How much oil is Daesh producing? Evidence from remote sensing

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Abstract

Many terrorist organizations and insurgencies such as Daesh – also known as ISIL/ISIS– tap oil as a revenue source. Accurately measuring oil production may assist efforts to address such threats by providing a tool for assessing their long-run economic potential, and may inform reconstruction strategies in conflict-affected areas. We use satellite multi-spectral imaging and ground-truth pre-war output data to effectively construct a real-time census of oil production in Daesh-controlled areas. We estimate a production that peaked at 33,000 barrels per day in July 2014, which then fell to a 2015 average of 19,000 barrels per day.

Introduction

The non-state insurgent organization known as Daesh (also sometimes called the Islamic State [IS], the Islamic State of Iraq and the Levant [ISIL], or the Islamic State of Iraq and al-Sham [ISIS]) has taken control of large swathes of territory in Syria and Iraq since mid-2013 (see map in Figure 1). Its rapid territorial expansion began when fighters from the Islamic State of Iraq (ISI) started operating in Syria in April 2013 and accelerated from early 2014 onwards when the group moved aggressively back into Iraq (*27*). Daesh is currently considered the richest jihadist group in the world and is thought to raise money from a variety of sources (*15*). Revenue from oil production in areas Daesh controls has been cited as the organization's largest potential source of revenue, with estimates of weekly oil revenue ranging from "several million" to US$28 million (*5,8*). Any reasonable assessment of the organization's long-run survival must account for these revenues and identify how sustainable they are (*21*).

Remotely measuring oil production using satellite imagery provides a way to make that assessment. In our case,combining multi-spectral imaging with available production data enables transparent replicable estimation of oil production in Daesh-controlled areas. We find that production levels decreased from a peak production of 33,000 barrels per day (bpd) in July 2014 to an average of 19,000 bpd throughout 2015.

Detailed study of news outlets reports, agencies' press releases and Institute for the Study of War (ISW) maps allow us to assign to control of Daesh at the daily level. We use data from Visible Infrared Imaging Radiometer Suite (VIIRS), sensor deployed on the NOAA/NASA Suomi NPP satellite, to assess the status of each of the sites and then impute the appropriate level of productivity. At a given moment, a site can be either actively flaring, venting or inactive 1. In the case of venting, ie the site is not burning excess gas yet there are enough electric lights to indicate human activity, we assign historic values of productivity. The calibration is carried out by matching Wood Mackenzie production data to the satellite detections using GIS files of fields in the region.

Our paper contributes to the literature that investigates the role of natural resources in shaping conflicts. For instance De la Sierra (2014) finds that positive prices shocks to a bulky commodity leads armed groups to create a monopoly of violence to impose taxation and regulate production in Eastern Congo. Along the same lines, Maystadt and al (2014) use mineral international price changes and data on historical concessions to show that armed groups tend to reduce violence in areas near the mines. This "protection effect" is consistent with violence reducing economic profitability through higher labor costs. Bellows and Miguel (2009), Humphreys and Weinstein (2006) suggest that fighting around diamond mines did not affect civilians in Sierra Leone, but was rather limited to violence among soldiers. This result is echoed by Ziemke (2008), which finds that violence against civilians was lower in diamond areas in Angola. Finally, Dube and Vargas (2013) find that price shocks have heterogeneous effects: in labor-intensive sectors, commodity price drops result in higher incentives to join armed groups, while in the capital-intensive sector the rise in the price elicits predatory behavior from armed groups.

The rest of the paper is structured as follows. Section 1 provides some context and describe our methodology, while section 2 presents and discusses the results of the analysis. Section 3 concludes. Details about the methods are availble in Appendix A; supplementary materials can be found in Appendix B.

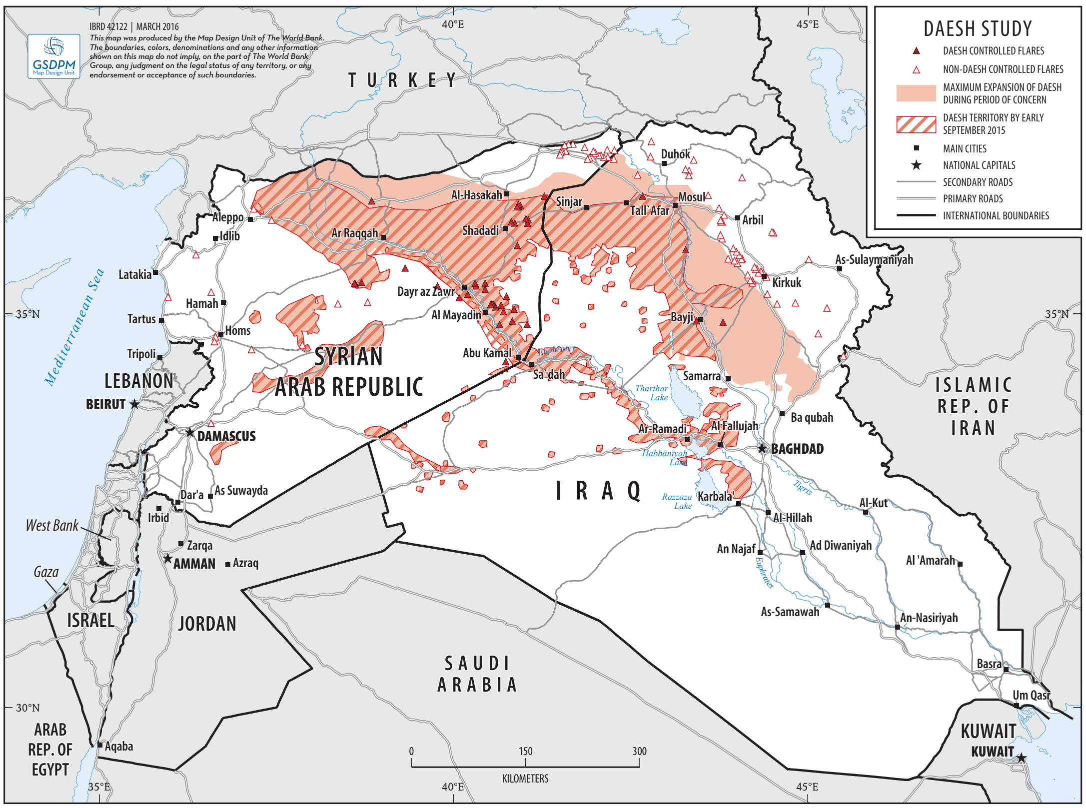
1 Background and methodology

1.1 Context

During our period of study, 42 production sites in both Syria and Iraq (34 in Syria and 8 in Iraq; see map on Figure 1) had been or are under Daesh control, out of a total of 75 identified oil sites in Syria and 114 in Iraq (see Annex A section 1.3 for details on the identification of oil assets and the delineation of Daesh territorial control).

Early accounts of Daesh oil production and the revenues generated indicated that oil is a significant source of financing for the organization. The 2014 Oil Market Report of the International Energy Agency estimates an output of 70,000 barrels per day (bpd) (*24*). Other news outlets give numbers around 50-60,000 bpd yielding an income of US$2.5m per day (*31*) to more than US$3m per day (*1*). Early estimates by the US Treasury Department put the organization's oil revenues at around US$1m per day (*38*). These estimates were then revised down to "a couple million dollars a week" after the U.S. started the airstrikes against the organization's assets (*4*). Views as to whether Daesh was financing itself through oil, external support, extortion, or taxes then evolved, with higher emphasis put on taxes and extortion as primary sources of revenues over time. Die Zeit for instance reported December 2014 oil revenues to be a mere US$370,000 per day or even lower at US$260,000 (*9*). An October 2015 article however gives an estimated output of 34-40,000 bpd, earning the organization an average of US$1.5m per day (*16*). In sum, there appears to be no consensus on these numbers.

Figure 1: Iraq and Syria Oil Production, Fields, and Daesh Control



1.2 Remote sensing estimation of oil production with gas flaring

Our approach relies on the property that the extraction of oil is associated with the liberation of natural gas, primarily methane, which is initially dissolved in crude oil in constant proportions. The gas is typically collected and flared unless infrastructure exists to either re-inject the gas into the field, utilize the gas on-site, or package and send the gas off to markets (*28*). Flaring is the generic method of natural gas disposal in Syria and most of Iraq, as it is in most of the world (*41*).[1] Remote sensing from the Visible Infrared Imaging Radiometer Suite (VIIRS) sensor deployed on the NOAA/NASA Suomi NPP satellite (*12*) allows the use of multi-spectral methods (*12, 14*) to estimate a flare's radiant heat (RH), a measure of the heat released with the combustion of the natural gas. RH is thus an indicator of the volume of gas flared, which in turn is a predictor of the volume of oil extracted.

