IMF Working Paper

Middle East and Central Asia Department

Assessing Oil and Non-Oil GDP Growth from Space: An Application to Yemen 2012-17

Prepared by Majdi Debbich[1]

Authorized for distribution by Subir Lall

October 2019

Abstract

This paper uses an untapped source of satellite-recorded nightlights and gas flaring data to characterize the contraction of economic activity in Yemen throughout the ongoing conflict that erupted in 2015. Using estimated nightlights elasticities on a sample of 72 countries for real GDP and 28 countries for oil GDP over 6 years, I derive oil and non-oil GDP growth for Yemen. I show that real GDP contracted by a cumulative 24 percent over 2015-17 against 50 percent according to official figures. I also find that the impact of the conflict has been geographically uneven with economic activity contracting more in some governorates than in others.

I. INTRODUCTION

Satellite images are increasingly used to assess economic outcomes. With the generation and dissemination of important quantities of data gathered from remote sensing instruments[2], it is now possible to approach human activity in places where conventional data suffer strong limitations. This is particularly relevant for countries with weak national statistics capabilities owing to structural issues or ongoing conflicts. Most importantly, the high-level of disaggregation of satellite data and the capacity of sensors to capture various sources of energy allows to characterize the location and the type of activity detected. This paper is an attempt to use an untapped source of nightlights and gas flaring data from 2012-17 to assess oil and non-oil GDP growth and characterize the conflict-related contraction of economic activity in Yemen.

The usefulness of nightlights intensity to assess economic outcomes has been extensively documented in the recent literature. In a seminal paper, Henderson et al. (2012) use a global sample of countries to uncover a positive and significant relationship between the change in nightlights intensity and real GDP growth. The authors combine nightlights-based predicted real GDP with national accounts data to compute an enhanced measure of true real GDP growth. Pinkovskiy et al. (2016) use nightlights data to assess the relative quality of GDP per capita and survey means and build a new measure of real GDP. The geographic granularity of nightlights data also allows to investigate income growth distribution at subnational levels. Dai et al. (2017), Basihos (2016), Bundervoet et al. (2015) and Bandhari et al. (2011) leverage this feature of the data to characterize changes in economic activity at subnational levels in China, Turkey, Kenya, Rwanda and India. Beyond national income growth, nightlights data have been used to assess the size of the informal sector in India (Gosh et al., 2010) or the distribution of income inequalities at subnational levels (Elvidge et al., 2012). These data can also prove helpful to assess the outcome of specific events such as the local economic impact of the World Cup in South Africa (Pfeifer et al. 2018), the association between natural amenity quality and economic development (McGregor et al., 2017) or the economic impact of natural disasters (Skoufias et al., 2017).

To date most papers have used annual data from the Defense Meteorological Satellite Program (DMSP) which recorded nighttime pictures of earth from 1992-2013. While the time dimension allowed for robust panel estimations, the data remains of limited use to study post-2013 events. Additionally, the inability of DMSP operational linescan system (OLS) instruments to discriminate between sources of lights[3] raises concern about the implicit assumptions made on national income elasticities to different sources of nightlights including

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[2] See https://earthdata.nasa.gov/user-resources/remote-sensors for examples of remote sensors of which data are supported by NASA's information system (EODIS).

[3] Infrared pixel values from DMSP-OLS recorded data correspond to a maximum temperature of 310 Kelvins, well below gas flaring temperature levels.

gas flaring from oil production. This also hinders the capacity to carry analyzes on oil producing countries where light from gas flaring represents a useful source of information to assess economic activity.

In response to these shortcomings, this paper makes the case for using a newer set of monthly data recorded since 2012 by the Visible Infrared Imaging Radiometer Suite (VIIRS) onboard the NOAA/NASA's Suomi National Polar-orbiting Partnership (NPP) satellite. These monthly data allow to account for different sources of radiance including light generated from gas flaring on oil fields which together with total nightlights can be leveraged to estimate oil production (Do et al., 2017). Using a sample of 72 countries from the MENAP and Caucasus and Central Asia (CCA) regions and sub-Saharan Africa (SSA) over 6 years (2012-2017), I estimate nightlights-based oil and total real GDP equations and predict non-oil GDP as the residual. I then use point estimates to characterize GDP growth in Yemen and the contributions of oil and non-oil sectors. Finally, I leverage flaring and nightlights intensity data at the subnational level to describe economic developments within Yemen over 2015-17.

Yemen was at the forefront of the uprising in Arab countries in 2011, being the third country after Tunisia and Egypt to witness popular protests. The following year, a transition process encompassing a national dialogue was set to address popular grievances by implementing ambitious political and constitutional reforms. Yet, the process' lack of inclusiveness and slow progress on moving beyond the political status quo further undermined the country's stability. After a year of internal conflict in March 2015, a coalition of Arab countries started a military intervention in Yemen. This marked the beginning of the worst contemporaneous humanitarian crisis according to the United Nations[4]. Since then, the conflict has imposed a heavy toll on populations and official institutions. The depletion of foreign exchange reserves–mainly related to the collapse of oil production–and the fragmentation of the central government leading to the interruption of public salary and pension payments in large parts of the country have hardened conditions to access basic food items and medicines[5]. Reports from specialized agencies have testified on the deterioration of the economic fabric at the local level (ILO, 2018; UNDP, 2015) but comprehensive country-wide economic information is still missing. While the statistical capacity of Yemen was already limited, the eruption of the conflict has further constrained the ability of the authorities to collect, process and disseminate official data[6]. This situation further deteriorated following the relocation of core administrative capacities, including the headquarters of the Ministry of Finance and the Central Bank of Yemen from Sanaa to Aden in September 2016. The latest country-wide

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[4] In 2019, Yemen remains the world's worst humanitarian crisis according to the United Nations Secretary-General: https://www.un.org/sg/en/content/sg/speeches/2019-02-26/remarks-pledging-conference-for-yemen.

[5] See Salisbury (2017) for a detailed overview of the political economy of the conflict in Yemen.

[6] According to the World Bank, Yemen has one of the World's lowest statistical capacity score in 2018. See http://datatopics.worldbank.org/statisticalcapacity/.

official data on national accounts date back to 2014[7]. In these circumstances, nightlights-based estimators of real GDP growth can provide a relevant alternative to approach economic developments.

Nightlights data in Yemen over 2012-17 suggest an important contraction of the economic activity following the beginning of the conflict in March 2015. The economic downturn was primarily driven by a sharp decrease in oil GDP following the withdrawal of several foreign oil companies in 2015. Through 2016, oil and non-oil GDP continued to decrease, and oil production started recovering in 2017 while the rest of the economy resumed contracting. Overall, nightlights-based predictions suggest that the shock to the economy was particularly important in 2015 while economic activity contracted further in the following two years but at a much slower pace. Point estimates show that the cumulative contraction of real GDP in Yemen over 2015-17 was around 24 percent (34 percent when taking the lower-bound of the confidence interval). The results also suggest that the impact of the conflict has been geographically uneven. Large contractions of economic activity have been observed in western and southern governorates–including Aden, Al Hudaydah, Ibb, Taizz and Sanaa–and two out of three oil-producing governorates–Hadramawt and Shabwah. Estimates also suggest that economic growth has been positive in Marib as well as in the eastern and northern governorates of Al Mahrah and Al Jawf which–at least in the former case–can be attributed to sustained trade interactions with neighboring countries due to more difficult trade logistics in the ports of Al Hudaydah and Aden. These governorates have contributed to mitigate the estimated aggregate collapse in economic activity. Other governorates exhibit negative to slightly positive contributions to aggregate real GDP growth over 2015-17.

The rest of the paper is organized as follows: section II presents the satellite data and other variables used in this paper as well as descriptive statistics; section III provides estimations results of oil and total real GDP equations; section IV derives real GDP growth rates in the case of Yemen and discusses the results; section V concludes and explores further areas of research.

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[7] The Ministry of Planning has resumed publishing real GDP growth figures after the beginning of the conflict but given the difficulties to undertake proper country-wide surveys in the conflict-setting it is highly possible that these estimates are not representative of the whole country.

II. DATA

This paper combines data from various sources to construct a panel dataset of 72 countries from the MENAP and CCA regions and sub-Saharan Africa from 2012-17. The dataset includes variables on total nightlights, gas flaring, oil and total real GDP as well as information on fragility.

