \end{cases}$$

$$S_2[B] = \begin{cases} STOP \\ Explore\ \ x \in \left[\frac{N+1}{2}, N\right]\ such\ that\ B(x) = 0 \end{cases} \tag{B3}$$

We define $\Pi_{ante}(B, x)$ as the expected profit for the rest of the game if tile x is explored in the current turn. This function is defined only for x such that $B(x) = 0$. The optimal strategy is given by:

$$S_1^{max}[B] = \begin{cases} STOP\ if\ max_{x \in \left[1, \frac{N+1}{2}\right]}\left(\Pi_{ante}(B, x)\right) < 0 \\ Explore\ \ x_0 \in \left[1, \frac{N+1}{2}\right]\ if\ \Pi_{ante}(B, x)\ is\ maximal\ at\ x_0 \end{cases} \tag{B4}$$

$$S_2^{max}[B] = \begin{cases} STOP\ if\ max_{x \in \left[\frac{N+1}{2}, N\right]}\left(\Pi_{ante}(B, x)\right) < 0 \\ Explore\ \ x_0 \in \left[\frac{N+1}{2}, N\right]\ if\ \Pi_{ante}(B, x)\ is\ maximal\ at\ x_0 \end{cases} \tag{B5}$$

We now define $\Pi_{ante}(B) = \max(max_x(\Pi_{ante}(B, x), 0))$ as the expected profit for the rest of the game if the optimal strategy is deployed. The optimal strategy is found using backwards induction. First, one computes the following function for all x such that $B(x) = 0$,

$$\Pi_{ante}(B, x) = P(B, x)\left(1 + \Pi_{post}(B_+)\right) + (1 - P(B, x))(-1 + \Pi_{post}(B_-)) \tag{B6}$$

In the equation above, $P(B, x)$ is the probability of discovery, which can be calculated using the formula introduced in appendix A. B_- stands for a modification of the landscape B where the tile x has been explored and the well was dry. Correspondingly, B_+ stands for a modification of the landscape B where the tile x has been explored resulting in a discovery. $\Pi_{post}(B_\pm)$ is the expected profit for the rest of the game, for a given landscape and a given player after his/her turn of exploration. It is given by:

$$(B7) \qquad \Pi_{post}(B_{\pm}) = \begin{cases} \Pi_{ante}(B_{\pm}) \; if \; S_2^{max}[B_{\pm}] = STOP \\ P(B_{\pm}, y)\Pi_{ante}\left(B_{\pm,+}\right) + \left(1 - P(B_{\pm}, y)\right)\Pi_{ante}\left(B_{\pm,-}\right) \; if \; S_2^{max}[B_{\pm}] = y \end{cases}$$

In the equation above, $B_{\pm,-}$ stands for a modification of the landscape B where the tile x has been explored resulting in a dry well (-) or a discovery (+), and where the tile y was explored by player two and the well was dry. Correspondingly, $B_{\pm,+}$ stands for a modification of the landscape B where the tile x has been explored resulting in a dry well (-) or a discovery (+), and where the tile y was explored by player 2 and a discovery was made.

By recursively computing Π_{ante} for landscapes with a smaller and smaller number of unopened drilling sites, one ends up eventually computing Π_{ante} for the situation where there is only one unexplored drilling site remaining, x_{final}. For this site the expected profit for the rest of the game is equal to:

$$(B8) \qquad \Pi_{ante}\left(B, \mathrm{x}_{final}\right) = P\left(B, \mathrm{x}_{final}\right) + (1 - P\left(B, \mathrm{x}_{final}\right))(-1)$$

Recognizing that the game can only end with either both players terminating exploration (two consecutive STOPs) or complete exploration, one can now recursively determine the chain of expected profits and thereby determine the optimal strategy for all possible landscapes.

C. An example of unequal exploration capabilities

In the main theoretical model presented in Chapter 4, agents were assumed to have equal exploration capabilities, and deployment was therefore modeled to occur sequentially and the first-mover advantage is assigned randomly. This is, however, a simplification of reality, as most neighboring landowners differ in their investment capabilities.