Figure 2 plots the relationship between yearly oil production and measured RH in 2012-15 for the 11 significant oil fields that are deemed comparable of the fields Daesh now controls. Each dot represents the logarithm of yearly oil production level (vertical axis) and the logarithm of yearly RH (horizontal axis) for any given oil field in our estimation sample.The line shows the slope of the oil-RH relationship estimated by ordinary least squares, while the shaded area is the 95 percent confidence interval.

Under the assumption that the oil-RH relationship estimated using data prior to the seizure of oil fields by Daesh still holds thereafter, we can make unbiased statistical inference about *contemporaneous* volume of crude oil extracted from *contemporaneous* measures of RH.

1.3 Remote sensing assessment of oil production with gas venting

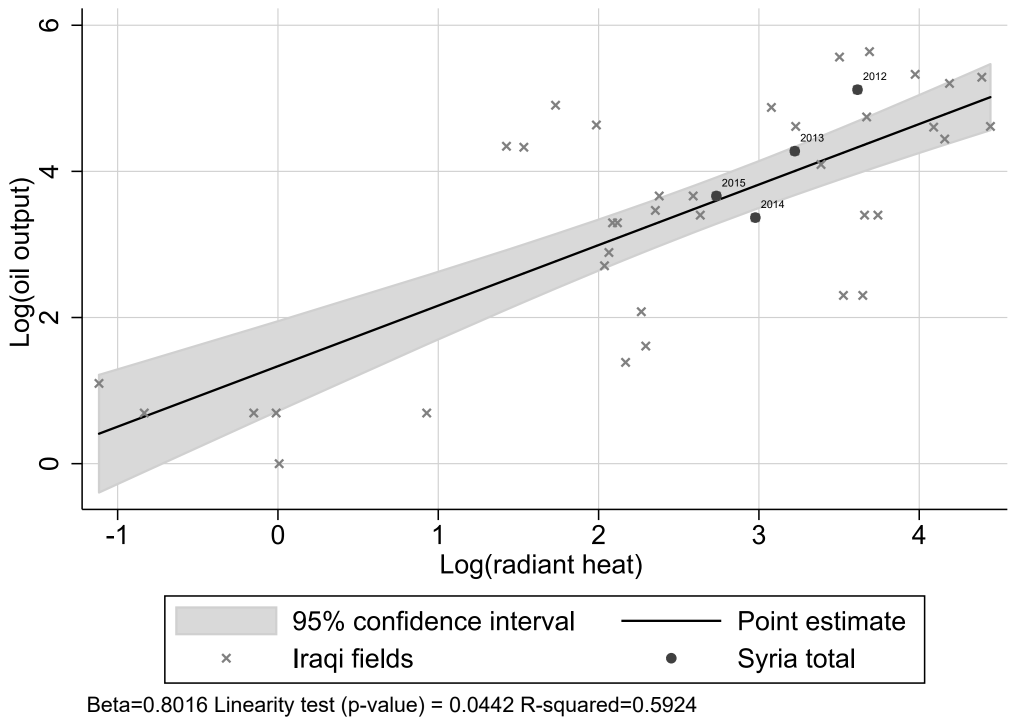
At any given moment, a site is in one of three *production states*:

- $S1$**: The site is producing with natural gas flaring** Iraq is among the countries with the highest volume of gas flared per unit of oil produced and like Syria, did not have any regulatory limits on flaring before the war (*41*). Oil production with flaring is thus the generic production state when a site is producing oil.

- $S2$**: The site is producing without gas flaring (i.e. venting)** A site that extracts crude oil could simply vent the accumulated natural gas. Although venting is wasteful and harmful

[1]Large fields in southern Iraq where Daesh is not present have undertaken flaring reduction projects to collect the natural gas for economic uses.

Figure 2: Radiant heat and oil output



Note: This figure plots the linear regression of the logarithm of field RH against the logarithm of field oil output on the vertical axis. (see Annex A section 1.4 for details on estimation sample). Data sources: (*39, 40*) and NOAA.

to the environment, methane is lighter than air so that controlled venting (e.g. through a stack) would not constitute a fire or explosion hazard. Venting would happen on a site if (i) the operator voluntarily shuts down the pilot flame in the flare stack, or (ii) long periods of inactivity extinguish the pilot, which is not re-ignited as production resumes.

- $S3$**: The site is inactive** A site might become inactive if fighting has damaged productive infrastructure or no qualified personnel are available to operate the site.

Distinguishing between these production states is important since the lack of RH does not necessarily imply an absence of oil production; venting remains a possibility. Because the narrow spectral bands used in the estimation of RH – the near-infrared (NIR) bands M7 and M8, the short-wave-infrared (SWIR) band M10, and the mid-wave-infrared (MWI) bands M12 and M13 – are not sensitive enough to detect low light from low-intensity flaring, we also make use of data from VIIRS' Day/Night band (DNB). DNB is a wide, visible, and NIR imaging spectral band, designed to detect moonlit clouds. The DNB's low detection limits make it possible to detect electric lighting present at the Earth's surface (*7, 26, 29, 35, 42*), which cannot be sensed in the infrared spectral channels; it is even sensitive to moonlight reflection on the Earth. DNB detection, once the effect of the lunar cycle has been accounted for (*11*), therefore allows discriminating between states $S2$ and $S3$ when no infrared signals are detected.

2 Results

Overall flaring activity at Daesh-controlled sites appears quite low. Using the classification approach above we find that the average Daesh site was in condition $S1$ (flaring) 14 percent of the time, in condition $S2$ (venting) 22 percent of the time; in the remaining 64 percent of the time, the average site is inactive (state $S3$).

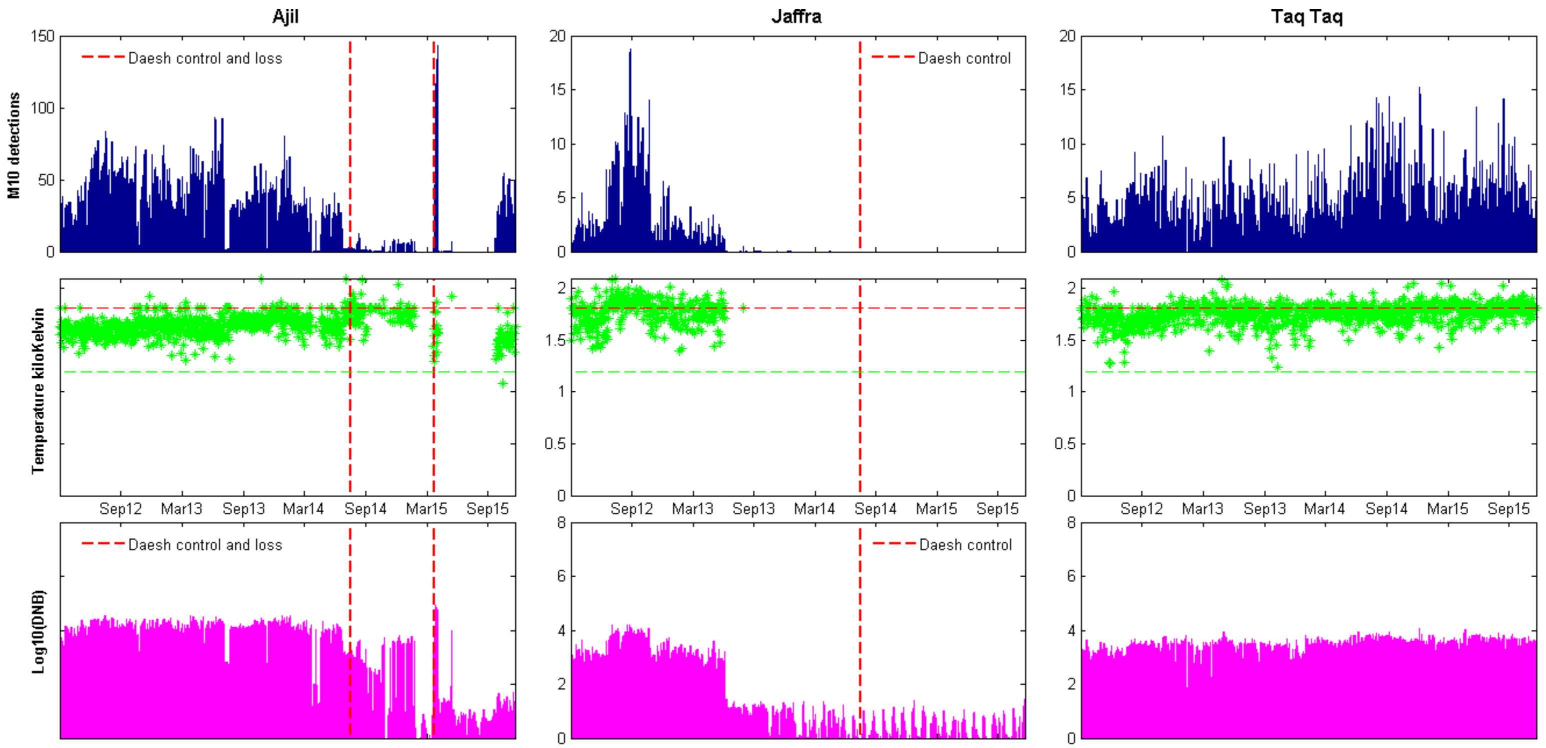
2.1 Interpreting remote sensing data: case studies

