Winning the Oil Lottery: The Impact of Natural Resource Extraction on Growth*

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Abstract

This paper provides evidence on the causal impact of oil discoveries on local development. Novel data on the drilling of 20,000 oil wells in Brazil allows us to exploit a quasi-experiment: municipalities where oil was discovered constitute the treatment group while municipalities with drilling but no discovery are the control group. The results show that oil discoveries significantly increase per capita GDP and urbanization. We find positive spillovers to non-oil sectors, specifically an increase in services GDP which stems from higher output per worker. The results are consistent with greater local demand for non-tradable services driven by highly paid oil workers.

Keywords: Oil and Gas, Economic Growth, Urbanization.

JEL: O13, O40

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"No other business so starkly and extremely defines the meaning of risk and reward - and the profound impact of chance and fate." Yergin (2008)

1 Introduction

Natural resource extraction influences a myriad of economic factors ranging from political economy to fiscal and monetary policy. However, no clear consensus has emerged on whether economies which discover natural resources should anticipate prosperous times or fear the much discussed Dutch Disease. Disentangling the various channels through which natural resources affect the economy has proven challenging. Even the pure market effect of natural resource extraction is not well understood. Natural resource extraction might crowd out other sectors of the economy by driving up local prices, or on the other hand could have positive spillovers which lead to the concentration of economic activity.

This paper uses the quasi-experiment generated by the random outcomes of exploratory oil drilling in Brazil in order to investigate the causal effect of natural resource discoveries on local development.[1] Specifically, we compare economic outcomes in municipalities where the national oil company Petrobras drilled for oil but did not find any, to outcomes in those municipalities in which it drilled for oil and was successful.[2] Drilling attempts were carried out in many locations with similar geological characteristics, but oil was found in only a few places. The "treatment assignment" is related to the success of drilling attempts: places where oil was found were assigned to treatment, while places with no oil are part of the control group. The treatment assignment resembles a "randomization" since (conditional on drilling taking place) a discovery depends mainly on luck. Therefore, places with oil discoveries are the "winners" of the "geological lottery". Since there were no significant royalty payments to municipalities in Brazil until several

[1]Oil and gas are also called petroleum or hydrocarbons. Throughout this paper we use "oil" to refer to "oil and gas". The oil industry is loosely divided into two segments: upstream and downstream. Upstream refers to exploration and production of oil while downstream refers to processing and transportation (refineries, terminals etc).

[2]There are three administrative levels in Brazil: federal government, states, and municipalities. Municipalities are autonomous entities that are able, for instance, to set property and service taxes. They are roughly equivalent to counties in the US. We use the words municipalities, local governments and local economies interchangeably.

decades after the first discoveries, we are able to isolate the *direct impact* of oil extraction from the effect of fiscal windfalls.

Our analysis uses novel data on the drilling of approximately 20,000 oil wells in Brazil from 1940-2000. The dataset covers the universe of wells drilled since exploration began in the country and provides information on three stages regarding oil extraction and production: drilling, discovery, and upstream production. We use this detailed information on the data generating process to distinguish those municipalities which were assigned to treatment from those which constitute the control group. Our focus is on an Intent-to-Treat (ITT) analysis where we regress our outcome variables of interest directly on discoveries. Discoveries take place in different locations over time, so we can exploit time and cross-sectional variations. The ITT analysis enables us to obtain a lower bound for the average treatment effect. We also estimate a Local Average Treatment Effect (LATE) by instrumenting for production with discoveries.[3] Besides, we study treatment intensity using detailed information on different types of wells. This allows us to retrieve a coefficient that can be interpreted as a weighted-average of per-unit treatment effect.

The baseline results show that locations which discover oil have a 24.6-25.9% higher *per capita* GDP over a span of up to 60 years compared to the control group. Furthermore, we document an increase in both manufacturing and services GDP *per capita* but no impact on agricultural GDP. While the measure of manufacturing GDP includes natural resource extraction (and as such an increase is not surprising), the increase in services indicates spillover effects of oil production impacting the rest of the economy. Additionally, we find evidence for an increase in urbanization of about 4% points. This increase in urbanization is consistent with the increase in services we document. We do not find any effect on population density. Using historical data on sectoral employment we calculate a measure of sectoral output per worker and show that oil discoveries increase GDP mainly by increasing output per worker. We also show that while both onshore and offshore discoveries increase manufacturing GDP (potentially in a mechanical way since it includes oil production), only onshore discoveries increase services GDP

[3] Endogeneity of production might be more of a problem for gas than for oil. While it is relatively easy to transport oil, gas requires a substantial investment in infrastructure such as pipelines.

and urbanization. We hypothesize that demand from well paid oil workers is responsible for the observed increase in services and urbanization. Oil municipalities become local service and commerce hubs which benefit from improved output per worker. The treatment intensity analysis suggests that major discoveries have a disproportionately larger impact on the local economy.

To shed light on whether our results are mainly driven by local price effects or real changes in the economy, we additionally look at recent microdata from the Brazilian employment and population censuses. We find that municipalities which discovered oil have larger services firms, a higher density of formal services workers, and a lower fraction of workers employed in the subsistence agricultural sector than the control group. The move from rural informal work to the formal services sector explains the observed increase in urbanization and services GDP *per capita*. We also show that wages in the services sector adjust upwards. Consequently, we find evidence for both nominal and real effects. Lastly, the density of non-oil manufacturing firms and workers is not affected by oil discoveries. Our findings, therefore, do not provide support for either the de-industrialization hypothesis of natural resource discoveries or for positive agglomeration effects in the manufacturing sector.[4]

Our results are robust to a variety of control groups, different control variables, and a restriction of the sample period to 1940-1996. The latter is important to verify whether our results are driven by direct market effects since from 1997 onwards royalty payments became an important part of municipal income. Lastly, we show that municipalities with oil discoveries have a higher probability of hosting major downstream oil facilities than the control group. To check whether our results are driven by these downstream facilities, we re-run the regressions excluding those municipalities which host them and find that this is not the case. It appears that upstream production does not only impact the local economy via downstream production but has also a direct effect.

Since the oil industry is at the center of the production network in many countries, its impact on the economy has been studied extensively. The usual approach to understand

[4]These results are detailed in Appendix C.

the effects of oil relies on cross-country evidence. Several papers have shown correlations between natural resources and adverse outcomes. For instance, Sachs and Warner (1995) show that resource-exporting countries tend to have lower growth rates, while Arezki and Brueckner (2011) and Isham, Woolcock, Pritchett, and Busby (2005) point out that resource-exporting countries have poorer governance indicators. However, cross-country evidence is sensitive to changing periods, sample sizes, and covariates (for an overview of the literature see van der Ploeg (2011)).[5] Additionally, cross-country studies usually use very aggregate variables and make it difficult to control for institutional and cultural frameworks, and for policy variation between different countries.

As a result, the literature has been shifting attention to a more detailed analysis to pin down specific mechanisms of how natural resources impact the economy. The main empirical challenge, however, is to deal with the issue of endogeneity of natural resource extraction since there are many unobservable variables that might be correlated with oil production and might also affect economic development. Notable papers in an emergent literature which tries to address these problems more directly are, among others, Michaels (2011), Monteiro and Ferraz (2012), Allcott and Keniston (2014), and Caselli and Michaels (2013) [6]. While Michaels (2011) and Allcott and Keniston (2014) focus on the US, we study a developing country.[7]

Our paper stands out from the existing literature in at least two important dimensions: Firstly, and perhaps most importantly, our novel identification strategy of comparing areas with oil drilling and discoveries to those with drilling but no discoveries, allows us to estimate the impact of oil discoveries on local development using a (quasi-experimental) difference-in-difference approach. Secondly, we examine the entire history of oil exploration in Brazil, while the literature limits attention mostly to post-discovery periods. This long historical analysis allow us to alleviate concerns about unobservable differences

[5]There is also a large theoretical literature which tries to explain how natural resource abundance might affect economic and political outcomes (e.g. Krugman (1987) and Caselli and Tesei (2011)).

[6]Also see Acemoglu, Finkelstein, and Notowidigdo (2013) and Dube and Vargas (2013).

[7]Caselli and Michaels (2013) focus on the effects of oil windfalls on government behavior and the provision of public goods in Brazil, while Monteiro and Ferraz (2012) also use windfalls in Brazil to study local political and economic outcomes. See also Brollo, Nannicini, Perotti, and Tabellini (2013) for an analysis of fiscal windfalls in Brazil. We study the direct effects of oil discoveries instead of the indirect effect via windfalls.

between the treatment and control group. Lastly, the use of worker-level data makes it possible for us to look in more detail at the exact mechanism through which oil discoveries impact economic development.

In terms of design and results our paper is also related to the literature on agglomeration externalities, especially the branch which investigates the impact of interventions on the concentration of economic activity (important contributions include Davis and Weinstein (2002), Greenstone, Hornbeck, and Moretti (2010)). Similarly to our research, these papers are motivated by the insights about the importance of within-country differences in output and wages (see Acemoglu and Dell (2010) and Moretti (2011)). Lastly, our focus on sectoral GDP links the paper to studies on the determinants of structural transformation, particularly the ones focusing on the role of the oil sector (Kuralbayeva and Stefanski (2013) and Stefanski (2014)).

Our results are consistent with the view that oil abundance is not necessarily a curse at the local level. It is important to stress, however, that we cannot comment on the aggregate impact of oil discoveries on the country as a whole. Compared to national economies, municipalities are much more open and face macroeconomic policies which are invariant to their idiosyncratic conditions. By construction our research design rules out any effect which operates through the nominal exchange rate, for example.

This article proceeds as follows. Section 2 provides the background on oil drilling and on the key institutional aspects of oil exploration in Brazil. Section 3 details the research design used to identify the impact of oil on growth. In this paper we combine several datasets which are detailed in a subsection of Section 3. Section 4 discusses the estimation strategy. Section 5 shows the results and robustness exercises. Section 6 concludes.

2 Background

2.1 Oil Drilling

Oil and Gas exploration is a risky business. Oil companies aim to find an oil field, which corresponds to a contiguous geographic area with oil. Oil companies search for areas with specific geological characteristics to drill for oil. For instance, oil companies search for areas that contain geological structures (subsurface contortions and specific rocks) for potential trapping of hydrocarbons. Geology and related disciplines provide guidance on where to search for oil traps and estimating the probability of discovery prior to drilling is an important aspect of petroleum exploration. However, only by drilling can the company be certain that hydrocarbon deposits really exist. In other words, the only direct way of confirming the *hypothesis* of oil presence is by drilling a well. Even with modern technology, it is only by drilling that the existence of oil can be confirmed. Oil companies may invest substantially in acquiring information to end-up with no discoveries or no profitable discoveries.

When an oil company drills a hole, the wells are classified according to the results of the attempt. A drilled well can be classified, among other categories, as a discovery well, a producer well, a dry hole, or an abandoned well (e.g., because of an accident). The likelihood of finding oil from drilling can be low even in areas with appropriate geological characteristics and learning-by-doing is an important aspect in the petroleum industry (Kellogg (2011)). Testing by drilling is expensive and may not reduce the uncertainty regarding the existence of oil. Numbers vary but in a newly explored area the likelihood of drilling for oil successfully can be very low and subjective probabilities are widely accepted in the petroleum industry (Harbaugh, Davis, and Wendebourg (1995)). Today, an exploration well (wildcat well[8]) can have a probability as low as 10% of finding viable oil, while a rank wildcat[9] has an even smaller chance of finding oil. Therefore, even with modern technology, drilling is not a “safe bet” since there is no guarantee that a company will find oil after drilling. Given the features of drilling, oil discovery depends both on geological characteristics and on “luck”.[10] Our data support the idea that discovering oil is sort of a “lottery”: for every exploration well drilled which was successful there were many more unsuccessful ones.

A large number of factors influence drilling success such as past drilling history, re-

[8]A well drilled a mile or more from an area of existing oil production.

[9]A well drilled in an area where there is no existing production.

[10]According to Harbaugh, Davis, and Wendebourg (1995), “luck is obviously a major factor in exploration”.

gional endowment, resource depletion, onshore or offshore drilling, and technological progress. While not immediately relevant for our research design it is worth pointing out that two of those factors changed during our period of analysis: the level of technology available and the availability of conspicuous targets of hydrocarbon deposits. A more detailed discussion of oil drilling is given in Appendix B.1.

2.2 Oil in Brazil

Our period of analysis is from 1940 to 2000. Under most of this period, only government-owned entities were able to explore and produce oil in Brazil. In 1938, under a dictatorship period (1937-1945), Federal Law n. 395/38 established the state control of oil development and only by 1997 (Federal Law n. 9,478/97) private companies would be allowed to autonomously explore and produce oil in Brazil. Federal Law n. 395/38 created the CNP (In Portuguese, *Conselho Nacional do Petróleo*), the only entity responsible for exploring oil from 1938 to 1953.[11] Afterwards, from 1953 to 1997, only one company was allowed to drill for oil in Brazil: the government-controlled Petrobras.[12] Petrobras is an integrated exploration and production company whose activities reach all phases of the oil supply chain. To be precise, under certain circumstances other oil companies could explore oil in Brazil, but only in partnership with Petrobras. Following the oil crisis in 1973, Petrobras and other oil companies could sign a so-called "risk contract" to explore specific areas between 1975 and 1987. The terms of the contracts varied, but usual aspects included that the oil found under this type of contract could not be exported and that Petrobras could explore simultaneously an adjacent area by itself.[13] There is a sharp contrast in terms of ownership of resources between the United States and Brazil. There are thousands of oil

[11] According to Federal Law n. 395/38, private oil companies could only operate via concessions given by CNP. Anecdotal evidence point out that it was difficult to operate in Brazil as a private oil company at that time.

[12] Petrobras was created in 1953 by Federal Law n. 2,004/53. Constitutional Amendment 09/1995 and Federal Law 9,478/97 changed the upstream industry in Brazil: after 1997, the upstream oil market was open to national and foreign oil firms and Petrobras started to face competition. Nowadays, Petrobras is one of the largest oil companies in the world. Petrobras is a leading company in oil exploration with contributions to technology, especially of deep water exploration.

[13] The first contracts were signed in 1976 through a public bidding. Out of the 10 bidding areas, 9 were offshore and 1 was in the Amazon basin. More than 100 risk contracts were signed during 12 years. According to the contracts, if oil was found, it should be sold internally until the country reached its self-sufficiency in oil production. Brazil reached its self-sufficiency three decades later, in 2006.

companies with various business models in the U.S.[14], while Brazil has been historically linked with Petrobras's monopoly.

Local governments had little space to influence Petrobras (or CNP) on where to search for oil and on the speed of drilling. First, Petrobras (as a National Oil Company) followed national goals that may be not correlated with local-level objectives. Petrobras had a long-term goal, namely, achieving Brazil's self-sufficiency in oil production (independent of preferences of the local authorities). Second, several factors which influence the exploration activity are determined exogenously such as the international price of oil (e.g., Mohn and Osmundsen (2008)). Third, Petrobras knew it could only drill in locations with selected geological characteristics.[15] One concern might be that Petrobras's "risk contract" partners might have been local companies with a local agenda. However, the large majority of those contracts were signed with profit-maximizing multinational oil companies. Three smaller Brazilian companies also signed exploration contracts with Petrobras. Out of these three companies, only one was a government-owned company: the "Paulipetro" created in 1979 by São Paulo state. Between 1980 and 1983, Paulipetro drilled 33 wells in one specific area. The drilling attempts lead to only one discovery well, but a non-economical one (Bosco (2003)). Apart from Petrobras, Paulipetro drilling had support of other national-level institutions such as the CPRM (Brazil's Mineral Resource Research Company). Even guided by state-level goals, Paulipetro attempts were probably not linked to any local-level (local governments') influence and either way proved unsuccessful.

