How Much Oil is the Islamic State Group Producing?

Evidence from Remote Sensing

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Abstract

Accurately measuring oil production in low-governance contexts is an important task. Many terrorist organizations and insurgencies—including the Islamic State group, also known as ISIL/ISIS or Daesh—tap oil as a revenue source. Understanding spatial and temporal variation in production in their territory can help address such threats by providing near real-time monitoring of their revenue streams, helping to assess long-term economic potential, and informing reconstruction strategies. More broadly, remotely measuring extractive industry activity in conflict-affected areas and other regions without reliable administrative data can support a broad range of public policy decisions and academic research. This paper uses satellite multi-spectral imaging and ground-truth pre-war output data to effectively construct a real-time day-to-day census of oil production in areas controlled by the terrorist group. The estimates of production levels were approximately 56,000 barrels per day (bpd) from July–December 2014, drop to an average of 35,000 bpd throughout 2015, before dropping further to approximately 16,000 bpd in 2016.
How Much Oil is the Islamic State Group Producing?
Evidence from Remote Sensing *

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Introduction

The non-state insurgent organization known as the Islamic State group (also sometimes called the Islamic State [IS], the Islamic State of Iraq and the Levant [ISIL], the Islamic State of Iraq and al-Sham [ISIS], or Daesh, its Arabic acronym) took control of large swathes of territory in Syria and Iraq beginning in 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.

For a time, the group was considered the richest jihadist group in the world and was thought to raise money from a variety of sources. In 2014 and 2015 revenue from oil production in areas the group controlled was often cited as its largest potential source of revenue flow, with estimates of weekly oil revenue ranging from “several million” to US$28 million. Any reasonable assessment of the organization’s long-run survival prospects had to account for these revenues and identify how sustainable they were. Beginning in late of 2015, Daesh steadily lost territory in both Iraq and Syria, but still maintained substantial territory in both countries at of early 2017.

Remotely measuring oil production using satellite imagery provides a way to make a consistent assessment of activity that would have been useful in 2014-15 and to track developments since then with some precision. In our case, combining multi-spectral satellite imagery with available production data enables transparent and reproducible estimation of oil production in Daesh-controlled areas. We find that production levels were approximately 56,000 barrels per day (bpd) from July-December 2014, later dropped to an average of 35,000 bpd throughout 2015, before further sinking to approximately 16,000 bpd in 2016. These estimates are in line with production reported for late-2014 in captured internal Daesh documents, as we discuss in

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1We henceforth use Daesh and Islamic State group/organization interchangeably.
Careful study of news outlets’ reports, agencies’ press releases and Institute for the Study of War (ISW) maps allow us to assign individual oil wells to the Islamic State group’s control at the daily level. We use data from the Visible Infrared Imaging Radiometer Suite (VIIRS) sensors deployed on the NOAA/NASA Suomi NPP satellite, to assess the status of each of the sites and then impute the appropriate levels of production.

Our approach relies on the property that the natural gas dissolved in oil underground expands when it reaches the surface. In our study context, the gas is subsequently flared, hence generating heat that is captured by VIIRS sensors. Using pre-war data on oil production obtained from several public and private sources, we estimate the relationship between production and VIIRS detection and infer contemporaneous production of Daesh-controlled oil fields. Alternatively, oil extraction can take place without gas flaring—a process called venting—in which case we assign historic output values as there will not be sensor detection.

Our paper contributes to two streams of literature. The first is the emerging literature that uses remote sensing to assess behavior in extractive industries in low-governance regions. Reliably external measures of resource forestry, mining, and oil production can enable better approaches to a broad range of challenges. In Colombia and Nigeria, for example, insurgent organizations have long controlled territory where oil is produced, and in many regions around the world reliable field-level production numbers are hard to come by. Estimating production remotely can enable governments and international organizations to identify illegal or untaxed production as well as to better understand the role production could play in post-conflict economies and the impact of sanctions, trade restrictions, and other policy interventions. Variants on the approach adopted here could be applied in a much broader set of places.

The second literature is the substantive one that investigates the role of natural resources in

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See, for example, [30] and [35] which use remote sensing to measure illegal mining activity in Myanmar and Colombia, respectively.
shaping conflicts. For instance [36] 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, [32] 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. Others find that fighting around diamond mines did not affect civilians in Sierra Leone, but was rather limited to violence among soldiers [3, 22]. This result is echoed by [49], which finds that violence against civilians was lower in diamond areas in Angola. Finally, [10] 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 describes our methodology, while section 2 presents and discusses the results of the analysis. Section 3 concludes. Details about the methods are available in Annex A; supplementary materials can be found in Annex 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 A.3 for details on the identification of oil assets and the delineation of Daesh territorial control).