Consider the situation of the South Pars/North Dome natural gas field located in the Persian Gulf. This hydrocarbon deposit is shared between Qatar and Iran. However, these two countries have very different drilling capabilities. Due to the sanctions imposed until recently by the European Union and the United States, Iran has had reduced access to modern petroleum technology and sources of financing. This means that Qatar can deploy wells at a relatively faster rate. The main model setup introduced in Chapter 4 does not describe such a situation, and its distributional predictions are therefore likely flawed. To address this limitation, the assumption of identical agents is relaxed, whereby one of the two is equipped with superior exploration capabilities. In the modified setup, agent B is provided with the first-mover advantage and the ability to complete exploration before his neighbor, agent A, can build any wells (Figure C.1).

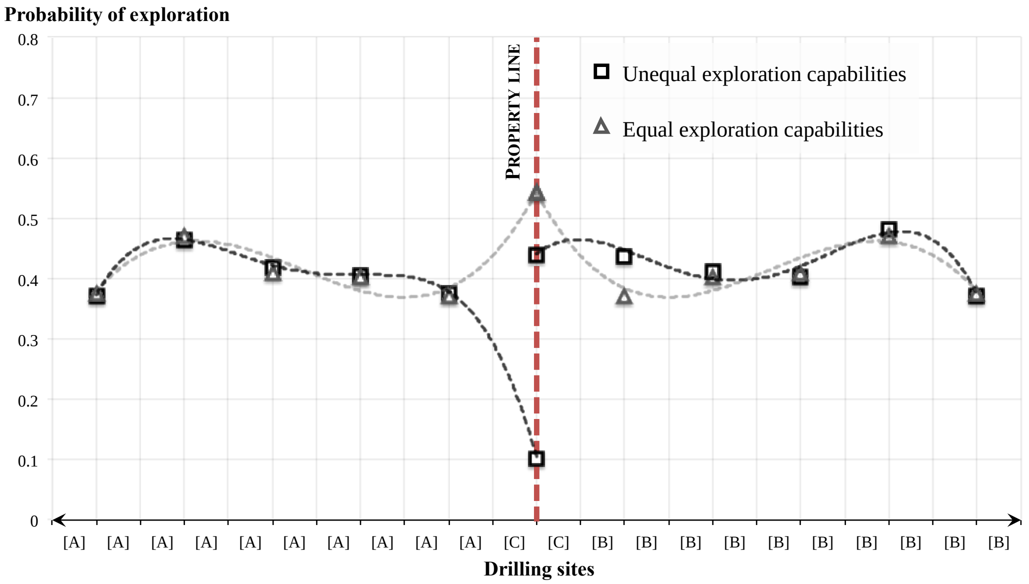


FIGURE C.1. CHANGING THE EXPLORATION CAPABILITIES

Notes: Dotted lines are fourth-order polynomial approximations. The drilling sites are categorized as follows: $\forall \in [A]$ access resources private to agent A, $\forall \in [B]$ access resources private to agent B, $\forall \in [C]$ access-contested resources. Agent B initiates and completes exploration before agent A is allowed to deploy any wells.

As Figure 4.5 illustrates, unequal exploration capabilities are predicted to result in the stronger party dominating the border area. The weaker agent is thus incentivized to avoid exploration of contested resources, since the first mover will already have drained a potential common pool deposit. This clarifies that border exploration can be discouraged if a dominant neighbor is already present. A non-symmetric distribution of wells around property lines thus serves as an indicator of systematically unequal exploration capabilities.

D. Deriving the Hotelling model with leakage

This appendix is dedicated to derivations omitted in the main text. Based on the framework of Khalatbari (1977), the Hotelling model introduced in Section 5.1 is derived. The market consists of *n* identical resource owners who operate under perfect competition and who each seek to maximize their individual discounted profit:

(D1)
$$\max_{R_{j,t}} \int_{t=0}^{t=\infty} P_t * R_{j,t} * e^{-it}\, dt$$

Attributing common pool characteristics to reserves however changes the constraint as resources can now migrate between owners. As discussed in the main text, the rate of leakage between neighbors is defined as “l” and flows are assumed identical in both directions. Incorporating this into the problem means that maximization in D1 must be subject to the following:

(D2)
$$\int_0^\infty R_t\, dt = \bar{S} = 1$$

(D3)
$$\dot{S}_{j,t} = \underbrace{-R_{j,t} - l * S_{j,t} + \frac{l}{n-1} * \left(S_{1,t}+\ldots+S_{j-1,t} + S_{j+1,t}+\ldots+S_{n,t}\right)}_{g\left(S_{j,t},\, R_{j,t},\, t\right)}$$

The Hamiltonian to this problem is:

(D4)
$$\mathcal{H} = P_t * R_{j,t} * e^{-it} + \omega_{j,t} * \left[g\left(S_{j,t}, R_{j,t}, t\right)\right]$$

As agents operate under perfect competition, the necessary conditions for maximizing discounted profit are:

(D5)
$$\mathcal{H}'_{R_{j,t}} = 0 \Rightarrow P_t * e^{-it} - \omega_{j,t} = 0 \Rightarrow P_t = \omega_{j,t} * e^{it}$$

(D6) $$\mathcal{H}'_{S_{j,t}} = -\dot{\omega}_{j,t} \Rightarrow \omega_{j,t} * (-l) = -\dot{\omega}_{j,t} \Rightarrow \dot{\omega}_{j,t} = l * \omega_{j,t}$$

Following on from D6:

(D7) $$\omega_{j,t} = \omega_j * e^{lt} \; where \; \omega_j > 0 \; and \; constant \; over \; time$$

"$\omega_{j,t}$" is the time-dependent marginal value of the resource for owner "j". Inserting D7 into D5 yields:

(D8) $$P_t = \omega_j * e^{lt} * e^{it} \Rightarrow P_t = \omega_j * e^{(l+i)t}$$

By utilizing the symmetry of agents, this expression can be summed over all resource owners:

(D9) $$n * P_t = \sum_{j=0}^{j=n} \omega_j * e^{(l+i)t}$$

Market demand for the resource is assumed to be isoelastic and defined by $P_t = R_t^{-v}$ where $0 < v < 1$ and $R_t = \sum_{j=0}^{j=n} R_{j,t}$. Inserting this in the expression above yields the following result:

(D10) $$R_t = n^{\frac{1}{v}} * \omega^{-\frac{1}{v}} * e^{-\frac{(l+i)t}{v}} \; where \; \omega = \sum_{j=0}^{j=n} \omega_j$$

From the resource constraint on total production, it is possible to identify the following:

(D11) $$\int_{t=0}^{t=\infty} R_t \; dt = 1 \Rightarrow \int_{t=0}^{t=\infty} n^{\frac{1}{v}} * \omega^{-\frac{1}{v}} * e^{-\frac{(l+i)t}{v}} \; dt = 1$$

Integration by parts yields:

(D12) $$\left[n^{\frac{1}{v}} * \omega^{-\frac{1}{v}} * \left(-\frac{v}{(l+i)}\right) * e^{-\frac{(l+i)t}{v}}\right]_{t=0}^{t=\infty} = 1$$

Using that $\lim_{t\longrightarrow\infty} e^{-\frac{(l+i)t}{v}} = 0$ and that $e^0 = 1$, D9 becomes:

(D13) $$n^{\frac{1}{v}} * \omega^{-\frac{1}{v}} * \frac{v}{(l+i)} = 1 \Rightarrow \omega^{-\frac{1}{v}} = \frac{(l+i)}{v} * n^{-\frac{1}{v}}$$

By inserting D13 into Equation D10, it is now possible to identify the optimal extraction path as:

(D14) $$R_t = \frac{(l+i)}{v} * e^{-\left(\frac{l+i}{v}\right)*t} \Rightarrow R_{j,t} = \frac{1}{n} * \left(\frac{(l+i)}{v} * \underbrace{e^{\left(\frac{-l-i}{v}\right)*t}}_{S_t}\right)$$

It should be noted, that the model introduced in this appendix rests on the assumptions that perfect forward markets exist, agents are rational and that arbitrage opportunities are instantly eliminated.

Furthermore, it is assumed that gas markets are local rather then global and prices are as a consequence endogenously determined in the model. This assumption rests on the observation that transport costs continue to limit the intergration of global gas markets. However, one might alternatively argue that gas prices are internationally determined and therefore exogenous to extraction decisions made in Colorado. To illustrate how this affects optimal extraction behavior it is useful to assume that global gas prices follow a classic Hotelling pathway, as presented in equation D15.