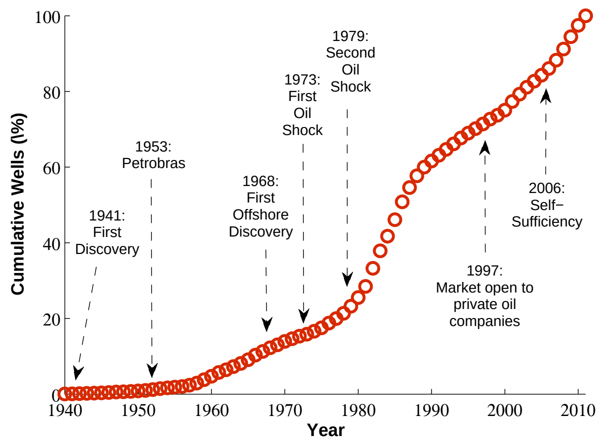
The Brazilian oil sector has experienced a substantial development from 1940 onwards. In 1939 the first onshore field was discovered (but non-commercial) and in 1941 the first onshore commercial producer well was drilled. The first oil discovery from an offshore well took place in 1968. In 2011, Brazil was the world's 13th largest producer of oil and gas with 2.2 millon barrels per day, which represents 2.6% of the total produced worldwide. Brazil was the world's 14th position in terms of proven petroleum reserves in the same

[14]Institutions such as the U.S. Energy Information Administration and the Independent Petroleum Association of America report the existence of several thousand oil operators in the U.S. economy.

[15]We show below in Figure 4(b) that all oil wells are located within sedimentary basis. Besides, Figure B.1 in Appendix B.1 shows a high correlation between drilling in Brazil and international oil prices.

year (ANP (2012)). The size of the oil sector is relevant to the Brazilian economy: in 2011 the oil sector represented 12% of the total Gross Domestic Product (CNI (2012)). Figure 1 summarizes domestic and international events related to oil exploration and production in Brazil.

Fig. 1: Events and Oil Drilling: 1940-2011



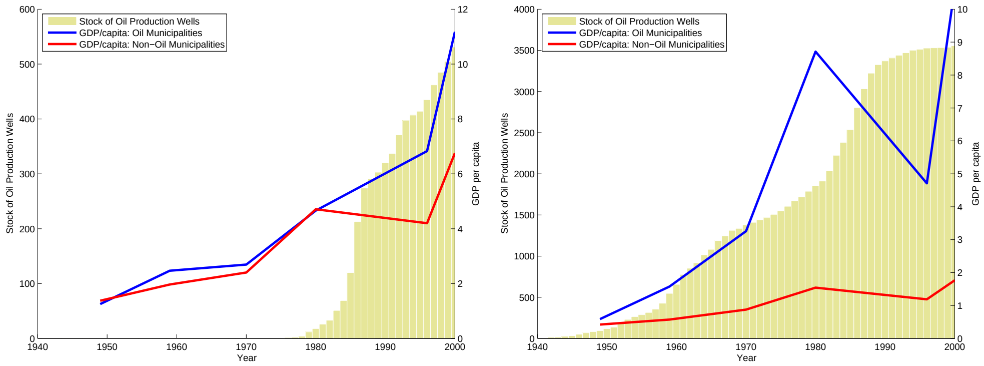
Notes. Figure show the cumulative of oil wells drilled in Brazil during the period from 1940 to 2011.

The oil business is crucial to several municipalities. Out of the top 10 municipalities with highest *per capita* GDP, several of them have their main economic activity associated with upstream or downstream oil industry. Municipalities in the top 10 list include São Francisco do Conde (with a refinery[16]), Triunfo (petrochemicals industry), Quissamã, Campos, and Macaé (the last three municipalities linked to offshore production). Anecdotal evidence suggests that municipalities which discovered large amounts of oil underwent a significant transformation and substantial economic growth. For example, Macaé, a fishing municipality, transformed from a rural place to a very urban place after Petrobras discovered offshore oil in the area and located some of its key production facilities in Macaé in the 1970's. There are also anecdotes of Petrobras hiring hundreds and thousands of rural workers to join drilling expeditions. In the 1960's, the municipality of Carmopólis, located in a historically sugarcane producing area, discovered oil. Since then, Carmopólis has changed its main business due to the presence of Petrobras

[16]The first refinery was constructed in 1949 in the municipality of São Francisco do Conde (located in Bahia state). The refinery is called RLAM (Refinaria Landulpho Alves-Mataripe) and is located near the very first wells that discovered oil in the country.

and related oil service companies. Carmopólis has had high GDP growth even though there are complains regarding the lack of connection between oil service firms and the community.[17] The municipality of Alagoinhas in Bahia discovered oil in 1964. A number of successive discovery wells lead Petrobras to locate some of its facilities in Alagoinhas in the late 1960s. Anecdotal evidence suggests that this lead to rapid economic growth in the area, particularly in the services sector. Alagoinhas became a services hub for the surrounding municipalities and large commercial outfits located there.[18]

Fig. 2: GDP *per capita* in Oil and Non-Oil Municipalities



(a) GDP *per capita* in Rio: 1940-2000 (b) GDP *per capita* in Bahia: 1940-2000

Notes. Figure shows the development of *per capita* GDP in municipalities which discovered oil (blue line) and those which did not discover oil (red line) in the state of Rio de Janeiro and Bahia from 1940 to 2000. Rio de Janeiro is the most important producer and the first oil discovery took place in the late 1970's. The first commercial oil well in Bahia was discovered in 1941.

Figures 2(a) and 2(b) show the development of GDP *per capita* for the period 1940-2000 in the states of Rio de Janeiro and Bahia (first state to discover oil), respectively. For each state, the graphs illustrate the evolution of GDP of municipalities with and without oil. It can be seen that a wedge in GDP per capita between oil producing municipalities and those without oil production emerges over the years. Furthermore, the timing seems to correspond quite closely to the development of the oil sector in each state. At a first pass, oil production thus seems to substantially increase local GDP. Two questions arise from this. Firstly, is the observed correlation causal? And secondly, how does the non-oil sector develop? Since oil extraction is a high value added activity, local GDP mechanically increase when oil is produced, bar any extreme "Dutch Disease" effect. We

[17]See http://www.uff.br/macaeimpacto/OFICINAMACAE/
[18]See http://pt.wikipedia.org/wiki/Alagoinhas

are interested in assessing whether the spillovers of oil production to other sectors are positive or negative.

Only after 1997 (Federal Law n. 9,496/1997), did royalties start to represent a significant amount of revenue to local government. In the robustness exercise, we restrict our analysis to the years 1940-1996 to capture only the direct effect of oil production rather than the indirect effect through royalties.

In the next section we discuss the identification strategy used to retrieve the effect of oil discoveries on growth of local economies in Brazil.

3 Research Design

We study the impact of oil by defining the analysis in terms of the treatment evaluation literature where we see oil production as our treatment of interest and oil discoveries as the assignment to treatment. In this section, we detail our research design which is based on exploiting the quasi-random nature of oil discoveries. Our research design exploits unconfounded assignment and we perform several exercises to guarantee adequate overlap between the treatment and control group (strong ignorability as in Rosenbaum and Rubin (1983)). While it is common in the literature on natural quasi-experiments to match on observable variables, our research design additionally provides several strategies to "match on unobservables". We start by describing the data and then discuss the exogeneity of oil discovery and its relation to the treatment assignment. We then turn to the issue of balance in the covariate distributions between treatment and control groups.

3.1 Data

The data on drilling is from *Agência Nacional do Petróleo, Gás Natural e Biocombustíveis* (ANP), the Brazilian oil and gas industry regulator. The well dataset contains detailed information on the drilling of 20,052 wells in Brazil spanning from 1940 to 2000. The dataset contains the latitude and longitude coordinates of the well, so we are able to know the exact location of each well. The dataset also has information on the exact date of the drilling, on the result of the drilling (whether oil was found, whether the well is a dry hole, whether only water was found, or whether the well was abandoned because of an accident.[19]) Furthermore, we have information on the viability of exploring the oil deposit (when oil was found), and on whether the oil company started production.

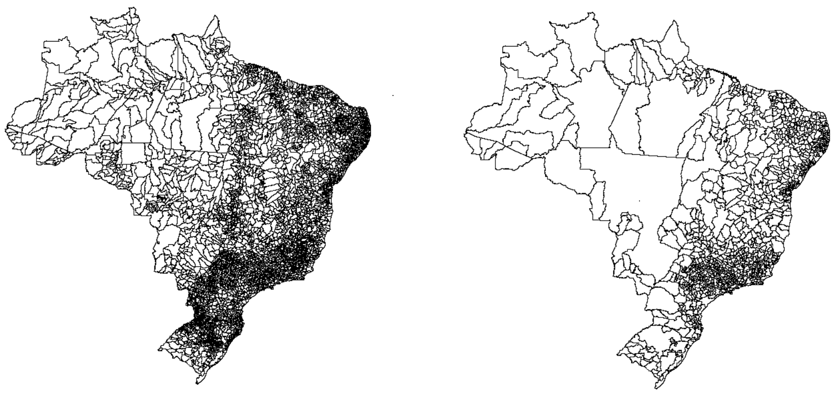
The richness of the well dataset allows us to study several possibilities regarding the stages of oil extraction and production (upstream oil industry). Given the data, we are able to separate places where drilling took place ($J = 1$) from places with no drilling ($J = 0$). We can also obtain information on places with oil discoveries (Z) and with oil production (D). As a first step we created a dummy variable for drilling (J), two different dummy variables for discovery (Z), and a dummy for well production (D). The dummies for drilling and production follow immediately from the well data. The drilling dummy equals one when at least one well was drilled in the municipality and the production dummy is one when there is at least one producer well in the municipality. In terms of discoveries, there are several possibilities as the data allow us to differentiate between a field discovery, a subfield (reservoir) discovery and a field extension discovery. We define two different discovery dummies as follows. Firstly, "All Discoveries": the dummy is one when at least one field, subfield or field extension discovery was made in the municipality. Secondly, "True Discoveries": The dummy is one when at least one field or subfield discovery and at least one field extension discovery was made in the municipality. The rationale for the latter is that any substantial discovery includes a field or subfield discovery and subsequent field extension discoveries to delineate the size of the oil field (see Appendix B.1). For now we will use the "All Discoveries" dummy to start with the most general possible definition of discoveries.

The spatial unit of analysis is the Minimum Comparable Area (MCA). The Brazilian federation has three administrative levels: federal government, states, and municipalities. One complication when dealing with municipalities in Brazil is the process of

[19]We obtain more the 50 different classifications from the dataset, but we were able to aggregate all of them in few major categories (see Table 2). The data differentiate between oil well, gas well, and oil and gas well. One limitation of the dataset is that we do not have information on the amount of oil produced by each individual producer well for the period of interest. Data on well production is available only from the 2000's onward.

detachments and splits that took place over the years. For instance, in 1940 there were 1,574 municipalities, while in 1997 there were 5,507 municipalities. In order to deal with the detachments, we used the concept of MCAs. MCAs consist of sets of municipalities whose borders were constant over the study period. Therefore, our data was aggregated to 1,275 Minimum Comparable Areas (MCAs) in 1940. Figure 3 shows the boundaries of municipalities in 1997 and the correspondent MCAs in 1940. More on MCA aggregation can be found in Da Mata, Deichmann, Henderson, Lall, and Wang (2007).

Fig. 3: Municipalities and Minimum Comparable Areas (MCAs)



(a) 5,507 Municipalities in 1997 (b) 1,257 MCAs in 1940

Notes. Figure 3(a) shows the administrative boundaries of the 5,507 municipalities that existed in 1997 in Brazil. Figure 3(b) shows the aggregation to the 1,275 Minimum Comparable Areas (MCAs) in 1940.

We allocate the wells into each MCA as follows. For onshore wells, we simply allocate the wells that were within the boundaries of each MCA. For offshore wells, we calculate the distance from each well to the nearest coastal MCA and allocate the offshore well to the selected nearest MCA. In the robustness section, we also use an alternative method to allocate offshore wells to MCAs (see Subsection 5.2).

Table 1 shows the number of wells discovered by decade. It contains information on the total number of discoveries, and on onshore and offshore discoveries. It also has information on the total number of units assigned to treatment over time. Table 2 shows the number of wells by category. Wells are classified broadly as exploratory wells and development wells. Exploratory wells are drilled to test for the presence of oil, while wells drilled inside the known extent of the field are called development wells (e.g.,

Table 1: Number of Discoveries by Decade

Decade	# of Wells: Discoveries			Units Assigned to Treatment		
	Total	Onshore	Offshore	Total	Onshore	Offshore
1940	9	9	0	3	3	0
1950	48	48	0	8	8	0
1960	212	206	6	19	18	1
1970	203	117	86	13	4	16
1980	671	434	237	15	11	8
1990	285	158	127	6	2	5

Notes. Data from ANP (Brazilian oil and gas industry regulator). The units assigned to treatment are Minimum Comparable Areas (MCAs). MCAs consist of sets of municipalities whose borders were constant over the study period.

producer wells).[20] Unsuccessful drilling is classified as a dry hole in both exploratory and development categories. See Appendix B.1 for a detailed explanation on the types of wells.

Table 2: Number of Wells by Category

Classification	Category of Well	Offshore	Onshore	Total
Exploratory Wells	Discovery of New Field	129	304	433
	Discovery of New Subfield (Reservoir)	88	234	322
	Discovery of Field Extension (Step-out)	258	419	677
	Dry Hole	1,067	2,556	3,623
Development Wells	Producer	1,368	9,101	10,469
	Carries Oil or Gas	7	1	8
	Production Non-Feasible	327	521	848
	Injection of Water, Steam or Gas	201	774	975
	Dry Hole	73	1,017	1,090
Other	Abandoned	421	554	975
	Special	62	369	431
	Missing category	30	171	201
	Total	4,031	16,021	20,052

Notes. Data from ANP (Brazilian oil and gas industry regulator). Wells are classified broadly as exploratory wells and development wells. Exploratory wells are drilled to test for the presence of oil. If the exploratory drilling has been proven unsuccessful, the well is classified as a dry hole. Wells to delineate the extension of the oil field (step-out wells) are also classified as exploratory wells. Every well drilled inside the known extend of the field is called development well (e.g., producer wells and injection wells). In the development well category, unsuccessful drilling is also classified as a dry hole. Special wells are water wells or the ones used for mineral research and experiments.