Early accounts of the group’s oil production and the revenues generated indicated that oil was 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) [25]. Other
news outlets give numbers around 50-60,000 bpd yielding an income of US$2.5m per day \[33\] to more than US$3m per day \[1\]. Early estimates by the US Departments of State and Treasury put the organization’s oil revenues at around US$1m per day \[42\]. These estimates were then revised down to “a couple million dollars a week” after the U.S. started air-strikes 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 was no consensus on the production numbers or revenue they created.

On 15 May 2015, U.S. Army special forces killed a senior Daesh leader known as Abu Sayyaf, who, according to the U.S. Department of Defense “helped direct the terrorist organization’s illicit oil, gas and financial operations.” This raid also yielded significant amounts of intelligence into the Daesh economy, including administrative data providing a retrospective look at Daesh oil production in certain regions. Below, we shall compare our estimates from remote sensing with the administrative data captured during the raid.

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 [29]. Flaring is the generic method of natural gas disposal in Syria and most of Iraq, as it is in most of the world [47]3. 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 [14, 12] 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 2012-2015 for the 22 significant oil fields that are deemed comparable to the fields Daesh now controls. Each point represents the logarithm of yearly oil production (vertical axis) and the logarithm of yearly RH (horizontal axis) for any given oil field in our estimation sample, with black symbols

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3Large fields in southern Iraq where Daesh is not present have undertaken flaring reduction projects to collect the natural gas for economic uses.
for Syrian fields and grey symbols for Iraqi ones. The black circles with labeled years report the same quantities as for Syria in total. 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.

Figure 2: Radiant heat and oil output

Note: Plot of linear regression of the logarithm of field RH against the logarithm of field oil output on the vertical axis. Each point represents an oil field annual average unless otherwise labeled. Linear regression and 95% confidence intervals also depicted. The fail to reject the null hypothesis that the slope equals one (see Annex section A.4 for details on estimation sample). Data sources: [45, 46, 24] and NOAA.

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 consistent 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:

- **$S_1$: 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 [47]. Oil production with flaring is thus the generic production state when a site is producing oil.

- **$S_2$: 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 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.

- **$S_3$: 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 [27, 7, 48, 31, 39], 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 $S_2$ and $S_3$ when no infrared signals are detected (see Annex A section [A.1] for more details).

2 Results

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. This figure highlights the fine temporal resolution of our approach at the field-level.

Ajil (top panel) 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 and regular radiant heat detections resume.

The radiance reading from the site of Jaffra (middle panel) 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 (bottom panel) provide a sense of what normal activity looks like for a flare in the 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

Note: Time series of M10 and DNB detections from March 2012 through November 2016 for Flares in Ajil and Taq Taq in Iraq, and Jaffra in Syria Temperatures are in kilo Kelvin. Black lines demarcate period of Daesh control.
2.2 Production Estimates

Analysis of the 42 sites that have ever been under Daesh control reveals that the group’s production peaked in July 2014, declined from much of 2015 before peaking again in late-2015 after which it declined precipitously to 16,000 bpd in 2016. Figure 4 shows production estimates with 95 percent confidence intervals (panel A) from January 2014 through November 2016 using the approach and assumptions discussed above. Column (1) shows the results assuming no production when we do not observe a radiant heat signal. That represents our low-end estimate. Column (2) shows the results when we assume that fields without a radiant heat signal are producing via venting on days with DNB detections above the lunar illumination threshold $S_2$.\textsuperscript{4}

Several precautions indicate these estimates represent an upper bound on Daesh oil production. First, as gas-to-oil ratio (GOR) gradually increase as oil is extracted, our inferences based on the assumption that the GOR remained constant at its pre-war level will overestimate 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. Last, we assign cloudy days the average of production at the site over the month. This method is generous since production is highly sporadic at some sites and even one day of production will be smoothed over the entire month. We performed a validation of this procedure where we randomly assigned clouds to 10% of the observations and obtained higher estimates.

In Annex A section A.4.5 we gauge the robustness of our inferences to alternative assumptions on the way we determine production states and compute RH. Resulting production

\textsuperscript{4}As noted on venting days we assume production at the median production level since Daesh’s takeover of the field.
estimates vary little and stay within a 30 percent range of our baseline specification.

Based on these estimates Daesh oil production peaked at roughly 86,000 bpd in late July 2014 and declined steadily thereafter, averaging approximately 56,000 bpd in the second half of 2014. Production dropped through most of 2015 until rising briefly in late 2015 to 72,000 bpd. Since there is significant uncertainty as to the prices Daesh earned for oil over time, we do not turn the production figures into revenue estimates.