To provide a precise understanding of how trends over time show up in our data, Figure 3 plots the time-series of M10 detection (top row), temperature (middle row), and DNB radiance (bottom row) for three fields in Iraq and Syria.

Ajil (left column) is situated northeast of Tikrit near the Hamrin Mountains in Iraq. Daesh took control of the field in June 2014 and continued production without interruption until January 2015. The field was set on fire by the group to counter an attack by Iraqi forces attacks in late-March 2015. An engineer at the site told Reuters in July 2014 that Daesh fighters were pumping low volumes of oil from the field (*20*). As shown in the M10 detection panel, the site saw normal flaring activity through mid-June 2014. At the time Daesh takes over, flaring intensity drops substantially but sporadic temperature detections continue through January 2015 and during that low-intensity period, the DNB measures are mostly greater than would be possible with electrical lighting. This activity is consistent with Daesh pumping small volumes of oil using the in-place infrastructure. From January to March 2015 there is no activity at the site; only the lunar cycle lighting is detected (bottom row). The spike in M10 detections and DNB intensity in late-March 2015 correspond to the reported burning of the field by Daesh forces. Fighting in the area continued into mid-April 2015, consistent with ongoing DNB detections which sometimes cross the threshold for flaring but could be battle-related (e.g. burning vehicles). After Tikrit is fully retaken in late-2015 and the surrounding area secured, there is continued low-level DNB radiance at the site, which could reflect human activity associated with efforts to resume production.

The radiance reading from the site of Jaffra (middle column) on the other hand tells a different story. The Jaffra oil field is in the western part of Deir Ezzour Governorate in Syria. This major field reportedly had a capacity of 25,000 bpd but it has not flared since June 2013 and there are no signs of activity since November 2013. The DNB band shows nothing but the lunar cycle. Conversely, the M10 and DNB detections for Taq Taq (right column) provide a sense of what normal activity looks like a flare in the an area controlled by the Kurdish Regional Government (KRG). Taq Taq oil field is southeast of Erbil. It shows a consistent and continuous production in our period of observation. In 2014, it produced at a rate of 103,000 bpd.

Figure 3: M10 and DNB over time



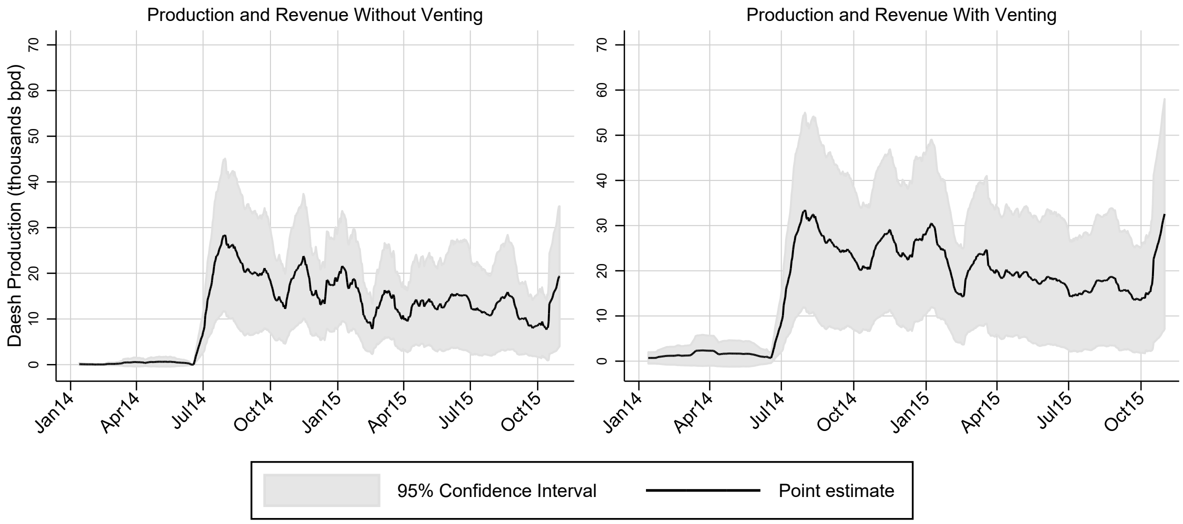
This figure shows the time series of M10 and DNB detections from 2012 through the present for Flares in Ajil and Taq Taq in Iraq, and Jaffra in Syria Temperatures are in kiloKelvin.

2.2 Production Estimates

The analysis of the 42 sites that have ever been under Daesh control reveals that the group's production peaked in July 2014 and has been slowly declining since then, with a possible small increase in late-2015. Figure 4 shows production estimates with 95 percent confidence intervals (panel A) from January 2014 through late-2015 using the approach and assumptions discussed above. Column (1) shows the results assuming no production when we do not observe flaring. That represents our low-end estimate. Column (2) shows the results when we assume that fields are producing with venting on days with DNB detections above the lunar illumination threshold but below the flaring one ($S2$).

Based on these estimates Daesh oil production peaked at roughly 33,000 bpd in late-July 2014 and declined steadily thereafter until rising again in late-2015. Though the 95 percent confidence interval on our estimates assuming significant venting is as high as 55,000 bpd in summer 2014, the differences between production estimates with and without venting are modest.

Figure 4: Production Over Time



Note: This figure shows the 28-day moving average of production estimates in barrels per day with 95 percent confidence intervals

These findings are consistent with other estimates for the early period of Daesh control that relied on captured documents (*8*). Yet they likely represent an upper bound on Daesh oil production. First, if the gas-to-oil ratio (GOR) has been increasing over time, inferences from our pre-war estimation, based on the assumption that the GOR remained constant, will over-estimate Daesh output when converting RH to oil production. Second, our assumptions are, by design, biased towards over-estimating rather than under-estimating production. For example, the cutoff value we choose to separate electric lights from low-intensity flaring is set at a level that rules out electric lights with probability one, while infrared detection still happens at much lower levels of radiance. In Annex A section 1.4.4, we gauge the robustness of our inferences to alternative assumptions on the way we determine production states and compute RH. Resulting production estimates vary little and stay within a 30 percent range of our baseline specification.

3 Conclusion

Based on estimates derived from remote sensing, the oil production in territory the group controlled peaked at 33,000 bpd in July 2014 and has been slowly declining since. These results lend support to the views that Daesh is financing itself out of other sources such as taxation and extortion rather than oil. For comparison, AFPC and DZPC fields (majority of which are now under Daesh control) used to produce around 110,000 bpd before the war (*6*), while Taq Taq field in the Kurdistan Region of Iraq (KRI) alone produced 103,000 bpd in 2014. On the revenue, side there is no reliable price data on which to base estimates. Early reports recount that Daesh was selling at a discounted price, ranging from \$20 to \$35 dollars in 2014 (*34*), while a more recent report indicates that prices depend on the field of origin, and that some fields charged \$40 to \$45 dollars per barrel (*17*).