We have the following numbers regarding oil discoveries in Brazil:

- Total number of MCA units = 1,275
- All Discovery MCAs = 64
- True Discovery MCAs = 45
- Dry hole MCAs = 158
- Neighbors of discovery MCAs= 156

We work with three main outcome variables: population density, the urbanization rate[21] and *per capita* GDP (overall as well as sectoral). Data on total population, pop-

[20] Note that the two instruments (true discoveries and all discoveries) are all exploratory wells.
[21] The urbanization rate is the proportion of the population living in urban areas.

ulation located in urban areas, and total area of the municipality come from historical Population Censuses. We also tabulated data on employment (total and sectoral) from historical Population Censuses. Data on municipal Gross Domestic Product (GDP) and on the share of manufacturing, agriculture, and services in GDP is from Ipeadata.[22] Using this information, we construct our outcome variables to obtain a panel from 1940 to 2000. In 1941, the first well started to produce oil, so the year 1940 is our pre-treatment year. The panel data is balanced and we do not observe any attrition. However, the time dimension is unequally spaced for GDP *per capita*. Because Population Censuses where historically only conducted every 10 years and there is no data on GDP for 1990 or 1991, we end up with GDP *per capita* data for the years 1949, 1959, 1970, 1980, 1996 and 2000. By contrast, our panel is virtually equally spaced for the other two dependent variables (urbanization rate and population density): 1940, 1950, 1960, 1970, 1980, 1991, 1996 and 2000.

Additionally we collected data on average temperature, average rainfall and average altitude from Ipeadata.[23] Further data comprise latitude and longitude coordinates of the MCAs as well as indicator variables regarding the location of the MCA (on the coast, Amazon region, and semiarid region).[24]

In further analysis we use microdata from the employment and population censuses. Ministry of Labor's RAIS (Relação Anual de Informações Sociais) provides matched employer-employee microdata. Table A.3 in Appendix A shows the summary statistics of the variables used in the analysis.

[22] GDP calculations are detailed in Reis, Tafner, Pimentel, Serra, Reiff, Magalhaes, and Medina (2004). GDP is deflated using the national implicit price deflator. In subsection 5.1, we use the composition of GDP to argue that we capture a variation in real local GDP instead of a price effect by showing that oil municipalities undergo an important structural transformation.

[23] Temperature is measured in degrees Celsius, precipitation in millimeters per month, and altitude in meters.

[24] To construct the shapefile of 1940 MCAs, we combined (i) the shapefile of 1997 municipalities with (ii) the matching between 1940 MCAs and the corresponding 1997 municipalities. From the shapefile of 1940 MCAs, we constructed the geographical coordinates and indicator variables.

3.2 Treatment Assignment

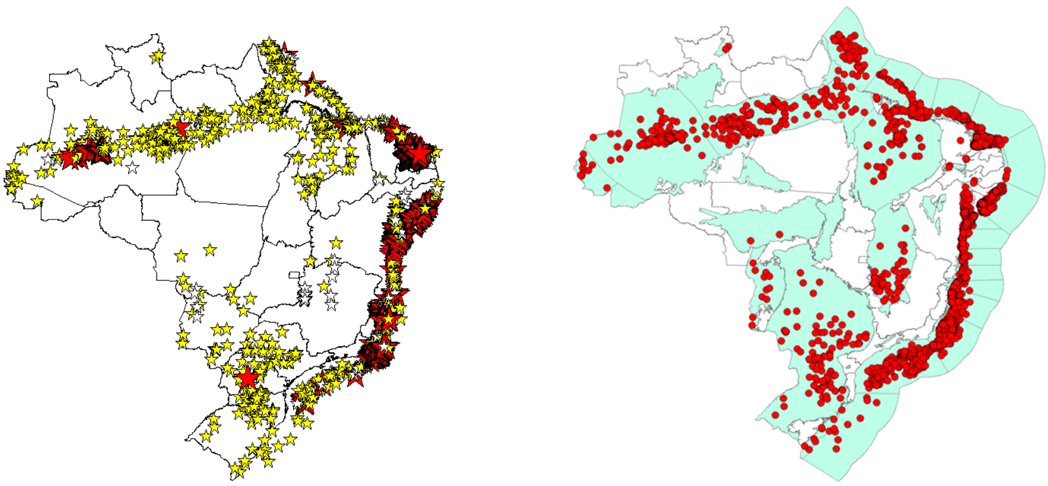
Municipalities which discovered oil are assigned to treatment. The untreated (control) group comprises the locations with drilling but no oil discoveries. Our treatment assignment process is very similar to a randomization: several attempts to drill oil were made, but nature has endowed only some places with oil. Drilling took place in locations with selected geological characteristics with little room for influence by local governments. Figure 4(b) shows that oil drilling in Brazil is concentrated in sedimentary basins. Since the location of oil reserves is determined by geology, selection into treatment is unlikely or impossible. In other words, municipalities had no control over the assignment mechanism and thus could not influence their treatment regime.

Note that we have some noncompliance with the assigned treatment, i.e., some locations discovered ($Z = 1$) but do not produce oil ($D = 0$). We have information on whether a recently discovered oil field is economically viable to begin production. Viability depends to the largest extent on the characteristics of the oil field but potentially also on some local characteristics. Part of the costs of producing oil may be systematically correlated with unobservable local characteristics. For instance, existing infrastructure and institutional support from the local and state governments might influence the decision to produce oil at the margin. As a result, the research design implies random assignment of locations to treatment and control groups, but allows for non-random selection of participants into treatment (once assigned to treatment). As part of our empirical strategy we will thus use discoveries as an instrumental variable for production.[25]

For our identification strategy to be valid, we need to show that (i) (the intensity of) drilling attempts are exogenous to local characteristics conditional on appropriate geographical controls and (ii) that conditional on drilling taking place, the discovery of oil is a “lottery”.

[25] Part of the non-compliance is due to MCAs discovering oil towards the end of our sample period but only starting production after 2000.

Fig. 4: Oil Wells in Brazil: 1940-2000



(a) Oil Wells: Discovery (red) vs. dry (beige) (b) Sedimentary Basins (light green)

Notes. The figures show the location of approximately 20,000 drilled wells (the universe of wells drilled in Brazil during the period from 1940 to 2000). In Figure 4(a), wells with Oil Discovery are in red, Dry Wells in yellow, and other are in white. Figure 4(b) shows the location of sedimentary basins in Brazil (in light green). Both figures show the administrative boundaries of the 27 states that exist since 1988 in Brazil. (See https://www.youtube.com/watch?v=_ZKdnUeBcOI for a short video on the geographic distribution of drilling activity in Brazil from 1940-2000.)

3.3 Assessing the Design

Our research design is based on the idea that drilling took place only in locations with selected geological features with no influence from local governments. We discussed thus far several points that support the exogenous nature (in the viewpoint of local economies) of drilling in Brazil: the risky characteristics of oil exploration, the self-sufficiency goal of Petrobras, and the concentration of drilling attempts in geological target areas in the Amazon and on the Coast (see Figure 4). We now provide further evidence of a lack of relationship between drilling and local characteristics.

Table 3 shows simple regressions between drilling attempts and pre-treatment characteristics. We consider our three main outcome variables (population density, urbanization, and *per capita* GDP) in the 1940's. We construct two variables related to drilling: a dummy that equals 1 if any drilling attempt happened in 1940-2000 in each Minimum Comparable Area (MCA) and another that equals the number of drilling attempts in each MCA. Using different models, we show that drilling attempts are uncorrelated with initial economic conditions. The correlations of Table 3 strongly support the patterns

Table 3: Correlation between Drilling Attempts and Pre-Treatment Characteristics

	(1)	(2)	(3)	(4)
Dependent variable:	**Drilling Dummy**		**Drilling Count**	
	Linear Probability	Logit	Linear Probability	Poisson
Urbanization in 1940	0.0575	0.481	28.32	1.284
	(0.0939)	(0.837)	(22.22)	(0.888)
Pop. Density in 1940	-0.000343	-0.00171	-2.722	-0.177
	(0.000249)	(0.00161)	(3.354)	(0.167)
GDP *per capita* in 1949	-0.00712	-0.0787	3.413	0.129
	(0.0144)	(0.156)	(8.567)	(0.404)
Semiarid Indicator	0.00742	0.0938	20.63	1.292*
	(0.0220)	(0.232)	(19.95)	(0.782)
Amazon Indicator	0.395***	2.292***	-7.137	-0.809*
	(0.0530)	(0.276)	(7.567)	(0.470)
Coastal Indicator	0.518***	2.776***	90.65***	3.001***
	(0.0443)	(0.243)	(34.54)	(0.651)
Constant	0.0934***	-2.314***	3.725	1.572***
	(0.018)	(0.184)	(8.538)	(0.374)
Observations	1,275	1,275	1,273	1,273
R-squared	0.255	-	0.053	-

Notes. Robust standard errors in parentheses. The regressions are for 1,275 Minimum Comparable Areas (MCAs). There are two dependent variables: a dummy variable if any drilling attempt happen during 1940 to 2000 (columns (1) and (2) of the table) and the number of drilling attempts during 1940 and 2000 (columns (3) and (4) of the table). Pre-treatment variables are: urbanization rate in 1940, population density in 1940 and *per capita* GDP in 1949. Geographical controls are indicator variables showing whether the MCA is located in the Semiarid region, in the Amazon region, or on the coast.
*** p<0.01, ** p<0.05, * p<0.1

from Figure 4: drilling is determined by geological and geographic characteristics and not by pre-treatment population, GDP, or urbanization.

As mentioned previously there are two different ways for us to capture discoveries. Table 4 compares the predictive power of the "All Discoveries" and "True Discoveries" dummies for explaining production. We include MCA and Year FE as well as the initial economic conditions and baseline geographic controls with time-varying coefficients. The "True Discovery" dummy is more closely related to production. It has the higher t-statistic and F-statistic, and its coefficient also turns out to be larger. Since any substantial field discovery will be followed by a field extension discovery, it is not surprising that the "True Discovery" Dummy is more closely related to actual production.

For the "True Discovery" dummy to be valid it is not sufficient to show that drilling is uncorrelated with initial conditions but we have to check whether conditional on a discovery, additional drilling is also unrelated to local economic development. Specifically, if Petrobras, following an initial discovery, tried harder to find a field extension discovery in a location which was growing fast, or which had high demand, this would bias our results. Table 5 shows that this is not the case. Unsurprisingly, drilling attempts increase

Table 4: Discovery Dummies: Analysis

Dependent Variable:	Oil Production Dummy (1)	Oil Production Dummy (2)
All Discoveries Dummy	0.681***	
	(0.0524)	
True Discoveries Dummy		0.777***
		(0.0472)
MCA FE	Yes	Yes
Year FE	Yes	Yes
Observations	8,901	8,901
Number of MCAs	1,273	1,273
Geography Controls	Yes	Yes
Initial Conditions	Yes	Yes
Estimation	FE	FE
F-Statistics	9.86	20.41

Notes. Standard errors clustered at the MCA level. Explanatory variables are two dummies related to oil discovery. Geographic controls and initial conditions have time-varying coefficients. The initial conditions with time-varying coefficients are: GDP/capita in 1949, Urbanization rate in 1940, and Population Density in 1940. The geographic controls with time-varying coefficients are: Latitude and Longitude coordinates, Dummy for Amazon, Dummy for Coastal. Total sample: 1,275 Minimum Comparable Areas (MCA).
*** p<0.01, ** p<0.05, * p<0.1

significantly after an initial discovery was made in an MCA. A first discovery is a strong signal and naturally Petrobras subsequently intensifies its efforts in that particular area. Importantly, however, there is no indication that drilling increases *more* in MCAs with higher GDP *per capita*, more urbanized MCAs or more densely populated ones. Both initial drilling attempts and follow-up drilling are thus orthogonal to local economic conditions.

Table 5: Drilling conditional on a Field Discovery

	(1)	(2)
Dependent variable:	Wells drilled per year	
Estimation:	OLS	Poisson
Field Discovery Dummy	5.502**	5.255***
	(2.259)	(0.514)
Field Discovery Dummy * log Population Density	-0.517	-0.0689
	(0.600)	(0.0721)
Field Discovery Dummy * log GDP/capita	0.849	0.107
	(1.121)	(0.135)
Field Discovery Dummy * Urbanization	4.706	0.690
	(5.925)	(0.829)
Constant	0.0285***	-3.557***
	(0.0104)	(0.366)
Observations	5,098	5,098

Notes. Robust standard errors in parentheses. The regressions are for 1,275 Minimum Comparable Areas (MCAs). The dependent variable is the count of drills per year. The explanatory variables are a dummy for a field discovery and the interactions between this dummy and GDP/capita, urbanization and population density.
*** p<0.01, ** p<0.05, * p<0.1

Until now we were concerned with the exogeneity of drilling attempts to local economic conditions. For our identification strategy to be valid we also have to show that conditional on drilling, discoveries are unrelated to local economic characteristics. We restrict the sample to only those municipalities which drilled for oil and we obtain that both (i) the number of discoveries and (ii) the ratio of successful drilling to unsuccessful drilling are unrelated to local economic characteristics. Table 6 shows thus that, conditional on drilling taking place, pre-treatment economic characteristics do not influence drilling success. It is in fact particularly reassuring that the success ratio is uncorrelated with all controls, i.e., conditional on drilling taking place, success is truly a lottery.[26]

Table 6: Discoveries conditional on drilling

	(1)	(2)	(3)
Dependent variable:	**Number of Discovery Wells**		**Drilling Success Ratio**
	Linear Probability	Poisson	Linear Probability
Urbanization in 1940	0.524	-0.844	0.121
	(9.766)	(1.478)	(0.125)
Pop. Density in 1940	0.435	0.108	-0.00255
	(0.912)	(0.169)	(0.0165)
GDP *per capita* in 1949	2.779	0.548	-0.00148
	(2.302)	(0.381)	(0.0300)
Semiarid Indicator	10.53	1.362**	0.104
	(7.595)	(0.562)	(0.0679)
Amazon Indicator	2.499	-0.377	-0.0263
	(3.733)	(0.746)	(0.0586)
Coastal Indicator	10.77**	1.704***	0.0595
	(5.190)	(0.535)	(0.0390)
Constant	0.783	0.834*	0.0622
	(3.059)	(0.471)	(0.052)
Observations	222	222	210
R-squared	0.070	-	0.031

Notes. Robust standard errors in parentheses. The regressions are for the 222 Minimum Comparable Areas (MCAs) in which Petrobras drilled for oil. "Drilling Success Ratio" corresponds to the ratio of exploratory wells with oil to exploratory dry wells. Pre-treatment variables are: urbanization rate in 1940, population density in 1940 and *per capita* GDP in 1949. Geographical controls are indicator variables showing whether the MCA is located in the Semiarid region, in the Amazon region, or on the coast.
*** p<0.01, ** p<0.05, * p<0.1

3.4 Assessing the Overlap of Covariates

Our baseline strategy to control for unobservables is to use municipalities where there was drilling for oil but no discovery as our control group. However, even if an oil-discovery place is sort of a "lottery winner", which would guarantee unconfoundedness, a lack of overlap (or common support) would still be a threat to internal validity. Figure 4 shows that oil deposits are not randomly distributed across the country, but rather concentrated in the basin of the Amazon River (onshore wells) and on the Atlantic Coast (offshore

[26]We repeat the analysis of Tables 3, 5, and 6 by running separate regressions for each of the three pre-treatment characteristics. The regressions show that each pre-treatment characteristic individually is unrelated to the dependent variables, conditional on geography.

wells).