Figure 4: Production Over Time

Note: 28-day moving average of production estimates in barrels per day with 95 percent confidence intervals.
Our findings, while lower than some accounts provided in the media, are consistent with some estimates for the early period of Daesh control that relied on extrapolation from pre-war field data [8] or captured documents [37]. In particular, administrative data captured from the Abu Sayyaf raid posits daily production ranging from 52,120 bpd to 55,560 bpd in the time frame from roughly June to October 2014. These numbers are well within the bounds of our 95-percent confidence intervals and actually very close to our point estimates (Figure 5).
Other figures available in the documents seized during the Abu Sayyaf raid, however, suggest potential problems with the Islamic State group’s own administrative data. For example, the captured documents indicate significant output from the At Tayyanah field in the Al Khayr Governorate, but for which our remote data detects no visual activity and was understood to be non-active prior to Daesh takeover. Other simple arithmetic inconsistencies also reduce confidence in the accuracy of this administrative data. It is possible that internal political motivations that may bias administrative data upwards.

In such circumstances, estimates from remote sensing serve as a complementary estimate of Daesh oil production and further allows real-time monitoring of said production.

3 Conclusion

Based on our method employing satellite data, we estimate oil production in territory under the Islamic State group’s control peaked briefly above 80,000 bpd in July 2014, declined steeply before a short rise in late-2015, after which it dropped steadily until another peak from November 2015 through February 2016, after which it dropped steeply to an average of less than 16,000 bpd in the rest of 2016. These results lend support to the view that Daesh is financing itself out of other sources such as taxation and extortion rather than oil. Moreover, the results show that Daesh was ineffective in comparison to historical trends at exploiting the fields under its control. For comparison, AFPC and DZPC fields (the majority of which remained under its control during the period of study) produced 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. With respect to revenues, 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.

The most consequential example of biased administrative data is probably China’s Great Leap Forward in which falsification by lower- and mid-level officials contributed to a famine that killed millions [44]. Recently Chinese air pollution figures have also been falsified in a similar dynamic [43].
while a subsequent report indicated that prices depend on the field of origin, and that some fields charged $40 to $45 dollars per barrel. At such levels, the annual revenue from oil would be far below many published estimates.

One reason why our estimates differ substantially from many publicly-available ones is likely sampling bias. To our knowledge, prior estimates all relied on what is effectively a survey of Daesh’s oil assets. Information was obtained from a few selected sites and at specific dates on the basis of key documents or interviewee self-reports, which were 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 and potentially 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 with daily temporal resolution. The estimates coming from our analysis are not inferences made from observations on a few selected sites and at a few selected dates but from all sites and in real time. Thus, they have the substantial advantage of enabling less bias than previous estimates of the impact of various kinds of events (e.g. attacks, leadership conflicts, territorial losses, etc.) on oil production.

Our study aims to help bridge the knowledge gap on 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. 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, as well as for assessing the impact of policy changes. We show that combining reliable records for
a subset of fields with remote sensing alongside area-specific knowledge can enable reliable production estimates at fine temporal scales in such settings.

In Syria and Iraq, 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 interventions.
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A Materials and Methods

A.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.6 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.7 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 ($S_1$). 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.6: Distribution of infrared detections by M10 sensor
Figure A.7: Distribution of SMI detection from electric lights

SMI for 4 non-flaring sites in Syria
number of days of inactivity are considered to assess the robustness of our results (see Figure A.11 and corresponding discussion in Annex section A.4.5).

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 $S_2$). 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 give the percentage of these days that were in states of flaring ($S_1$), venting ($S_2$), and inactive ($S_3$), respectively. Sites under Daesh control are inactive on average 68 percent of the time, while actual flaring is detected only 10 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 30 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 A.4.5).

A.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 hereafter. 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 | Days controlled | Production(%) | Venting(%) | Inactive(%) |
|-------|----------------|---------------|------------|-------------|
| 86    | 1051           | 17            | 31         | 53          |
| 87    | 1051           | 4             | 13         | 83          |
| 89    | 1051           | 5             | 6          | 89          |
| 96    | 1051           | 0             | 12         | 88          |
| 102   | 842            | 0             | 2          | 97          |
| 118   | 865            | 0             | 3          | 97          |
| 128   | 196            | 7             | 93         | 0           |
| 137   | 878            | 23            | 9          | 69          |
| 143   | 878            | 0             | 2          | 98          |
| 144   | 878            | 63            | 15         | 22          |
| 158   | 879            | 0             | 3          | 97          |
| 159   | 879            | 1             | 4          | 95          |
| 164   | 879            | 4             | 83         | 13          |
| 166   | 879            | 38            | 19         | 43          |
| 169   | 879            | 1             | 27         | 73          |
| 171   | 879            | 21            | 79         | 1           |
| 182   | 878            | 4             | 56         | 40          |
| 183   | 879            | 0             | 1          | 99          |
| 184   | 878            | 0             | 1          | 99          |
| 187   | 878            | 14            | 8          | 78          |
| 188   | 879            | 0             | 1          | 99          |
| 193   | 864            | 52            | 47         | 1           |
| 194   | 878            | 0             | 1          | 99          |
| 195   | 864            | 0             | 11         | 89          |
| 196   | 580            | 0             | 12         | 88          |
| 197   | 864            | 22            | 27         | 51          |
| 199   | 580            | 0             | 9          | 91          |
| 200   | 580            | 0             | 3          | 97          |
| 202   | 580            | 0             | 4          | 96          |
| 208   | 863            | 29            | 39         | 32          |
| 209   | 878            | 0             | 2          | 98          |
| 210   | 864            | 0             | 23         | 77          |
| 211   | 863            | 0             | 2          | 97          |
| 212   | 485            | 0             | 1          | 99          |
| 247   | 858            | 6             | 89         | 5           |
| 259   | 758            | 36            | 23         | 41          |
| 271   | 858            | 2             | 40         | 58          |
| 280   | 858            | 7             | 32         | 60          |
| 313   | 226            | 33            | 24         | 43          |
| 319   | 226            | 0             | 1          | 98          |
| 333   | 229            | 0             | 6          | 93          |
| 786   | 878            | 26            | 43         | 31          |