Nightlights

I use nightlights data generated using visible and infrared imagery from the Visible Infrared Imaging Radiometer Suite (VIIRS) onboard the NOAA/NASA's Suomi National Polar-orbiting Partnership (NPP) satellite which was launched in October 2011. The satellite is primarily intended to study *cloud and aerosol properties, ocean color, sea and land surface temperature, ice motion and temperature, fires, and Earth's albedo*[8]. The VIIRS instrument succeeded the Defense Meteorological Satellite Program (DMSP) operational linescan system (OLS) instrument which produced annual nightlights data from 1992 to 2013. Since Henderson et al. (2012), most nightlights-based research have concentrated on using data from the DMSP-OLS instrument. While the data derived from this instrument provided strong evidence to support the relationship between nightlights intensity and economic activity, it suffered several limitations–including lower spatial resolution, over-saturation and inability to discriminate lights based on the magnitude of thermal radiation–as compared to the data produced by the VIIRS instrument.
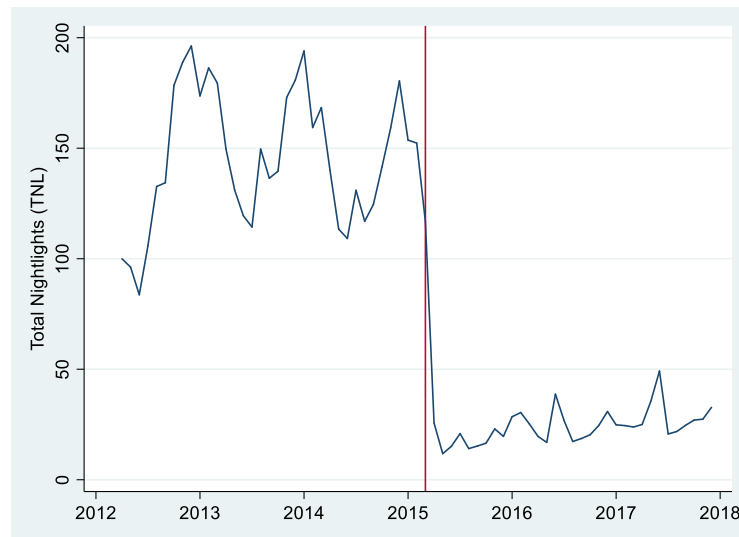

Figure 1. Total nightlights in Yemen (100 = TNL in March 2012)

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[8] See the VIIRS webpage on NASA's website for further details: https://jointmission.gsfc.nasa.gov/viirs.html.

The Earth Observation Group from NOAA releases monthly cloud-free composite images of the globe recorded by the VIIRS instrument[9] that are processed to extract nightlights intensity by pixel. The data are then aggregated at the country level but suffer from noise arising from ephemeral lights and relatively high radiance in winter months among other factors (Zhao et al., 2017). As a result, the VIIRS instrument intermittently tends to record positive levels of radiance in subnational regions where visual inspection validates the absence of light from human activity or ephemeral events such as fires. This is particularly true in the case of Yemen where positive radiance was recorded in large uninhabited remote areas of the Arabian desert in winter. The aggregation of the monthly data at the annual level and the introduction of year and country fixed-effects in regressions resolve part of this problem. But heterogenous errors of measurement in nightlights data have serious implications for the quality of the predictions that I discuss further below.

Figure 1 represents the sum of nightlights in Yemen cleaned from data generated in regions with no urban centers or no human activity–such as oil production plants–to limit noise in the data. The seasonal pattern before 2015 reflects the relatively high radiance in winter months as compared to other periods of the year. It is remarkable that total nightlights collapsed in March 2015 (red vertical line) marking the beginning of the conflict and plateaued at a low level afterward. A visual inspection of composite images confirms the dramatic decrease in nightlight intensity between end-2014 and end-2017. The collapse in brightness is particularly noticeable in urban centers affected by the conflict including the capital city of Sanaa, and oil-producing regions (red circles in Figure 2). This pattern reflects a long-lasting contraction in the production and consumption of light that can be traced back to a reduction in economic activity.

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[9] Composite images from the VIIRS can be downloaded from: https://www.ngdc.noaa.gov/eog/download.html.
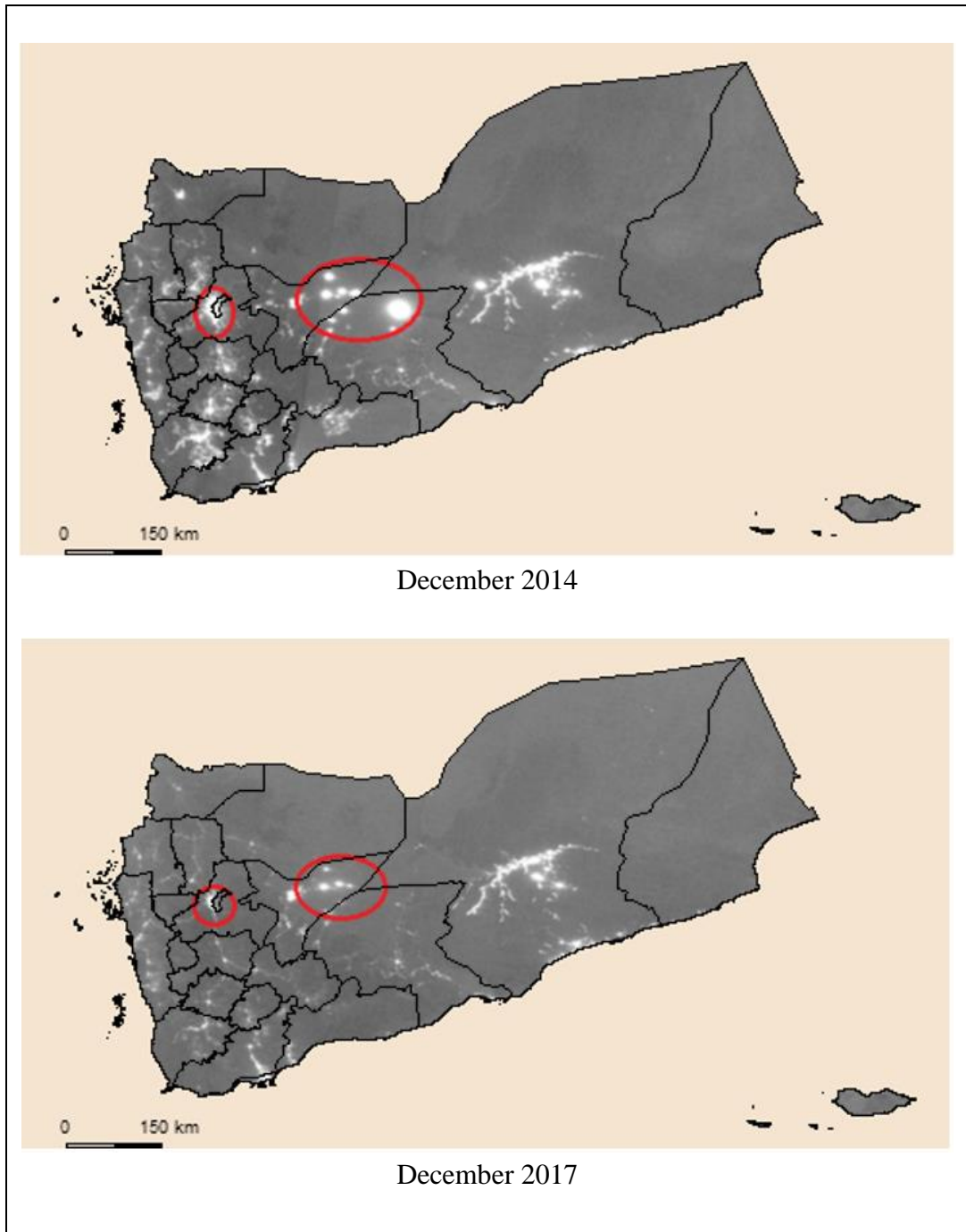
8

December 2014

December 2017

Figure 2. VIIRS composite images of Yemen

Gas flaring

As emphasized in the introduction, a main limitation of the DMSP-OLS nightlights data largely used so far in the literature remains its inability to discriminate between sources of light and to specifically account for radiant heat emanating from gas flaring in oil fields. Natural gas is a common byproduct of oil extraction. The gas which is accidentally extracted can be either processed and sold, reinjected in oil fields, vented or flared. Flaring is often privileged in low-income and emerging countries as it is the most economical way to dispose of natural gas (see Figure 3 for examples of gas flaring activity on oil production sites in Yemen). The light generated by the gas flaring process which is recorded on satellite images provides a rich source of information when it can be disentangled from other sources of artificial light. Flaring generally results in much brighter light than regular artificial light from urban centers. The specific pattern of gas flaring activity can be seen on Figure 2 where flares in Marib and Shabwah regions of Yemen (right red circle) produce as much light as the capital city Sanaa (left red circle). Accounting for gas flaring in the estimation of the elasticity of real GDP to nightlights intensity is therefore critical to relax assumptions on the estimated coefficients given that underlying value added in real terms may be significantly different.

Research papers using DMSP-OLS data–including Henderson et al. (2012)–either do not control for gas flaring in regressions or circumvent the related issues by getting rid of nightlights data recorded in regions where oil fields are located. Yet, apart from econometric considerations, this practice also limits the potential to carry analyzes on oil-producing economies and infer oil output and its contribution to real GDP growth in the absence or lack of reliable official data. This is particularly detrimental for countries where oil GDP represents a significant share of total GDP but also for countries where public revenues are disproportionately reliant on oil production. In Yemen, while oil production and its contribution to GDP had always been limited–around 10 percent of GDP–oil revenues had remained the main source of foreign exchange and financing to the government's budget– representing roughly 50 percent of total revenues and grants. Characterizing the evolution of oil production and its contribution to GDP in countries like Yemen is therefore critical to understanding economic developments and shed light on the sources of humanitarian crises.