(D15) $$P_t = P_0 e^{it}$$

Drawing on this exogenous pricepath, one can rewrite the resource owner's maximization problem as follows:

(D16) $$\max_{R_{j,t}} \int_{t=0}^{t=\infty} P_0 * R_{j,t}\, dt$$

This remains subject to D2 and D3 as the exogenous price path does not alter the resource constraint. One can therefore write the Hamiltonian as follows:

(D17) $$\mathcal{H} = P_o * R_{j,t} + \omega_{j,t} * \left[g\left(R_{j,t}, S_{j,t}, t\right)\right]$$

The necessary conditions for maximizing discounted profit are therefore:

(D18) $$\mathcal{H}'_{R_{j,t}} = 0 \Rightarrow P_0 - \omega_{j,t} = 0 \Rightarrow P_0 = \omega_{j,t}$$

(D19) $$\mathcal{H}'_{S_{j,t}} = -\dot{\omega}_{j,t} \Rightarrow \omega_{j,t} * (-l) = -\dot{\omega}_{j,t} \Rightarrow \dot{\omega}_{j,t} = l * \omega_{j,t}$$

Following on from D19:

(D20) $$\omega_{j,t} = \omega_j * e^{lt}\ where\ \omega_j > 0\ and\ constant\ over\ time$$

Again "$\omega_{j,t}$" is the time-dependent marginal value of the resource for owner "j". Inserting D20 into D18 yields:

(D21) $$P_0 = \omega_j * e^{lt}$$

This condition only holds for all values of t if $l = 0$. For any positive leakage rate ($l > 0$), there is no incentive to postpone extraction. By utilizing the symmetry of agents, one can identify the optimal extraction outcome as:

(D22) $$R_{j,t} = \frac{1}{n} * \bar{S} \; for \; t = 0 \;\; and \; R_{j,t} = 0 \; for \; t \in \,]0, \infty]$$

This simple example illustrates that resource leakage induces accelerated extraction independent of whether prices are exogeonous or endogenously determined. This result applies as long as there is a positive margin between resource prices and marginal extraction costs.

E. Countries and their NOCs

E.1. COUNTRIES IN THE SAMPLE

Country	*Main National Oil Company*	*Voice and Accountability ranking (WGI)*
Equatorial Guinea	*GEPetrol*	1.9
Saudi Arabia	*Saudi Aramco*	2.8
Sudan	*Sudapet*	3.3
Syria	*Syrian Petroleum Company*	3.8
Iran	*NIOC*	4.3
China	*CNPC*	5.2
Azerbaijan	*SOCAR*	10.9
Yemen	*None*	11.4
Vietnam	*Petrovietnam*	11.8
Kazakhstan	*KazMunayGas*	14.2
DR Congo	*SNPC*	15.6
Angola	*Group Sonangol*	16.1
Iraq	*INOC*	16.6
Egypt	*EGPC*	18.0
UAE	*Abu Dhabi National Oil Company*	18.5
Russia	*Rosneft*	19.0
Oman	*Oman Oil Company S.A.O.C.*	19.4
Libya	*National Oil Corporation*	19.9
Venezuela	*Petróleos de Venezuela, S.A.*	21.8
Algeria	*Sonatrach*	22.7
Qatar	*Qatar Petroleum*	23.7
Gabon	*GOC*	24.2
Nigeria	*NNPC*	27.5
Kuwait	*Kuwait Petroleum Corporation*	28.4
Brunei	*Brunei Shell Petroleum**	32.2
Guatemala	*None*	35.5
Malaysia	*Petronas*	37.4
Ecuador	*Petroecuador*	39.8
Turkey	*TPAO*	40.8
Colombia	*Ecopetrol*	44.1
Tunisia	*ETAP*	44.5
Bolivia	*YPFB*	46.0

*Notes: The Voice and Accountability ranking is the WGI percentile rank among all countries in 2013 (ranges from 0 (lowest) to 100 (highest) rank); *50 percent owned by the government of Brunei*

Sources: Kaufmann et al. 2014 and World Bank 2008