Total 33041 9.9 21.6 68.5
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.11 and corresponding discussion in Annex section A.4.5).

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.

### A.3 Identifying oil assets and assigning control

#### A.3.1 Identifying flaring sites

All nighttime VIIRS data over Syria and Iraq, spanning March 2012 through November 2016, 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[6].

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.8 shows an example of a site with infrastructure and a site without.

[6]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.8: Examples of sites with and without oil production infrastructure

This figure an example of a site in ISIS territory without oil production infrastructure and an example of a site in Daesh 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.
A.3.2 Delineating Daesh territorial control

Daesh territorial control spanned from the east of Fallujah to the north of the city of Aleppo [26]. 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 [13], while Al Arabiya indicates that Tanak field fell under Daesh control on July 4th [4]. 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 [12]. 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 [11]. 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 [6]. On July 15th, the Syrian Observatory for Human Rights reported that 90 percent of the governorate had gone under Daesh control [7] and Al Jazeera announced that the group had seized all the fields in the governorate [22]. 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 [16], while Al Thayem was reportedly seized in July 2014 and released in January 2015 [5].

**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 [10].

**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 [14], Al Arabiya announced that the group had consolidated its control over the three district capitals by January 13th [2] and Asharqalarabi reports that all the fields in Raqqa were seized in that month [11]. 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 [18], while International Business Times had announced that the four fields had fallen around the same time in June [17]. 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 [19]. Similar pattern of territorial loss along and sabotage happened in the Qayarrah area, were wells burned for several weeks before engineers were able to restore production [8 21].
A.3.3 Removal of warfare events

We removed from the sample in the main analysis a number of isolated high radiance and low temperature events that are not consistent with oil production. There are two cases that cause these observations: air strikes and sabotage (by fire) by Daesh fighters. Coalition air strikes have damaged infrastructure in Iraq and Syria, and caused fires, while Daesh set fire to some wells to curb the advance of Iraqi forces and deter air strikes. In this section we provide evidence from news, daytime images, and temperature to establish the case for each observation we removed.

Table A.2: Al Omar field area

| Dates Removed       | Temperature (K) |
|---------------------|-----------------|
| October 21, 2015    | 1239            |
| October 31, 2015    | 1290            |
| November 1, 2015    | 930             |
| November 3, 2015    | NA              |
| November 12, 2015   | 1166            |

Al Omar Area: This major field was the target of repeated Coalition and Russian air strikes. Reports confirm strikes on the 21st of October where B-1 bombers and other allied warplanes hit 26 targets in the field [24, 3, 25]. Similarly on the 3rd and 12th of November 2015, the Syrian Observatory for Human rights and local news outlets documented air strikes generated fires in the field [23, 20]. These reports confirm the existence of large scale fires in the facilities because of such interventions. We also exclude October 31st and November 1st from the sample because the temperatures below 1300 K are not consistent with oil production and the reports of air strikes before that date indicate strikes were successful at destroying the infrastructure needed to operate the field in the short run. No daytime imagery of this site was available in this period.
Table A.3: Qayarrah field

| Dates Removed       | Temperature (K) |
|---------------------|-----------------|
| June 9, 2016        | 1040            |
| June 12, 2016       | 1051            |
| June 13, 2016       | 1055            |
| June 14, 2016       | 1049            |
| June 15, 2016       | 1163            |
| June 16, 2016       | 1156            |
| July 3, 2016 to August 24, 2016 Average = 1160 Max = 1488 |

**Qayarrah Area:** Prolonged confrontation between Daesh fighters and Iraqi forces occurred at the site near Qayarrah city, southeast of Mosul. While Al Jazeera reported the presence of Iraqi forces in the area as early as June 2016 [8], the earliest reports of fires at the field date to early July [21]. These fires continued throughout the second half of 2016: Daesh lost control of the site 24 August 2016 and fires continued until at least December 2016 [15].

