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Summary

Managing greenhouse gas (GHG) emissions is imperative to effectively tackle climate change and meet the goals of the Paris Agreement, necessitating comprehensive, transparent, timely and accurate measurement of emissions. Parties to the Paris Agreement are obligated to submit a national inventory of GHG emissions regularly, adhering to guidelines developed by the Intergovernmental Panel on Climate Change (IPCC). However, numerous countries, particularly developing ones, face significant challenges in measuring GHG emissions.

The challenges associated with measuring GHG emissions may account for some of the discrepancies observed between different emission estimates. Such variations might arise from the utilization of different boundaries for measurement, divergent methods employed in building estimates, or uncertainties in the assumptions and modeling adopted. For example, notable discrepancies exist in methane (CH_4) emission estimates for Saudi Arabia between the national GHG inventories submitted by the Saudi government to the United Nations Framework Convention on Climate Change (UNFCCC) and those produced by external data providers, including the International Energy Agency (IEA) and the European Commission's Emissions Database for Global Atmospheric Research (EDGAR).

There exist trade-offs between various methods for measuring GHG emissions. For example, the bottom-up IPCC (2006) method promotes comprehensiveness in national GHG inventories but incurs timeliness costs, resulting in a considerable lag between the reporting and data years. Conversely, emerging satellite-based methods can offer near-real-time measurements of emissions but may lack the sectoral disaggregation provided by bottom-up methods.

Satellite technology has multiple advantages that enable it to play a critical role in measuring GHG emissions. First, it provides a non-intrusive solution for detecting and quantifying GHG emissions globally. Second, it addresses the issue of timeliness through near-real-time measurements. Third, it promotes transparency in GHG emission measurement and can help verify estimates or explain observed discrepancies between conflicting estimates.

In this paper, we demonstrate how satellite technology can facilitate the measurement and tracking of CH_4, carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions in Saudi Arabia. Our satellite estimates are derived from a collaboration with Kayrros, a leading environmental intelligence company.

In the case of total CH_4 emissions, our satellite-based estimates are around three million tons each year in the studied period or around 84 million tons of CO_2 equivalent (CO_2e). Our estimates indicate that in Saudi Arabia, the oil and gas sector accounts for a minor share of total CH_4 emissions, aligning with the country's most recent national GHG inventory submission to the UNFCCC. This contrasts with the estimates by the IEA and EDGAR, which suggest that the oil and gas sector in Saudi Arabia accounts for the vast majority of total CH_4 emissions. For the oil and gas sector, only the estimate from the national GHG inventory submitted by Saudi Arabia falls within our satellite estimate's uncertainty range. The IEA's and EDGAR's estimates of CH_4 emissions for the Saudi oil and gas sector are markedly higher than the upper bounds of our satellite-based estimate, while the granular estimate by Saudi Aramco for upstream CH_4 emissions is lower than our lower bounds. The reasons for these discrepancies could be any combination of high instrumentation error of the satellites, parameters and assumptions used in modeling emissions, the use of inaccurate emissions factors to convert activity data into emission data, challenges with ground-based sensor coverage and differences in the boundaries of

emission measurement. For example, in the case of Saudi Aramco, there may be sub-contracted operations in the vicinity of oil and gas fields that produce CH_4 emissions that are picked up by satellites and accounted for by the IEA and EDGAR that Aramco does not account for based on its boundary of "wholly-owned operated assets" (Saudi Aramco, 2023a). Given that Aramco only measures the CH_4 emissions generated by facilities that are wholly owned and operated by the company, its estimate of CH_4 emissions from oil and gas would naturally fall below national-level estimates that include all oil and gas facilities, whether fully or partially owned by Aramco and operated by them or other companies.

In the case of CO_2 emissions from power generation (including desalination), we find that the sector generates between 200 and 250 million tons of CO_2 emissions annually. Although there appears to be an upward-sloping trend in power sector emissions between 2018 and 2022, it is challenging to confirm the existence of such a trend, given the size of the uncertainties associated with our satellite-based estimates of CO_2 emissions. The impact of COVID-19 in 2020 is also difficult to ascertain, given these uncertainties. Nonetheless, our satellite-based estimates are largely consistent with other estimates of CO_2 emissions in the electricity and desalination sectors, although our estimates tend to be roughly 10% to 20% lower on average. Unlike CH_4, discrepancies in CO_2 emission estimates between different data providers are relatively smaller, indicating that there are relatively fewer challenges associated with CO_2 measurement when compared to CH_4.

In the case of N_2O, our satellite-based estimates for emissions from agricultural soils were found to be smaller than those reported in Saudi Arabia's inventory submission to the UNFCCC and estimates by EDGAR and the Food and Agriculture Organization. Compared to CH_4 and CO_2, there are fewer sources with which our N_2O estimates can be compared. Our estimates reveal that N_2O emissions from agricultural soils in Saudi Arabia vary from 5.1 to 6.1 kilotons or 1.3 to 1.6 million tons of CO_2e.

Significant uncertainties are associated with all our satellite-based estimates for all three GHGs. Through our joint project with Kayrros, we have approximated the uncertainty ranges for these satellite-based estimates, leveraging uncertainty estimates from the literature combined with expert judgment. Nevertheless, further work is needed to better quantify the uncertainty in satellite-based estimates and understand the factors contributing to this uncertainty.

Our exploration of satellite technology for measuring GHG emissions has important global policy implications. Meeting the goals of the Paris Agreement necessitates a comprehensive, transparent, timely and accurate measurement of emissions. Employing a combination of bottom-up activity-based methods with ground-based sensors and top-down aerial and satellite methods will help to maximize comprehensiveness, transparency, accuracy and timeliness. Using multiple methods to measure GHG emissions can thus help overcome the flaws inherent in each method, leading to better and more trusted information on GHG emissions to guide more effective climate action.

Regarding precision and accuracy, there are conflicting estimates of GHG emissions for countries, particularly in the case of CH_4, making it difficult to ascertain the current standings of countries, their progress toward achieving their goals, and the sectors and GHGs that decision-makers need to target with climate actions. Countries would, therefore, benefit from regularly using satellite technology to measure their CH_4 emissions and combining that top-down data with bottom-up data. Global providers of emission data, such as the IEA and EDGAR, would also benefit from employing satellites to refine their estimates. Higher-quality data from such providers would yield higher-quality outputs from the many models that rely on their data as inputs.

Satellites also enhance transparency, as they offer a consistent, non-intrusive solution for quantifying and verifying GHG emissions globally. Currently, IPCC guidelines do not encourage countries to use satellite technology in their emission measurements. Developments in IPCC guidelines are needed to encourage countries to incorporate satellite data into their national GHG inventory submissions, aiding in achieving the transparency goals outlined in the Paris Agreement. However, encouraging countries to use satellite data for emission measurement through the IPCC and UNFCCC processes will be challenging.

At the national level, our analysis provides several policy recommendations for decision-makers in Saudi Arabia. In the case of CH_4, we show how satellite technology can be used to measure super-emitting events, which would likely go unnoticed by conventional bottom-up methods. Defined as a facility emitting CH_4 at abnormally high rates, our estimates reveal that oil and gas sector super-emitters in Saudi Arabia represented less than 0.5% of total CH_4 emissions in that sector over the study period. We also detected several super-emitting events originating from urban activities. In fact, the super-emitting events from urban activity were relatively larger than those from the oil and gas sector. These urban activity super-emitting events likely arose from landfills or industrial wastewater, indicating substantial potential for reducing those emissions. Monitoring such super-emitting events allows regulators to respond promptly and achieve significant abatement. Satellite remote sensing could provide Saudi ministries and regulators with a proven and timely method to track and regulate super emitters in the Kingdom. For example, such satellite monitoring could be housed in a new unit within the Ministry of Energy tasked with supervising and monitoring CH_4 super-emitters. With appropriate regulations in place, once a super-emitter is detected, the Ministry of Energy could inform the responsible entity to act, and regulations imposing financial penalties on super-emitters that do not respond promptly could be enforced.

Looking ahead to the future of Saudi Arabia, there are large-scale, ongoing projects for planting trees, with the goal of planting 10 billion trees by 2050. Satellites can be used to monitor and track the growth of such new green areas. This will not only help in gauging the removal of emissions from the atmosphere but also any potential increases in emissions that might result from increased fertilizer use due to the greening initiative.

There remain limitations surrounding the use of satellite technology to directly measure GHGs, including CO_2, which is the gas that accounts for the largest share of global GHG emissions. Additional investments are needed to further develop satellite technology and improve its accuracy. Ultimately, employing a mixture of bottom-up methods and top-down methods like satellites will help maximize the comprehensiveness, transparency, accuracy and timeliness of GHG emission estimates, aiding in the achievement of global climate goals.

Introduction

Managing greenhouse gas (GHG) emissions to effectively tackle climate change and meet the goals of the Paris Agreement requires comprehensive, transparent, timely and accurate emission measurements. Emission measurement is one component of the widely used term measurement, reporting and verification (MRV), which originated under the United Nations Framework Convention on Climate Change (UNFCCC). MRV comprises three closely related elements: the measurement (M) of different forms of GHG emission data, the reporting (R) of this information in standardized formats and the verification (V) of the reported information to ensure accuracy.

The MRV requirements for GHG emissions are outlined in Article 13 of the Paris Agreement (2015), which mandates that parties regularly provide a national inventory of GHG emissions following guidelines developed by the Intergovernmental Panel on Climate Change (IPCC). Specifically, the measurement and reporting requirements for GHG emissions are incorporated in the Enhanced Transparency Framework (ETF) established by Article 13. With the recent finalization of the ETF, parties to the Paris Agreement are transitioning to the ETF's new MRV system (UNFCCC 2022a). During this transition, parties are encountering more stringent requirements for tracking GHG emissions. They are expected to report their emissions more frequently through biennial transparency reports. The interval between the inventory submission year and reporting year has been reduced, and parties must measure emissions using an updated version of the IPCC guidelines. However, flexibility provisions exist for developing country parties to use in light of their circumstances.

Despite the previous, less stringent measurement and reporting requirements, numerous countries, particularly developing ones, have faced challenges in measuring GHG emissions. The new and more stringent MRV requirements laid out in the ETF enhance transparency but are expected to make measurement even more challenging moving forward (UNFCCC 2022a).