The VIIRS instrument proves helpful to remedy these issues and integrate oil producing regions in the analysis because it allows to account for different sources of light. Infrared sensors allow to discriminate between sources of nightlights based on radiant heat intensity (Elvidge et al., 2013) and therefore identify light arising from gas flaring activity. The VIIRS data I use to identify gas flaring are retreated to eliminate detections under 1.500 degree Celsius that could be caused by ephemeral fires such as forest fires[10]. I use geographic coordinates and exclusive economic zone boundaries to relate onshore and offshore gas flaring sites to

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[10] VIIRS data on flaring are retreated by SkyTruth, a non-profit organization specialized in environmental protection. Data can be downloaded from https://skytruth.org/viirs/.

corresponding countries. Radiant heat from each recorded flaring event is then averaged to construct monthly observations at the country level.

Shabwah, November 2014 – 15º20'30"N 46º49'30"E

Hadramawt, January 2015 – 15º41'41"N 47º57'29"E
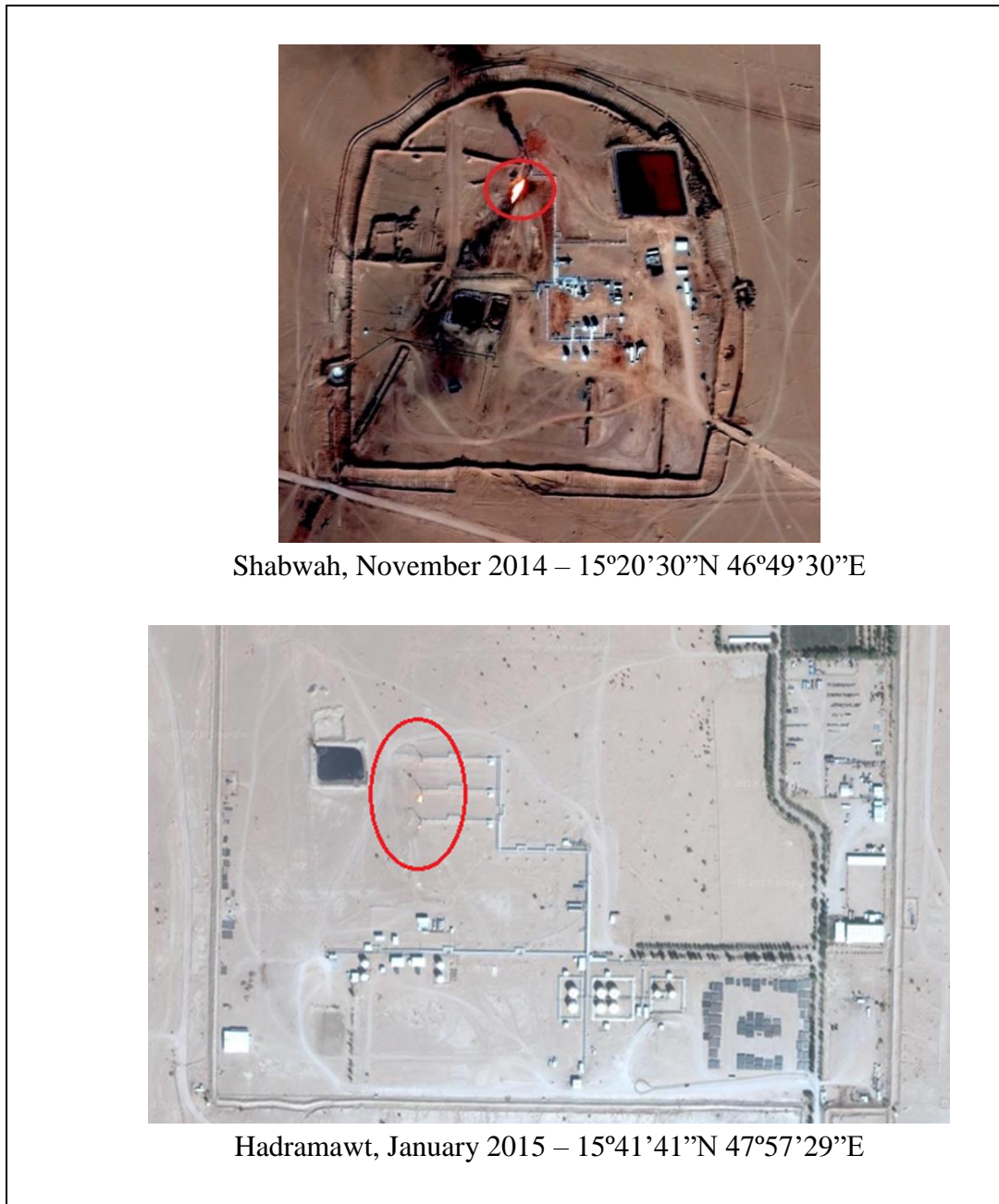
Figure 3. Gas flaring on oil production sites in Yemen from Google Earth

Gas flaring in Yemen since 2012 exhibits a decreasing pattern (Figure 4) even before the eruption of the ongoing conflict which can be traced back to a long-term decreasing trend in oil production owing to the progressive depletion of oil wells. It is then noticeable that flaring collapsed more significantly following the beginning of the conflict in March 2015 (red

vertical line), mostly due to the withdrawal of foreign oil companies. This is confirmed by visual inspection on Figure 2 where the bright spots in the right red circle have significantly decreased in intensity or faded away. In particular, the brightest spot in the northern part of Shabwah in December 2014–which corresponds to OMV's production plant–has completely disappeared in December 2017, reflecting the cessation of oil production activity following the departure of the company. Aggregate flaring data then show a slight recovery of oil production activity through 2017 although gas flaring levels remained well below pre-conflict.
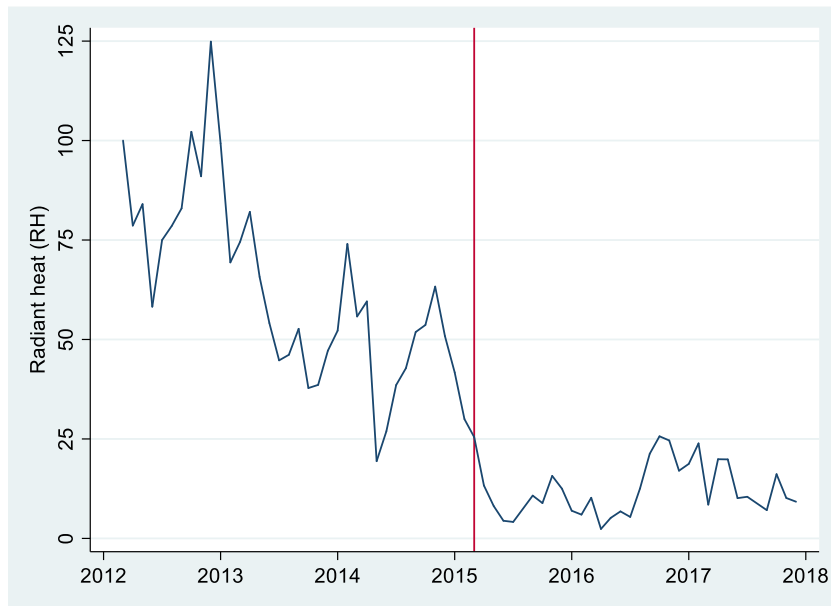

Figure 4. Radiant heat from gas flaring in Yemen (100 = RH in March 2012)

Real GDP and Oil output

I use data from the World Economic Outlook (WEO) database for oil and total real GDP in constant local currency unit (LCU) and in purchasing power parity (PPP, constant 2011 U.S. dollars) from 2012-2017. I also use data on oil production from the U.S. Energy Information Administration (EIA)[11]. Oil output is a good proxy for real oil GDP in the short-run given that adjustments in production technology and input needs may take time to be implemented. I use oil production to illustrate the relationship between gas flaring and output levels and to test the robustness of the estimations of oil GDP in the regressions section.

There is a positive relationship between nightlights intensity and real GDP level for the sample of 72 countries I use in the regressions section (Figure 5). Data points tend to be close to the linear prediction for most countries except for a few outlier countries which can result from the poor quality of national accounts data in these countries, the noise in nightlights data

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[11] Global data on oil production can be downloaded from: https://www.eia.gov/beta/international/.

or the specific structures of these economies. For instance, it has been argued in the literature that agriculture activities may consume less electricity than activities in the secondary and tertiary sectors to produce a given amount of GDP. A major argument to support this view is that agriculture activities tend to take place during daytime and therefore may not generate light that can be captured by satellites. This argument however puts aside the importance of revenues derived from such activities that would still translate into increased consumption and therefore higher production and use of electricity at night.
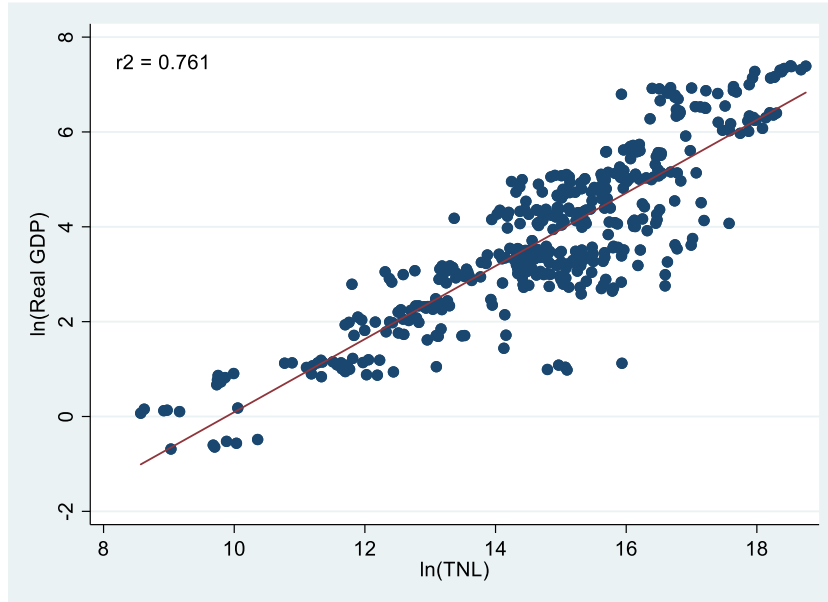