One reason why our estimates differ dramatically from many of the publicly-available ones primarily has to do with sampling issues. These estimates all rely on what is effectively a *survey* of Daesh's oil assets. Information is obtained from a few selected sites and at specific dates on the basis of key documents or interviewee self-reports, which are then extrapolated. In spite of being supplemented with expert opinions, generalizations to the universe of Daesh-controlled oil facilities are intrinsically imprecise in that the underlying data have observations that are few and might not be representative, therefore leading to imprecise if not biased inferences. Updating these estimates over time faces similar methodological challenges.

The approach proposed here instead conducts a *real-time census* of Daesh oil production facilities. The estimates coming from our analysis are thus not inferences made from observations on a few selected sites and at a few selected dates but from all sites and in real time.

Our study aims to help bridge the knowledge gap on the economic activity in Daesh-controlled territories. The results here can be built on to inform planning for short-term humanitarian assistance and long-term reconstruction. We also provide a methodological contribution in that reliable external measures of oil output can enable better approaches to a broad range of policy challenges. In Colombia and Nigeria, for example, insurgent organizations have long controlled territory where oil is produced. Across the world's poorly governed States, few report reliable oil production numbers. Yet assessing production is critical for making sound economic policy and can enable governments and international organizations to identify illegal or untaxed production.

Understanding the structure of the economy in Daesh-controlled areas is important as it allows having a better image of the welfare of the local population and anticipating potential humanitarian needs in the region. Furthermore, taking stock of the status of the oil infrastructure will help design reconstruction plans, and inform post-conflict redistributive policy intervention.

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A Materials and Methods

1.1 Classification of production states

Infrared detection rules out venting and site inactivity, as the observed radiance indicates night fires that are almost surely natural gas flares given the location of the observed signal. The flaring site is thus in state of production with flaring when infrared signals are detected. However, depending on the temperature and the surface area of the gas flare, detection on one or more sensors will occur. Figure A.5 shows the distribution of radiance for M10 detections in our study sample. No infrared signal was detected with a radiance below 0.01 $W.sr^{-1}.m^{-2}.nm^{-1}$.

While lower-intensity flares fail to trigger an M10 detection, they always do so on the wide-band DNB. Thus, when no infrared signal is detected, we rely on DNB to assess which state a given flaring site is in, since low-intensity flaring could well go undetected by infrared sensors. However, given the sensitivity of DNB to lunar illuminance, we first proceed by suppressing the radiance effects stemming from moonlight reflection on the Earth or on clouds at night. Such procedure yields the Spike Median Index (SMI), which allows detecting the presence of surface lighting and ranking the brightness of sources over extended periods of time (*11*).

Figure A.6 shows the distribution of SMI measurement over four sites which are relatively isolated: three small towns in Syria and a regional airport in Lebanon. The only source of nighttime lighting in these four sites is electric.

As indicated on the histogram, no signal above an SMI value of .6 was detected over the period March 2012 to October 2015, at the exception of a few outliers. We thus consider that SMI levels observed on flaring sites above .6 are associated with low-intensity flaring, so that the site is in state of production with flaring ($S1$). Conversely, when SMI indicates that no significant night-time light is detected above the lunar cycle for a period of 7 consecutive days, we rule out venting and determine that the site is inactive. Alternative cutoffs for SMI and

Figure A.5: Distribution of infrared detections by M10 sensor

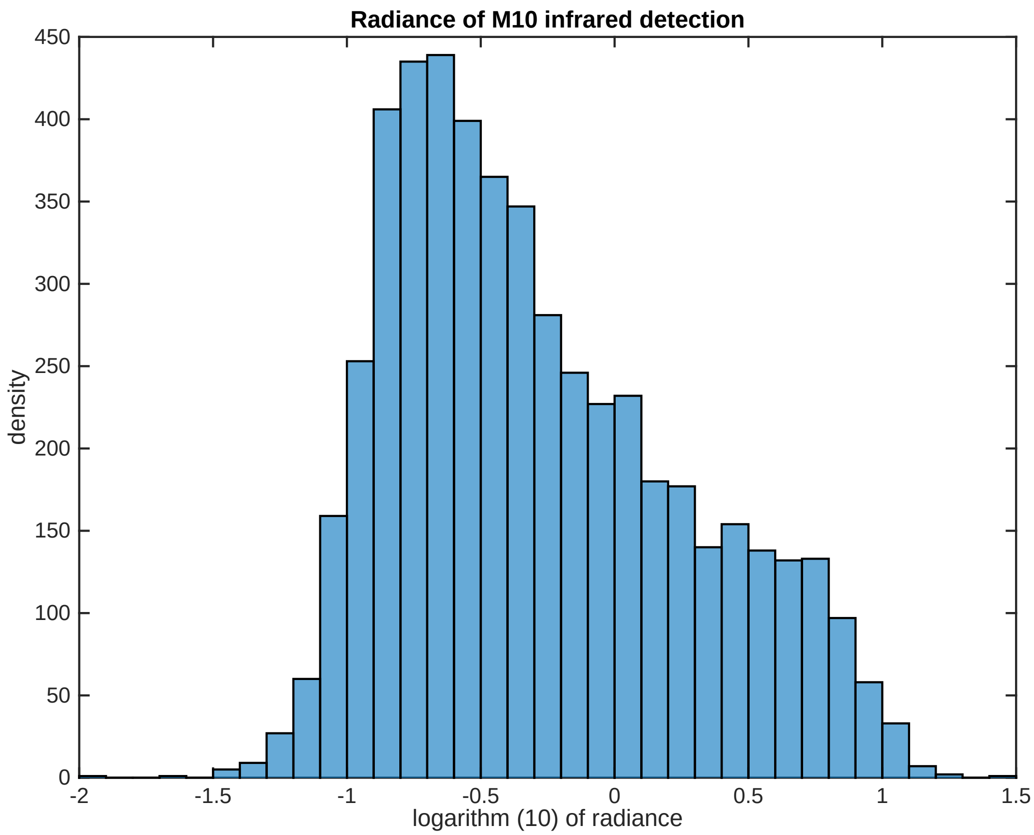
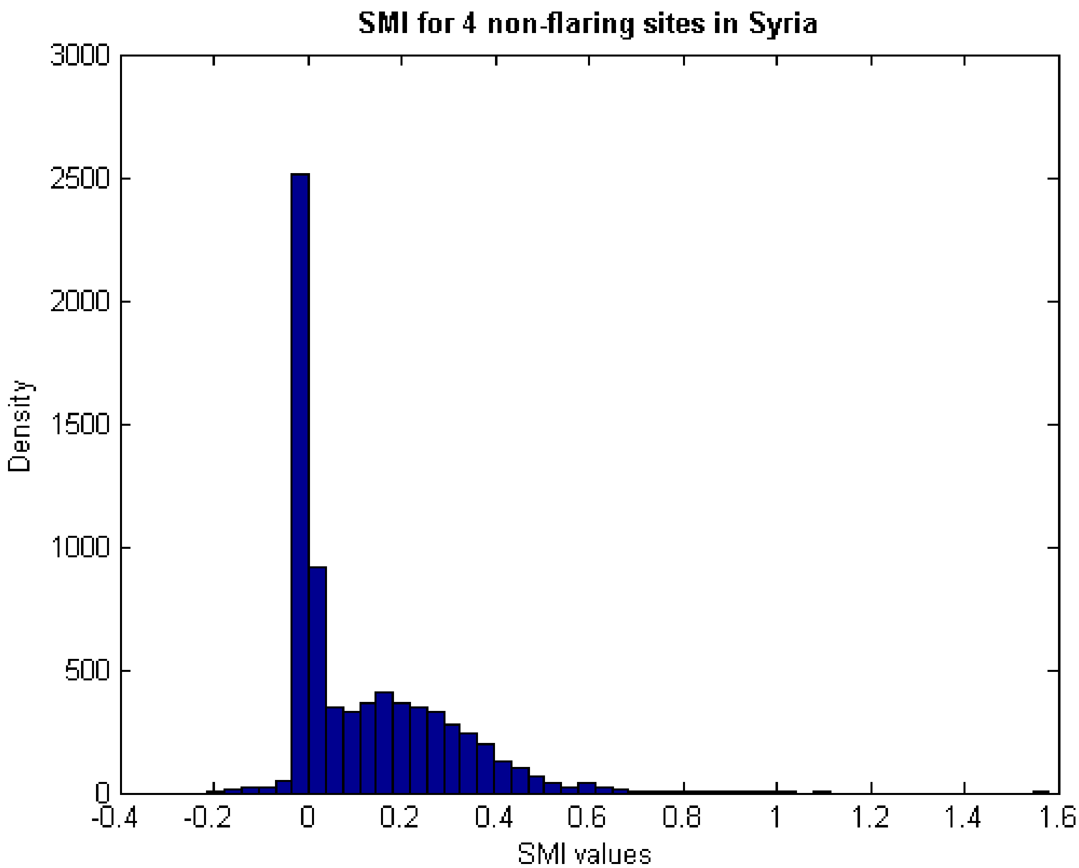


Figure A.6: Distribution of SMI detection from electric lights



number of days of inactivity are considered to assess the robustness of our results (see Figure A.8 and corresponding discussion in Annex B section 1.4.4).