Daytime images are consistent with the news reports that large fires began in July 2016. Images were available at four dates around the drop in temperature at this site: 1 May 2016, 28 June 2016, 16 July, and 19 July. Analysis of these images shows large smoke plumes on 16 and 19 July but no apparent smoke 1 May and 28 June.

While several low temperature nights were observed in June 2016 (June 9 – June 16), the last date with temperature observed above 1500 K was 2 July 2016. A structural break test of temperature indicated the greatest likelihood of a change in the temperature pattern on 9 June 2016. To remain conservative in our estimates and consistent with the qualitative evidence, we drop observations from this site June 9 to June 16, 2016 included and all dates after 3 July 2016 included.

**Ajil and Hamrin Area:** As Daesh rapidly lost territory in Iraq in March 2015, three adjacent sites were all lit on fire as Daesh ceded control. Landsat images of the sites were available
March 1, 2015, March 17, 2015, and April 2, 2015. There is no evidence of smoke on March 1 image. Smoke plumes from the three oil production sites are visible in the March 17, 2015 image and portions of the sites display smoke on April 2. Large-scale smoke, evidence of fighting, is visible over the area on 18 April 2015 Landsat.

Table A.4: Ajil field

| Dates Removed | Temperature (K) |
|---------------|-----------------|
| March 5, 2015 | 1356            |
| March 6, 2015 | 1297            |
| March 7, 2015 | 1350            |

First, Ajil 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 in starting March 5, 2015 \[9\] and Daesh ceded control of the site on March 8, 2015. Fires reportedly continued for a few weeks as Iraqi engineers worked to put the site back to production and data corroborate this activity at the site: temperature observations after Daesh lost control generally remain below 1400 degrees K until 19th March 2015.

Table A.5: Hamrin area 1

| Dates Removed | Temperature (K) |
|---------------|-----------------|
| March 5, 2015 | 1270            |
| March 6, 2015 | 1282            |

Second, we reached similar conclusions for nearby Hamrin sites. Like Ajil, Daesh fighters set fires in wells in the Hamrin Mountains during March 2015 to curb the same advance of the Iraqi forces before they lost control of the area on March 7th, 2015. The same Landsat images depict Hamrin on March 1, 2015, March 17, 2015, and April 2, 2015. Smoke plumes from the oil field are visible in the March 17, 2015 image and there is no definitive evidence of smoke on March 1 and April 2.
Table A.6: Hamrin area 2

| Dates Removed | Temperature (K) |
|---------------|-----------------|
| March 7, 2015 | 1273            |
| March 8, 2015 | 1810            |
| March 9, 2015 | 972             |

Last, in another site in the Hamrin vicinity, Daesh again set fires before it ceded control March 10th 2015. Landsat Images are available March 1, 2015, March 17, 2015, and April 2, 2015. Smoke plumes from portions of the oil field are visible in the March 17, 2015 image and smoke plumes are visible in other portions April 2, 2015. There is no definitive evidence of smoke on March 1.

Table A.7: Al Hussein North

| Dates Removed                                           | Temperature (K) |
|---------------------------------------------------------|-----------------|
| October 26, 2015 to November 23, 2015 Average = 1725    | Average = 1725  |

Al Hussein North Area: A final site located near the border of Ar-Raqqah and Homs Syrian governorates was removed due to irregular activity in November 2015. The site displayed infrequent low-intensity production and during and before the period of Daesh control. We observed a sudden spike in uncharacteristically high production in November 2015 (Figure A.9). We interpreted the irregular spike immediately prior to indefinite inactivity as evidence of an air strike or warfare that destroyed infrastructure at the site.

In support of this interpretation, we observed that the radiant heat signals during this period were generally lower than expected for oil production. Most temperatures observed in this period were below 1600K; however, for several days there were no detections in the M10 band and we assumed the temperature was 1810K. Thus the high average temperature generally reflects our generous assumption of activity when the signal was poor. Qualitative evidence of the activity at this location was not available. Landsat images were available November 8, 2015.
and November 24, 2015; however, we were unable to observe activity at the site at 30 meter pixel resolution. Thus, we present our results including Al Hussein North for comparison in Table A.9.

Figure A.9: Al Hussein North Observations

This figure shows the time series of M10 and DNB detections from March 2012 through November 2016 at Al Hussein North. Temperatures are in kilo Kelvin. Black lines demarcate period of Daesh control.