Figure 5. Real GDP in PPP (constant 2011 U.S. dollars) and total nightlights intensity

There is also a positive correlation between gas flaring and oil production (Figure 6) although less pronounced than for real GDP and total nightlights. Indeed, the quantity of gas flared for a given quantity of oil extracted depends much on the technology employed and the geological properties of the oil fields. Gas flaring is only observable when gas is neither processed, nor reinjected in the field or vented. Also, the intensity of flares is a function of the gas-to-oil ratio i.e. the amount of gas associated to a given amount of oil extracted. Countries displaying data points below the linear fit tend either to have higher gas-to-oil ratios or to rely heavily on flaring to dispose of natural gas. On the contrary, the points above the linear fit represent countries that tend to have lower proportions of their oil production associated to gas flaring. These countries are generally more developed and regardless of their gas-to-oil ratio, they tend to rely more on processing technologies to limit the use of gas flaring which is also detrimental for the environment.
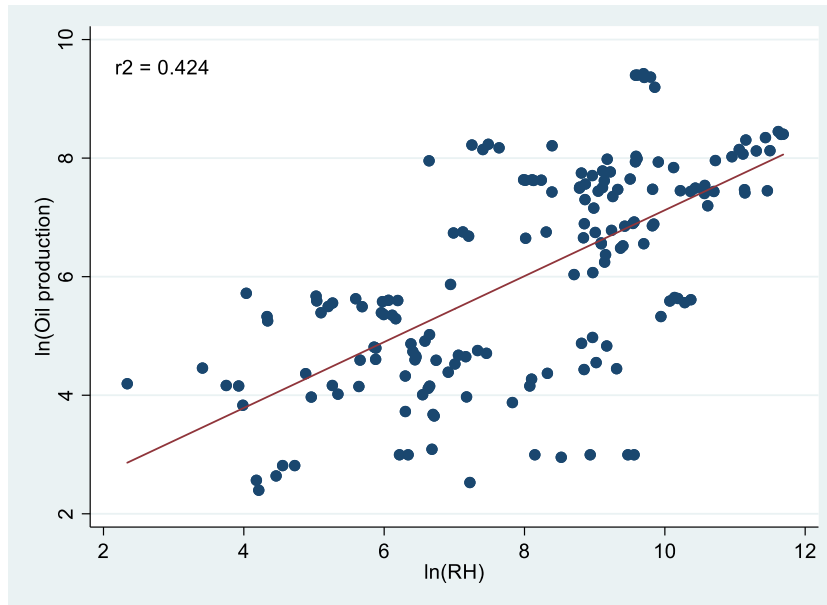
Figure 6. Radiant heat from gas flaring and oil production
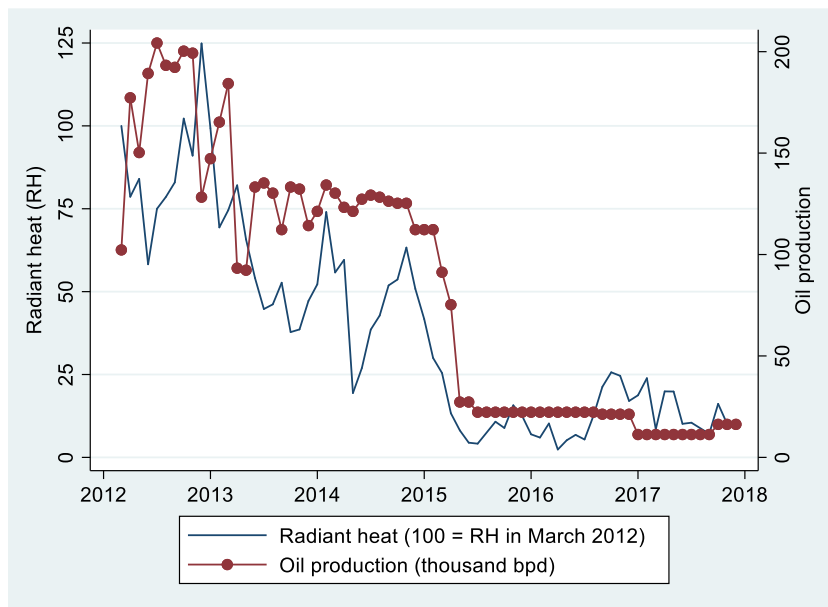
Figure 7. Radiant heat from gas flaring and oil production in Yemen

In the case of Yemen, monthly oil production data from the U.S. EIA tend to follow closely the evolution of satellite recorded radiant heat suggesting the heavy reliance on flaring by oil companies as a way to dispose of the accidentally extracted natural gas (Figure 7). A visual inspection on Google Earth of major oil drilling sites in Yemen as those shown in Figure 3 tends to confirm the systematic presence of flares or gas flaring installations. As the conflict erupted in Yemen in March 2015, the data on oil production from the U.S. EIA started

displaying a strong decline and then remained constant for longer periods of time. This reflects the difficulty to access information on the evolution of production volumes in the current circumstances. Since the beginning of the conflict in Yemen, publicly available oil production data have failed to reproduce the pattern in gas flaring as compared to previous–years. In particular, the increase in gas flaring which could reflect an increase in oil output starting in late 2016 is not captured by the U.S. EIA data. In this setting, gas flaring data can prove particularly useful as an alternative to approximate oil production and infer oil GDP.

Other variables

Estimating a simple linear relationship between real GDP and nightlights intensity amounts to assume a stable link between both variables that translates into a constant elasticity across countries. Yet, it is highly plausible that such a relationship may be altered in exceptional circumstances such as natural disasters or conflicts as in the case of Yemen. To account for this potential non-linearity and cover the broader concept of fragility rather than conflict only[12], I use the Fragile States Index (FSI) from the Fund for Peace (FFP)[13]. The FSI is a multidimensional index accounting for economic, political and social developments. The index is designed such that the higher it is, the more fragile the country is assessed to be. It is originally conceived as an early warning instrument to identify mounting pressures in countries that can potentially translate into conflicts. Yemen has always had one of the highest FSI among the 178 countries covered by the FFP survey. The FSI in Yemen deteriorated in 2013 before receding in 2014 and deteriorating further in the wake of the ongoing conflict (Figure 8). The FSI then slightly decreased in 2017, driven by small improvements on the economic dimensions, the security apparatus, refugees and demographic pressures. Yet, Yemen was still ranked fourth in the 2017 FSI global ranking, behind South Sudan, Somalia and Central African Republic[14].

Finally, I introduce a control variable to account for the noise in the monthly nightlights data recorded by the VIIRS instrument. Disturbances in the data are unevenly distributed across time and across countries. Aggregating the data at the annual level and controlling in regressions for country and year fixed-effects allows to account for part of the noise in the data but can prove insufficient. In particular, in 2017 several countries–including Yemen–exhibit a

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[12] The Uppsala conflict data provides an alternative to test for non-linearity arising from exceptional circumstances such as conflicts. However, only a few countries from the sample have positive conflict-related casualties and even fewer are concerned by large scale conflicts. I therefore privilege relying on the FSI which covers fragility, as a broader concept.

[13] The FSI data by country and details on the methodological aspects of the index can be found at: https://fragilestatesindex.org/.