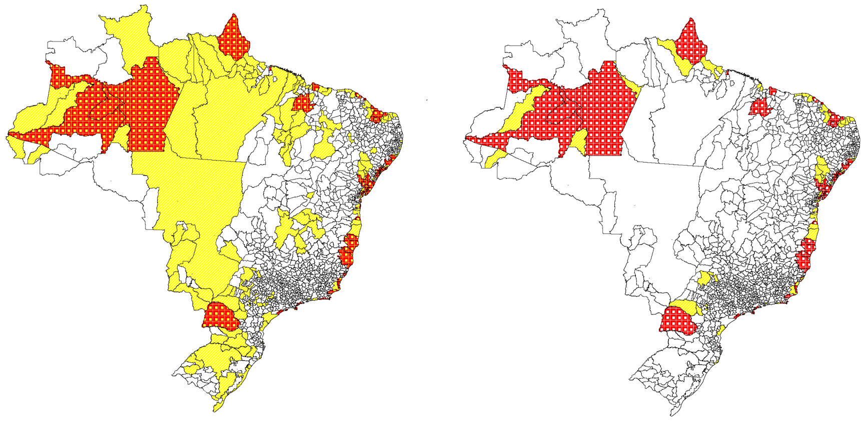
We investigate systematic differences between the assigned to treatment and the control group. Rubin (2001) proposes a set of criteria to check for overlap. In this paper, we use the normalized (or standardized) difference to assess the difference in location in the covariate distributions (Imbens and Wooldridge (2009)). Standardized differences are not influenced by sample size, unlike t-tests and other statistical tests.

We detailed the results of this assessment in Appendix A. Our dry-drilling control group presents a good performance in terms of pre-treatment characteristics such as urbanization and population density. However, it does not pass the standardized difference assessment in some geographical controls such as longitude and coastal dummy. In fact, the dry-drilling group is more spread out in the Brazilian territory. As a result, to improve overlap, we created a matched subsample of the "drilling but no discovery" group. Propensity score matching (or trimming) is a common way to improve overlap (Imbens and Wooldridge (2009)). We choose the 64 municipalities out of the set of "drilling but no discovery" with the highest propensity score and call this control group "matched dry drilling".[27] It is useful to emphasize that while may it improve internal validity, the matching may reduce the external validity of the results because we are now focusing on a subset of the original sample (Imbens and Wooldridge (2009)).

As an alternative we also use direct neighbors as one of our control groups. This is a strategy widely employed in the literature. Neighbors are likely to have similar geographical and institutional characteristics and are likely to be very similar across other unobservables. Additionally, we consider all non-oil MCAs in oil states, all dry drilling MCAs which are not neighbors of discovery MCAs (dry drilling, no neighbor) and a trimmed subsample of the neighboring MCAs. The idea is to create multiple comparison groups to strengthen the results.

[27]The set of pre-treatment characteristics used in the propensity score model includes: population density in 1940, urbanization rate in 1940, GDP *per capita* in 1949, share of manufacturing out of the total GDP in 1949, share of services in 1949, share of agriculture in 1949, indicator variables for location (whether the MCA is located in the coast, whether in the Semiarid region, and whether in the Amazon region), historical average rainfall and temperature, and geographic coordinates. Since the very large share of relevant discoveries happened after the creation of Petrobras in 1953 (recall from Table 1 that only 9 wells discovered oil during the 1940's), GDP variables in 1949 can be considered pre-treatment.

Fig. 5: Treatment and Control Groups



(a) Discovery (Red), Drilling (Yellow) (b) Discovery (Red) and Matched Dry Drilling Sample (Yellow)

Notes. Figures show 1,275 Minimum Comparable Areas (MCAs) in 1940. The discovery dummy is the "All Discoveries" dummy (which equals one when at least one field, subfield or field extension discovery was made in the municipality).

Figure 5 shows the maps with the location of the two most relevant control groups. Figure 5(a) shows the places with discoveries and the set of MCAs where drilling took place and no oil was found. Figure 5(b) displays the matched dry-hole subpopulation.

An implicit assumption in the analysis is the stable unit treatment value assumption, i.e. that there is no interference of the treatment on the control group. One might fear spillovers from the intervention: in the presence of spillover effects, neighboring locations may also receive part of the treatment. To alleviate doubts about spillovers we have included the "dry drilling, no neighbor" group as one of our control groups. The next section discusses the empirical strategy used to recover the main estimand of interest.

4 Estimation

We now briefly discuss the empirical strategy to recover the impact of oil discoveries. The estimand of interest is the Intention-to-Treat (ITT): the average impact of being assigned to treatment. Let y_i is the potential outcome for local economy i and let the indicator of treatment assignment be $Z_i = \{0, 1\}$. The ITT estimand is represented by $ITT = \mathbb{E}[y_i|Z_i = 1] - \mathbb{E}[y_i|Z_i = 0]$.

In the discussion below, the oil discovery dummy is represented by Z_{it} (treatment assignment): Z_{it} equals 1 if oil was discovered in the MCA unit i in period $\bar{t} \leq t$, where $\bar{t}$ is the time of the discovery. A regression using Z_{it} is an intent-to-treat (ITT) analysis. We assume an additive and linear empirical specification to estimate an ITT effect as follows:

$$Y_{it} = \alpha + \tau_{ITT} Z_{it} + \beta_t' X_i + \gamma_i + \rho_t + \epsilon_{it}, \tag{1}$$

where Y_{it} is the outcome variable, X_i are time-invariant MCA characteristics including the pre-treatment level of the dependent variables, ϵ_{it} is an error term, ρ_t are year fixed effects and γ_i denotes MCA fixed effects. The time span t goes from 1940 to 2000. The (exogenous) source of cross-sectional and time variation is given by the discovery of oil in unit i at time t. As a result, the parameter τ_{ITT} should capture an intent-to-treat effect. Note that ITT is considered a lower bound for the average treatment effect. We add γ_i to capture time-invariant characteristics and ρ_t to capture common aggregate shocks that hit all locations.

We also use a set of additional covariates X_i in equation (1). Recall that we trim by using propensity score to create some control groups for robustness exercises. After matching by using the propensity score, model dependence is not eliminated but will normally be reduced. Parametric procedures have the potential to improve causal inferences even after matching when the match is not exact (Ho, Imai, King, and Stuart (2007)). Moreover, the trimming used to create the control groups also helps with the common trend assumption. Lastly, note that policy variation takes place at the MCA level and errors may be correlated within the spatial units. Therefore, standard errors are clustered at the MCA level in all regressions (Bertrand, Duflo, and Mullainathan (2004)).[28]

[28] Time can be a threat for identification if discoveries took place in boom periods: places where oil was discovered during a boom may have had a better opportunity to promote local growth. Our use of time fixed-effects helps to alleviate this issue. Additionally, the bulk of drilling activity (and some important discoveries) took place in the 1980s, a decade labeled as the "lost decade" because of its low GDP growth. Therefore, important discoveries did not happen during boom periods in Brazil.

5 Results

This section is divided into four parts. The first and main part discusses the baseline results and a host of robustness exercises regarding the effects of oil discoveries. We then show an additional subsection which compares onshore to offshore discoveries. The last two parts discuss oil production and treatment intensity, and the link between upstream and downstream oil production, respectively.

5.1 ITT Results

As discussed in the estimation section (see Section 4), we include MCA and year fixed effects and cluster standard errors at the MCA level in all regressions. Additionally we control for geographic characteristics and initial conditions with time varying coefficients. Controls included in all regressions are: *per capita* GDP in 1949, Urbanization rate in 1940, Population Density in 1940, Latitude, Longitude, a dummy for being in the Amazon area and a dummy for being on the coast.

Table 7: Intention-to-Treat Effect of All Oil Discoveries: Socio-Economic Outcomes

	Dry Drilling			Matched Dry Drilling		
	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	ln Population Density	ln GDP *per capita*	Urbanization Rate	ln Population Density	ln GDP *per capita*	Urbanization Rate
Discovery Dummy	-0.0390	0.125*	0.0283	-0.0400	0.146*	0.0253
	(0.0579)	(0.0728)	(0.0187)	(0.0626)	(0.0783)	(0.0199)
MCA FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,776	1,332	1,776	1,024	768	1,024
Number of MCAs	222	222	222	128	128	128
Geography Controls	Yes	Yes	Yes	Yes	Yes	Yes
Initial Conditions	Yes	Yes	Yes	Yes	Yes	Yes
Estimation	FE	FE	FE	FE	FE	FE

Notes. Standard errors clustered at the MCA level. Geographic controls and initial conditions have time-varying coefficients. Discovery is defined as "All Discoveries".
*** p<0.01, ** p<0.05, * p<0.1

Results for Socio-Economic Variables. Table 7 shows the baseline ITT results using the "All Discovery" dummy as our treatment assignment. We show results for both our preferred control group (dry drilling) and for the matched dry drilling sample. The key independent variable is a dummy and both *per capita* GDP and population density are expressed as logs. Therefore, we can interpret the coefficient in those regressions as a percentage change. Urbanization is a rate bounded between 0 and 1 so that we can interpret the coefficient on oil production as a change in percentage points. GDP *per capita* increases by 12.5-14.6% over a 60 year period as a result of oil discoveries. Population density and the urbanization rate are unaffected by oil discoveries in this specification. As discussed previously the "All Discovery" dummy has some drawbacks both conceptually as well as in terms of its ability to predict oil production. The "True Discoveries" dummy excludes both MCAs where initially oil was discovered but then there were no follow-up discoveries (i.e. the oil field was very small) and MCAs where there was no field discovery but only a field extension (i.e. the bulk of the field lies in a different municipality).[29]

Table 8: Intention-to-Treat Effect of True Oil Discoveries: Socio-Economic Outcomes

	Dry Drilling			Matched Dry Drilling		
	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	ln Population Density	ln GDP *per capita*	Urbanization Rate	ln Population Density	ln GDP *per capita*	Urbanization Rate
Discovery Dummy	-0.00864	0.246***	0.0443**	-0.0127	0.259***	0.0430**
	(0.0676)	(0.0856)	(0.0202)	(0.0731)	(0.0910)	(0.0213)
MCA FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,776	1,332	1,776	1,024	768	1,024
Number of MCAs	222	222	222	128	128	128
Geography Controls	Yes	Yes	Yes	Yes	Yes	Yes
Initial Conditions	Yes	Yes	Yes	Yes	Yes	Yes
Estimation	FE	FE	FE	FE	FE	FE

Notes. Standard errors clustered at the MCA level. Geographic controls and initial conditions have time-varying coefficients. Discovery is defined as "True Discovery".
*** p<0.01, ** p<0.05, * p<0.1

Table 8 shows the baseline ITT results using our preferred treatment assignment ("True Discoveries"). Unsurprisingly, the coefficients are markedly higher than in Table 7. The increase in *per capita* GDP is estimated at 24.6-25.9%. While population density is not significantly affected, urbanization increases by 4.3-4.4% points over the period as a consequence of oil discoveries. In other words, when we compare municipalities with significant discoveries to municipalities where Petrobras drilled for oil and either did not find any or made no substantial discovery then we find a strong positive impact on *per capita* GDP and urbanization.

[29]Implicitly, other recent papers on the impacts of oil abundance have also defined relevant discoveries. For example, Michaels (2011) uses a threshold of 100 millions barrels of reserves and Allcott and Keniston (2014) use a cutoff of a production of $100 U.S. dollars per habitant.

Robustness. Firstly, we verify that changing the time period to 1940-1996 does not change the results. Table 9 shows that the results are virtually the same when we set 1996 as the final year. This is important because it supports the claim that our findings are driven by the direct effect of oil production rather than the indirect effect through royalties (recall the discussion in Subsection 2.2).

Table 9: Intention-to-Treat Effect of Oil Discoveries: Robustness 1996 final year of analysis

	Dry Drilling			Matched Dry Drilling		
	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	ln Population Density	ln GDP *per capita*	Urbanization Rate	ln Population Density	ln GDP *per capita*	Urbanization Rate
Discovery Dummy	-0.0291	0.200**	0.0459**	-0.0242	0.225**	0.0449**
	(0.0645)	(0.0926)	(0.0203)	(0.0698)	(0.0969)	(0.0210)
MCA FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,776	1,332	1,776	1,024	768	1,024
Number of MCAs	222	222	222	128	128	128
Geography Controls	Yes	Yes	Yes	Yes	Yes	Yes
Initial Conditions	Yes	Yes	Yes	Yes	Yes	Yes
Estimation	FE	FE	FE	FE	FE	FE

Notes. Standard errors clustered at the MCA level. Number of observations is smaller because the final year in the panel is 1996 instead of 2000. Geographic controls and initial conditions have time-varying coefficients. Discovery is defined as "True Discovery".
*** p<0.01, ** p<0.05, * p<0.1

The results are also both quantitatively and qualitatively robust to using alternative control groups (see Table 10). Our additional control groups are: all non-oil MCAs in oil discovery states, dry drilling MCAs which are not adjacent to discovery MCAs (which we call dry drilling, no neighbor), all MCAs which are adjacent to discovery MCAs and a matched subsample of adjacent MCAs (matched neighbors). The results for the dry drilling, no neighbor control group are reassuring in the sense that any potential spillovers should be particularly limited for this group. The matched neighbors group on the other hand is susceptible to spillovers but offers a good control group in terms of observable MCA characteristics. Overall, the results are remarkably similar across control groups, perhaps highlighting that our controls and the parametric fitting (the linear and additive specification represented by Equation (1)) are doing a good job in providing a precise estimate of the effects of oil on the municipalities in Brazil.[30] The estimate for *per capita* GDP ranges from 19.5-27.7% while urbanization is estimated to increase 3.6-5.2% as a

[30] Results are also robust to excluding major urban centers, i.e. state capitals.

consequence of oil discoveries.[31]

Table 10: Intention-to-Treat Effect of Oil Discoveries: Robustness to alternative control groups

	Non-Oil Municipalities in Oil States			Dry Drilling, No Neighbors		
	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	ln Population Density	ln GDP *per capita*	Urbanization Rate	ln Population Density	ln GDP *per capita*	Urbanization Rate
Discovery Dummy	-0.0560	0.262***	0.0519***	-0.0302	0.195**	0.0362*
	(0.0610)	(0.0781)	(0.0190)	(0.0751)	(0.0906)	(0.0214)
MCA FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	6,200	4,649	6,200	1,344	1,008	1,344
Number of MCAs	775	775	775	168	168	168
Geography Controls	Yes	Yes	Yes	Yes	Yes	Yes
Initial Conditions	Yes	Yes	Yes	Yes	Yes	Yes
Estimation	FE	FE	FE	FE	FE	FE

	All Neighbors			Matched Neighbors		
	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	ln Population Density	ln GDP *per capita*	Urbanization Rate	ln Population Density	ln GDP *per capita*	Urbanization Rate
Discovery Dummy	0.0114	0.247***	0.0434**	0.0341	0.277***	0.0419**
	(0.0641)	(0.0819)	(0.0195)	(0.0645)	(0.0863)	(0.0206)
MCA FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,760	1,320	1,760	1,024	768	1,024
Number of MCAs	220	220	220	128	128	128
Geography Controls	Yes	Yes	Yes	Yes	Yes	Yes
Initial Conditions	Yes	Yes	Yes	Yes	Yes	Yes
Estimation	FE	FE	FE	FE	FE	FE

Notes. Standard errors clustered at the MCA level. Geographic controls and initial conditions have time-varying coefficients. The initial conditions with time-varying coefficients are: GDP/capita in 1949, Urbanization rate in 1940, and Population Density in 1940. The geographic controls with time-varying coefficients are: Latitude and Longitude coordinates, Dummy for Amazon, and Dummy for Coastal. Discovery is defined as "True Discovery".
*** p<0.01, ** p<0.05, * p<0.1

Table 11 shows that our baseline results are also robust to including the additional geographic controls which are available, namely average temperature and average rainfall over the last 50 years, average altitude of the MCA, and a dummy for being located in a semiarid region. The impact of oil discoveries on *per capita* GDP is marginally lower than in the analogous regressions without the additional controls. However, since the overall fit barely improves and the coefficients on the additional controls tend to be insignificant we prefer to exclude them to avoid a problem of over-controlling. Either way, including them only somewhat changes the results quantitatively but not qualitatively in all specifications.