A.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 $\Gamma_i$ is the gas-to-oil ratio (GOR) that is also field-
and time-specific. Substituting implies the following theoretical relationship: $O_{it} = \frac{A_{R_{it}}}{\Gamma_{it}}$ that can be expressed in logarithmic terms as:

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

(1)

Our estimating equation is thus

$$o_{it} = \alpha + \beta_1 r_{it} + \beta_2 \gamma_{it} + \epsilon_{it},$$

(2)

where lower-case notations indicate natural logarithm of corresponding upper-case variables and $\epsilon_{it}$ is the disturbance term that we assume to be independently and identically distributed across sites and time. We examined the estimated $\epsilon_{it}$ to ensure symmetry and normality. The results of the model validation and estimation are reported in [A.4.3]. 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

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

(3)

where $\hat{\alpha}$, $\hat{\beta}_1$, and $\hat{\beta}_2$ are estimated by ordinary least squares (OLS). A consistent estimate of the level of oil production needs to adjust for the fact that the expectation of the exponential of a random variable is not equivalent to the exponential of its expectation.

A.4.1 Consolidating oil production and field characteristics data

To construct the dataset used to estimate equation (2) we combine data on field-level characteristics (including oil output and GOR) with flare-level radiant heat measures. In this section, we describe the sources and preparation of calibration data.

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7The statistical software package used to that end is STATA version 14.
Information on oil field locations and production were collated from multiple sources. Oil field boundaries for Syria and Iraq were obtained from [27] and [28]. 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 [27, 28, 24]. 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, 45 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 29 oil fields. One field (Miran West) were dropped for having no production data. In total, 28 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 26 oil fields. Last, four fields, Gebibe, Hamrin, Hawler, and Tawke, were dropped due to 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 22 oil fields. Further, some individual years were missing
production data. In Syria, no fields were observed in 2013 nor 2014. Twelve fields in Syria were observed only in 2012 and two fields were observed in 2012 and 2013. One field in Iraq was missing data in two years and had no RH in another year. The final data thus has 48 field year observations.  

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. 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.

A.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 A.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 Annex A section A.3 for discussion of infrastructure).

8 Four observations for the whole country of Syria were added to the final data for robustness check.
9 Data were obtained from http://www.energy-redefined.com/
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 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. If flares from the same field have heterogeneous productivity, the log of the sum does not equal the sum of the logs. To address this concern, we repeated the calibration estimation with the subsample of sites with only one flare so that there was no aggregation.

### A.4.3 Estimation results

Table A.8 shows the result of the estimation of equation 2. In column (1), we do not include GOR in the regression, while column (2) shows the full specification shown in equation 2. Column (3) excludes fields with more than one flare site.

| VARIABLES                     | (1) Logarithm oil output | (2) Logarithm oil output | (3) Logarithm oil output |
|-------------------------------|--------------------------|--------------------------|--------------------------|
| Logarithm of radiant heat     | 0.984***                 | 1.017***                 | 0.958***                 |
|                               | (0.101)                  | (0.123)                  | (0.170)                  |
| Logarithm of oil to gas ratio | 0.264                    | 0.383                    |
|                               | (0.311)                  | (0.473)                  |
| Constant                      | 0.776**                  | -0.775                   | -1.870                   |
|                               | (0.308)                  | (2.001)                  | (2.931)                  |

Observations | 52 | 48 | 28 |
R-squared     | 0.733 | 0.731 | 0.788 |
Linearity test (p-value) | 0.874 | 0.894 | 0.894 |

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Note: Sample includes 22 unique oil fields in Syria and Iraq pooled over four years. Column (2) includes an additional four observation of Syria aggregated. Column (3) limits the sample to only fields with one flare site.

The R-squared of the regression is .73 with the full sample and .78 with only single flare site.
fields. The model still leaves roughly 25 percent of the variation in oil output data unexplained. The error term in the model represents two primary possibilities. First, there exists some measurement errors as both oil output and RH data could not be reported or measured precisely. Second, the might be 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.

In Figure A.10 we plot the residuals of the estimation in Table A.8 Column 2 as an alternative validation of model. We provide additional plots for comparison. In the top panel, the linear model residuals are plotted against a normal distribution. The linear model residuals are estimated from a regression of oil output on radiant heat and gas to oil ratio in levels. In the bottom panel, the analogous residuals from the model in logs are plotted against a normal density. We observe that while the linear model residuals deviate substantially from the normal distribution, the nonlinear model residuals are a good approximation of the normal distribution. The normality of the nonlinear residuals supports the premise that the model of Table A.8 Column 2 is appropriate for calibrating radiant heat to oil production.