[14] The latest FSI data for Yemen show that since 2017, the situation has resumed deteriorating. In 2019, Yemen had the highest FSI among the 178 countries covered by the FFP.

massive increase in total nightlights that cannot be traced back to any dramatic change in economic activity or other country-specific conditions. This brutal increase in nightlights is purely noise but because it does affect only some countries in 2017, it is not properly taken into account neither by the year fixed-effects nor by the country fixed-effects. For the quality of the predictions, it is essential to account for this specific pattern in the data, otherwise countries specifically affected by the noise in 2017 may end up with over-optimistic predictions. To do so, I construct a dummy variable that clusters countries into two groups along the median change in nightlights intensity between 2016 and 2017. The first group is made of countries that exhibit nightlights increases greater than the full sample median change in nightlights intensity and the second group is made of countries that exhibit nightlights increases smaller than the median change.
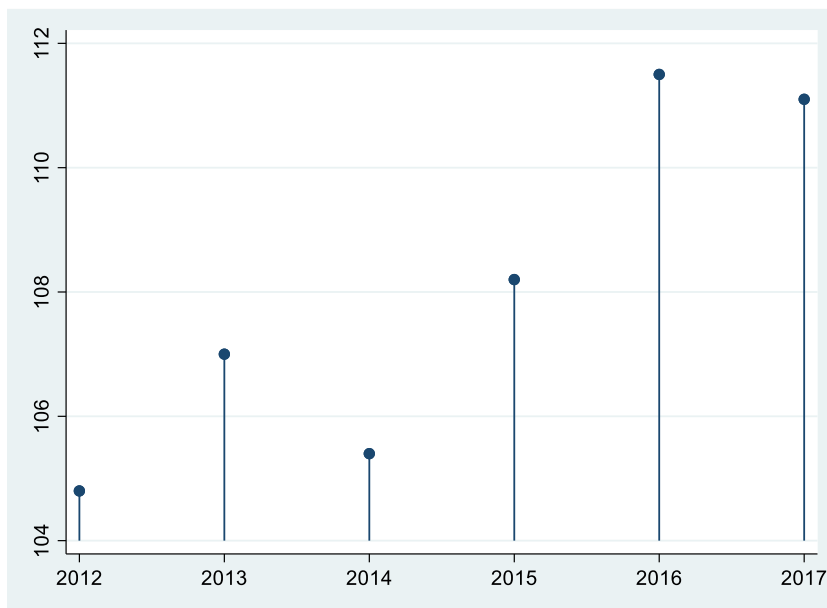

Figure 8. Fragile States Index for Yemen

III. REGRESSIONS

I use ordinary least squares panel regressions to estimate separate equations for oil GDP and total real GDP and then derive non-oil GDP as the difference between the two estimators. The samples contain 72 countries for total real GDP and 28 countries for oil GDP from the MENAP, CCA and SSA regions across a period of 6 years (2012-17)[15].

Oil GDP

The intensity of gas flaring or radiant heat recorded by the VIIRS instrument primarily depends on the quantity of natural gas flared in the oil production process at a given point in time. Because in the short-run, oil GDP is primarily driven by the volume of oil production, gas flaring intensity can help proxy for changes in oil GDP. But as discussed in the previous section, the flaring intensity does not only depend on the level of oil production. It also depends on the quantity of natural gas associated to a given quantity of oil extracted–measured by the gas-to-oil ratio–and, on the extraction technology. Indeed, when natural gas is present in the oil reservoir, it can either be processed and subsequently sold, reinjected in the field, vented or flared. Flaring is usually privileged in low-income countries as it is the cheapest way to dispose of the accidentally extracted natural gas in the absence of processing infrastructures.

Similar to Do et al. (2017), the recorded intensity of gas flaring can be represented as a function of the quantity of gas actually flared:

$$RH_{it} = (G_{it})^{\varphi} \tag{1}$$

Where φ is the elasticity of recorded radiant heat (RH_{it}) to the quantity of gas flared (G_{it}) for country i at time t. The quantity of gas flared can then be represented as a function of the level of oil production (OP_{it}), the gas-to-oil ratio (GOR_{it}) i.e. the quantity of natural gas associated to each unit of extracted oil, and a technological parameter ($TECH_{it}$) to account for the share of extracted gas actually flared[16]:

$$RH_{it} = (OP_{it}.GOR_{it}.TECH_{it})^{\varphi} \tag{2}$$

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[15] The list of countries used to construct the panel dataset can be found in the appendix.

[16] This simplified specification assumes that for any given amount of oil extracted, there is a constant share of the production that generates gas flaring. In reality, the relationship may be non-linear and oil production could at some point increase without triggering any increase in flaring. This happens in particular when aggregating data from different oil fields–with different gas-to-oil ratios and extraction technologies–at the country level. The oil output that does not translate into visible flaring may however be reflected in total nightlights intensity. To account for this, I also control for total nightlights in the oil GDP regressions.

Inverting the equation to express oil production as a function of radiant heat, gas-to-oil ratio and technology, and taking the natural logarithm–represented by lower-case letters–I obtain:

$$op_{it} = \frac{1}{\varphi}.rh_{it} - gor_{it} - tech_{it} \qquad (3)$$

It is worth noting that the gas-to-oil ratio and technology are oil field and time specific. In that sense, both variables in equation (3) represent weighted averages at country i level of oil field specific characteristics at time t. Indeed, the geological properties of oil fields evolve as oil is extracted and production processes tend to change with time and circumstances. To simplify, I assume that these changes are however taking place in the medium- to long-run and given the time dimension of the panel dataset I use (six years), I consider the gas-to-oil ratio and technology to be time-invariant.

The oil production equation I estimate becomes:

$$op_{it} = \pi.rh_{it} - gor_i - tech_i + \delta_t + \varepsilon_{it} \qquad (4)$$

Where $\pi = \frac{1}{\varphi}$. The gas-to-oil ratio and technology parameters are then estimated as a single country fixed-effect while δ_t is a time fixed-effect and ε_{it} is a country and time-specific error term. I use this specification to estimate oil GDP as it is primarily driven by the volume of oil production in the short-term. The oil GDP equation writes:

$$ogdp_{it} = \gamma.rh_{it} - gor_i - tech_i + d_t + e_{it} \qquad (5)$$

Total real GDP

Most research papers estimating the elasticity of real GDP to nightlights have generally not fully considered the importance of accounting for flaring intensity. Gas flaring from oil production tends generally to produce a disproportionate amount of light as compared to the size of the oil sector in total GDP. In Yemen for instance, pre-conflict satellite images show that up to 40 percent of total nightlights were generated by flaring activity while the oil sector represented less than 10 percent of total GDP. In this setting, relating total real GDP to total nightlights without accounting for flaring amounts to assume that there is a constant relationship between total nightlights and real GDP regardless of the underlying light-producing activity. However, there is no reason why this should be the case. Additionally, this is detrimental when it comes to making predictions because the magnitude of the variation in real GDP should be as much as possible calibrated on the underlying activity. In that sense, it is critical to control for light generated from gas flaring when estimating the relationship

between real GDP and total nightlights. Drawing from the standard specification in the literature and adding radiant heat, the baseline equation of real GDP for country i at time t can therefore be written as:

$$gdp_{it} = \eta.rh_{it} + \lambda.tnl_{it} + \mu_i + \tau_t + \xi_{it} \qquad (6)$$

Where variables are in logarithm and η is the elasticity of real GDP to radiant heat, λ the elasticity of real GDP to total nightlights, μ a country fixed-effect, τ a time fixed-effect and ξ a country and time-specific error term.

Results

Table 1 presents the results of the estimation of oil output for a balanced panel of 28 oil-producing countries over 6 years. These countries are a sub-sample of the 72 countries I use to estimate real GDP equations and they are scattered across the MENAP and CCA regions and sub-Saharan Africa. Columns 1 to 4 report regressions using oil production as the dependent variable while columns 5 to 8 use oil GDP. Estimated coefficients are very close by construction as oil GDP and oil production are related. Column 6 shows that oil GDP is significantly related to radiant heat and total nightlights which also measures electric light emitted at night. As already discussed, the oil production process produces light when flaring is involved to dispose of the natural gas accidentally extracted. Oil production may also not produce flaring when the gas-to-oil ratio is marginal in a given specific field or when the technology employed allows to process, reinject or vent the natural gas extracted. In that case, the oil production process still produces light because of the physical installations needed but this light comes from electric sources. The introduction of the total nightlights variable in the regressions allows to capture the underlying oil production process not directly related to flaring activity.

As mentioned in the previous section, monthly nightlights data recorded by the VIIRS instrument suffer from noise, especially in 2017 for some countries that exhibit a massive increase in total nightlights. To account for this pattern and avoid over-optimistic predictions for 2017, I interact a cluster dummy variable with year-fixed effects. The dummy variable clusters countries into two groups based on the magnitude of total nightlights change between 2016 and 2017. I introduce this variable in columns 3-4 and 7-8. Results for oil GDP in column 8 show that the introduction of the cluster interaction term decreases the coefficient on radiant heat while increases that on total nightlights and the within country R^2 which stands at 0.42. I use the results of this last specification to predict oil GDP for the 28 countries of the oil-producing sub-sample.

Table 2 presents the results of the estimation of real GDP in constant local currency units for the whole sample of 72 countries from 2012-17[17]. As for the estimation of oil GDP, I account for the unevenly distributed noise in the data in 2017. Column 1-3 report regression results without controlling for the noise while columns 4-6 present the regression results with the cluster interaction term. I first regress real GDP on total nightlights alone and then introduce the gas flaring variable to account for the differences in elasticities of lights generated by different types of activities. The coefficients on both variables are significant in the different specifications. In columns 3 and 6, I add the Fragile States Index (FSI) variable to account for the potential non-linearity arising from fragility and conflict in the relationship between real GDP and total nightlights. The interaction term between total nightlights and FSI is negative suggesting that for a given change in nightlights intensity, the underlying change in real GDP may be slightly lower for fragile countries. I use regression results from column 6 to predict real GDP for the sample of 72 countries.

Figure 9 and Figure 10 report official data and predicted values for oil and real GDP for selected countries. In Figure 9, the predictions of oil GDP for countries on the left of the panel tend to be in line with official data except that predicted oil GDP tends to exhibit higher volatility. On the right of the panel, the countries exhibit official data for oil GDP that intermittently fall outside of the confidence interval for the predicted values. In Niger for instance, the model predicts a contraction in oil GDP through 2016 while official data reported a recovery for that year. In Uzbekistan, the predicted values suggest that oil GDP contracted since 2012 and started recovering in 2017 although official data reported a continuous contraction. Finally, for Yemen, the model suggests that oil GDP may have been overestimated before the conflict started in 2015. It then shows that oil GDP collapsed but at a slower pace than suggested by available oil production data. The model also suggests that oil production recovered slightly in 2017.