The challenges associated with measuring GHG emissions may contribute to the discrepancies observed between different emission estimates. Luomi, Al Shehri, and Howarth (2021) highlighted some discrepancies between estimates of total carbon dioxide (CO_2) emissions for Saudi Arabia. These differences may stem from the use of different boundaries for measurement, the application of diverse methods to construct estimates, or uncertainties stemming from the assumptions and modeling employed. In the case of Saudi Arabia, we observed significant differences in the estimates of methane (CH_4) emissions between the national GHG inventories submitted by the Saudi government to the UNFCCC and those of other external producers of emission data, including the International Energy Agency (IEA) and the European Commission's Emissions Database for Global Atmospheric Research (EDGAR). Similar conflicting estimates exist for numerous other countries (Zavala-Araiza et al. 2015).

While various methodologies can be used to measure GHG emissions, contributing to divergence and a lack of comparability between estimates, the IPCC (2006) guidelines are arguably the most widely used method. Parties to the Paris Agreement are required to use the IPCC (2006) guidelines, but these guidelines have also influenced the methods of other producers of GHG emission data. For example, in measuring CO_2 emissions in the power sector, the IEA (2022) employs the IPCC (2006) equations in their calculations. However, such organizations are not required to follow IPCC guidelines and may combine conventional and unconventional methods to generate their emission data. In the case of CH_4 emissions in the oil and gas sector, the IEA (2022) conducts a granular measurement of CH_4 emissions for the U.S. oil and gas sector but then applies scaling factors to estimate CH_4 emissions for the same sector in other countries.

There are trade-offs between methodologies for measuring GHG emissions. For example, the IPCC (2006) guidelines provide countries with a comprehensive set of equations for building a bottom-up GHG emission inventory. This process is generally carried out by multiplying activity data, categorized by sector and subsector, by various emission factors. The IPCC's (2006) bottom-up approach, also known as an activity-based method, promotes comprehensiveness in national GHG inventories but comes at the cost of timeliness (National Academies of Sciences, Engineering, and Medicine, 2022). As noted by Kosma and Gallagher (2023), the average lag between reporting years and data years was 2.5 years for Annex I (developed) countries and 4.23 years for non-Annex I (developing) countries. This reporting lag is expected to decrease as countries transition to the ETF's new MRV system with its more stringent requirements. Historically, there have also been issues with the frequency at which countries report their GHG inventories, which should also be addressed through the ETF's new requirements.

Satellite technology has multiple advantages that position it to play a critical role in measuring GHG emissions. First, it offers a non-intrusive solution for detecting and quantifying GHG emissions globally through repeated, universal and consistent measurements across the globe. Second, satellite technology can help address the issue of timeliness. Unlike bottom-up inventories, which take years to prepare, satellite measurement of emissions is possible in a near-real-time manner. Such near-real-time measurements can potentially allow for rapid mitigation actions to address sudden increases in emissions, such as in the case of emission leakages (Barre et al. 2021). Third, satellite technology promotes transparency in measuring GHG emissions (Aganaba-Jeanty and Huggins 2019). It can be used to verify estimates or help explain some observed discrepancies between conflicting emission estimates.

Despite the advantages afforded by satellite technology, there are challenges and limitations. First, dealing with raw remote sensing data at a national scale is technically demanding and resource-intensive. Converting raw satellite data into meaningful GHG emission estimates requires a specialized skillset and substantial computing resources. This may be particularly challenging for less-developed countries that lack these resources, necessitating global initiatives to support and help build capacity. Such initiatives include the Google Earth Engine, Amazon Sustainability Data Initiative and Digital Earth Africa Initiative. Second, as discussed in this paper, relatively large uncertainties are associated with satellite-based estimates. More validation and ground-truthing efforts, like those described by Sherwin (2023), are needed to fully understand and quantify the uncertainties associated with satellite-based estimates. Third, the technology does not yet possess the capabilities to comprehensively cover all emissions sources across all sectors. The detection threshold of existing satellites, especially public ones, remains limited. GHG emissions must be large enough to be detected by satellite technology, which would overlook smaller emitters.

Focusing on using satellite technology to measure GHG emissions, this paper makes several contributions. First, it explores how the widely used IPCC guidelines address the use of satellite technology to measure emissions. Second, it provides an overview of satellite missions launched over the last two decades to measure emissions. Third, the research outlined in this paper presents and discusses results from a collaboration with Kayrros (2023) to measure using satellites the emissions of three key GHGs in Saudi Arabia: CO_2, CH_4 and nitrous oxide (N_2O). The satellite-based estimates are used to improve our understanding of the conflicting estimates of GHG emissions for Saudi Arabia. Finally, this paper discusses the policy implications of using satellites to measure GHG emissions.

The IPCC Guidelines on the Use of Satellite Technology

Given the significant international role that IPCC guidelines play in measuring GHG emissions, exploring how these guidelines address remote sensing and satellite technology is beneficial. In the 2006 IPCC guidelines, only a few mentions of such technologies are found (IPCC 2006). These mentions primarily focus on their use as tools to independently verify national GHG inventories, detect leakages from CO_2 geological storage sites as proxy tools, and, most importantly, measure land-use activity changes. The 2006 IPCC guidelines highlighted that this technology was still in its infancy. However, considering these guidelines were published nearly two decades ago, satellite technology, sensors and image processing capabilities have undergone extensive improvements since then.

The most recent update to the IPCC guidelines is detailed in the 2019 Refinement to the 2006 IPCC Guidelines (IPCC 2019). As noted by the IPCC (2019), the "2019 Refinement does not revise the 2006 IPCC Guidelines, but updates, supplements, and/or elaborates the 2006 IPCC Guidelines where gaps or out-of-date science have been identified." Given the advancements in satellite technology since 2006, we examined how the 2019 Refinement addresses such technologies. We found that the 2019 Refinement includes all mentions of satellite technology from the 2006 IPCC guidelines, providing additional elaboration and details. There is a considerable increase in the number of mentions of remote sensing or satellite technology in the 2019 Refinement. However, the role of such technologies remains limited even in this most recent IPCC refinement.

In its elaboration on satellite technology, the 2019 Refinement states that these technologies are "expected to contribute" and "are expanding." It outlines how "multiple new satellite missions with enhanced capabilities for GHG observations are in preparation…so the emission estimates using satellite data will steadily improve." However, the 2019 Refinement still describes satellite technology as experimental, primarily presenting it as a tool for measuring land-use activity data or for verifying emissions or removals. (See Appendix A for a more detailed review of all mentions of remote sensing and satellite technology in the IPCC guidelines.) Nevertheless, since 2019, remote sensing and satellite technology have continued to evolve rapidly and are starting to play an increasingly important role in measuring GHG emissions.

Developments in Satellite Technology for Measuring GHG Emissions

Over the last two decades, there have been extensive developments in launching new space missions to measure GHG emissions. These developments started with the launch of the ENVISAT satellite in 2002 to collect global observations of atmospheric trace gases (Frankenberg et al., 2015). In 2009, the Japanese Aerospace Exploration Agency launched the Greenhouse Gases Observing Satellite (GOSAT-1), marking the launch of the first GHG-dedicated satellite to monitor the density of Earth's atmospheric CH_4 and CO_2. In the same year, NASA attempted to launch the first mission of the Orbiting Carbon Observatory (OCO) to provide global space-based observations of atmospheric CO_2. Although the OCO-1 mission failed to reach orbit due to technical challenges, it paved the way for the successful launch of OCO-2 and OCO-3 in 2014 and 2019, respectively. These early missions were primarily aimed at studying atmospheric CO_2 and CH_4 globally rather than measuring emissions at much higher resolution. Nevertheless, technology has rapidly advanced with the development of new sensors and platforms, and some of the latest satellites are capable of monitoring GHG emissions down to the point source level.

Currently, 33 satellite missions and sensors have the potential to contribute to GHG emission measurement, focusing on three main GHGs: CO_2, CH_4 and N_2O. These missions were identified in the GHG Monitoring from Space report (GEO, ClimateTRACE, and WGIC 2021) and classified by the organization(s) that developed and funded them. These missions are run by public agencies (21 missions, 13 of which are operational), private companies (seven commercial missions, three of which are operational) and a collaboration of public, private and non-profit entities (five missions, all in development). Most public missions offer open data access, while private missions require payment for data access. Table 1, inspired by Jacob et al. (2022) and GEO, ClimateTRACE, and WGIC (2021), lists some of the satellites and instruments currently used for GHG monitoring, including those utilized in this study.

Table 1. Examples of satellite missions, sensors and various satellite parameters.

Satellite mission[1] (instrument)	Organization[2] (public/private)	Launch year	Spatial resolution	Coverage	Temporal resolution	Notes	Reference
Senitel-5P (TROPOMI)	ESA (Public)	2017	5.5 km	Global	1 day	Emission data for CH_4 for a complete year became available in 2019. Satellite used in our analysis.	Lorente et al. (2021)
Landsat-8 (OLI)	USGS (Public)	2013	30 m	Global	16 days	Satellite used in our analysis.	Ehret et al. (2022)
Landsat 9 (OLI-2)	USGS (Public)	2021	30 m	Global	16 days	Satellite used in our analysis.	Jacob et al. (2022)
Sentinel-2 (MSI)	ESA (Public)	2015	20 m	Global	2-5 days	Satellite used in our analysis. This is a constellation of two satellites (2A and 2B), with the second being launched in 2017.	Varon et al. (2023)
EMIT on the ISS	NASA (Public)	2022	60 m	Global	Variable	The true temporal resolution is variable based on the instrument's orbital cycle aboard the ISS.	Green et al. (2020)
PRISMA (HYC)	ASI (Public)	2019	30 m	Targeted coverage	29 days	PRISMA can acquire images as far as 1,000 km in a single pass, reducing the temporal resolution to less than a week.	Guanter et al. (2021)
OCO-2 (OCO-2)	NASA	2014	2.25 km	Global	16 days	OCO-2 is a replacement for OCO-1, which was lost due to a rocket separation failure in 2009.	Guo et al. (2023)
OCO-3 on the ISS	NASA	2019	2.25 km	Global	Variable	The true temporal resolution is variable based on the instrument's orbital cycle aboard the ISS and the imaging mode.	Kiel et al. (2021)
GHGSat	GHGSat Inc. (Private)	2016	25 m	Targeted coverage	1-7 days	A constellation of nine satellites is in orbit as of August 2023. Three more are planned to be launched by the end of 2023.	Jervis et al. (2021)
Metop-A/B/C (IASI)	EUMETSAT	See Notes	25 km	Global	Variable	The IASI instrument is on board three missions: A, B and C, launched in 2006, 2012 and 2018, respectively.	Barret et al. (2021)

GHG Emission Estimates for Saudi Arabia Using Satellites

This paper utilizes satellite technology to generate annual estimates of GHG emissions for Saudi Arabia, focusing on three primary GHGs: CH_4, CO_2 and N_2O. Our satellite estimates are derived from a joint project with Kayrros (2023). Kayrros, a leading environmental intelligence company, has a proven track record of providing geospatial analytics services and has previously collaborated with the International Energy Forum (IEF 2021) and the IEA (2023). For this project, we worked closely with Kayrros to measure and monitor CH_4 emissions from Saudi oil and gas fields, CO_2 emissions from Saudi power and desalination plants and N_2O emissions from Saudi agricultural lands. Our estimates showcase the potential of satellite technology, highlight some of its limitations and explain some of the differences in conflicting emission estimates. (Further information on this joint collaborative project and the members involved can be found in the Acknowledgements.)