A.4.4 Inferring oil production

To compute the level of oil production for each flare observation, we start with the results of the estimation of equation (2). We impute log production for 200 draws from the estimated joint distribution of $\hat{\beta}_1$ and $\hat{\beta}_2$. After converting to the level of oil production for each observation for each draw, we compute the daily sum of all draws for all Daesh flares. Last, we compute the expectation (average), 5th, and 95th percentiles of total Daesh production each day over the 200 draws. The implications of this method are notable in the results: confidence intervals are asymmetric with greater mean than median because the exponential of a uniform random variable is positively skewed.
Figure A.10: Distribution of Calibration Regression Residuals

Table A.9: Annual Mean Production Summary (‘000 bpd)

| Year  | Main sample | Main sample and Al Hussein North |
|-------|-------------|---------------------------------|
| 2014  | 56          | 56                              |
|       | (28, 109)   | (28, 109)                       |
| 2015  | 35          | 39                              |
|       | (18, 67)    | (20, 70)                        |
| 2016  | 16          | 16                              |
|       | (8, 27)     | (8, 27)                         |

Note: Estimates are reported in thousands of barrels per day. 95% confidence interval reported below in parenthesis. Year 2014 includes July 1, 2014 to December 31, 2014. Year 2016 includes January 1, 2016 to November 31, 2016. Estimates assume venting.
Such procedure allows inferring daily oil production at any site, which we can then aggregate to obtain yearly production as reported in Table A.9. Column 1 repeats the estimates with the main sample, cited in the text, assuming venting when no radiant heat is observed. We also report our estimates including the November 2015 observations at Al Hussein North in Column 2. The inclusion of Al Hussein North results in an increase of 5,000 bpd on average in 2015.

A.4.5 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.11 displays the estimated July 1 to December 31, 2014 Daesh 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 July 1 to December 31, 2014 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 from 56,000 bpd to around 83,000 bpd.
Figure A.11: 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.

B.1 Daesh vs. non-Daesh RH Measures

Figure B.12 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.
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—$S_1$, the site is producing with natural gas flaring; $S_2$, the site is producing without gas flaring (i.e. venting); or $S_3$, 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.