In Figure 10, I report predicted and official real GDP for selected countries. As in Figure 9, countries on the left of the panel tend to exhibit predictions that are closely in line with official data and on the right of the panel, I report countries for which there are significant discrepancies. It is notable in the case of Cameroon that while official data report a steady real GDP growth across the period, predicted real GDP suggests a contraction in 2016. This predicted contraction could be in line with the commodities crisis that hit the CEMAC region at that time. Official real GDP exhibits the same steady growth in Uzbekistan while predicted real GDP suggests a contraction and stagnation through 2015 before growth became positive in 2016. In the case of Yemen, as for oil GDP, the model suggests that real GDP may have been overestimated before the conflict by some 24 percent when considering point estimates. In the wake of the conflict, predicted real GDP shows a contraction that is less pronounced than the collapse in economic activity suggested by official data. The model shows that real GDP collapsed dramatically in 2015 and then continued contracting but at a decelerating pace.

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[17] The results of the estimation using real GDP in PPP (constant 2011 U.S. dollars) are presented in the appendix.

The predicted real GDP suggests that economic activity then stagnated between 2016 and 2017.

Overall, these country examples show that discrepancies between the model's predictions and official data can be sizeable in terms of levels–as in the case of Yemen–but mostly in terms of patterns in the data. Official data tend generally to be less volatile and to suggest smooth GDP growth paths while nightlights-based estimators reveal more volatile patterns that can be linked to regional economic developments as in the case of Cameroon.

In the following section, I use point estimates of real GDP and oil GDP in Yemen to decompose the drivers of economic growth since 2013. I then use the geographic distribution of total nightlights and gas flaring from production to infer the regional contributions to real GDP growth.

Table 1. Oil Output and Radiant Heat

	ln(Oil prod.) (1)	ln(Oil prod.) (2)	ln(Oil prod.) (3)	ln(Oil prod.) (4)	ln(Oil GDP) (5)	ln(Oil GDP) (6)	ln(Oil GDP) (7)	ln(Oil GDP) (8)
ln(Radiant heat)	0.288***	0.240***	0.287***	0.160***	0.280***	0.208***	0.279***	0.116*
	(0.049)	(0.051)	(0.049)	(0.047)	(0.062)	(0.063)	(0.061)	(0.059)
ln(TNL)		0.272***		0.774***		0.414***		0.995***
		(0.099)		(0.123)		(0.123)		(0.153)
Cluster in 2017	No	No	Yes	Yes	No	No	Yes	Yes
Observations	168	168	168	168	168	168	168	168
Countries	28	28	28	28	28	28	28	28
Within R^2	0.248	0.289	0.296	0.462	0.162	0.228	0.227	0.420

All regressions include country and year fixed effects.
Standard errors in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 2. Real GDP (constant LCU) and Total Nightlights

	ln(GDP) (1)	ln(GDP) (2)	ln(GDP) (3)	ln(GDP) (4)	ln(GDP) (5)	ln(GDP) (6)
ln(TNL)	0.080***	0.053**	0.219***	0.157***	0.119***	0.305***
	(0.026)	(0.026)	(0.078)	(0.033)	(0.033)	(0.079)
ln(Radiant heat)		0.109***	0.108***		0.101***	0.099***
		(0.022)	(0.021)		(0.022)	(0.020)
FSI			0.006			0.009
			(0.012)			(0.012)
ln(TNL)*FSI			-0.002**			-0.002***
			(0.001)			(0.001)
Cluster in 2017	No	No	No	Yes	Yes	Yes
Observations	432	432	432	432	432	432
Countries	72	72	72	72	72	72
Within R^2	0.208	0.258	0.368	0.245	0.287	0.407

All regressions include country and year fixed effects.
Standard errors in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Figure 9. Official and predicted Oil GDP for selected countries: 2012-17[18]

(100 = Official Oil GDP in 2012)

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[18] For Yemen, official oil GDP after 2014 is estimated using data on oil production from the U.S. EIA.
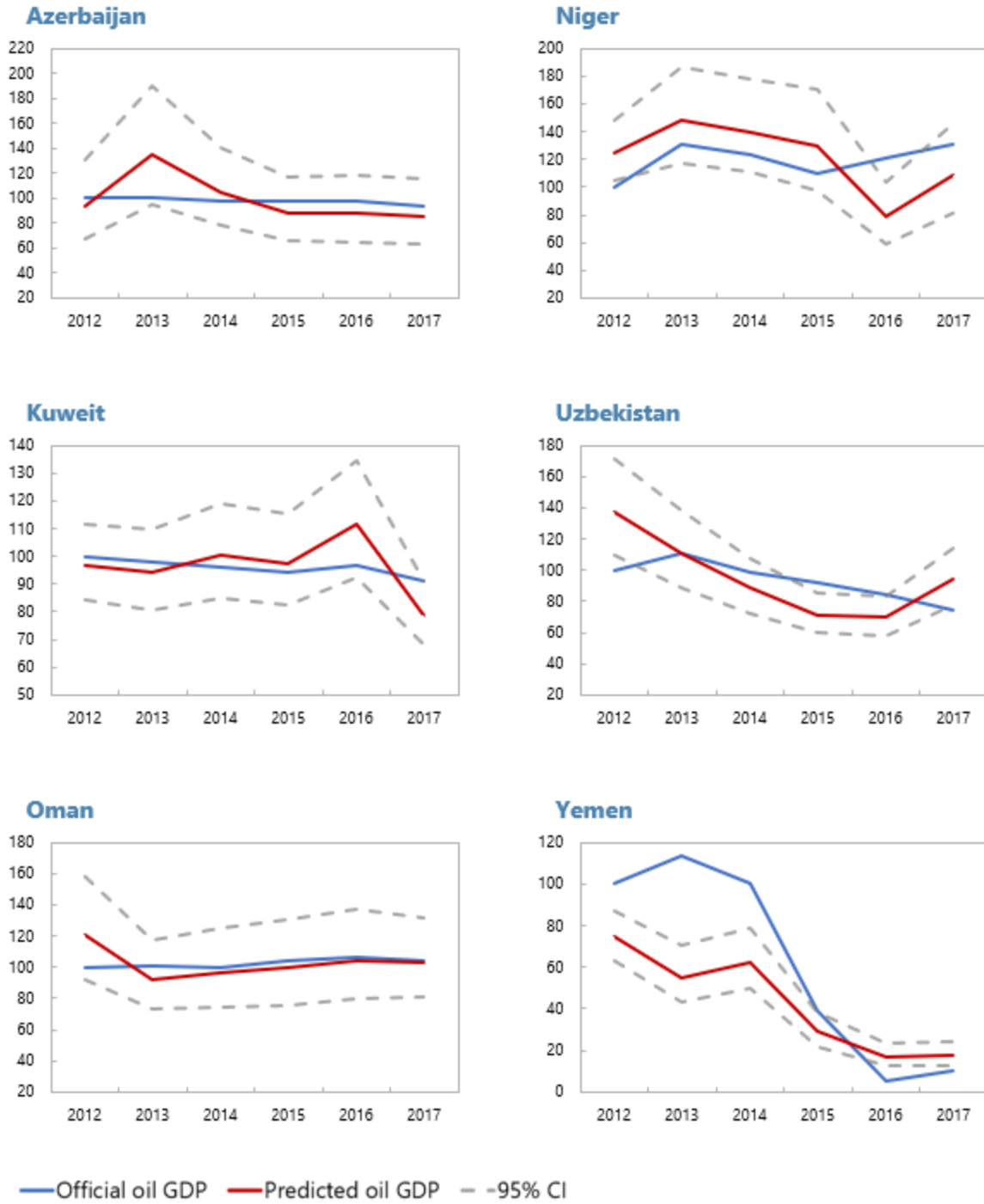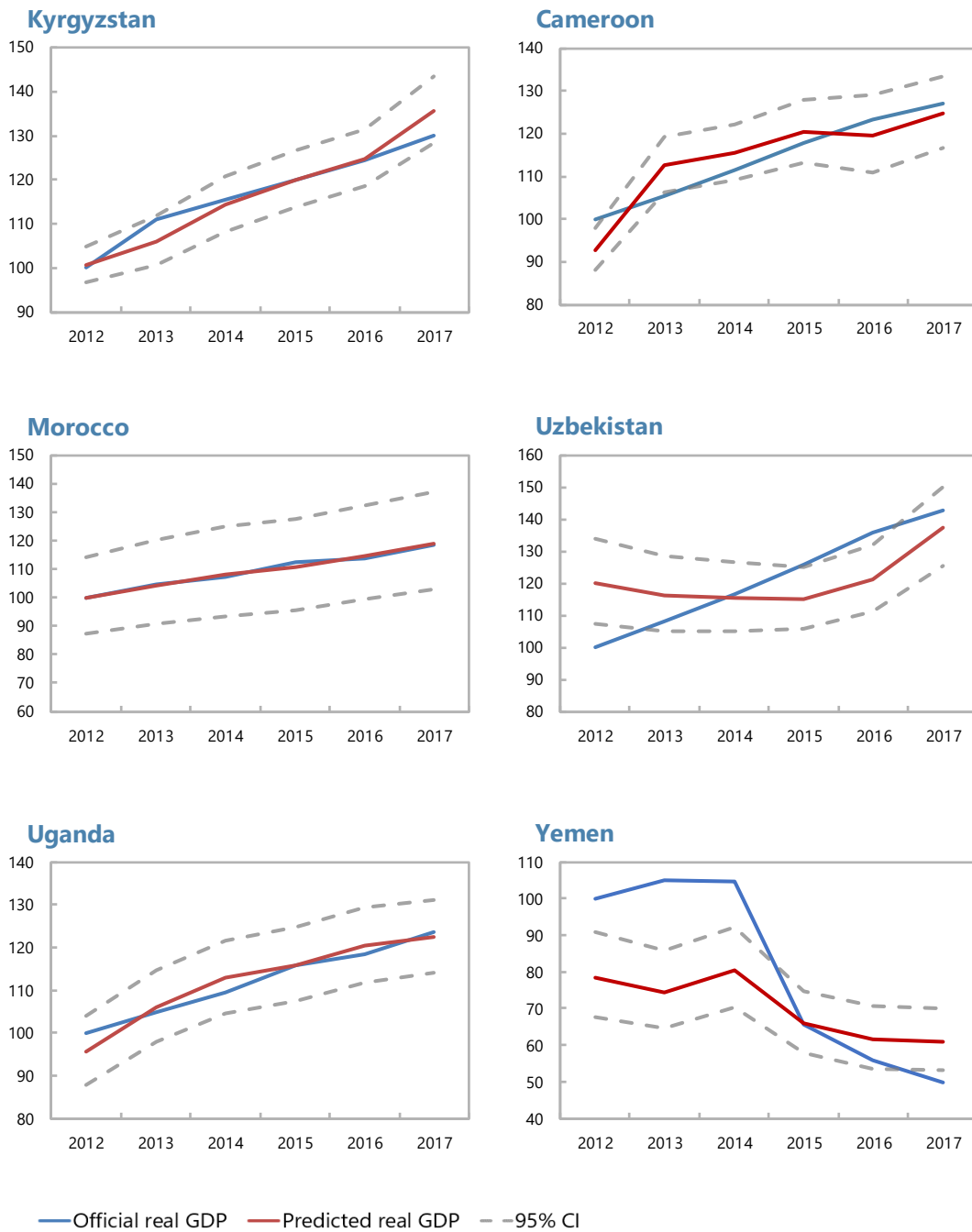
Figure 10. Official and predicted Real GDP for selected countries: 2012-17[19]