Finally, when venting cannot be ruled out because either (i) SMI is low enough so that electric lighting could be the sole source of light detected, or (ii) SMI is high enough to rule out site inactivity, we determine that oil is extracted without natural gas flaring (state $S2$). The DNB signals are thus posited to come from infrastructure or automative electric lighting.

The results of the production state identification exercise are summarized in Table A.1. For each site, column (2) indicates the number of days it has been under Daesh control, while the three other columns gives the percentage of these days that were in states of flaring ($S1$), venting ($S2$), and inactive ($S3$), respectively. Sites under Daesh control are on average inactive 64 percent of the time, while actual flaring is detected only 14 percent of the time. The remainder are cases where, because we cannot rule it out, are assumed cases of venting and consist of 22 percent of our daily observations. Out of the 42 sites ever under Daesh control, regular flaring activity (with more than 10 percent of days with flaring) is identified for 12 sites, while 18 sites have been active less than 50 percent of the time.

We look at the robustness of our results by adopting alternative site production classifications (see section 1.4.4).

1.2 Imputing radiant heat

When signals have been detected in two or more infrared bands, we follow the multispectral methods outlined in (*14*) and (*12*), which we briefly summarize here after. The first step consists of using the radiances in the spectral bands with detection in Planck curve fitting. The fitting involves adjusting two parameters, temperature and emission scaling factor (esf). The Planck curve fitting thus requires detection in at least two spectral bands. Once a fit is derived, the esf is multiplied by the size of the VIIRS pixel footprint, which varies as a function of scan angle,

Table A.1: Summary of Daesh controlled flare states

Flare	(1) Days controlled	(2) Production(%)	(3) Venting(%)	(4) Inactive(%)
86	657	23	47	30
87	657	4	16	80
89	657	8	10	82
96	657	0	2	98
102	450	0	2	98
118	473	0	5	95
128	196	7	93	0
137	486	41	15	43
143	486	0	2	98
144	486	85	15	0
158	486	0	3	97
159	486	0	5	95
164	486	5	95	0
166	486	68	32	0
169	486	1	44	54
171	486	24	76	0
182	485	7	84	9
183	486	0	1	99
184	485	0	3	97
187	485	23	16	61
188	486	0	1	99
193	471	77	23	0
194	485	0	1	99
195	471	0	14	86
196	471	0	2	98
197	471	33	32	36
199	471	0	3	97
200	471	0	2	98
202	471	0	2	98
208	471	45	55	0
209	485	0	2	98
210	471	0	5	95
211	471	0	2	97
212	471	0	1	99
247	465	4	91	5
259	465	30	21	49
271	465	3	6	91
280	465	9	30	62
313	226	42	31	27
319	226	0	0	99
333	229	0	3	96
786	485	44	54	2
Total	**19725**	**14**	**22**	**64**

to estimate the source size of the hot object. Radiant heat (measured in MW) is then calculated with temperature and source size using the Stefan-Boltzmann law.

In case of single-spectral infrared detection, Planck curve fitting is thus no longer feasible; we instead set temperature at 1810K, which is the temperature of an object with peak radiant emissions at the M10 wavelength. Alternative temperature assignment rules are considered (see Figure A.8 and corresponding discussion in Annex B section 1.4.4).

Finally, if we do not have infrared detection and have yet determined that the site is flaring (state $S1$), we measure DNB radiance and, as above, set temperature to 1810K to apply the Stefan-Boltzmann law and derive the associated RH. Note however that in such instance, the observed radiance aggregates radiance from gas flaring and any other source of lights not filtered out by the SMI such as facility or automotive electric lighting; the resulting measure is then an overestimate of RH from gas flaring.

When a site is deemed inactive (state $S3$), a value of $RH = 0$ is then assigned for each day of these 7-day periods.

Finally, when a state of production with venting is identified (state $S2$), we make the assumption that the site is producing at a level equivalent to the median of its historical production since being taken over by Daesh. If such level is equal to zero or is not defined because there was no detected infrared signal, we instead set venting production at the median pre-war level: we assign the median RH of all measured RH prior to July 2012.

1.3 Identifying oil assets and assigning control

1.3.1 Identifying flaring sites

All nighttime VIIRS data over Syria and Iraq, spanning March 2012 through October 2015, were processed with the VIIRS nightfire algorithms (*14*). The detections were ingested into a spatial database for analysis. Sites were included when (i) one multispectral band detection occurred over the period March 2012 - October 2015 with a temperature above 1300K, or (ii) two detections occurred regardless of temperature. The resulting set of pixels was then visually inspected and manually edited to remove low temperature sites (under 1300 K) located in agricultural settings, deemed to be the outcomes of biomass burning.

To further ensure that the flaring sites identified by the algorithm described above did correspond to natural gas flaring associated with oil production, we verified the presence of oil production infrastructure around the detected flares. Daytime satellite imagery were obtained from Google Earth and Esri's World Imagery Map. Google Earth combines imagery dating to as early as 2004 from a range of providers at varying resolutions over the area. Esri's World Imagery Map also collates satellite and aerial imagery from a range of providers; however, Digital Globe provided the majority of images in the ISIS region of interest at 0.5 meter resolution during 2010-2012.[2]

A site was classified as having infrastructure if a flare stack was observed within 750 meters (the size of the pixels in the VIIRS data) of the detection coordinates in any of the available images.

Included images typically showed production facilities with a pipeline to the flare stack, though even sites with primitive infrastructure, such as simply a stack with a wall, were also included. Excluded sites fell into two categories. Either the site had no infrastructure, suggestive of agricultural burning or bombing, or the site had industrial facilities inconsistent with oil production, such as oil refineries. Figure A.7 shows an example of a site with infrastructure and a site without.

[2]The Esri data is available at `http://www.arcgis.com/home/item.html?id=10df2279f9684e4a9f6a7f08febac2a9`. The list of providers by region is documented at `http://help.arcgis.com/en/communitymaps/pdf/WorldImageryMap_Contributors.pdf`

Figure A.7: Examples of sites with and without oil production infrastructure

(a) Site without infrastructure

(b) Site with infrastructure

This figure an example of a site in ISIS territory without oil production infrastructure and an example of a site in ISIS territory with infrastructure. Panel A marks coordinates (40.561188, 35.029762) over image from Digital Globe on 28 June 2012. Panel B marks coordinates (40.56361, 35.115139) over the same image.

1.3.2 Delineating Daesh territorial control

Daesh territorial control spanned from the east of Fallujah to the north of the city of Aleppo (*17*). Most of the oil assets in Syria under Daesh control are in the eastern part of the country, i.e. in the governorates of Deir Ezzour and Hassaka, and to a lesser extent Raqqa. In Iraq, Daesh controls the Ajil field and oil wells in the Hamrin Mountains, the Qayara and Najma fields, and had access to parts of the Baiji refinery until October 2015. We assign control of fields by determining the date at which a site is taken by or away from Daesh using news reports in both English and Arabic and verifying this assignment with maps published by the U.S. Department of Defense, the New York Times, and the Institute for the Study of War.