CH_4

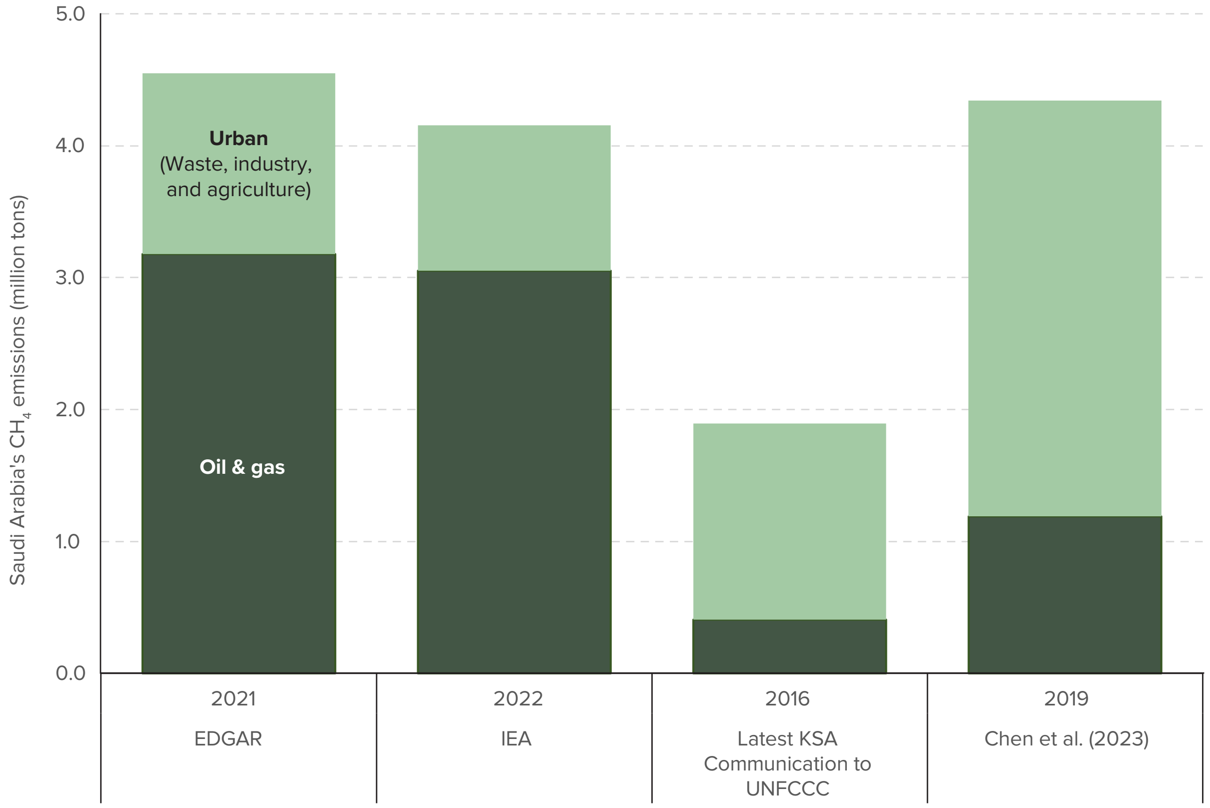
Current State of CH_4 Emission Inventories for Saudi Arabia

Only a few sources produce CH_4 inventories for Saudi Arabia. EDGAR (2022) and IEA (2023) claimed that the majority of Saudi Arabia's CH_4 emissions originate from the upstream and downstream oil and gas sector. However, the most recent communication from the Saudi government to the UNFCCC, submitted by Saudi Arabia's Clean Development Mechanism Designated National Authority (CDM-DNA 2022), suggests otherwise. Saudi Arabia's CDM-DNA is responsible for the country's national GHG inventory submissions to the UNFCCC. According to the CDM-DNA's (2022) national GHG inventory, the vast majority of CH_4 emissions in Saudi Arabia come from industrial wastewater and landfills. According to the CDM-DNA (2022), CH_4 emissions from oil and gas production amounted to 0.14 million tons in 2016. Additionally, oil and gas transport and distribution; gas transmission, processing and storage; and well servicing, testing and drilling contributed an extra 0.27 million tons of CH_4.

Chen et al. (2023) recently utilized satellites to measure CH_4 emissions for several countries in the Middle East and North Africa. Chen et al. (2023) reported approximately 1.2 million tons of CH_4 for 2019 using satellite technology for the entire Saudi oil and gas sector. Contrary to the claims of the IEA and EDGAR, their study also demonstrated that the majority of CH_4 emissions result from urban activities. Although the total CH_4 emissions reported by

Chen et al. (2023), approximately 4.3 million tons, are closer to the totals estimated by IEA and EDGAR, the sectoral breakdown by Chen et al. (2023) aligns with the CDM-DNA's (2022) submission to the UNFCCC. Figure 1 illustrates the CH_4 emission values presented by these four sources.

Figure 1. CH_4 emissions by sectoral classification in Saudi Arabia.



Sources: EDGAR 2022; CDM-DNA 2022; IEA 2023; Chen et al. 2023.

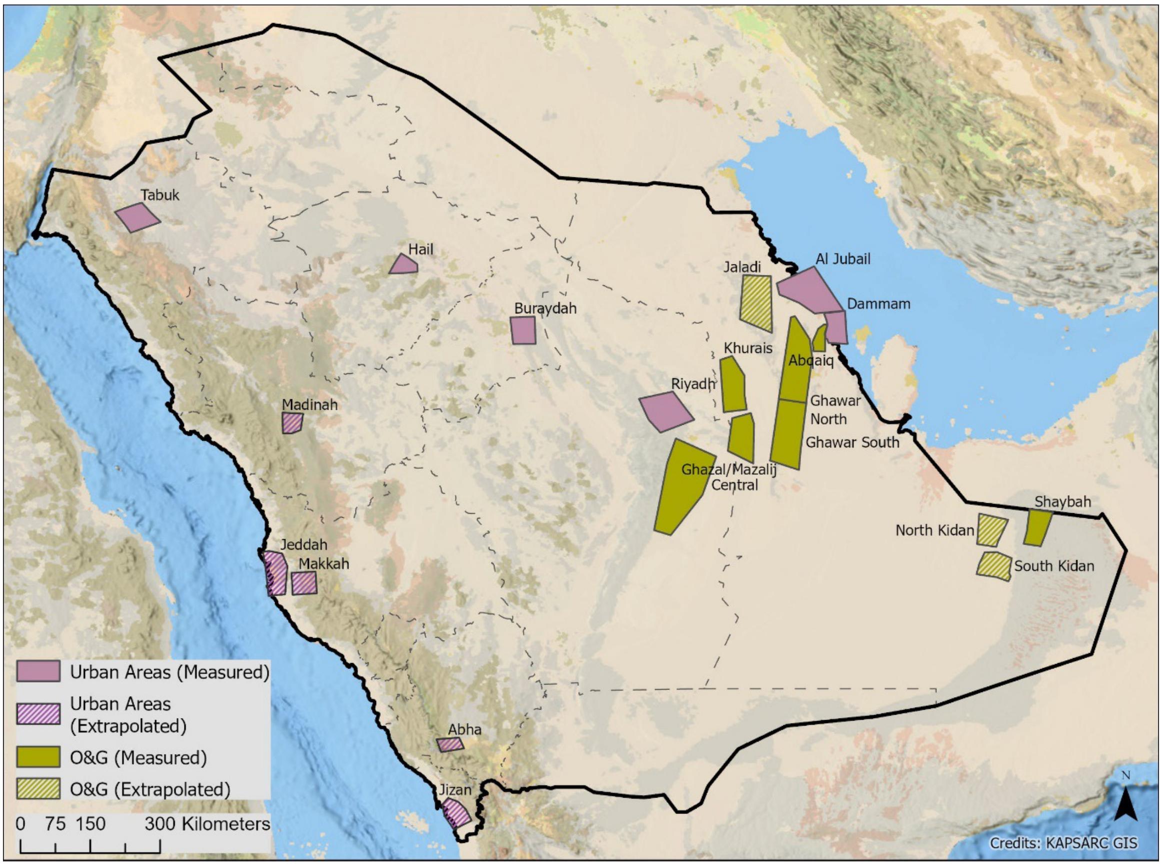
Methodology for CH_4 Emissions

CH_4 emissions were estimated using satellite technology for the years 2019-2022 for oil and natural gas fields and urban areas. The primary sources of urban activity emissions are agricultural lands, municipal solid waste, industrial processes and industrial wastewater within urban areas. The European Space Agency's Sentinel-5 Precursor (Sentinel-5P), Sentinel-2 and NASA's Landsat-8/9 were used for the estimations.