(100 = Official Real GDP in 2012)

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[19] For Yemen, official real GDP after 2014 is constructed using estimations of real GDP growth from the Yemeni Ministry of Planning.

IV. GROWTH IN YEMEN

Aggregate real GDP growth

Since 2013, real GDP growth in Yemen has been volatile. Political developments before the conflict combined with a structural decrease in oil production had already affected the potential of the economy and the country remained fragile. The eruption of the conflict further weakened the economy with a major contraction in economic activity. The collapse in 2015 was remarkable in the oil industry because several foreign companies left the country when hostilities started. The non-oil sector, which drives most of the economic activity in Yemen, also suffered a substantial contraction although less important than in the oil industry. Both sectors resumed contracting in 2016 although at slower paces and in 2017 the economy stagnated. Point estimates for 2017 suggest that real GDP growth stood at -1 percent while oil production slightly recovered.
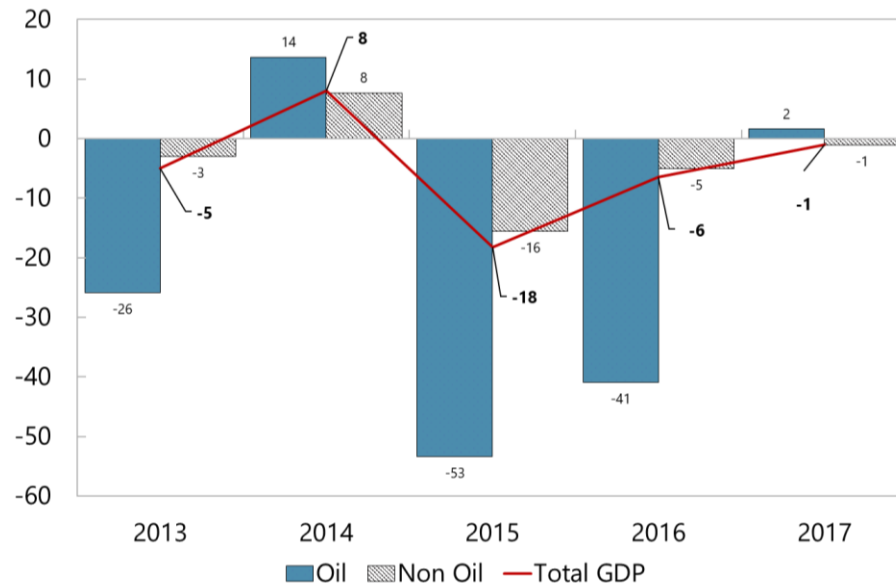
Figure 11. Decomposition of predicted real GDP growth in Yemen

Overall, point estimates suggest that throughout the conflict i.e. from 2015 to 2017, real GDP contracted by around 24 percent. A lower-bound estimate indicates that real GDP contracted at most by 34 percent. This figure is much lower than the figure suggested by official data from the Yemeni Ministry of Planning (2018) which assesses the economic contraction since the beginning of the conflict to be around 50 percent. Yet, it is worth noting that the humanitarian crisis in Yemen while in part driven by the contraction in economic activity, has been mainly driven by the collapse of public and foreign exchange revenues–mostly from oil production–and the suspension of public salary payments in large parts of the

country. Cumulatively, it is estimated that oil GDP contracted by 72 percent throughout the conflict.

Regional distribution of real GDP growth

Since March 2015, aggregate predictions for oil GDP and non-oil GDP growth show important contractions of economic activity. Oil GDP and non-oil GDP are estimated to have contracted by 72 percent and 21 percent respectively. Yet, while these estimates are lower than official figures from the Ministry of Planning and available oil production data from the U.S. EIA, these also hide a heterogenous situation at the sub-national level.
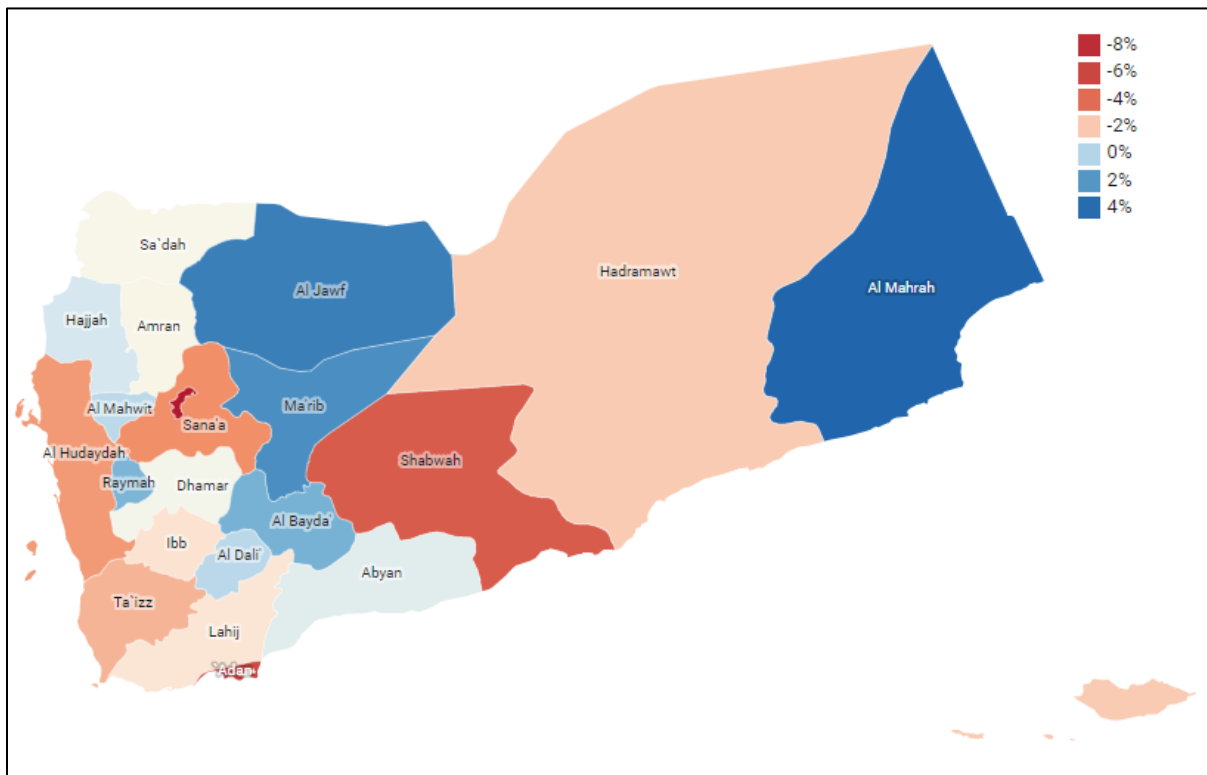
Figure 12. Governorate contributions to cumulative real GDP growth: 2015-17

In order to investigate the geographical distribution of economic developments in Yemen since the beginning of the conflict in March 2015, I use data on total nightlights and gas flaring at the governorate level. I redistribute the predicted oil and real GDP data for each year based on the share of each governorate in total nightlights and gas flaring data. Gas flaring data is available for the three oil producing governorates of Marib, Hadramawt and Shabwah. To disentangle light from electric sources and from flaring in these regions, I estimate the share of lit-pixels from gas flaring and apply this share to total nightlights. While this method is not optimal because it assumes that lit-pixels from gas flaring and from electric sources generate the same light intensity, it remains a good proxy of the share of total nightlights from flaring

activities. For regional oil GDP, I redistribute predicted oil GDP based on the relative intensity of gas flaring in the three oil-producing governorates. I then substract oil GDP from predicted real GDP at the aggregate level to obtain a measure of non-oil GDP. This predicted measure of non-oil GDP is then distributed across governorates based on the intensity of nightlights from electric source, including oil-producing governorates. Doing so, I obtain estimates of real GDP and non-oil and oil GDP at the governorate level from 2012 to 2017. I then compute growth rates at the subnational level and contributions to aggregate real GDP growth throughout the conflict.