B.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          | Period Referenced (if not article date) | Daily Revenue ($1,000/day) | Daily Production (1,000 bpd) | Source                                                                 | Citation                                                                 | Link                                                                 |
|---------------|----------------------------------------|-----------------------------|----------------------------|------------------------------------------------------------------------|--------------------------------------------------------------------------|------------------------------------------------------------------------|
| Jul-14        | Interview with Robin Mills (energy analyst) and Theodore Karras (think tank research director) | $3,000                      | n/a                        | 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.syradiaply.org/articles/2014/07/05isis-3-million-day-selling-oil-analysts  | http://www.reuters.com/article/mideast-crisis-airstrikes-oil-idUSL1N14Q1BN20160106 |
| Aug-14        | n/a                                    |                             | 30-70                      | Mathieu, Vanessa. "State Economy Runs on Extortion, Oil Piracy in Syria In Iraq," IPSJ. The Wall Street Journal, 24 Aug. 2014. Web. 07 Jan. 2016. | http://www.wsj.com/articles/islamic-state-fills-coffers-from-illicit-economy-in-syria  | http://www.ft.com/intl/cms/s/2/34e874ac-5ae8-11e4-bd61-01446ab10001.html#axzz3FjGlscp6 |
| Sep-14        | NY Energy Information Administration and Iraq Energy Institute, reported in Financial Times | $3,200                      | 80                          | Daragahi, Borzoo, and Ethik Solomon. "Fueling the Inc." Financial Times. N.p., 21 Sep. 2014. Web. 11 Jan. 2016. | http://www.bloomberg.com/apps/article/2014-09-11million-a-day-from-oil-sales-from-airstrikes-began/2014/10/23/34e874ac-5ae8-11e4-bd61-01446ab10001.html#axzz3FjGlscp6 |
| 14-Oct-14     | Summer 2014                            | n/a                        | 70                          | International Energy Agency. "2014 IEA Market Report," 14 October, 2014. Web. 07 Jan. 2016. | https://www.iea.org/images/PDFs/energy-outlook/2014/04/01409175458.pdf  | http://www.reuters.com/article/mideast-crisis-airstrikes-oil-idUSL1N14Q1BN20160106 |
| Oct-14        | Interview with Daniel Cohen, Treasury Depu Undersecretary | $1,000                      | 34                          | 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. | http://www.washingtonpost.com/polICY-analysis/view/terrorist-financing-and-the-islamic-state  | https://www.washingtonpost.com/wp-ads/Documents/other/LevittStatement20150202-v3.pdf |
| Nov-14        | n/a                                    | $1,000                      | 48                          | Shelley, Lionel. "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/irag2014-11-30/blood-money |
| Jan-15        | n/a                                    | $-300                       | n/a                        | Bloomberg, interview with Treasury Undersecretary Cohen | BloombergView.com, 26 Jan. 2015. BloombergView, 26 Jan. 2015. Web. 07 Jan. 2016. | http://www.bloomberg.com/articles/2015-01-26/us-attacks-islamic-state-oil-revenue  | http://www.bloomberg.com/articles/2015-01-26/us-attacks-islamic-state-oil-revenue |
| Feb-15        | Interview with Matthew Levitt at Washington Institute for Near East Policy | $750-$1300                 | n/a                        | Matthew Levitt at Washington Institute for Near East Policy | https://www.foreignaffairs.com/articles/iraq/2014-11-30/blood-money  | https://www.foreignaffairs.com/articles/iraq/2014-11-30/blood-money |
| Apr-15        | n/a                                    | $800 - 1600                | n/a                        | International Business Times | http://ibtimes.co.uk/isis-inside-struggling-islamic-state-economy-in-iraq-and-syria-1495726  | http://www.ibtimes.co.uk/isis-inside-struggling-islamic-state-economy-in-iraq-and-syria-1495726 |
| May-15        | n/a                                    | $300                       | n/a                        | Almudhtat, 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?_r=0  | http://www.nytimes.com/interactive/2015/05/19/world/middleeast/isis-finances.html?_r=0 |
| Jul-15        | Interview with Daniel Glaser, Asistant Sec for Terrorist Financing at Treasury, speaking at Aspen | $1,400                      | n/a                        | Daniel Glaser, Assistant Sec for Terrorist Financing at Treasury, speaking at Aspen | https://aspeninstitute.org/wp-content/uploads/2015/07/Iraq-or-Syria-Warning-Now-Than-Before.pdf  | http://aspeninstitute.org/wp-content/uploads/2015/07/Iraq-or-Syria-Warning-Now-Than-Before.pdf |
| Oct-15        | n/a                                    | $-1,300,000,-1,700         | 40-50                      | Statements made to AP by a Ibrahim Bahre al-Olyoum, a member of Iraq's parliamentary energy committee and a former oil minister | http://business.ap.org/article/2015-07-06/73a3299 44688b920b0ed9567ef/b despite-us-led-campaign-islamic-state-monthly-revenue-total-80-million-is-the-says | http://www.aspeninstitute.org/wp-content/uploads/2015/07/Iraq-or-Syria-Warning-Now-Than-Before.pdf |
| Dec-15        | n/a                                    | $1,100                     | n/a                        | Hendawi, Hamza, and Qassim Abdal-Zahra. "Despite US-led Campaign, Islamic State Rakes in Oil Earnings." The Big Story, Associated Press, 23 Oct. 2015. Web. 11 Jan. 2016. | http://www.aspeninstitute.org/wp-content/uploads/2015/07/Iraq-or-Syria-Warning-Now-Than-Before.pdf  | http://www.aspeninstitute.org/wp-content/uploads/2015/07/Iraq-or-Syria-Warning-Now-Than-Before.pdf |
| Dec-15        | under 40                               |                             | The Economist              | "Degraded, Not Yet Destroyed." The Economist. The Economist Newspaper, 12 Dec. 2015. Web. 07 Jan. 2016. | http://www.aspeninstitute.org/wp-content/uploads/2015/07/Iraq-or-Syria-Warning-Now-Than-Before.pdf  | http://www.aspeninstitute.org/wp-content/uploads/2015/07/Iraq-or-Syria-Warning-Now-Than-Before.pdf |
| Dec-15        | n/a                                    | $1,000                     | 40                          | "Facilities Showing Progress." Time. Time, 13 Dec. 2015. Web. 07 Jan. 2016. | http://www.aspeninstitute.org/wp-content/uploads/2015/07/Iraq-or-Syria-Warning-Now-Than-Before.pdf  | http://www.aspeninstitute.org/wp-content/uploads/2015/07/Iraq-or-Syria-Warning-Now-Than-Before.pdf |
| 6-Jan-16      | n/a                                    | $1,000                     | 45                          | Reuters (quoting Defense officials) | http://www.reuters.com/article/mideast-crisis-islamic-state-oil-revenues-u-s-20150606.html  | http://www.aspeninstitute.org/wp-content/uploads/2015/07/Iraq-or-Syria-Warning-Now-Than-Before.pdf |
| After October 5, 2015 | n/a  | $1,000     | 34     | "Cut Islamic State Oil Revenues -U.S." Reuters, Thomson Reuters, 06 Jan. 2016. Web. 07 Jan. 2016. | http://www.reuters.com/article/mideast-crisis-islamic-state-oil-revenues-u-s-20150606.html  | http://www.aspeninstitute.org/wp-content/uploads/2015/07/Iraq-or-Syria-Warning-Now-Than-Before.pdf |

Note: The dates and references provided are for the purpose of illustration and may not be exhaustive or accurate representations of the sources or dates mentioned in the original document.
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