Sentinel-5P is characterized by a daily revisit frequency and a spatial resolution of 5 km. It requires an emission flow rate of at least 5 tons per hour to detect CH_4 in the atmosphere. Thus, it is used to measure CH_4 emissions over oil and gas fields, which are situated far from other assets, and for super-emitting events. Sentinel-2 and Landsat-8/9 are used for measurements over cities, given their finer 30 m spatial resolution and lower detection threshold of 1 ton of CH_4 per hour. Sentinel-2 is also used to measure super-emitting events. The trade-off is that Sentinel-2 and Landsat-8/9 revisit sites of interest only once a week. Figure 2 depicts all oil and gas fields and urban areas covered in this analysis, classified based on whether they were predominantly measured by satellite technology or extrapolated. North and South Kidan were initially included, but both fields are currently inactive.

The satellite-based quantification of CH_4 emissions was conducted in four steps. The first step involved obtaining satellite images of oil and gas assets or urban areas and filtering the images. Subsequently, the images were wind-rotated to align the wind direction with the gaseous plumes being analyzed. The satellite images were then aggregated before the final step of converting the CH_4 plume image into a quantity of emitted CH_4, measured in thousands or millions of tons.

Figure 2. Oil and gas assets and urban areas covered in this analysis.



Note: The methane emissions from offshore oil and gas fields in the Eastern Region were also extrapolated, but those offshore fields are not shown on this map.

Sources: KAPSARC and Kayrros 2023.

It is important to underscore that due to current public satellite capabilities, coverage and measurement frequencies, CH_4 was the only GHG directly measured through satellite imagery in this study. After capturing the images of CH_4, subsequent image processing and modeling were required to produce emission estimates. The CH_4 present in the atmosphere was subtracted from the measured CH_4 concentration for each asset. This subtraction was performed to estimate only the CH_4 emitted from the assets of interest. In addition to image processing, modeling addressed several issues:

First, cloud cover can obscure satellite images, rendering some of the often-limited number of images unusable due to overcast skies. Second, estimates needed to be produced between satellite revisit times through interpolation. Third, a significant challenge arose from the inability of the satellites used to detect CH_4 emissions above offshore oil and gas assets, coastal areas and assets located on mountainous terrain. Publicly available data were thus employed to extrapolate the satellite estimates to the assets and urban areas where satellite-based measurements were not possible.

For the oil and gas sector, extrapolation is done based on the shares of oil and gas production for each field (EIA 2017; Hydrocarbons-Technology 2023; Munro 2018; Offshore-Mag 2017; Saudi Aramco 2019). For urban areas, extrapolations are based on an urban activity indicator we developed, calculated as the average of each urban area's population, agricultural activity and industrial activity shares. These data were obtained from GASTAT (2023) and Hamieh et al. (2022).

In summary, for the oil and gas sector, we measured CH_4 emissions by satellite for oil and gas fields that cover 57% of oil and gas production in Saudi Arabia. For the remaining 43% of oil and gas production, the CH_4 emissions were extrapolated. In the urban area sector, CH_4 emissions from 31% of urban areas were measured based on our urban activities indicator, while for the remaining 69% of urban areas, CH_4 emissions were extrapolated.

Estimation Results

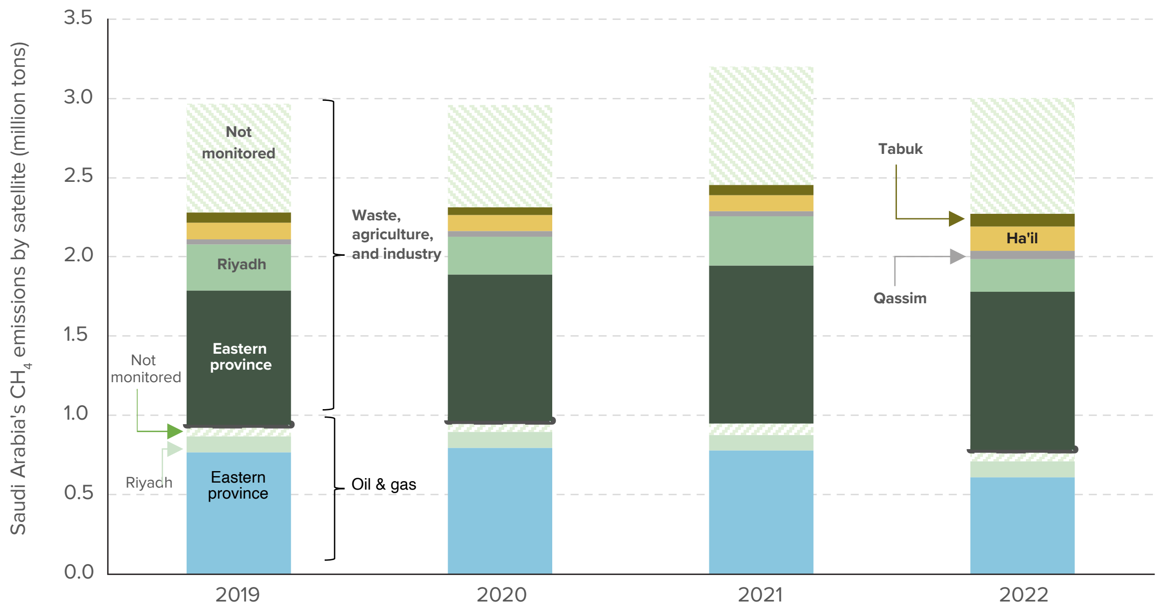
Total Saudi CH_4 emissions from 2019 to 2022 are illustrated by region in Figure 3. As expected, the total estimates show that the Eastern Province is the largest contributor to CH_4 emissions from oil and gas and urban areas. Western provinces, such as Makkah and Madinah, encompass extensive urban areas but are categorized into non-monitored areas owing to the limitations of satellite technology in navigating their terrain. The mean estimates of total CH_4 emissions hover around three million tons each year within the studied period. The estimates show that CH_4 emissions from the oil and gas industry in Saudi Arabia constitute a minor share, approximately one-third, aligning with the most recent national GHG inventory submitted by CDM-DNA (2022). Our satellite estimates for the Saudi oil and gas sector only pertain to oil and gas fields, including emissions from production and partially accounting for the transporting of hydrocarbons and processing of gas occurring within the vicinity of the fields. Operations situated further downstream are excluded.

In Saudi Arabia, oil and gas fields are predominantly isolated, allowing satellite estimates to be attributed to these assets. In contrast, within the urban areas sector, agricultural, industrial and municipal areas are situated in close proximity, complicating the attribution of CH_4 emissions to any of these three subsectors.

There is naturally some level of uncertainty stemming from instrumentation errors or the modeling techniques employed. The uncertainty assessment in this study is grounded in the peer-reviewed work of Schneising et al. (2020), which focused on oil and gas fields located outside Saudi Arabia. Due to the absence of parameters for an accurate uncertainty calculation, we adapted their results to this analysis, drawing on the similarities between the study's fields and those in Saudi Arabia. Specifically, a ±50% uncertainty range was allocated to urban areas or oil and gas fields situated near other emitters or those with low satellite coverage. An uncertainty range of ±30% was designated for isolated cities or fields with high satellite coverage.

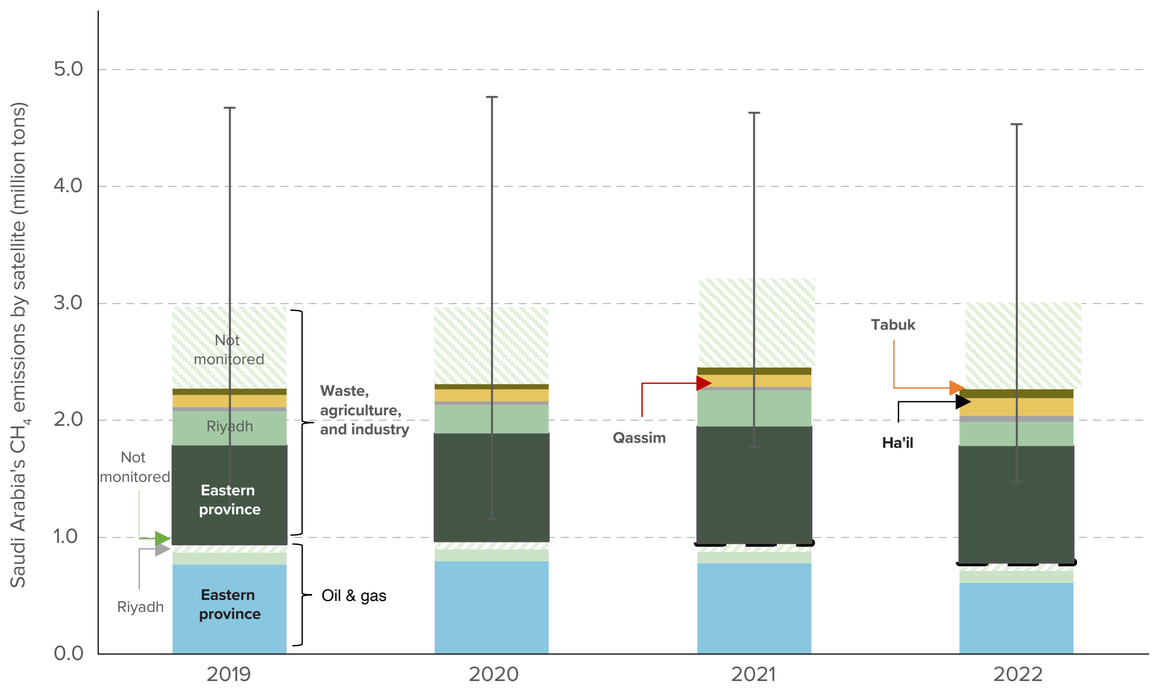
The uncertainty ranges for our satellite-based estimates are shown in Figure 4 for each year. The error bars in these estimates are large enough that we cannot reliably interpret the temporal variation. For instance, the total CH_4 emissions uncertainty for 2022 was ±1.53 million tons, compared to a mean value of 3 million tons. Figure 5 presents these figures exclusively for the oil and gas sector for enhanced clarity. The uncertainty for oil and gas sector CH_4 emissions in 2022 was ±0.35 million tons, compared to a mean value of 0.78 million tons of CH_4 emissions for the sector in 2022. The uncertainty range, as a percentage of emissions, was lower in the oil and gas sector, since the estimates for this sector were less reliant on extrapolation than the urban activity sector.