Governorate contributions to real GDP growth over 2015-17 are represented in Figure 12[20]. This map shows that while Yemen suffered a massive contraction of economic activity at the aggregate level, some governorates were particularly affected while some others contributed positively to real growth despite the ongoing conflict. In particular, Aden and the capital city Sanaa which concentrated most economic activity together contributed to about 15 percentage points of the aggregate contraction. As oil production collapsed to very low levels throughout the conflict, the governorates of Hadramawt and Shabwah contributed subtantially to the aggregate contraction with a combined contribution of -6 percentage points. Western governorates of Al Hudaydah, Ibb and Taizz also displayed massive contractions. On the countrary, the governorates of Al Jawf and Al Mahrah stood as exceptions as their contributions to real GDP growth have been positive throughout the conflict (around 7 percentage points). A common feature of these two governorates is their proximity with neighboring countries and the existence of trans-national trading relationship which in the case of Al Mahrah may somehow have helped mitigate the adverse impact of the conflict. Finally, Marib contributed positively to aggregrate GDP growth benefiting from business relocations from the capital Sanaa and trade flows diversion. Among the three oil-producing governorates, it is also the only one where oil GDP growth was positive.

V. CONCLUSION

Using an untapped source of satellite-recorded nightlights data for a sample of 72 countries over 6 years, I estimated and characterized the contraction of economic activity in Yemen throughout the ongoing conflict that erupted in March 2015. I showed that while economic fundamentals were already weak before 2015, the economy drastically contracted as a consequence of ongoing hostilities. I estimate the cumulative contraction of real GDP over 2015-17 to be around 24 percent–with a lower-bound estimate of 34 percent. This contraction has been driven both by oil and non-oil GDP with the former decreasing faster than the latter at the beginning of the period and then recovering in 2017.

The data also suggest the impact of the conflict has been geographically uneven. While the predicted aggregate collapse in real GDP may have been lower than official figure from

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[20] Detailed figures on contributions to real GDP growth are reported in Table A4 in the appendix.

the Yemeni Ministry of Planning suggest, predicted growth contributions at the governorate level show that some regions have been much more impacted than others. In particular, most regions across Yemen exhibited a contraction in economic activity, but some appeared to contribute positively to aggregate real GDP growth.

It is also worth noting that while the model's predicted contraction in economic activity is smaller than that presented in official data, it *does not* imply that the current humanitarian crisis has been less harsh than presented by humanitarian agencies. In particular, the collapse in oil GDP–documented in the predictions–which remained the first source of revenues to the government and the suspension of public salaries payments are the main causes of the humanitarian crisis. Additionally, the geographic heterogeneity of the impact of the conflict could also explain that despite a milder predicted contraction of economic activity, Yemen remains the worst contemporaneous humanitarian crisis.

Overall, this paper shows that in conflict-settings, satellite images provide a precious tool to assess and characterize economic developments. This technique is also particularly useful for countries with low statistical capacity to confront the quality of national accounts data and detect anomalies. Future research could leverage other sources of satellite images such as records of infrastructure development and other physical assets in order to cross-check the conclusions drawn from nightlights-based techniques in Yemen but also more widely in conflict-afflicted countries.

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APPENDIX

Table A1. Summary Statistics

Variables	Mean	SD	Min	Max	Count	Sample
ln(TNL)	14.645	2.475	1.665	18.749	432	Full
ln(GDP), cst LCU	6.480	3.049	-1.685	15.758	432	Full
ln(GDP), PPP cst 2011 US$	3.806	1.760	-0.686	7.395	432	Full
ln(Radiant heat)	1.675	0.812	-0.225	3.514	168	Oil producers
ln(Oil GDP)	5.216	3.262	-0.041	14.288	168	Oil producers
ln(Oil prod.)	6.016	1.777	2.398	9.424	168	Oil producers
Fragile States Index	85.687	15.114	43.700	114.900	432	Full
Statistical Capacity Index	61.470	15.307	20.000	95.556	396	N/a for Bahrain, Kuwait, Oman, Qatar, Saudi Arabia and UAE

Table A2. List of Countries for Panel Regressions

Real GDP equation (72 countries)		Oil GDP equation (28 countries)
Afghanistan	Liberia	Algeria
Algeria	Libya	Angola
Angola	Madagascar	Azerbaijan
Armenia	Malawi	Bahrain
Azerbaijan	Mali	Cameroon
Bahrain	Mauritania	Chad
Benin	Morocco	Democratic Republic of the Congo
Botswana	Mozambique	Egypt
Burkina Faso	Namibia	Equatorial Guinea
Burundi	Niger	Gabon
Cabo Verde	Nigeria	Ghana
Cameroon	Oman	Iran
Central African Republic	Pakistan	Iraq
Chad	Qatar	Kazakhstan
Comoros	Republic of Congo	Kuwait
Côte d'Ivoire	Rwanda	Libya
Democratic Republic of the Congo	Saudi Arabia	Niger
Djibouti	Seychelles	Nigeria
Egypt	Sierra Leone	Oman
Equatorial Guinea	Somalia	Qatar
Eritrea	South Africa	Republic of Congo
Ethiopia	Sudan	Saudi Arabia
Gabon	Swaziland	Sudan
Georgia	São Tomé and Príncipe	Tunisia
Ghana	Tajikistan	Turkmenistan
Guinea	Tanzania	United Arab Emirates
Guinea-Bissau	Gambia	Uzbekistan
Iran	Togo	Yemen
Iraq	Tunisia	
Jordan	Turkmenistan	
Kazakhstan	United Arab Emirates	
Kenya	Uganda	
Kuwait	Uzbekistan	
Kyrgyzstan	Yemen	
Lebanon	Zambia	
Lesotho	Zimbabwe	

Table A3. Real GDP (PPP, constant 2011 U.S. dollars) and Total Nightlights

	ln(GDP) (1)	ln(GDP) (2)	ln(GDP) (3)	ln(GDP) (4)	ln(GDP) (5)	ln(GDP) (6)
ln(TNL)	0.080***	0.053**	0.211***	0.156***	0.119***	0.296***
	(0.026)	(0.026)	(0.078)	(0.033)	(0.033)	(0.078)
ln(Radiant heat)		0.107***	0.106***		0.099***	0.098***
		(0.022)	(0.020)		(0.022)	(0.020)
FSI			0.005			0.008
			(0.012)			(0.012)
ln(TNL)*FSI			-0.002**			-0.002**
			(0.001)			(0.001)
Cluster in 2017	No	No	No	Yes	Yes	Yes
Observations	432	432	432	432	432	432
Countries	72	72	72	72	72	72
Within R^2	0.212	0.262	0.373	0.250	0.291	0.411

All regressions include country and year fixed effects.
Standard errors in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A4. Governorate contributions to cumulative real GDP growth in Yemen: 2015-17

Governorate	Total GDP *in percent*	Non-Oil GDP *in percent*	Oil GDP *in percent*
Abyan	-0.1	-0.2	-
Aden	-5.8	-6.2	-
Al Bayda	0.4	0.4	-
Al Dali	0.0	0.0	-
Al Hudaydah	-3.4	-3.6	-
Al Jawf	3.1	3.4	-
Al Mahrah	4.2	4.6	-
Al Mahwit	0.0	0.0	-
Amanat Al Asimah (Sanaa city)	-9.7	-10.4	-
Amran	-0.5	-0.6	-
Dhamar	-0.4	-0.4	-
Hadramawt	-1.9	-1.3	-10.1
Hajjah	-0.1	-0.1	-
Ibb	-1.0	-1.1	-
Lahij	-0.8	-0.9	-
Marib	2.5	2.6	1.2
Raymah	0.2	0.2	-
Saadah	-0.5	-0.5	-
Sanaa	-3.6	-3.8	-
Shabwah	-4.2	0.2	-63.2
Taizz	-2.6	-2.8	-
Total	-24.2	-20.7	-72.0

Estimates based on the methodology described in section IV.