Sectoral GDP Results. While the results for urbanization point in a different direction, there might be a concern that the increase in GDP *per capita* is purely mechanical

[31] We also constructed trimmed (rather than matched) subsamples of the dry drilling and neighbors control groups. Results are robust to using those.

Table 11: Intention-to-Treat Effect of Oil Discoveries: Robustness adding more Geographic Controls

	Dry Drilling			Matched Dry Drilling		
	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	ln Population Density	ln GDP *per capita*	Urbanization Rate	ln Population Density	ln GDP *per capita*	Urbanization Rate
Discovery Dummy	-0.00147	0.218**	0.0372*	-0.0165	0.217**	0.0390*
	(0.0723)	(0.0885)	(0.0216)	(0.0808)	(0.0944)	(0.0231)
MCA FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,776	1,332	1,776	1,024	768	1,024
Number of MCAs	222	222	222	128	128	128
Geography Controls	Yes	Yes	Yes	Yes	Yes	Yes
Initial Conditions	Yes	Yes	Yes	Yes	Yes	Yes
Estimation	FE	FE	FE	FE	FE	FE

Notes. Standard errors clustered at the MCA level. Additional geographic controls are: Average Temperature, Average Rainfall, Average Altitude, Dummy for Semiarid. Geographic controls and initial conditions have time-varying coefficients. The initial conditions with time-varying coefficients are: GDP/capita in 1949, Urbanization rate in 1940, and Population Density in 1940. The geographic controls with time-varying coefficients are: Latitude and Longitude coordinates, Dummy for Amazon, Dummy for Coastal, Average Temperature, Average Rainfall, Average Altitude, Dummy for Semiarid. Discovery is defined as "True Discovery".
*** p<0.01, ** p<0.05, * p<0.1

in the sense that there are no spillovers from oil production to other sectors of the economy. To investigate this, Table 12 shows the impact of oil discoveries on sectoral GDP. GDP is broken up into manufacturing, services and agriculture. Natural resource extraction is included in the manufacturing sector. While ideally we would like to decompose this further the data does not allow us to do so. As such it is not surprising or particularly insightful that manufacturing GDP increases significantly with oil discoveries. Importantly, however, services GDP increases by about 20% while agricultural GDP is unaffected. This is interesting for two reasons. First of all, it is reassuring in terms of our research design, that agricultural GDP is not affected. An increase in agricultural GDP might have raised the doubt that we are mainly picking up local price effects rather than changes in real municipal GDP. Secondly, the results suggests that there are spillovers from oil discoveries to the services sector. A candidate for a channel might be direct demand from oil firms and high-paid oil workers. In terms of thinking about a test of local dutch disease the result that agricultural GDP is not affected is also interesting. Agricultural output is a tradable and as such might be expected to decrease if a strong local cost effect were present.

Output per Worker. To investigate the sectoral GDP results in more detail, we collected data on sectoral employment by municipality going back to 1940 using historical censuses. We then constructed a measure of output per worker by dividing the sectoral

Table 12: Intention-to-Treat Effect of Oil Discoveries: Sectoral GDP *per capita*

	Dry Drilling			Matched Dry Drilling		
	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	Manufacturing GDP *per cap*	Service GDP *per cap*	Agriculture GDP *per cap*	Manufacturing GDP *per cap*	Service GDP *per cap*	Agriculture GDP *per cap*
Discovery Dummy	0.449**	0.213**	0.0569	0.456**	0.215**	0.0664
	(0.182)	(0.0968)	(0.107)	(0.189)	(0.104)	(0.109)
MCA FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,325	1,321	1,328	765	764	765
Number of MCAs	222	222	222	128	128	128
Geography Controls	Yes	Yes	Yes	Yes	Yes	Yes
Initial Conditions	Yes	Yes	Yes	Yes	Yes	Yes
Estimation	FE	FE	FE	FE	FE	FE

Notes. Standard errors clustered at the MCA level. Geographic controls and initial conditions have time-varying coefficients. Discovery is defined as "True Discovery".
*** p<0.01, ** p<0.05, * p<0.1

GDP data by the sectoral employment data for every MCA.[32].[33]

Table 13: Intention-to-Treat Effect of Oil Discoveries: Sectoral Output per Worker

	Dry Drilling			Matched Dry Drilling		
	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	Manufacturing Y/L	Service Y/L	Agriculture Y/L	Manufacturing Y/L	Service Y/L	Agriculture Y/L
Discovery Dummy	0.265*	0.221**	-0.0717	0.222	0.188*	-0.0535
	(0.139)	(0.106)	(0.0881)	(0.143)	(0.113)	(0.0871)
MCA FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,533	1,542	1,547	883	891	891
Number of MCAs	222	222	222	128	128	128
Geography Controls	Yes	Yes	Yes	Yes	Yes	Yes
Initial Conditions	Yes	Yes	Yes	Yes	Yes	Yes
Estimation	FE	FE	FE	FE	FE	FE

Notes. Standard errors clustered at the MCA level. Geographic controls and initial conditions have time-varying coefficients. Discovery is defined as "True Discovery".
*** p<0.01, ** p<0.05, * p<0.1

Table 13 shows that oil discoveries increase output per worker in the manufacturing sector by slightly over 20% (recall again that this includes oil production) and by roughly 20% in the services sector. The agricultural sector in not affected. While the result is significant for the services sector for both control groups it is marginally insignificant at conventional levels in one of the two regressions for the manufacturing sector. Comparing the estimated coefficients with the increases in sectoral GDP *per capita* which we documented in Table 12 it seems that while the increase in services GDP is largely accounted

[32]This is a rough approximation to labor productivity if we assume a Cobb-Douglas production function, for example.

[33]We obtain sectoral output per worker data for the years 1950, 1960, 1970, 1975, 1980, 1985, 1996 and 2000. Since GDP data is available for 1949 and 1959 but employment data for 1950 and 1960, we use the 1949 and 1959 GDP data to get estimates of the 1950 and 1960 output per worker.

for by increased productivity, the manufacturing sector is also experiencing an increase in employment. These results are consistent with the anecdotal evidence we discussed in Section 2.2. Oil discovering municipalities become local services and commerce hubs for the surrounding area, with these large outfits presenting a significantly higher output per worker than the traditional small scale service providers.[34]

Summary of Baseline Results. Taken together, our results suggest that local GDP *per capita* and urbanization increase significantly as a result of oil discoveries. While the increase in GDP *per capita* we document is large, the ITT estimates lie within the range estimated for the United States in the literature. Michaels (2011) finds that income is 05-28 log points higher in oil abundant counties than non-oil counties in the US south. He also shows that population density is 30-100 log points higher in oil abundant counties. Allcott and Keniston (2014) look at the impact of resource booms in the US and also find strong results: resource booms increase both labor income (by about 0.3-0.5 percent points per year during a boom) and employment density (by 60-80 percent) in treated counties. As far as we are aware there are no previous reliable estimates for the impact of oil discoveries on local economic variables for developing countries. We find that the increase is services GDP is driven by increased productivity but the increase in manufacturing GDP must also be driven by an increase in employment.

We do not find a statistically significant increase in population density but we do document an increase in urbanization.[35] Our sectoral GDP results indicate that oil municipalities might be experiencing a move from rural agricultural activities to service provision in the city. In Appendix C we investigate the underlying mechanism in detail, by exploiting microdata from the Brazilian employment and population censuses for the year 2000. We show that oil discoveries lead workers to move from subsistence agriculture to service provision in the local urban center. Service firms grow and there is some upward adjustment of wages in the services sector. [36]

[34]The results for sectoral GDP and output per worker are robust to all of the above robustness exercises but we do not report those tables in the interest of space. Tables are available from the authors upon request.

[35]The result on population density is confirmed when instead we use overall employment density.

[36]Migration as a consequence of oil production in Brazil seems to have been from the countryside to the city within the same MCA rather than from non-oil MCAs to oil MCAs. Inter-municipal migration

In the remainder of this section, we proceed as follows. We first split discoveries into onshore and offshore and show that only onshore discoveries seem to have significant positive spillovers on average. We then use an alternative empirical strategy and estimate a regression which allows us to retrieve the Local Average Treatment Effect of oil production. Additionally, we investigate treatment intensity. Lastly, we explore the connection between downstream and upstream oil production and show that our results are robust to excluding municipalities with large processing production facilities such as refineries and main storage and transportation hubs.[37]

5.2 Onshore versus Offshore Discoveries

We distinguish between onshore and offshore discoveries since some of the channels which we believe can lead to spillovers (such as the physical presence of well paid oil workers) might be more obviously present for onshore than for offshore locations. In fact, the offshore production is very concentrated of the coast of Rio de Janeiro, and most personnel is stationed in the municipality of Macaé.

Table 14: Onshore versus Offshore Discoveries 1

	Matched Dry Drilling			
	(1)	(2)	(3)	(4)
VARIABLES	GDP *per cap*	Manufacturing GDP *per cap*	GDP *per cap*	Manufacturing GDP *per cap*
Onshore Discovery Dummy	0.3429***	0.5270**		
	(0.1067)	(0.2157)		
Offshore Discovery Dummy			0.2081	0.4537*
			(0.1315)	(0.2303)
MCA FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	768	891	768	891
Number of MCAs	128	128	128	128
Geography Controls	Yes	Yes	Yes	Yes
Initial Conditions	Yes	Yes	Yes	Yes
Estimation	FE	FE	FE	FE

Notes. Standard errors clustered at the MCA level. The main explanatory variable is the number of injection wells. The number of injection and production wells is instrumented with the number of discovery wells. Geographic controls and initial conditions have time-varying coefficients. The control group is the matched dry drilling sample.
*** p<0.01, ** p<0.05, * p<0.1

GDP *per capita* in the manufacturing sector increases significantly in both onshore and

flows in Brazil tended to be mainly from the northeast of the country to the big urban centers in the southeast (Sao Paulo and Rio de Janeiro), and not within regions (de Lima Amaral (2013)).

[37] In the interest of space, we only report tables for our preferred control group (matched dry drilling) from now on, but as before all results are very stable across different control groups and all results are available upon request.

offshore municipalities. However, when we focus on our measures of spillovers, namely productivity in the services sector and the urbanization rate, we see that neither of those is affected by offshore discoveries, but there is a large positive impact of onshore discoveries. Labor productivity in the services sector increases by 28% while the urbanization rate increases by over 5% points (see Tables 14 and 15). The increase in manufacturing GDP shows that offshore discoveries do increase GDP in a mechanical sense. However, we do not find any impact on the local economy. It is also worth pointing out, however, that the estimated increase in manufacturing GDP is very similar for onshore and offshore discoveries, perhaps indicating that the impact of oil discoveries on non-oil manufacturing is rather limited also for onshore discoveries.[38]

Table 15: Onshore versus Offshore Discoveries 2

	Matched Dry Drilling			
	(1)	(2)	(3)	(4)
VARIABLES	Service Y/L	Urbanization Rate	Service Y/L	Urbanization Rate
Onshore Discovery Dummy	0.280**	0.0542**		
	(0.135)	(0.0237)		
Offshore Discovery Dummy			0.0187	0.0135
			(0.126)	(0.0313)
MCA FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	891	1,024	891	1,024
Number of MCAs	128	128	128	128
Geography Controls	Yes	Yes	Yes	Yes
Initial Conditions	Yes	Yes	Yes	Yes
Estimation	FE	FE	FE	FE

Notes. Standard errors clustered at the MCA level. The main explanatory variable is the number of injection wells. The number of injection and production wells is instrumented with the number of discovery wells. Geographic controls and initial conditions have time-varying coefficients. The control group is the matched dry drilling sample.
*** p<0.01, ** p<0.05, * p<0.1

5.3 Oil Production and Treatment Intensity

We now turn to estimating the impact of oil production rather than oil discoveries on economic outcomes. There are 46 municipalities which have at least one oil production well.

[38] While assigning onshore discoveries to municipalities is straightforward, the mapping is not as clear for offshore discoveries (see Section 3.1). To verify whether the offshore result is driven by our measure of offshore discoveries we used an alternative one: facing areas, used by the Brazilian Oil and Gas regulator (ANP) to distribute royalties. It is a complex measure, but essentially captures whether a municipality's maritime borders face an oil field (see Monteiro and Ferraz (2012) for a detailed discussion). The resulting measure is substantially broader than ours, since only one MCA can be the closest to a well, but many MCAs can potentially face it. It thus is ex-ante less likely to pick up spillovers from production. The correlation between the two measures of offshore discoveries is 0.53. We re-ran the regressions using the alternative measure of offshore discoveries but the results are unchanged.

As noted above production might be endogenous. We estimate the following equation:

$$Y_{it} = \alpha + \tau_{AT} D_{it} + \beta_t' X_i + \gamma_i + \rho_t + \epsilon_{it}, \tag{2}$$

where we instrument for the production indicator (D_{it}) using our discoveries indicator (Z_{it}) to recover a Local Average Treatment Effect. Table 16 qualitatively confirms our earlier ITT results. The estimated coefficients are, as expected, larger. GDP *per capita* increases by over 40% and urbanization by over 6% points as a consequence of oil production. Similarly, the impact on sectoral GDP is larger.[39] It is intuitive that the ITT results are scaled up by the proportion of compliers. Since the producing municipalities are not a perfect subset of the true discovery municipalities the instrumental variables specification is not our favourite one and we prefer to report the ITT results as a safe lower bound on the treatment effect.

Table 16: Local Average Treatment Effect of Oil Production

	Matched Dry Drilling					
	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	ln Population Density	ln GDP *per capita*	Urbanization Rate	Manufacturing GDP *per cap*	Service GDP *per cap*	Agriculture GDP *per cap*
Production Dummy	-0.0190	0.411***	0.0644**	0.725**	0.343**	0.105
	(0.106)	(0.143)	(0.0314)	(0.295)	(0.166)	(0.166)
First Stage F-Stat.	27.38	13.74	27.38	13.33	14.48	13.89
MCA FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,024	768	1,024	765	764	765
Number of MCAs	128	128	128	128	128	128
Geography Controls	Yes	Yes	Yes	Yes	Yes	Yes
Initial Conditions	Yes	Yes	Yes	Yes	Yes	Yes
Estimation	FE	FE	FE	FE	FE	FE

Notes. Standard errors clustered at the MCA level. Geographic controls and initial conditions have time-varying coefficients. Discovery is defined as 'True Discovery'.
*** p<0.01, ** p<0.05, * p<0.1

In a second step we try to measure the effect of treatment intensity. We ask how the outcome is related to the "dose" of the treatment. The literature on treatment intensity emphasizes the estimation of a weighting function to capture which group or observation is contributing the most to the results (e.g., Angrist and Imbens (1995), Frölich and Lechner (2010)). In the spirit of Angrist and Imbens (1995), our goal is to estimate a coefficient that can be interpreted as a weighted-average of per-unit treatment

[39] Same for sectoral output per worker (not reported).

effect. We thus estimate the following equation:

$$Y_{it} = \alpha + \tau prod_{it} + \beta_t' X_i + \gamma_i + \rho_t + \epsilon_{it}. \tag{3}$$

where we instrument the number of production wells ($prod_{it}$) with the number of discovery wells (field, subfield and field extension wells) (($disc_{it}$)).[40] As an alternative measure of treatment intensity, we use the number of injection wells. Reservoir's pressure is a key element in oil production because it drives oil and gas out of the reservoir. Normally, after some time, pressure decreases and the oil company needs to (artificially) add pressure to the well. The oil company then starts to drill "injection wells" to inject water, gas, chemicals or steam to supplement falling pressure. Injection wells give us indirect information on the producing life of the oil field because injection wells are used only to enhance production. Efforts to enhance production are costly and are dependent upon the potential oil recovery volume. In other words, it is only viable to design injection wells to enhance production above a certain level. Therefore, we use injection wells as a measure of treatment intensity.[41] Note that while the t-statistic on the number of discovery wells in the first stage is always very high, the F-Statistic for the GDP regressions are not particularly strong, indicating a potential weak instrument problem.