Figure 3. Total CH_4 emissions in Saudi Arabia estimated by satellite from 2019 to 2022.



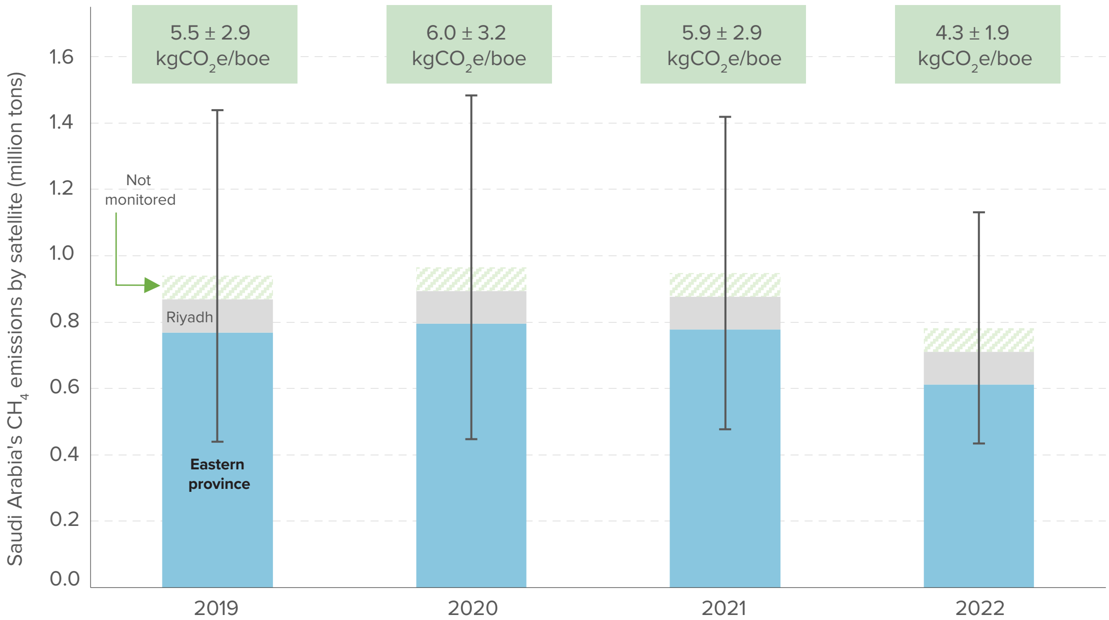
Source: Kayrros 2023.

Figure 4. Total CH_4 emissions in Saudi Arabia from 2019 to 2022 with approximated uncertainty ranges.



Source: Kayrros 2023.

Figure 5. CH_4 emissions by the Saudi oil and gas sector from 2019 to 2022 with an approximated uncertainty range.



Source: Kayrros 2023.

Figure 5 also shows the oil and gas CH_4 intensities, measured in kilograms (kg) of CO_2e per barrel of oil equivalent (boe), implied by the satellite estimation. A 100-year global warming potential (GWP) of 28 was used to convert tons of CH_4 into tons of CO_2e (IPCC 2021). IPCC (2021) indicated that the mean GWP over 100 years for CH_4 ranges between 27 and 29.8, with an uncertainty range of ±11; this additional source of uncertainty was not incorporated in our analysis. The mean values for the oil and gas industry point to a CH_4 intensity that decreased in 2022 when compared with the preceding three years. The CH_4 intensity was 4.3 ± 1.9 kilograms of CO_2e (kgCO2e) per boe in 2022.

Table 2 breaks down our total oil and gas estimate for 2022 by asset. In total, 0.43 million tons of CH_4 were produced by assets that were directly measured. The Ghawar Field in the Eastern Province emitted the largest quantity, at around 0.15 million tons, followed by the fields in the central region close to Riyadh. Offshore fields are estimated to have emitted 0.25 million tons of CH_4, based on extrapolation, as none of their emissions were detectable via satellite.

Table 2. Oil and gas CH_4 emissions by asset in 2022.

Oil and Gas Fields	CH_4 Emissions (million tons)	Share that is measured
Central Oil Fields	0.10	100%
Ghazal/Mazalij	0.08	100%
Khurais	0.06	100%
Shaybah	0.04	100%
Ghawar	0.15	96%
Abqaiq	0.02	11%
Assets That Are Not Monitored	0.07	0%
Eastern Region—Offshore	0.25	0%
Jaladi	2.5×10^{-3}	0%

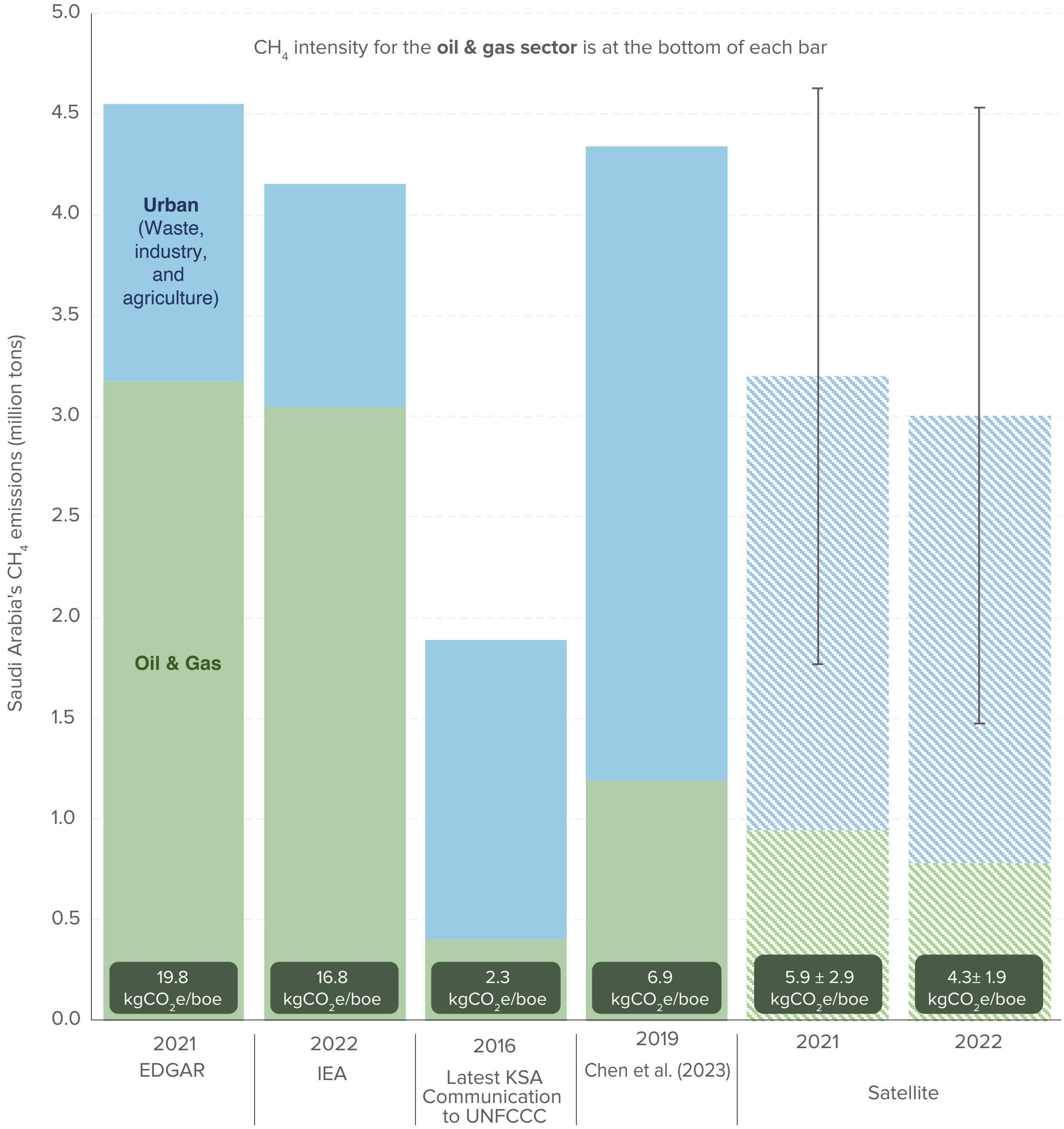
Source: Kayrros 2023.

At the national level, our total CH4 emission estimates obtained by satellite encompass those presented by EDGAR (2022), IEA (2023), Chen et al. (2023) and CDM-DNA (2022) within their uncertainty bounds. However, the sectoral breakdown of our satellite-based estimates aligns more closely with CDM-DNA (2022) and Chen et al. (2023), as we observed that the oil and gas sector contributes a minor share to Saudi Arabia's total CH_4 emissions. This minor share is consistent with Saudi Aramco's initiative to reduce GHG emissions from the oil and gas sector in Saudi Arabia. For instance, Saudi Aramco (2023b) reported a 16.5% decline in flaring intensity in 2022 compared to the preceding year, attributed to the enhanced use of flare gas recovery systems.

Figure 6 compares our total CH_4 satellite estimates with those from other sources for Saudi Arabia and underscores the CH_4 intensity of the oil and gas industry based on the emission estimate from each source. This intensity accounts for both upstream and midstream activities in the production and processing of crude oil, natural gas, natural gas liquids and condensates. Our estimates predominantly include upstream operations, focusing on the oil and gas fields. The information on the total boe produced was sourced from Saudi Aramco (2017, 2023b).

For the years shown in the chart, the CDM-DNA (2022) CH_4 emission estimate implies the lowest CH_4 intensity of 2.3 kg CO_2e per boe produced. Chen et al.'s (2023) estimates for the oil and gas sector imply a CH_4 intensity of 6.9 kg CO_2e per boe. The estimates from IEA and EDGAR are the highest, at 17.8 and 19.8 kgCO_2e per boe, respectively. Our mean satellite estimates for 2021 and 2022, of 5.9 and 4.3 kgCO_2e per boe, respectively, were more closely aligned with the CDM-DNA (2022) and Chen et al. (2023) estimates. Taking uncertainty into account, the range for our 2022 estimate could be anywhere from 2.4 to 6.2 kg CO_2e per boe. Given the uncertainty bounds, our satellite estimates of oil and gas CH_4 emissions were broadly consistent with CDM-DNA (2022) and Chen et al. (2023), but they suggest that there may be issues with the EDGAR (2022) and IEA (2023) estimates. Lastly, it is noteworthy that some other estimates, such as CDM-DNA (2022), account for all hydrocarbon processing and transport activities, while we only considered those activities that occurred in the vicinity of the oil and gas fields. Our satellite estimates might have been marginally higher if those activities conducted outside the vicinity of the oil and gas fields had been included.