Deir Ezzour: In this governorate, Daesh consolidated its control of the western part of the governorate within a few days. CNN reports the seizure of Al Omar field on July 3rd 2014 (*10*), while Al Arabiya indicates that Tanak field fell under Daesh control on July 4th (*3*). The rest of the western fields are not covered individually by news reports. Asharq Al Awsat announced that major fields in the governorate had been seized by July 11th (*9*). The hegemony of Daesh over that part of the governorate is confirmed around that time also; we thus assign the fields of Jaffra, Izba, Sijan, Abu Hardan, and others using the date of control of either the closest major field or the district capital. Al Arabiya reports that Al Mayadin city fell under Daesh control by the end of June, while Al Hayat and other sources report that Abu Kamal did so on July 1st (*1*). Finally the city of Deir Ezzour was contested for a while, and Al Jazeera announced on July 14th that the group seized control of a number of neighborhoods in this city, chasing out the opposition and other Islamist groups (*5*). On July 15th, the Syrian Observatory for Human Rights reported that 90 percent of the governorate had gone under Daesh control (*6*) and Al Jazeera announced that the group had seized all the fields in the governorate (*16*). On the Eastern side, there are only two major fields: local websites and social media feeds report

Al Kharrata field falling as soon as June 9th (*12*), while Al Thayem was reportdly seized in July 2014 and released in January 2015 (*4*).

Hassaka: The presence of Daesh in this governorate has been mostly restricted to the south and east of Hassaka city. The northern fields are still under the control of Kurdish forces. We date the control of Shadadi, Jebeisse, and Al Hol fields to July 18th, as reported by local news outlets such as Aljomhuria (*7*).

Raqqa: Individual reports on fields controlled by Daesh in Raqqa governorate are very limited. We instead look at reports on Daesh territorial control within the governorate to assign oil asset control. While Deutsche Welle reports that the governorate was not fully under Daesh control until August 2014 (*11*), Al Arabiya announced that the group had consolidated its control over the three district capitals by January 13^{th} (*2*) and Asharqalarabi reports that all the fields in Raqqa were seized in that month (*8*). We thus assign control of Raqqa oil fields to Daesh starting in January 13 2014.

Iraq: We assign control of the fields of Qayarra, Najma, Ajeel and Hamrin to Daesh starting June 24th. Reuters had reported the seizing of two of these fields (*14*), while International Business Times had announced that the four fields had fallen around the same time in June (*13*). Iraqi forces regained control of Ajeel and Hamrin fields on March 4 2015, as reported by Reuters; Daesh forces set fire to the oil wells as they were fleeing the scene (*15*).

1.4 Inferring oil output

To infer oil production we estimate a parametric model predicting pre-war liquid production estimates at the oil-field level with measured radiant heat and other field-level characteristics. As predicted by theory and documented by (*14*), there is a linear relationship between R_{it}, the radiant heat measured in period t at site i, and the volume G_{it} of gas flared: there thus exists a constant A such that $G_{it} = A \cdot R_{it}$. Furthermore, the constant ratio of natural gas dissolved in crude oil can be written $G_{it} = \Gamma_{it} \cdot O_{it}$, where Γ_i is the gas-to-oil ratio (GOR) that is also field- and time-specific. Substituting implies the following theoretical relationship: $O_{it} = \frac{A \cdot R_{it}}{\Gamma_{it}}$ that can be expressed in logarithmic terms as:

$$o_{it} = a - \gamma_{it} + r_{it} \tag{1}$$

Our estimating equation is thus

$$o_{it} = \alpha + \beta_1 r_{it} + \beta_2 \gamma_{it} + \varepsilon_{it}, \tag{2}$$

where lower-case notations indicate natural logarithm of corresponding upper-case variables and ε_{it} is the disturbance term that we assume to be independently and identically distributed across sites and time. A linear relationship between crude oil extraction and radiant heat would imply $\beta_1 = 1$.

Under the assumption that the relationship estimated in equation 2 is valid after the onset of the war, estimates $\hat{o}_{it}$ of oil production are obtained according to

$$\hat{o}_{it} = \hat{\alpha} + \hat{\beta}_1 r_{it} + \hat{\beta}_2 \gamma_{it}, \tag{3}$$

where $\hat{\alpha}$, $\hat{\beta}_1$, and $\hat{\beta}_2$ are estimated by ordinary least squares (OLS). The statistical software package used to that end is STATA version 14.

To construct the dataset used to estimate equation 2, we combine data on field-level characteristics (including oil output and GOR) with field-level radiant heat measures.

1.4.1 Consolidating oil production and field characteristics data

Information on oil field locations and production were collated from multiple sources. Oil field boundaries for Syria and Iraq were obtained from (*18*) and (*19*). The map lists the field name, operator, operational status, type, and utilization for each field. To supplement this data in Iraq, additional fields were digitized and added from IHS Global Exploration and Production Service's map of Iraq. This map displays the oil and gas field boundaries, field name, field status, as well as oil and gas well points. Yearly field-level production data in barrels per day from 2012 to 2015 in Iraq and Syria were obtained from (*18, 19*). Production data was matched to the field locations using the field name.

A few restrictions were applied to the sample of included fields. Including Syria and Iraq, 34 fields with production data could be assigned to boundaries according to their name. First, to ensure differences in the geology and production technology between oil fields southern Iraq and Daesh-controlled fields did not bias the estimation, 16 oil fields in south Iraq were removed. South Iraq oil fields were defined as any field below the southern most flare in Syria, 34.64 degrees latitude. Removing south Iraq reduced the sample to 18 oil fields. One field (Miran West) were dropped for having no production data. In total, 17 fields outside of southern Iraq were matched and included data.

Second, two fields were dropped due to inconsistencies in the production data. Ain Zalah (West Butmah) oil field, was removed due to data reliability: oil output was reported invariant during the entire production history, while corresponding RH levels differed significantly. Likewise, output was reported invariant during all years with data at Bijeel, 2014-2015, yet RH varied substantially. Removing fields with inconsistent production data results in 15 oil fields. Last, four fields, Gebibe, Hamrin, Hawler, and Tawke, were dropped due to a year to year changes in production that were not in proportion to the change in RH, indicating alterations in the technology or production process that would affect the stability of the oil to flaring relationship.

The final sample consists of 11 oil fields. Further, some individual years were missing production data. The two fields in Syria were missing production data in 2014 and 2015 and one field in Iraq was missing data in two years and had no RH in another year. The final data thus has 37 field year observations.[3]

The estimation employs additional data on the geological characteristics of each flare site to account for heterogeneity in the estimation of the flaring-production relationship. Field-level GOR were obtained from Energy-Redefined, and matched to the field locations according to the field name.[4] Each flare was subsequently assigned the GOR of the nearest field with a known GOR. We do not have field-level GOR data for recent years, so that our statistical inferences assume constant GOR. Field GOR however increases over time as the field ages and crude oil is being extracted. This implies that the assumption of constant GOR will lead to inferences on oil output that are biased upward.

1.4.2 Aggregating RH data

Since the dependent variable, field oil production, is measured yearly and at the field level, we aggregate daily observations on flare-level radiant heat into one yearly field-level measure. The linear relationship between RH and the volume of crude oil extracted allows linear aggregation.

First, each oil field in the production data was linked to gas flares located within its boundaries. In some instances, oil fields were linked to gas flares located beyond the boundaries if clear pipeline infrastructure linking the gas flare to wells within the boundary was observed in daytime satellite imagery (see section 1.3 in annex A for a discussion of the use of satellite imagery). Oil fields were not linked to sites in the VIIRS output where no oil stack infrastructure was observed in daytime imagery, even if the site's coordinates were within the boundary (see section 1.3 in annex A for discussion of infrastructure).

Finally, the radiant heat of each flare at each observation was averaged to obtain the flare-level yearly average radiant heat for 2012 to 2015. In calculating the averages, observations

[3]Four observations for the whole country of Syria were added to the final data for robustness check.

[4]Data were obtained from `http://www.energy-redefined.com/`

where the site was cloudy were excluded. Last, the yearly averages of all sites linked to a field were summed to obtain the field's yearly radiant heat. Since the VIIRS data does not include January and February of 2012, the production data was scaled to 306/366 of the year's total. Similarly, the 2015 data was scaled to 304/365 to adjust for November and December.

1.4.3 Estimation results

Table A.2 shows the result of the estimation of equation 2. In the first column, we do not include GOR in the regression, while column (2) shows the full specification shown in equation 2.