The sign in the various regressions is as before and so we focus on quantifying the average per unit effect on GDP *per capita* and urbanization. The results are reported in Table 17. GDP *per capita* increases by 0.066% per production well and by roughly 1% per injection well. The urbanization rate increases by 0.007% per production well and by 0.15% per injection well. The coefficients on production wells are quite small. With the average producer MCA having 160 production wells this gives an average impact of oil production of 160*0.0007=11.2%<20%. On the other hand, the coefficients for injection wells seem very large. This is a consequence of their ability to isolate the large production

[40] We obtained production data by field from ANP for the year 2000 to construct production volume by MCA and compare it to the number of production wells. While the correlation between the two is high, it is higher for onshore than offshore production.

[41] Tabulations from Brazil support this fact. For the year 2000, for onshore fields, those MCAs with discovery wells and injection wells have much higher production volume of both oil and gas than those with discovery wells but without injection wells. In other words, in the data those MCAs with injection wells are the ones with a lot of production.

Table 17: Treatment Intensity

	Matched Dry Drilling			
	(1)	(2)	(3)	(4)
VARIABLES	ln GDP *per capita*	Urbanization Rate	ln GDP *per capita*	Urbanization Rate
Number of Production Wells	0.000664**	7.55e-05**		
	(0.000317)	(3.70e-05)		
Number of Injection Wells			0.0123**	0.00146*
			(0.00573)	(0.000871)
First Stage F-Stat.	6.98	15.92	6.29	31.21
MCA FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	768	1,024	768	1,024
Number of MCAs	128	128	128	128
Geography Controls	Yes	Yes	Yes	Yes
Initial Conditions	Yes	Yes	Yes	Yes
Estimation	FE	FE	FE	FE

Notes. Standard errors clustered at the MCA level. The main explanatory variable is the number of injection wells. The number of injection and production wells is instrumented with the number of discovery wells. Geographic controls and initial conditions have time-varying coefficients. The number of discovery wells is used an as instrument.
*** p<0.01, ** p<0.05, * p<0.1

fields very well. In fact, only a handful of large fields onshore in the northeast and of the coast of Rio de Janeiro have any significant number of them. Our interpretation of these results is that large discoveries have a disproportionately large impact.

5.4 Oil and Gas Processing Production Facilities

For a sample of U.S. counties Greenstone, Hornbeck, and Moretti (2010) show that there are important local spillovers from the opening of large manufacturing plants. This might also hold true for large downstream oil production facilities such as refineries. Clearly, the decision of where to locate such facilities is likely to be correlated with many unobservables. We therefore do not aim to formally evaluate the impact of downstream production on local economic development, but we want to test whether downstream production facilities are driving most of our observed results (as some places with upstream production have also downstream facilities).

To investigate this hypothesis we collected data on the location and date of construction of all refineries, directly oil related factories (such as petrochemicals plants) and oil terminals. We also collected data on thermoelectric power plants, which are associated with the oil and gas industry.[42] We observe that discoveries increase the probability of hosting a downstream facility by roughly 10% which is not negligible but not overwhelm-

[42] See Appendix A for details on data construction.

Table 18: Excluding Locations with Downstream Production

	Matched Dry Drilling					
	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	ln Population Density	ln GDP *per capita*	Urbanization Rate	Manufacturing GDP *per cap*	Service GDP *per cap*	Agriculture GDP *per cap*
Discovery Dummy	-0.00430	0.211***	0.0424*	0.455**	0.255**	0.0789
	(0.0730)	(0.0738)	(0.0238)	(0.194)	(0.107)	(0.117)
MCA FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	904	678	904	676	675	674
Number of MCAs	113	113	113	113	113	113
Geography Controls	Yes	Yes	Yes	Yes	Yes	Yes
Initial Conditions	Yes	Yes	Yes	Yes	Yes	Yes
Estimation	FE	FE	FE	FE	FE	FE

Notes. Standard errors clustered at the MCA level. Geographic controls and initial conditions have time-varying coefficients. Discovery is defined as 'True Discovery'.
*** p<0.01, ** p<0.05, * p<0.1

ing either. This rises to 15% when we use an ad-hoc measure for large discoveries (top 20 in the year 2000 in terms of number of discovery wells).

There is thus some support for the hypothesis that discoveries tend to lead to the establishment of downstream production facilities in an MCA. To evaluate the pure impact of the upstream sector we thus exclude those municipalities which host a downstream production facility from both the treatment and the control group and re-estimate our baseline specification. As can be seen by comparing Table 18 with Tables 8 and 12 the results do not seem to be driven by downstream production facilities only. Upstream oil production thus directly impacts the local economy, even when it generates no significant royalties and does not lead to the establishment of downstream production facilities.

6 Conclusion

We investigated the effects of natural resource extraction on local economic development and documented a positive growth effect of oil discoveries. We find a positive impact of oil discoveries on urbanization as well as an increase in services GDP, services output per worker and the size of services firms. We do not find evidence of de-industrialization in oil municipalities. By comparing municipalities where drilling turned up dry wells to those where oil was discovered, we constructed an unique control group based on random assignment. Since we examine the entire track of oil discoveries in Brazil we are able to provide evidence that there are no pre-treatment differences between our treatment and control groups.

It is important to highlight that our results apply to a specific institutional framework, given that we are studying the effects of oil discoveries on the local development of only one country. For instance, the U.S. has a more widespread ownership of resources than Brazil. There are thousands of oil companies in the U.S. in contrast to the historical monopoly of Petrobras in Brazil. Due to this market structure, oil services are more likely to be concentrated in just a few places in Brazil. By contrast, in the U.S. an entire chain of small oil services can be located close to the more widespread oil firms. Finally, we cannot rule out the hypothesis that oil discoveries affect local development of oil municipalities positively but have adverse effects at the national level, through, for example, a nominal appreciation. We show that at the local level, oil discoveries are not a curse per se, and the pure market effect without any fiscal windfalls benefits development. In light of the results on fiscal windfalls in the literature, it seems that the impact of the windfall effect of resource wealth on the local economy might be much less beneficial on average. While natural resource extraction can foster local growth, defining good policies and institutions of how to use the associated fiscal windfalls thus remains a key policy challenge.

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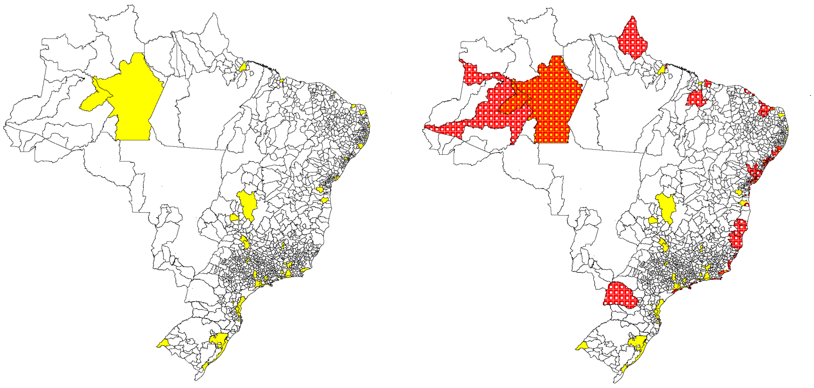
A Appendix

A.1 Downstream Production Data

Fig. A.1: Processing Production Facilities



(a) Processing Facilities (Yellow) (b) Discovery (Red), Facilities (Yellow)

Notes. Figures show 1,275 Minimum Comparable Areas (MCAs) in 1940. The discovery dummy is the "All Discoveries" dummy (which equals one when at least one field, subfield or field extension discovery was made in the municipality).

Here we discuss the role of the downstream industry in Brazil (processing and transportation facilities). Information on the construction date of each refinery, each onshore and offshore terminal is from Petrobras and Transpetro. Information on the construction date of petrochemical plants and thermoelectric power plants is from Petrobras and various online sources. By the year 2000 there were 15 refineries or directly oil related factories, 18 onshore oil terminals, 22 offshore terminals and 2 thermoelectric power plants in Brazil. Using this data we constructed an indicator which equals 1 if an MCA has at least one of those oil related production facilities. To evaluate the link between the upstream and downstream oil sector we regress the production facilities dummy on the indicator for "True Discoveries". As before a full set of controls is included. Additionally, we again include MCA and year fixed effect and cluster standard errors at the MCA level. Regardless of the control group, the coefficient on the discovery dummies is positive and significant.

We also collected data provided by ANP (2001) detailing which municipalities they classify as the main production and main production support sites, respectively. The idea is to perform an additional test of the hypothesis that production facilities are more likely to be located in MCAs which discovered large reserves of oil. Main production sites are defined as locations with facilities for processing, treating, storing and transporting oil. Support sites are those with ports, airports, heliports, offices or similar facilities used to support the extraction, production and processing of oil. We match this municipal data to the relevant MCAs and then construct a new indicator at the MCA level. Unfortunately, this data is only available for the year 2000 and we do not know the first year in which

Table A.1: Discoveries and Processing Production Facilities

	Matched Dry Drilling	
	(1)	(2)
VARIABLES	Production Facilities Dummy	Production Facilities Dummy
Discovery Dummy	0.102**	
	(0.0486)	
Large Discovery Dummy		0.147**
		(0.0709)
MCA FE	Yes	Yes
Year FE	Yes	Yes
Observations	896	896
Number of MCAs	128	128
Geography Controls	Yes	Yes
Initial Conditions	Yes	Yes
Estimation	FE	FE

Notes. Standard errors clustered at the MCA level. Geographic controls and initial conditions have time-varying coefficients. The initial conditions with time-varying coefficients are: GDP/capita in 1949, Urbanization rate in 1940, and Population Density in 1940. The geographic controls with time-varying coefficients are: Latitude and Longitude coordinates, Dummy for Amazon, Dummy for Coastal. Discovery is defined as 'True Discovery'. 'Large Discovery' is a discovery which makes the hosting municipality one of the top 20 in terms of wells.
*** p<0.01, ** p<0.05, * p<0.1

municipalities became main production or support sites. We, therefore, cannot use these variables in a panel regression. Nevertheless it is worth pointing out that the correlations between having had a discovery and being a main production or main production support site are 0.2466 and 0.2747, respectively.

A.2 Comparison of Treatment and Control Groups

The normalized difference (ND) for continuous variables is given by

$$ND = \frac{\mu_t - \mu_c}{\sqrt{\sigma_t^2 + \sigma_c^2}},$$

where μ_t and σ_t^2 is the mean and variance of the treated group, and μ_c and σ_c^2 are the corresponding values for the control group.

The ND for dichotomous variables is defined as

$$ND = \frac{p_t - p_c}{\sqrt{p_t(1-p_t) + p_c(1-p_c)}},$$

where p_t and p_c are the proportions (prevalence) for the treated and control group respectively.

Imbens and Wooldridge (2009) suggest that for a standardized difference of more than 0.25 "linear regression methods tend to be sensitive to the specification" (p.24). Table A.2 systematically investigates the differences between the assigned to treatment and control groups using standardized differences. As can be seen the matched dry drilling MCAs constitute a good control group in terms of observables.

Table A.2: Overlap of Treated and various Control Groups

Variable		(I) Oil Discovery	(II) Dry Drilling	(III) Matched Dry Drilling	(IV) No Discovery in Oil States	(V) Neighbors	(VI) Matched Neighbors	(VII) Dry No Neighbor
Pop Density 1940	Mean	32.89	30.33	35.09	30.15	24.54	31.74	35.2
	S.D.	51.35	132.29	104.47	78.22	50.13	72	153.1
	Standardized Difference	-	0.018	-0.019	0.029	0.116	0.013	-0.014
Urbanization 1940	Mean	0.27	0.22	0.24	0.21	0.18	0.21	0.23
	S.D.	0.18	0.18	0.2	0.15	0.14	0.16	0.19
	Standardized Difference	-	0.196	0.111	0.256	0.395	0.249	0.153
GDP per capita 1949	Mean	0.67	0.88	0.69	1.13	0.61	0.57	1.06
	S.D.	0.42	0.89	0.75	0.98	0.5	0.5	1
	Standardized Difference	-	-0.213	-0.023	-0.431	0.092	0.153	-0.360
Manufacturing/GDP 1949	Mean	0.19	0.13	0.13	0.13	0.13	0.13	0.11
	S.D. 0.15	0.16	0.17	0.14	0.15	0.15	0.12	
	Standardized Difference	-	0.274	0.292	0.292	0.283	0.283	0.416
Services/GDP 1949	Mean	0.38	0.37	0.4	0.36	0.34	0.36	0.37
	S.D.	0.2	0.21	0.23	0.18	0.2	0.22	0.2
	Standardized Difference	-	0.034	-0.066	0.074	0.141	0.067	0.035
Agriculture/GDP 1949	Mean	0.43	0.51	0.48	0.52	0.55	0.53	0.52
	S.D.	0.24	0.24	0.26	0.23	0.25	0.27	0.23
	Standardized Difference	-	-0.236	-0.141	-0.271	-0.346	-0.277	-0.271
Altitude	Mean	78.81	229.15	143.38	384.27	179.48	109.39	276.4
	S.D.	97.96	247.65	212.68	273.19	206	104.12	259.1
	Standardized Difference	-	-0.565	-0.276	-1.053	-0.441	-0.214	-0.713
Avg Rainfall	Mean	118.46	127	122.23	108.34	121.78	118.78	120.9
	S.D.	38.79	43.65	51.44	36.96	49.24	47.1	37.63
	Standardized Difference	-	-0.146	-0.059	0.189	-0.053	-0.005	-0.045
Avg Temperature	Mean	24.95	23.96	24.35	22.9	24.28	24.8	23.42
	S.D.	1.9	2.97	2.7	2.91	2.72	2.16	3.06
	Standardized Difference	-	0.281	0.182	0.590	0.202	0.052	0.425
Latitude	Mean	-11.88	-13.72	-12.62	-15.85	-12.03	-11.49	-15.8
	S.D.	6.44	9.67	8.6	8.05	8.27	7.47	9.72
	Standardized Difference	-	0.158	0.069	0.385	0.014	-0.040	0.336

Continued on next page

Table A.2 – *Continued from previous page*

Variable		Oil Discovery	Dry Drilling	Matched Dry Drilling	No Discovery in Oil States	Neighbors	Matched Neighbors	Dry No Neighbor
Longitude	Mean	-40.65	-46.94	-43.5	-44.53	-44.32	-42.65	-46.83
	S.D.	6.46	7.31	7.6	5.18	8.46	8.33	5.42
	Standardized Difference	-	0.645	0.286	0.469	0.345	0.190	0.733
Coastal Indicator	Prop.	0.59	0.3	0.53	0.11	0.19	0.42	0.29
	Standardized Difference	-	0.431	0.086	0.823	0.636	0.244	0.448
Semiarid Indicator	Prop.	0.19	0.15	0.23	0.25	0.25	0.28	0.13
	Standardized Difference	-	0.075	-0.070	-0.103	-0.103	-0.151	0.116
Amazon Indicator	Prop.	0.08	0.3	0.17	0.1	0.23	0.15	0.25
	Standardized Difference	-	-0.413	-0.194	-0.049	-0.300	-0.156	-0.333
	Number of MCAs	64	158	64	711	156	64	104

Note: Oil Discovery is the treated group of 64 MCAs. Six control groups are shown: (i) MCAs where drilling took place but nothing was found (column II: "Dry Drilling"), Propensity Score Matched Sample of MCAs where drilling took place but nothing was found (column III: "Matched Dry Drilling"), (iii) MCAs with no oil discovery but in states where other MCAs have discovered oil (column III: "No Discovery in Oil States", (iv) MCAs that are adjacent to the treated MCAs (column IV: "Neighbors"), (v) Propensity Score Matched Sample of MCAs that are adjacent to the treated MCAs (column VI: "Matched Neighbors"), and (vi) MCAs where drilling took place but nothing was found which are not adjacent to treated MCAs (column VII: "Dry, No Neighbour"). (i) and (ii) are our baseline control groups. We use the other four in a robustness exercise. The last row corresponds to the total number of MCAs in each control group.