Figure 6. Comparison of total CH_4 emissions in Saudi Arabia between sources.



Sources: Chen et al. 2023; EDGAR 2022; IEA 2023; Kayrros 2023; Saudi Aramco 2017, 2023b.

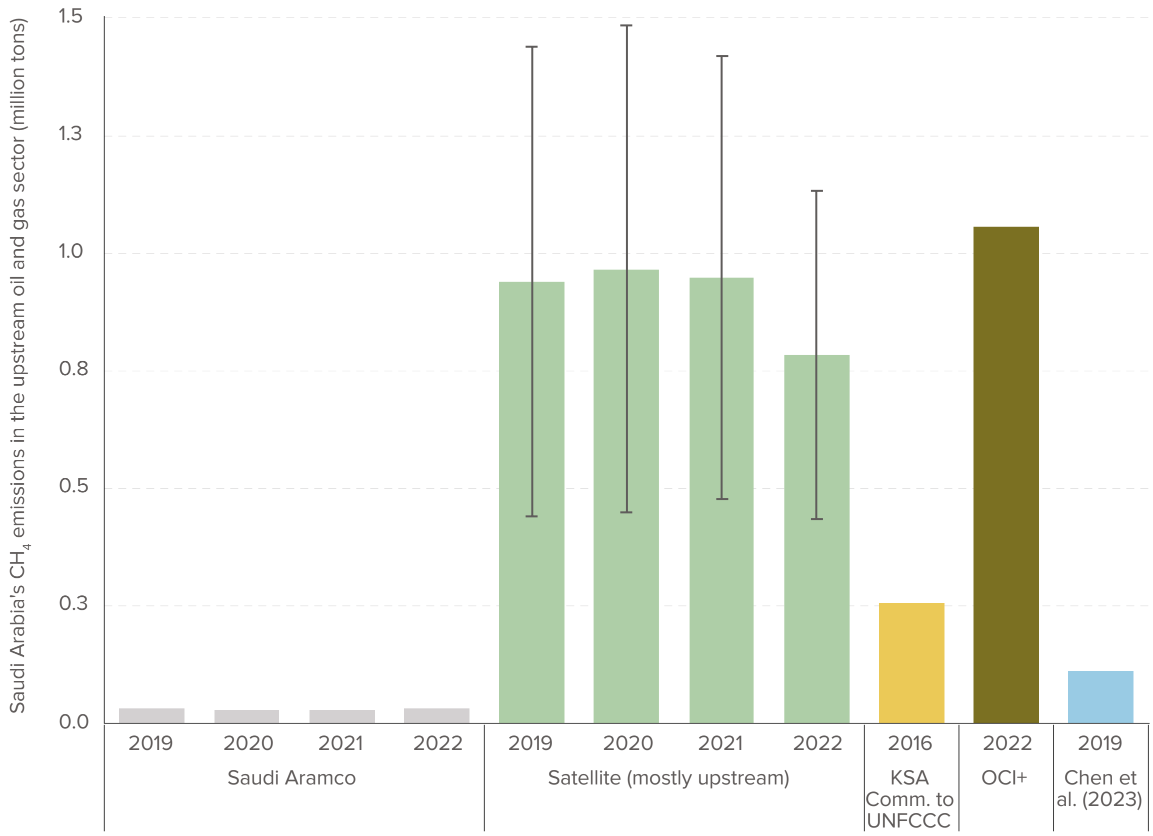
CH_4 Emission Reporting by Saudi Aramco

Saudi Aramco (2019) reported that only 2% of its total Scope 1 and 2 emissions in 2018 were CH_4, amounting to 48.8 kilotons of CH_4, or 1.37 million tons CO_2e, using a GWP of 28. Saudi Aramco (2023a) validated this number on its website for subsequent years, citing upstream CH_4 emissions of 29.4 kilotons in 2019 and 29.2 kilotons in 2022, with a decline in the intermediate years due to lower oil and gas production. These upstream CH_4 emission values represented about 60% of the company's total CH_4 emissions in 2018.

Although there are differences in the boundaries of corporate and national reporting of emissions, we have tried to compare estimates. Figure 7 shows a comparison of our oil and gas satellite estimates and those of Saudi Aramco (2023a), the Oil Climate Index plus Gas (OCI+) (2023) developed by the Rocky Mountain Institute, Chen et al. (2023) and the latest Saudi Fourth National Communication (CDM-DNA 2022). OCI+ focuses on GHG emissions from the oil and gas industry and uses peer-reviewed models of oil and gas operations and data collected by satellites to produce its estimates.

We limited the CH_4 emission figures from Saudi Aramco, OCI+, Chen et al. (2023) and CDM-DNA to upstream operations. Chen et al. (2023) stated that all CH_4 emissions from oil production can be attributed to upstream operations. In contrast, emissions from gas production are split into upstream, midstream and downstream operations. Chen et al. (2023) estimated the upstream oil and gas emissions to be 0.11 million tons of CH_4. While we cannot assert that our satellite estimates solely incorporate upstream operations, we can state that our estimates primarily include upstream operations, as we monitored CH_4 emissions above the oil and gas fields. Some transport and processing might occur in these areas, but the majority of the product transport, oil refining and downstream operations predominantly take place outside the areas covered in Figure 2. Our satellite estimates and the latest KSA communication were markedly higher than the figures reported by Saudi Aramco.

Figure 7. Comparison of upstream oil and gas estimates by Saudi Aramco, satellites and the latest KSA communication to the UNFCCC.



Sources: Chen et al. 2023; Kayrros 2023; OCI+ 2023; UNFCCC 2022.

The discrepancies between Saudi Aramco, the OCI+, Saudi Arabia's inventory submission to the UNFCCC, Chen et al. (2023) and our satellite-based estimates could be due to any combination of reasons. One crucial source for the discrepancy with Saudi Aramco relates to the boundaries of measurement. For example, it is possible that there are subcontracted operations in the vicinity of the oil and gas fields that produce CH_4 emissions that are detected by satellites but not incorporated by Aramco based on their corporate boundary of "wholly-owned operated assets" (Saudi Aramco 2021, p. 76). There may also be assets that produce CH_4 emissions that are partially owned by Saudi Aramco and therefore not included by the company given its measurement boundaries, whereas all the other estimates, which focus on national emissions of CH_4 by all assets within Saudi Arabia, would include the emissions from such partially-owned assets. Other possible reasons for the observed discrepancies include high instrumentation error of the satellites, parameters and assumptions used in modeling emissions, inaccurate emission factors used, and the challenges of utilizing ground-based sensors (such as issues in sensor coverage) to detect CH_4. Further investigation by additional satellites may be warranted to better understand these discrepancies and ascertain the true level of CH_4 emissions.

Super-Emitting Events

There is no universally accepted definition of what constitutes a super-emitting event. Such events exhibit emission rates that are abnormally higher than what is typically observed (NASA 2022). Zavala-Araiza et al. (2017) defined super-emitters as the top 1% of emitters at their observed sites, with a threshold of 26 kg per hour of unintended CH_4 release to meet the definition. Casey et al. (2021) incorporated super-emitters with median emissions ranging from 20 kg per hour for oil refineries to 468 kg per hour for waste facilities. The U.S. Environmental Protection Agency (2022) proposed defining super-emitters as those emitting at least 100 kg of CH_4 per hour. It is important to note that the satellite equipment used in this analysis cannot detect any emissions below 1,000 kg of CH_4 per hour.

Defining a super-emitter as a facility that emits at least 1 ton of CH_4 per hour, Kayrros identified several super-CH_4-emitting events in Saudi Arabia from 2019 to 2022. These events represented significant releases or leakages of CH_4, with six occurrences in 2019, two in 2020, five in 2021 and 14 in 2022. It is important to note that only the flow rates of CH_4 were detected, not the duration. In 2022, six super-emitting events were detected above urban areas, and 27 events were related to oil and gas activities. As summarized in Table 3, 19 of those 27 could be measured. Some events could not be measured, as the image signal was noisy, but the flow rate significantly exceeded the detection thresholds of the satellites. If each event in our study period lasted for 24 hours—the revisit frequency of Sentinel-5P—it can be estimated that 0.22% of the total mean CH_4 emissions in the Kingdom were due to super-emitting events. Even if we assumed that all Sentinel-2 measurements lasted for seven days — the satellite's revisit frequency — super-emitters would still only have represented 0.43% of total mean CH_4 emissions in Saudi Arabia.

Table 3. Super-emitting events for CH_4 in Saudi Arabia between 2019 and 2022.

Occurrence date	CH_4 emission rate (tons per hour)	Sector	Satellite
August 6, 2019	3.75	Oil and gas	Sentinel-2
August 23, 2019	2.46	Oil and gas	Sentinel-2
August 23, 2019	2.77	Oil and gas	Sentinel-2
September 5, 2019	3.45	Oil and gas	Sentinel-2
September 12, 2019	9.21	Oil and gas	Sentinel-2
October 3, 2019	48.57	Oil and gas	Sentinel-5P
June 21, 2020	5.41	Oil and gas	Sentinel-2
June 28, 2020	4.81	Oil and gas	Sentinel-2
May 27, 2021	2.35	Oil and gas	Sentinel-2
June 1, 2021	2.56	Oil and gas	Sentinel-2
November 3, 2021	Could not be measured	Oil and gas	Sentinel-5P
November 6, 2021	Could not be measured	Oil and gas	Sentinel-5P
November 30, 2021	2.50	Oil and gas	Sentinel-2
January 8, 2022	Could not be measured	Oil and gas	Sentinel-5P
January 8, 2022	Could not be measured	Oil and gas	Sentinel-5P
February 6, 2022	Could not be measured	Oil and gas	Sentinel-5P
February 9, 2022	28.42	Oil and gas	Sentinel-2
May 29, 2022	2.32	Oil and gas	Sentinel-5P
August 15, 2022	Could not be measured	Oil and gas	Sentinel-5P
August 29, 2022	25.85	Oil and gas	Sentinel-2
September 19, 2022	1.08	Oil and gas	Sentinel-5P
October 17, 2022	Could not be measured	Urban	Sentinel-5P
October 23, 2022	Could not be measured	Urban	Sentinel-5P
October 24, 2022	47.33	Urban	Sentinel-5P
October 29, 2022	53.43	Urban	Sentinel-5P
November 22, 2022	27.50	Urban	Sentinel-5P
November 23, 2022	Could not be measured	Urban	Sentinel-5P
November 23, 2022	1.19	Oil and gas	Sentinel-2

Source: Kayrros 2023.