Table A.2: Oil output and radiant heat - estimation results

	(1) Logarithm oil output	(2) Logarithm oil output
Logarithm of radiant heat	0.828***	0.802***
	(0.0974)	(0.0949)
Logarithm of oil to gas ratio		0.305*
		(0.171)
Constant	1.334***	-0.468
	(0.314)	(0.995)
Observations	41	37
R-squared	0.564	0.592
Linearity test (p-value)	0.0859	0.0442

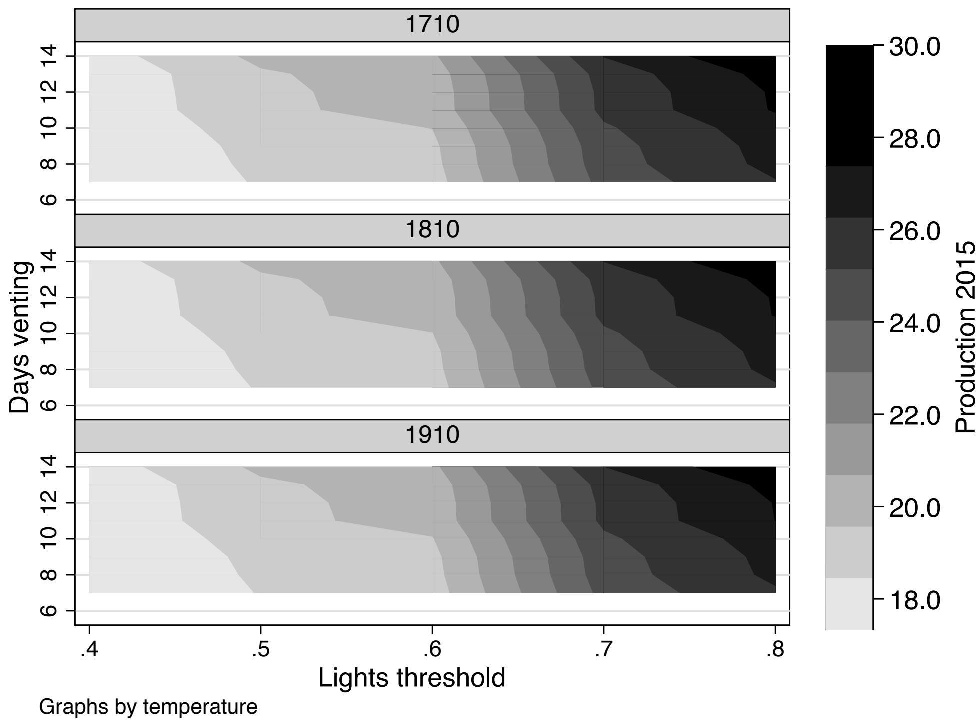
Robust standard errors in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

The R-squared of the univariate regression is .564 and .592 when GORs are controlled for. The model still leaves more than 40 percent of the variation in oil output data unexplained. The reasons include measurement errors as both oil output and RH data might not be reported or measured precisely and model specification errors whereby the relationship between oil output and RH are more complex than what is suggested by equation (2) as other factors (flare stack characteristics, wind conditions, etc.) might affect the RH-oil output relationship.

1.4.4 Alternative site production state classifications

In this section we show the results are not sensitive to the alternative RH assignment rules for sites that are deemed to be venting and discusses the resulting inferences. Figure A.8 displays the estimated 2015 ISIS oil production in thousands of barrels per day for various assignments of parameters employed in the production estimate. The y-axis represents the number of consecutive days a site without electric lights is assumed to be venting before it is declared non-productive. The x-axis represents the absolute deviation from the lunar cycle that must be achieved to determine electric lights are present. A lower threshold allows observations with faint light to qualify as lit with electric lights. The panels 1710, 1810, and 1910 represent the temperature in K that is assigned in the computation of radiant heat when there is a single spectral band detected. Last, the shaded area shows the 2015 Daesh production in thousand of barrels per day with the corresponding values for venting days, electric lights threshold, and temperature are assigned. The primary estimates in the paper assume 7 days venting, lights threshold of .6, and temperature of 1810. The figure shows that this estimate is invariant to the assumptions. The upper bound of the estimate considering all parameters increases to around 28,000 bpd from 22,000 bpd.

Figure A.8: Venting assumptions contour plot



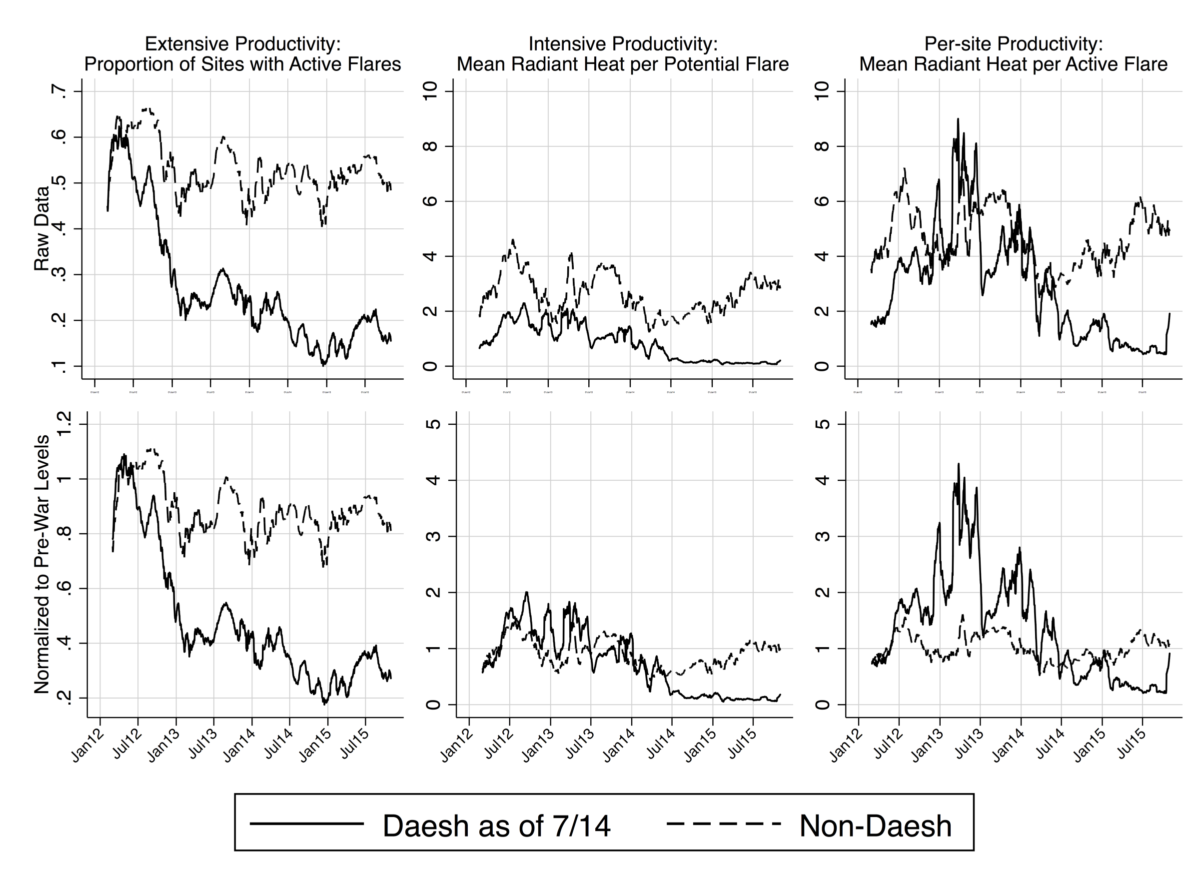
B Supplementary Materials

The supplementary materials contain a number of additional analyses that are useful context for the analysis in the main text.

2.1 Daesh vs. non-Daesh RH Measures

Figure B.9 provides three simple ways of viewing trends in oil production in Daesh held territory using remote sensing data. We assign all flares for this figure as Daesh or Non-Daesh according to the extent of Daesh territorial control in July 2014. Column 1 shows the number of sites flaring on any given day. Column 2 shows the average intensity of flaring activity over all sites, which is a rough proxy for total production. Column 3 shows the average RH measured at active sites, which captures in a rough way the intensity of production among working sites. The top row shows raw values, while the bottom row normalizes by activity levels measured before the war escalated (March-June 2012) as a way to highlight changes over time. As illustrated, Daesh's productive base was small to start with and dropped rapidly long before the group took over (column 1). Moreover, its total productivity has generally fallen since January 2014 (column 2), and the productivity per well after its takeover, as measured by flaring activity, is quite poor compared to that in non-Daesh areas of Iraq and Syria.