A.3 Summary Statistics

Table A.3: Summary statistics: Minimum Comparable Areas

Category	Variable	Mean	Std. Dev.	Min.	Max.	N
Outcome Variables	Urban Population/Total Population	0.458	0.253	0.015	1	10,197
	Log of Population Density	3.199	1.316	-3.222	9.186	10,198
	Log of GDP per capita	0.501	0.985	-4.602	6.38	7,645
	Share of GDP: Manufacturing	0.195	0.169	0	0.971	11,436
	Share of GDP: Services	0.431	0.171	0.001	0.975	11,443
	Share of GDP: Agriculture	0.362	0.232	0	1	11437
Oil Variables	All Discovery dummy	0.024	0.151	0	1	77,775
	Oil production dummy	0.017	0.131	0	1	77,775
	True Discovery dummy	0.016	0.125	0	1	77,775
	Stock of producer wells	2.47	35.322	0	1814	77,775
	Stock of discovery wells	0.371	4.761	0	218	77,775
	Stock of injection wells	0.252	4.078	0	131	77775
Geography	Average altitude	439.119	303.067	0	1278	77,775
	Average temperature	22.669	2.841	14.965	27.88	77,775
	Average rainfall	109.93	34.287	34.63	258.358	77,775
	Indicator: Amazon region	0.073	0.26	0	1	77,775
	Indicator: Semiarid region	0.231	0.422	0	1	77,775
	Indicator: Coastal MCA	0.107	0.309	0	1	77,775
Pre-Treatment Variables	Log of Population density in 1940	2.701	1.305	-3.228	7.562	77,714
	Urbanization ratio in 1940	0.219	0.154	0	1	77,775
	Log of GDP per capita in 1949	-0.326	0.854	-4.602	1.828	77,653

Notes. Data from ANP (Brazilian oil and gas industry regulator) and Ipeadata. Data aggregated and treated for 1,275 Minimum Comparable Areas (MCAs). The total number of observations corresponds to the number of MCAs times the number of years in our sample (from 1940 to 2000). Temperature is measured in degrees Celsius, precipitation in millimeters per month, and altitude in meters.

B Appendix: More Details on Oil Extraction and the Institutional Background

B.1 On Oil Drilling and Production

There is an extensive literature on the principles and practises of oil drilling and production (e.g., from petroleum geology and petroleum engineering). In this appendix, we aim to clarify selected aspects of drilling and production that are relevant to our research design, without detailing every single aspect of oil (and gas) exploration and production.

Oil exploration and production are associated with risk. Although there are several technical methods for appraising hydrocarbon resources, the industry always works with limited information on the existence of hydrocarbon deposits. The uncertainty is related to the location, volume, and quality of hydrocarbon deposits. Even with enough geological information, there is always the risk of drilling a dry exploratory hole or not discovering commercial quantities of oil. There are also risks during the production phase such as the price of oil, costs and taxes, institutional uncertainty, regulation, natural disasters, and accidents. Offshore drilling in deep water presents even greater challenges. According to Harbaugh, Davis, and Wendebourg (1995), luck is a major factor in oil exploration. The name for an exploratory well (called a "wildcat") talks by itself regarding the inherent risk of oil business.

The petroleum industry is loosely divided into two segments: upstream and downstream. Upstream industry comprises exploration and production activities. By production activities, the process of recovering petroleum from the subsurface is meant. Upstream activities occur both onshore and offshore. In turn, downstream industry entails processing, retailing and transporting petroleum.

Oil exploration involves several steps using a compilation of knowledge from geology, geophysics, and geochemistry. The oil company aims to find an oil field - a contiguous geographic area with oil. First, petroleum professionals collect useful geological information on a "prospect" (a delimited area that possesses certain geological features that may induce drilling). By "useful information", they mean a source rock, a reservoir, and a trap[43]. A *source rock* is a rock within which oil or gas is generated from organic material (Petroleum Extension Service (2005)). A source rock is usually a shale rock. Nevertheless, not every shale has enough biogenic material to be classified as a source rock. The *reservoir* accumulates hydrocarbons and is made from porous rocks. Rocks must have porosity to accumulate hydrocarbons and basically only sedimentary rocks are porous enough. Typical sedimentary rocks forming a reservoir include sandstone and limestone. The "quality" of the oil inside the reservoir can vary depending on its properties and impurities (e.g., the presence of sulfur and metals). The company also looks for areas with specific geological features called *traps*. The hydrocarbon trap is composed of two elements: a structure (subsurface contortion) and a seal. Hydrocarbon molecules are

[43] There are three type of rocks according to how they are formed: ignite (from magma), sedimentary (from erosion) and metamorphic (a heated sedimentary or a heated ignite rock). Sedimentary rocks are more interesting because petroleum accumulation chiefly occur in them. An example of a sedimentary rock is the shale rock, originated by clay compacted by subsurface pressure and weight. Other examples of sedimentary rocks include sandstone (from sand) and limestone (from shells).

lighter than water, and there are subsurface contortions that induce the hydrocarbons moving upward towards the surface (e.g., anticlines and faults). Therefore, there is a need of a "seal" to prevent the hydrocarbons from spilling out on the surface. A seal is another rock with low permeability (as porosity to accumulate hydrocarbons in the reservoir is important, the degree of connections between pore spaces of the rock formation is relevant to have a seal rock). Shale rock is typically a good seal to avoid the spilling because it has low permeability. Shale rock has porosity too, but it has very low permeability (thus it is a good seal).

In sum, the area should contain selected characteristics, such as abundant sandstone reservoir rocks, shale for hydrocarbon source rock and numerous geological structures for potential trapping of hydrocarbons. Each oil field has a "fingerprint" and its unique characteristics lead to a case-by-case analysis of drilling attempts. Wells are very expensive to drill, so previous studies must be as accurate and precise as possible.

After inferring the subsurface and if there are strong indications of potentially oil-bearing formations, the oil company may drill an exploratory well. Even with all positive indications of oil presence, only by *making a hole* can the company be sure of the presence (or absence) of oil. During the drilling process, data acquisition is key. There are several logging (recording information) procedures during the drilling phase so as to, for example, differentiate permeable and impermeable rock formations (called "'logging-while-drilling").[44] Depending on the outcome of the exploratory drilling, the company evaluates the well's hydrocarbon potential. Not even an evidence of hydrocarbon deposit as told by logs is a guarantee that producing oil is really possible. One can assign *a priori* probabilities before drilling, and revise the probability of success given the proven result of the drilling attempt. Updated probabilities can be used as a source of experience to be transferred to future drilling attempts. Depending on the preliminary information received during drilling, the well can be abandoned or not. In the end, using all information available the company decides whether the drilling had generated a discovery or a *dry hole*.

After a discovery, the appraisal continues: additional drilling is required to delineate the size and extension of the oil field[45]. "Step-out" wells (delineation or appraising wells) are the wells used to evaluate the extent of the field. The more is known about the oil field, the easier and less expensive to drill additional wells. Generally, the number of step-out wells is positively correlated with the magnitude of the field that was discovered. Once the oil company has delineated the oil field and is secure on the viability of production, it starts to (i) *complete* the existing wells and (ii) to drill additional production wells (producer wells). To complete a well means to perform the necessary operations to bring fluids to the surface (Petroleum Extension Service (1997)). After completion and the drilling of producer wells, oil and gas production cycle begins. Production cycle occurs after exploration has proven successful. An economic assessment of the production cycle should entail reserve and risk calculations (Hyne (2001)).

The production cycle involves a natural phase and enhanced phase. Initially, natural pressure from the reservoir brings oil from the reservoir to the surface. As production proceeds, the reservoir pressure goes down. However, pressure is important because it drives oil and gas out of the reservoir. Normally, after some time producing from an oil well, pressure decreases and the oil company needs to (artificially) add pressure to the well. The addition of artificial pressure to optimize production is broadly called "enhanced oil

[44]One example is the logging from the drilling fluid.

[45]"Play" is the name used to describe the extent of a hydrocarbon-bearing formation.

recovery" and is divided into primary, secondary, and tertiary recovery. *Primary recovery* (or primary production) means to use an artificial method of lifting. The most common artificial lift system is a *beam pump* to pump up the oil. During primary recovery, only a small percentage of the hydrocarbon deposits are produced. *Secondary recovery* aims at restoring the reservoir pressure by injecting water (waterflooding) or gas. Secondary recovery is costly because it deals with huge amounts of water and gas. To supplement falling pressure due to production, new wells are drilled (injection wells) to inject water and gas usually at the edges of the oil field. This injection aims to either slow production decline or to increase production. Finally, *tertiary recovery* happens when there is injection of steam or special chemicals (chemical flooding) into the reservoir. In practise, all three recovery phases can occur concomitantly[46].

Enhanced recovery is so important in the petroleum industry that the location of the producer well is chosen with the secondary well (injection well) in mind. As mentioned before, efforts to enhance recovery are costly and are dependent upon the state of the economy and potential oil recovery volume. Consequently, repeated monitoring of a reservoir is essential to locate injection wells. The idea is to design an optimal distribution of injection wells to optimize long-term production.

There are several types of wells: wildcat well, rank wildcat well, step-out well, producer well, injection well, etc. Since there are different steps to obtain oil, wells are classified broadly as exploratory wells and development wells. Examples of *exploratory wells* are wildcat wells (drilled a mile or more from an area of existing oil production) and rank wildcat wells (drilled in an area where there is no existing production). If the exploratory drilling is proven successful, the company starts to drill step-out wells (also included in the exploratory well category). After the oil field has been delineated, the company starts to drill production wells in the known extent of the field. Every well drilled inside the known extent of the field is called *development wells* (Hyne (2001)). The development well category includes producer wells and injection wells (recall that injection wells are to enhance oil recovery). Different categories of wells have different probabilities of finding oil. A rank wildcat exploratory well have on average lower success ratio than a step-out well. An oil company can rank wells in terms of probability even working under uncertainty. The American Petroleum Institute reported that in 2000 the success rate for wildcat well was 39% (Hyne (2001)). Note that an unsuccessful drilling is classified as a dry hole in both exploratory and development well categories.

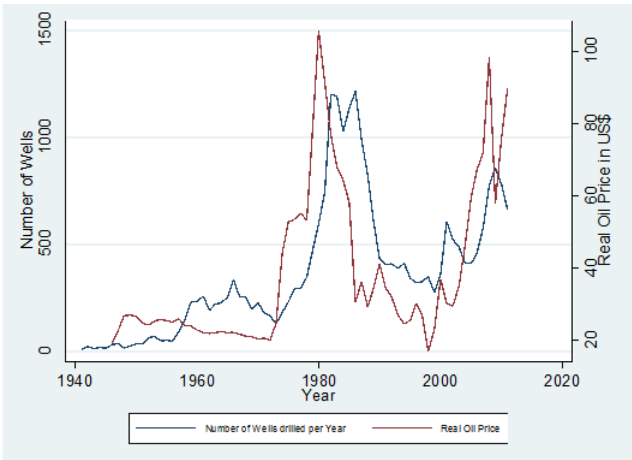
The evolution of knowledge to identify potentially oil-bearing formations also helps to understand the oil industry. This evolution comprises both advances of the theory on petroleum-bearing formations and ever-improving technology. In the very beginning of oil exploration, conspicuous targets were searched in order to extract oil without any geology theory (e.g., surface pools in the form of natural oil seeps) or using geology knowledge (e.g., anticlines and salt domes). Surface investigation (topography) of the region could point out conspicuous areas of oil-bering formations. In 1920's and 1930's, aerial photographic expanded the possibilities for mapping areas suitable for drilling. In the mid 1900's, seismic technology improved subsurface mapping to locate potential petroleum-bearing formations. By and large, seismic activities produce sound waves that aim at interpreting subsurface formations, i.e., sound waves are generated and recorded by receivers to infer rock formations. The idea is to map the subsurface rock layers by using sound waves as different rock layers have different acoustical properties. The recorded sounds are processed and assembled to be interpreted. Existing seismic and

[46] There are other forms of well stimulation such as hydraulic fracturing.

well information highlights the potential for exploration of large hydrocarbon resources. Computerization of seismic data provided a leap to the extraction industry: high amount of data could be processed at high speed and precision. Another big revolution was the $3D$ visualization that made possible a more reliable selection of the best targets to the drilled. Moreover, $4D$ visualization (repeated $3D$ through time) helped the planning of well life-time operation. More recently, in the last decade the discussion on automated drilling (the evolution of automation in drilling) is an ongoing topic. Modern technology helps the decisions regarding the best drill sites. Computers and satellite images improved the assessment of deposits. Nevertheless, ultimately it is only by drilling that a company can be certain that hydrocarbon deposits really exist. In other words, even investing substantially in using modern technology, it is only by drilling that the existence of oil can be confirmed.

One important information for the identification strategy of the paper is the relationship between drilling effort and international oil prices. Figure B.1 shows a striking correlation between wells drilled and international oil prices, in accordance with the literature of the role of oil prices (e.g. Mohn and Osmundsen (2008)).