CO_2

Current State of CO_2 Emission Inventories for Saudi Arabia

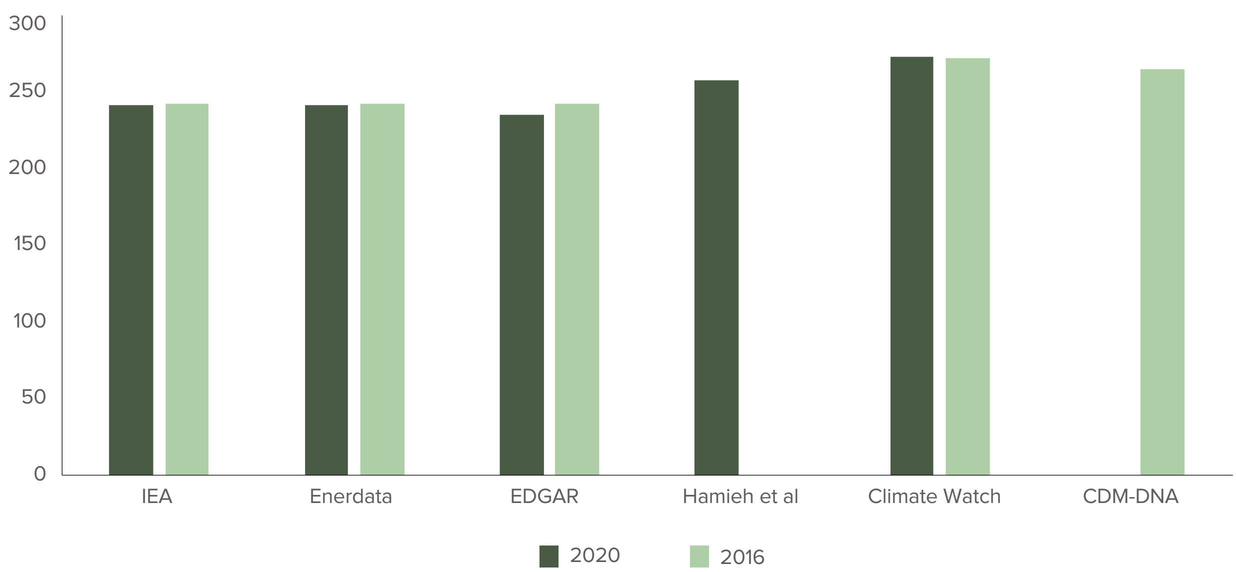
Multiple sources have estimated the total national CO_2 emissions for various countries, including Saudi Arabia (Luomi, Al Sheri, and Howarth 2021). These sources include CDIAC (2023), Climate Watch (2023), Saudi Arabia's CDM-DNA (2022), EDGAR (2022), E.I. (2023), Enerdata (2023), PRIMAP-hist (Gütschow and Mika 2023), IEA (2022) and the Global Carbon Project (GCP 2022). When compared with other GHGs, such as CH_4 and N_2O, more estimates are available for CO_2 emissions, likely because CO_2 contributes the majority of GHG emissions, and calculating CO_2 emissions from fuel combustion is relatively straightforward, given the available data on fuel consumption. While total CO_2 estimates are generally consistent, Luomi, Al Shehri, and Howarth (2021) demonstrated that there are some significant differences among estimates from these data providers.

At the sectoral level, however, there are fewer estimates of CO_2 emissions compared to economy-wide estimates. For the power sector, one of the largest sources of CO_2 emissions in Saudi Arabia, the only global datasets providing estimates for Saudi Arabia are Climate Watch (2023), IEA (2022), EDGAR (2022) and Enerdata (2023).

Apart from these global data providers, the CDM-DNA (2022), responsible for submitting Saudi Arabia's national GHG inventories to the UNFCCC, offers a detailed breakdown of emissions by sector in each submission, with the latest in 2022 reporting data for 2016. Additionally, a recently published study measured CO_2 emissions in the Saudi power sector for 2020 (Hamieh et al. 2022).

The six available estimates of CO_2 emissions for the Saudi power sector underscore the challenges related to emission measurement. One such challenge is timeliness. The most detailed estimates of GHG emissions were provided by the CDM-DNA (2022), but this level of detail likely contributed to the six-year lag between the publication year (2022) and the data year (2016). Hamieh et al. (2022) employed granular methods to measure CO_2 emissions in facilities across Saudi Arabia, generating an estimate of power sector emissions in 2020. In contrast, Climate Watch (2023), IEA (2022), EDGAR (2022) and Enerdata (2023) provide a time series of power sector CO_2 emissions in Saudi Arabia, but reporting lags vary across these sources. For example, the IEA (2022) data currently only extends to 2020, while Enerdata's (2023) estimates are available up to 2022. Given the different reporting years, Figure 8 compares these estimates of CO_2 emissions in the power sector for 2016 and 2020.

Figure 8. Comparison of power sector CO_2 emissions from multiple sources.



Sources: CDM-DNA 2022; Climate Watch 2023; EDGAR 2022; Enerdata 2023; Hamieh et al. 2022; IEA 2022.

The mean value of CO_2 emissions for the sector was 252.9 million tons in 2016 and 249.8 million tons in 2020, with respective standard deviations of 12.8 and 14.0 million tons. Although the estimates were generally consistent, the differences between them are not negligible. These differences likely stem from varying methodologies, assumptions, data sources and boundaries. Given Saudi Arabia's arid climate, desalination is a key water source in the country. Sea water is desalinated using various technologies, primarily through thermal plants that co-produce electricity and desalinated water or reverse osmosis plants that consume electricity to produce desalinated water (Al-Sahlawi 1999). While CDM-DNA (2022) and Hamieh et al. (2022) provided separate estimates for CO_2 emissions by desalination plants, such a breakdown was not provided by other sources, making it challenging to ascertain the differences in measurement boundaries.

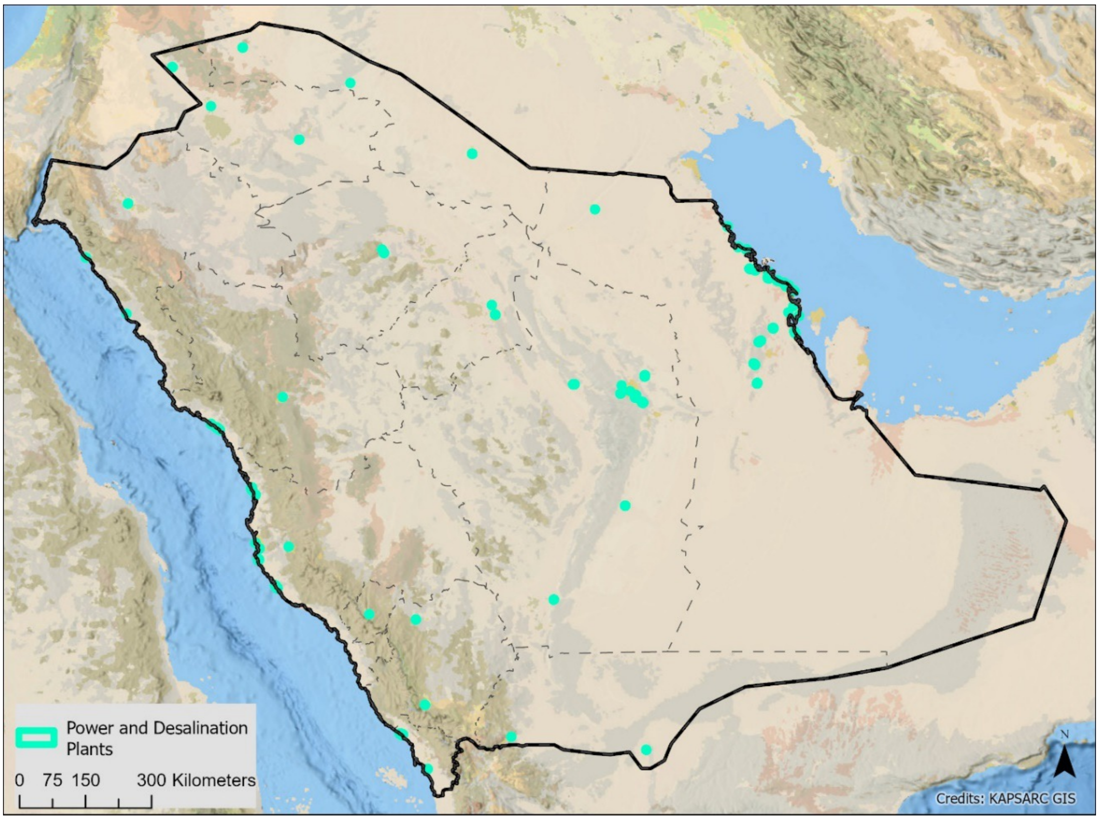
Methodology for CO_2 Emissions

Unlike CH_4, the currently available public satellites lack the capabilities needed to directly measure CO_2 gases emitted from assets, such as power plants. Instead, satellites measure activities driving CO_2 emissions, and these activity data were combined with other data sources to derive our satellite-based CO_2 emission estimates.