Figure B.9: Output productivity: Daesh versus non-Daesh



This figure shows the time series of RH estimates for Daesh and non-Daesh areas in Iraq and Syria.

Interestingly, the share of Daesh sites in each of our three production conditions—$S1$, the site is producing with natural gas flaring; $S2$, the site is producing without gas flaring (i.e. venting); or $S3$, the site is not producing—changes little over time. This is likely because flaring activity had already dropped dramatically at most of those sites before Daesh took over. Fields Daesh would control at some time after June 2014 had substantially reduced flaring activity by mid-2013, both in terms of the share of days flaring, average radiant heat per site, and average radiant heat per active flare. This is not surprising, since the fields in Syria were in a hotly contested war zone for two years before Daesh began taking substantial territory in mid-2014.

2.2 Daesh oil revenues: a compilation of media reports

This section provides a brief compilation of media reports on Daesh oil revenues. We reviewed a wide range of media reports. The table below summarizes representative estimates from June 2014 through December 2015, recording the source in the article and providing full citations for each piece.

Date of Article	Period Referenced (if not article date)	Daily Revenue ($1,000/day)	Daily Production (1,000 bpd)	Source	Citation	Link
Jul-14		$3,000	n/a	Interview w/Robin Mills (energy analyst) and Theodore Karasik (think tank research director)	Leigh, Karen. "ISIS Makes Up To $3 Million a Day Selling Oil, Analysts Say." *Syria News*. N.p., 28 July 2014. Web. 07 Jan. 2016.	http://www.syriadeeply.org/articles/2014/07/5856/isis-3-million-day-selling-oil-analysts/
Aug-14		n/a	30-70	Wall Street Journal	Malas, Nour, and Maria Abi-Habib. "Islamic State Economy Runs on Extortion, Oil Piracy in Syria, Iraq." *WSJ*. The Wall Street Journal, 28 Aug. 2014. Web. 07 Jan. 2016.	http://www.wsj.com/articles/islamic-state-fills-coffers-from-illicit-economy-in-syria-iraq-1409175458
Sep-14		$3,200	80	US Energy Information Administration and Iraq Energy Institute, reported in Financial Times	Daragahi, Borzou, and Erika Solomon. "Fuelling Isis Inc." *Financial Times*. N.p., 21 Sept. 2014. Web. 11 Jan. 2016.	http://www.ft.com/intl/cms/s/2/34e874ac-3dad-11e4-b782-00144feabdc0.html#axzz3FfGlccp6
14-Oct-14	Summer 2014	n/a	70	International Energy Agency	"2014 Oil Market Report" 14 October, 2014 International Energy Agency,	https://www.iea.org/media/omrreports/fullissues/2014-10-14.pdf
Oct-14	Jun-14	$1,000	n/a	WaPo from David Cohen, Treasury Dep Undersecretary	DeYoung, Karen. "Before Airstrikes, Islamic State Was Making $1 Million a Day from Oil Sales to Middlemen and Even Assad Regime." *Washington Post*. The Washington Post, 23 Oct. 2014. Web. 07 Jan. 2016.	https://www.washingtonpost.com/world/national-security/islamic-state-was-making-1million-a-day-from-oil-sales-before-airstrikes-began/2014/10/23/34e1b0c4-5ae8-11e4-bd61-346aee66ba29_story.html
Nov-14		$1,000	48	Foreign Affairs/CFR	Shelley, Louise. "Blood Money." *Foreign Affairs*. N.p., 30 Nov. 2014. Web. 7 Jan. 2016. <https://www.foreignaffairs.com/articles/iraq/2014-11-30/blood-money>.	https://www.foreignaffairs.com/articles/iraq/2014-11-30/blood-money
Jan-15		~$300	n/a	Bloomberg, interview with Treasury Undersecretary Cohen	Hunt, Albert R. "Cutting Islamic State's Purse Strings." <i>BloombergView.com</i>. BloombergView, 26 Jan. 2015. Web. 07 Jan. 2016.	http://www.bloombergview.com/articles/2015-01-26/u-s-attacks-islamic-state-oil-revenue
Feb-15		$750-$1300	n/a	Matthew Levitt at Washington Institute for Near East Policy	Levitt, Matthew. Feb, 2 2015. "Terrorist Financing and the Islamic State." URL: http://www.washingtoninstitute.org/policy-analysis/view/terrorist-financing-and-the-islamic-state	https://www.washingtoninstitute.org/uploads/Documents/other/LevittStatement20150202-v3.pdf
Apr-15		$800 - 1600	n/a	IB Times	Crowcroft, Orlando. "Isis: Inside the Struggling Islamic State Economy in Iraq and Syria." *International Business Times RSS*. N.p., 10 Apr. 2015. Web. 07 Jan. 2016.	http://www.ibtimes.co.uk/isis-inside-struggling-islamic-state-economy-iraq-syria-1495726
May-15		$300	n/a	NYT	Almukhtar, Sarah. "ISIS Finances Are Strong." The New York Times. The New York Times, 18 May 2015. Web. 07 Jan. 2016.	http://www.nytimes.com/interactive/2015/05/19/world/middleeast/isis-finances.html?smid=tw-nytimes&_r=0
Jul-15	"earlier this year"	$1,400	n/a	Daniel Glaser, Asstant Sec for Terrorist Financing at Treasury, speaking at Aspen	Daniel Glaser, "Remarks on Aspen Institute Panel Regarding Iraq/Syria: Worse Now Than Before?" (The Aspen Institute, Aspen, Colorado, July 23, 2015), http://aspensecurityforum.org/wp-content/uploads/2015/07/Iraq-or-SyriaWorse-Now-Than-Before.pdf	http://aspensecurityforum.org/wp-content/uploads/2015/07/Iraq-or-Syria-Worse-Now-Than-Before.pdf
Oct-15		~$1,300-1,700	40-50	Statements made to AP by a Ibrahim Bahr al-Oloum, a member of Iraq's parliamentary energy committee and a former oil minister	Hendawi, Hamza, and Qassim Abdul-Zahra. "Despite US-led Campaign, Islamic State Rakes in Oil Earnings." *The Big Story*. Associated Press, 23 Oct. 2015. Web. 11 Jan. 2016.	http://bigstory.ap.org/article/061e7a83299644868c920bed0667eb9c/despite-us-led-campaign-islamic-state-rakes-oil-earnings
Dec-15		$1,100	n/a	IHS	"Newsroom." *Islamic State Monthly Revenue Totals $80 Million, IHS Says*. IHS, 7 Dec. 2015. Web. 07 Jan. 2016.	http://press.ihs.com/press-release/aerospace-defense-security/islamic-state-monthly-revenue-totals-80-million-ihs-says
Dec-15		n/a	under 40	The Economist	"Degraded, Not Yet Destroyed." *The Economist*. The Economist Newspaper, 12 Dec. 2015. Web. 07 Jan. 2016.	http://www.economist.com/news/middle-east-and-africa/21679802-self-styled-caliphates-income-taking-pounding-degraded-not-yet-destroyed
Dec-15		$1,000	40	Time	Thompson, Mark. "U.S. Bombing of ISIS Oil Facilities Showing Progress." *Time*. Time, 13 Dec. 2015. Web. 07 Jan. 2016.	http://time.com/4145903/islamic-state-oil-syria/
6-Jan-16	Before October 2015	n/a	45	Reuters (quoting Defense officials)	Torbati, Yeganeh. "U.S.-led Air Strikes Have Cut Islamic State Oil Revenues -U.S." Reuters. Thomson Reuters, 06 Jan. 2016. Web. 07 Jan. 2016.	http://www.reuters.com/article/mideast-crisis-airstrikes-oil-idUSL1N14Q1BN20160106
6-Jan-16	After October 2015	n/a	34	Reuters	Torbati, Yeganeh. "U.S.-led Air Strikes Have Cut Islamic State Oil Revenues -U.S." Reuters. Thomson Reuters, 06 Jan. 2016. Web. 07 Jan. 2016.	http://www.reuters.com/article/mideast-crisis-airstrikes-oil-idUSL1N14Q1BN20160106

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