Fig. B.1: Drilling in Brazil and International Oil Prices

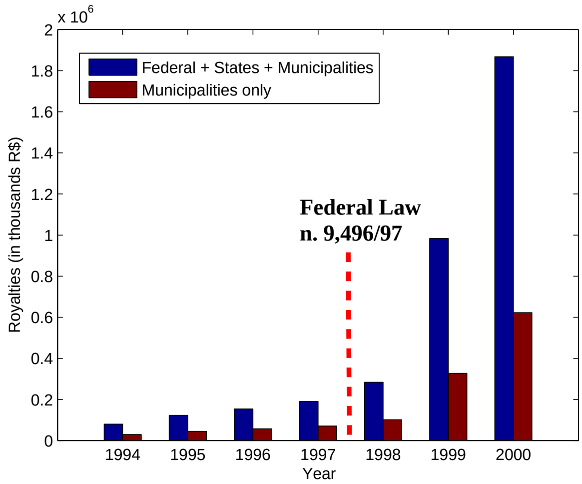


Notes. The figure shows the evolution of approximately 28,000 wells drilled (the universe of wells drilled in Brazil during the period from 1938 to 2013). The figure also shows the evolution of international price of crude oil during the period (in red). We use monthly WTI (West Texas Intermediate) oil price in real US Dollar per barrel.

Up to this point, we described some general aspects of the upstream industry. Downstream industry includes the refining industry, petrochemicals plant, and distribution facilities (e.g., ports and terminals). Crude oil and natural gas are of little use in their raw state (Petroleum Extension Service (1997)). Refining and processing to select groups of components (called "fractions") is what creates value. Refining means applying chemical processes to convert fractions into commercial products. Oil and gas vary in their hydrocarbon compounds and impurities (such as sulfur and metals). For instance, there are light crude oils as well as heavy and thick crude oils. The complexity of the composition of petroleum fractions leads to more than 2,000 individual refinery products (Fahim, Al-Sahhaf, and Elkilani (2009)). Examples of refining products include gasoline, jet fuel, kerosene, diesel fuel, and feedstocks for the petrochemical industry.

B.2 Royalties and Oil in Brazil

Fig. B.2: Distribution of Royalties: 1994-2000



Notes. In 1997, Federal Law n. 9,496/97 changed the rules for distributing royalties.

The distribution of Royalties started in 1953. Federal Law n. 2,004/53 stipulated that 5% of the revenue from onshore oil production should be distributed to states (80%) and municipalities (20%) in the form of Royalties. Offshore oil royalties paid to states and municipalities were introduced by 1986. In 1997, Federal Law n. 9,496/97 changed the formula to distribute Royalties (e.g., the international price of oil started to be used in the distribution formula). This led to a huge increase in royalty payments as illustrated below in Figure B.2, transforming it from a minor to a very significant source of income for municipalities.

The rules following the 1997 law require that an oil company must allocate between 5% and 10% of the value of the gross output in the form of royalties. Royalties are then divided among the three administrative levels in Brazil (National, States, and Municipalities). Municipalities are eligible to receive royalties based on (i) geography (if the production takes place in their territory or, in the case of offshore production, if it is a "facing" municipality, i.e., there is an oilfield that lies inside the municipality's maritime border), (ii) oil-related infrastructure (if within their borders there is storage, transportation, or landing of oil and gas), and (iii) an equalization rule (there is a "special fund" that allocates part of the royalties' revenue to all Brazilian municipalities). For some municipalities, royalties represent a significant part of their total revenue (more than half of total revenue in extreme cases). According to ANP (Brazil's oil and gas industry regulator), over R$ 4.5 billions (circa US$ 2.2 billion) in oil windfalls were distributed to the Brazilian municipalities in 2010, which represented on average 2.5% of the total revenue of municipalities receiving oil windfalls.

For a much more detailed description of the history and technicalities of royalty payments in Brazil see Caselli and Michaels (2013) and Monteiro and Ferraz (2012).

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C Appendix: Oil Discoveries, the Services Sector, and Labor Informality

A number of question naturally arise from the analysis in the main body of the paper which, due to data constraints, cannot be studied using our preferred difference-in-difference identification strategy. Important follow-up questions include 1) Are the results mainly driven by local price effects? 2) What happens to non-oil manufacturing? and 3) What happens to the agricultural sector?

In this appendix we shed some light on these questions by employing a cross-sectional identification for the year 2000. We use micro data from the employment and population censuses. The Ministry of Labor's RAIS (Relação Anual de Informações Sociais) provides microdata on formal workers and firms. To be precise, the RAIS dataset has information on each formal worker of each plant in Brazil. In 2000 there were 36,907,953 workers in the dataset. We use this information to construct measures of average wages, as well as number of workers and firms by skill and sector at municipal level. Since RAIS only looks at formal workers we complement this data with the 2000 population census, collected by the Brazilian Institute for Geography and Economics (IBGE). The population census allows us to calculate the fraction of workers employed in the formal sector by municipality, labor force participation, sectoral employment shares, etc. We use cross-sectional data for the year 2000 because this is the first year in which high quality data from both the employment and the population censuses is available.[47]

To guarantee maximum comparability with the results in the main text, we again aggregate municipalities to 1940 MCA level. MCAs which had a discovery prior to 2000 are assigned to treatment, while MCAs which drilled for oil but did not find any, constitute the control group. We will focus on the matched subsample in this appendix but results are unchanged when using the full sample of dry drilling MCAs. In terms of the identification, recall that we showed in Tables 3, 5 and 6 that drilling attempts depend on geographic and geological characteristics and are not correlated with the development level of the MCAs at the time of drilling. Given that discoveries are random conditional on drilling, even a cross-sectional comparison of treatment and control groups allows for some insights into at least the qualitative impact of oil discoveries.

Table C.1 summarizes the baseline results. The first three columns confirm the results from the main paper and show that in 2000 the assigned to treatment group has a higher GDP *per capita* and is more urbanized than the control group but population density is not affected by oil discoveries. Columns (4)-(6) show that MCAs which discovered oil have higher average wages and a higher worker density but firm density is the same in the discovery and the control group.[48] MCAs which discovered oil are thus richer, more urbanized, pay higher wages and have more formal workers. Two question naturally arise: i) Which sectors are affected by oil discoveries? And ii) how is it possible that the density of workers significantly increases with discoveries but population density is not affected? To investigate the former we construct sectoral measures of firm and worker

[47] RAIS data is collected annually since the late 1980s but is considered to be of a high quality only since the mid-1990s. The population census is collected once per decade, making 2000 the first year in which it overlapped with reliable RAIS data.

[48] Densities are specified as the number of firms and workers, respectively, per square kilometer.

density. Importantly, we can exploit sub-sector identifiers in the micro-data to construct worker and firm variables at the desired level of aggregation. In order to study question (ii), we rely on population census data which allows us to show that oil discoveries are associated with a higher fraction of workers employed in the formal sector, thereby increasing observed formal worker density without changing population density.

Table C.1: Oil Discoveries, Wages, Worker Density and Firm Density

	Matched Dry Drilling					
	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	ln Population Density	ln GDP *per capita*	Urbanization Rate	ln Worker Density	ln Firm Density	ln Average Wage
Discovery Dummy	-0.0269	0.396***	0.0551*	0.506*	0.384	0.185**
	(0.129)	(0.120)	(0.0301)	(0.287)	(0.285)	(0.0739)
Observations	128	128	128	128	128	128
Number of MCAs	128	128	128	128	128	128
Geography Controls	Yes	Yes	Yes	Yes	Yes	Yes
Initial Conditions	Yes	Yes	Yes	Yes	Yes	Yes
Estimation	OLS	OLS	OLS	OLS	OLS	OLS

Notes. Standard errors clustered at the MCA level. Discovery is defined as 'True Discovery'.
*** p<0.01, ** p<0.05, * p<0.1

Table C.2 highlights that the manufacturing sector (excluding natural resource extraction) and the agricultural sector are not affected by oil production. Neither formal firm nor worker density differs between discovery and control groups. We thus do not find any evidence for a Dutch disease style crowding-out of the manufacturing sector nor of positive spillovers from oil production to manufacturing. On the other hand, the number of formal workers in the services sector substantially increases with oil discoveries.

Table C.2: Oil Discoveries, Worker Density and Firm Density by Sector

	Matched Dry Drilling					
	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	ln Manufacturing Firm Density	ln Service Firm Density	ln Agriculture Firm Density	ln Manufacturing Worker Density	ln Services Worker Density	ln Agriculture Worker Density
Discovery Dummy	0.308	0.426	0.274	0.338	0.796**	0.546
	(0.338)	(0.302)	(0.286)	(0.450)	(0.353)	(0.359)
Observations	128	128	128	128	128	128
Number of MCAs	128	128	128	128	128	128
Geography Controls	Yes	Yes	Yes	Yes	Yes	Yes
Initial Conditions	Yes	Yes	Yes	Yes	Yes	Yes
Estimation	OLS	OLS	OLS	OLS	OLS	OLS

Notes. Robust standard errors in parenthesis. Discovery is defined as 'True Discovery'.
*** p<0.01, ** p<0.05, * p<0.1

To understand the impact of oil production on the services sector in more detail, Table C.3 disaggregates the worker data further. First, we can observe that average firm size in the services sector is significantly higher in the assigned to treatment group. We know from the labor literature (see Idson and Oi (1999), for example) that larger establishments tend to be more productive and this could thus a driver of local development. Secondly, both the number of skilled and unskilled workers is higher in oil MCAs, but while the average skilled wage is also significantly higher the unskilled wage is not affected.[49] An interesting picture thus emerges. In municipalities which discovered oil, more workers are employed in the services sector, services firms are larger and the skilled workers in the services sector receive higher wages. In other words, the local services sector grows

[49]Skilled workers are defined as those with completed high school or more.

with oil discoveries. The fact that the skilled wage is higher but the unskilled wage is not points to differences in the supply curve for skilled and unskilled workers. The elasticity for unskilled workers seems to be so high that more workers can be attracted at virtually no higher pay, while the supply of skilled workers is relatively more inelastic. The interesting question is thus where the new services workers are drawn from. Neither population density increases, nor does formal employment density in non-services sectors decrease. In other words, there is no significant in-migration, nor sectoral relocation of formal workers. While we cannot rule out that there are changes which are on average too small for us to detect, it seems unlikely that these can fully explain the 'new services workers'. What appears more likely, is that they are mainly drawn from the informal sector.

Table C.3: Oil Discoveries and the Services Sector

	Matched Dry Drilling					
	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	ln Firm Size	ln Skilled Worker Density	ln Unskilled Worker Density	Skilled Worker Fraction	ln Avg. Skilled Wage	ln Avg. Unskilled Wage
Discovery Dummy	0.370***	0.711*	0.685**	-0.0188	0.168**	0.0860
	(0.118)	(0.363)	(0.346)	(0.0260)	(0.0793)	(0.0611)
Observations	128	128	128	128	128	128
Number of MCAs	128	128	128	128	128	128
Geography Controls	Yes	Yes	Yes	Yes	Yes	Yes
Initial Conditions	Yes	Yes	Yes	Yes	Yes	Yes
Estimation	OLS	OLS	OLS	OLS	OLS	OLS

Notes. Robust standard errors in parenthesis. Discovery is defined as 'True Discovery'.
*** p<0.01, ** p<0.05, * p<0.1

In the 128 Brazilian MCAs in our sample on average only 35 percent of workers are formally employed and only 25 percent have a valid workers identification card.[50] The informal sector is thus very large. Table C.4 shows that oil discoveries are associated with a larger fraction of workers employed in the formal sector. The higher formalization rate offers an explanation for where the additional workers in the services sector come from; they move from the informal to the formal sector. Since the pool of workers in the informal sector tends to be predominantly unskilled this also explains the higher elasticity of labor supply for unskilled workers.

In columns (3) and (4) of Table C.4 we additionally check whether labor force participation increases and the fraction of self-employed workers decreases with oil discoveries (as workers from low productivity self-employed services provision move to larger formal services firms, for example). We find evidence for a decline in self-employment but no evidence for a higher labor force participation rate.

To gauge from which informal sector workers move to the formal services sector we use the population census and decompose the overall workforce into broad categories. Column (1) in Table C.5 confirms that in the discovery group a significantly larger fraction of the overall workforce is employed in extractive industries than in the control group. Recall from above, that we showed that the number of formal employees in the agricultural sector does not differ between the assigned to treatment and control group. However, column (2) of Table C.5 shows that overall the agricultural sector employs significantly less workers in oil municipalities. The number of *informal* workers in agriculture must

[50]The definition of formal employment here is taken from the Brazilian Institute for Geography and Economics (IBGE) and includes workers with a valid work card, those who work in the military, navy or judiciary and self-employed workers who contribute to social security.

Table C.4: Oil Discoveries and Labor Informality

	Matched Dry Drilling			
	(1)	(2)	(3)	(4)
VARIABLES	Percentage of Workers in the Formal Sector	Percentage of Workers with Valid Employment Card	Labor Force Participation Rate	Percentage of Workers which are self-employed
Discovery Dummy	4.352**	4.481***	0.0660	-2.627**
	(1.710)	(1.635)	(0.850)	(1.316)
Observations	128	128	128	128
Number of MCAs	128	128	128	128
Geography Controls	Yes	Yes	Yes	Yes
Initial Conditions	Yes	Yes	Yes	Yes
Estimation	OLS	OLS	OLS	OLS

Notes. Robust standard errors in parenthesis. Discovery is defined as 'True Discovery'.
*** p<0.01, ** p<0.05, * p<0.1

therefore be lower. Columns (3) and (4) confirm the earlier results for the manufacturing and services sector, i.e. no impact on employment in the manufacturing sector and an increase of employment in the services sector.

Brazil still had a large subsistence farming sector in 2000 which employed a substantial number of people with a very low productivity. In municipalities which produce oil we can observe a move of these informal agricultural workers to an expanding services sector. Our results indicates that this is the main positive externality from oil discoveries. Overall then, municipalities which discover oil have larger, more productive services sectors, probably driven by an increase in local demand for non-tradables from oil workers and the oil producing firms. The increased labor demand leads to more workers being pulled into the services sector and an increase in the wage for skilled workers. The unskilled wage does not increase as there is ample supply of unskilled workers in the informal agricultural sector. This move from rural informal work to the formal sector in the cities also explains the observed increase in urbanization.

Table C.5: Oil Discoveries and Sectoral Employment

	Matched Dry Drilling			
	(1)	(2)	(3)	(4)
VARIABLES	Percentage of Workers Employed in Extractive Industries	Percentage of Workers Employed in Agriculture	Percentage of Workers Employed in Manufacturing	Percentage of Workers Employed in Services
Discovery Dummy	0.579***	-5.364**	-0.0206	4.452**
	(0.214)	(2.632)	(0.742)	(2.191)
Observations	128	128	128	128
Number of MCAs	128	128	128	128
Geography Controls	Yes	Yes	Yes	Yes
Initial Conditions	Yes	Yes	Yes	Yes
Estimation	OLS	OLS	OLS	OLS

Notes. Robust standard errors in parenthesis. Discovery is defined as 'True Discovery'.
*** p<0.01, ** p<0.05, * p<0.1

It is worth noting that no impact on the manufacturing sector was found. This is, as all of the results, likely to be somewhat specific to the particular situation of a developing country with relatively little large-scale manufacturing in the affected regions. The impact of oil discoveries on wages for skilled workers in the services sector hinted at the possibility that in locations where there is no ample supply of labor in the informal, subsistence agriculture sector, an upward sloping labor supply curve would drive up manufacturing wages and potentially lead to the local Dutch-disease type effects often hypothesized. On the other hand, positive technological spillovers from oil production might also exist in regions where there is an important nucleus of high-end manufacturing. These questions will have to be studied in the context of a developed country. In the Brazilian case, the presence of an oil sector and the associated increase in local demand for non-tradables was able to have a strong impact on the development of the local services sector and precipitated a decrease in the highly unproductive subsistence farming sector and thus furthered local economic development.