For the power sector, CO_2 emissions from 2016 to 2022 were estimated by aggregating emissions from individual power plants. Specifically, the European Space Agency's Sentinel-2 satellite was used to detect whether a power plant was operational. This on-off signal was identified either by capturing images of fumes emanating from power plant chimneys (optical imagery) or by detecting thermal signatures above operating plants (thermal imagery). The signal was obtained at approximately weekly intervals due to satellite revisit rates, with linear interpolations used to fill gaps between satellite revisits. The daily activity data were then combined with information on individual power plant capacities in Saudi Arabia to estimate daily electricity production, measured in kilowatt-hours (kWh), which were then aggregated monthly and, subsequently, annually. The main fuel used in each power plant was obtained from Hamieh et al. (2022), and CO_2 emission factors (in kg CO_2 per kWh) were used to convert the electricity production data into CO_2 emissions for each plant.

For power plants where obtaining an on-off signal through satellite imagery was not possible, extrapolation was used to scale our satellite-based estimates to encompass all power plant capacity in Saudi Arabia. Approximately 72% of power plant capacity was monitored using satellite technology, with extrapolation being used to scale up the estimates to include the remaining 28% of unmonitored capacity, primarily comprising combined cycle and steam turbine power plants. Scaling up the estimates to include unmonitored plants was essential to ensure comparability between our satellite-based estimates and other estimates of CO_2 emissions in the Saudi power sector. Figure 9 displays the locations of all the power and desalination plants included in this analysis.

Figure 9. Identified power and desalination plants for satellite measurement analysis.



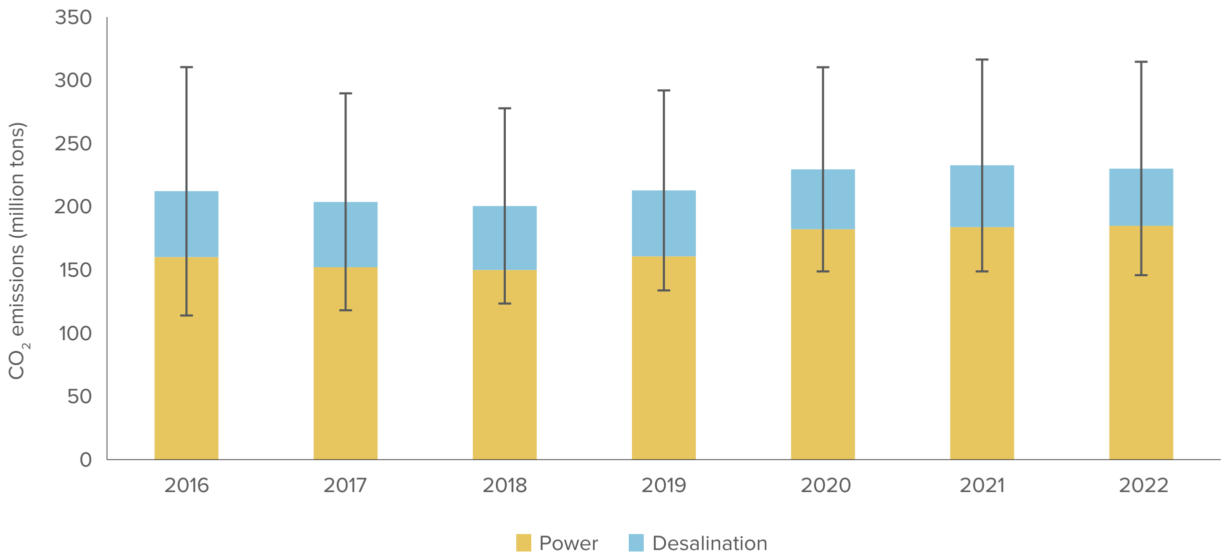
Sources: KAPSARC and Kayrros 2023.

Estimation Results

Total Saudi CO_2 emissions from 2016 to 2022, as estimated using satellite technology, are shown in Figure 10. These estimates, which are broken down by pure power plants and desalination plants, reveal that the electricity and desalination sector in Saudi Arabia is responsible for approximately 200 to 250 million tons of CO_2 emissions annually. While there seems to be an upward trend in emissions from 2018 to 2022, establishing the existence of such a trend is challenging due to the substantial uncertainties associated with satellite-based estimates, as indicated by the relatively large error bars.

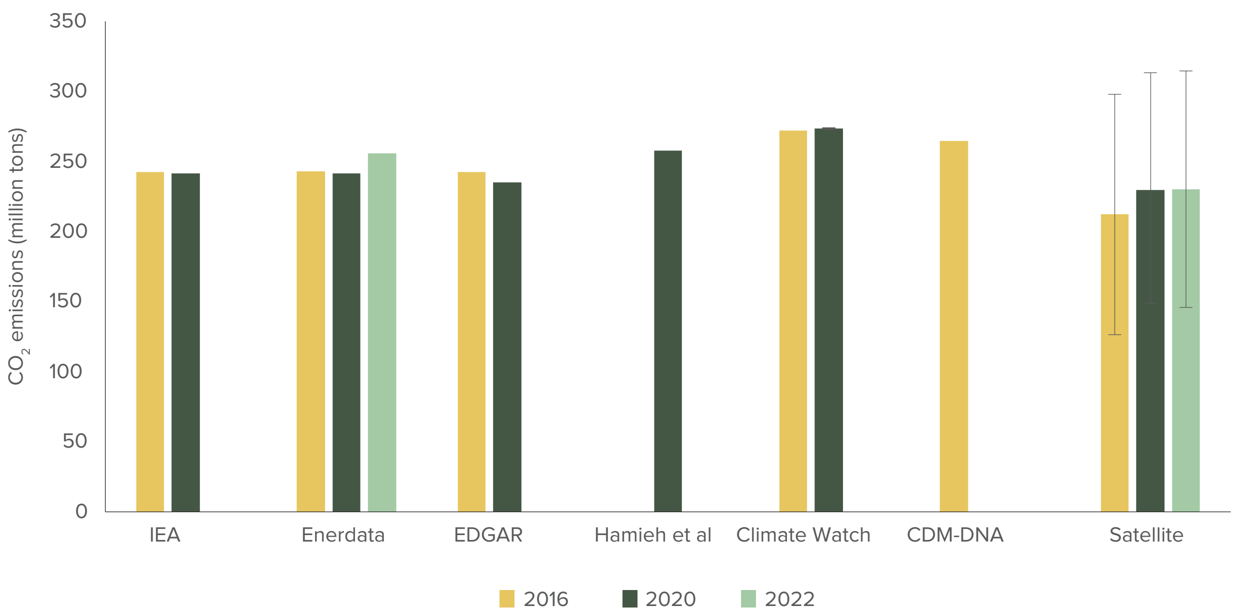
Figure 11 compares our satellite-based estimates with other available estimates for the same sector, demonstrating that our findings are consistent with alternate estimates of CO_2 emissions in the electricity and desalination sectors. However, our satellite-based estimates were roughly 10% to 20% lower on average. Given the challenges related to timeliness, Enerdata is currently the only source offering estimates for CO_2 emissions in the sector for the year 2022. For that year, Enerdata reported 255.7 million tons of CO_2, compared to the 230.2 million tons measured by satellite.

Figure 10. Satellite-based estimates of CO_2 emissions in the Saudi electricity and desalination sector.



Source: Kayrros 2023.

Figure 11. Comparison between satellite-based estimates and other estimates of CO_2 emissions in the Saudi electricity and desalination sector.



Sources: CDM-DNA, 2022; Climate Watch 2023; EDGAR 2022; Enerdata 2023; Hamieh et al. 2022; IEA 2022; Kayrros 2023.

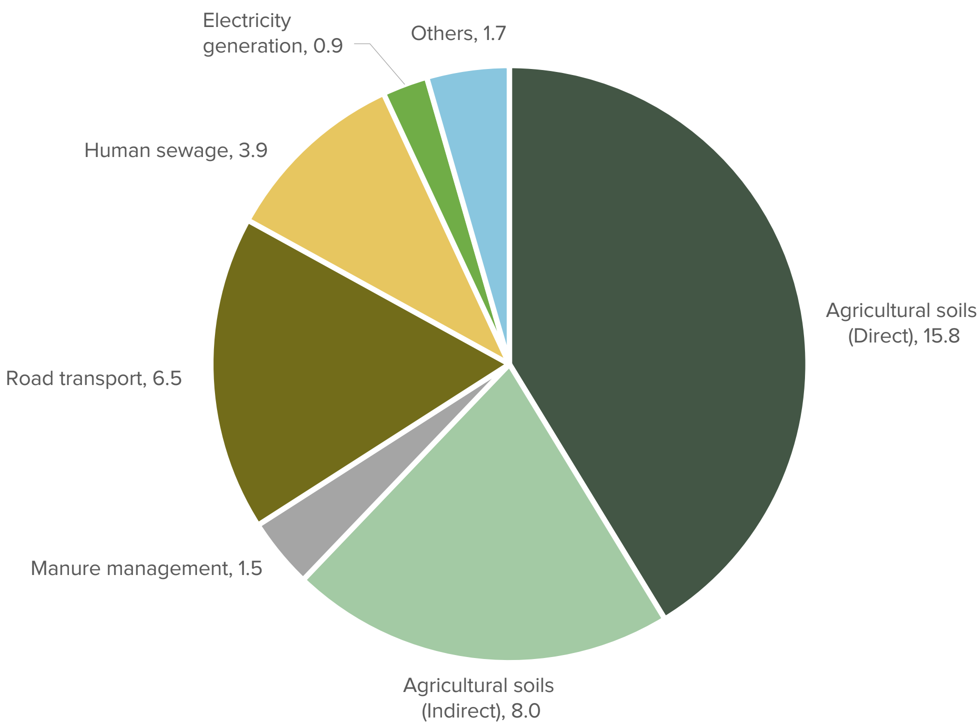
N_2O

Current State of N_2O Emission Inventories for Saudi Arabia

Compared to CO_2 and even CH_4, there are significantly fewer publicly available estimates of N_2O emissions in Saudi Arabia. The most recently submitted KSA Fourth National Communication to the UNFCCC (CDM-DNA 2022) offers one of the most detailed breakdowns of N_2O emissions by sector. This submission highlights that the largest share of N_2O emissions comes from the agricultural sector, particularly from soil management, followed by road transport. Of the total 38.2 kilotons of N_2O emissions reported nationally in 2016, nearly 62% were generated from agricultural soils, at 15.8 kilotons and 8 kilotons for direct and indirect agricultural soil emissions, respectively. Figure 12 shows the N_2O emission breakdown reported by the CDM-DNA (2022).

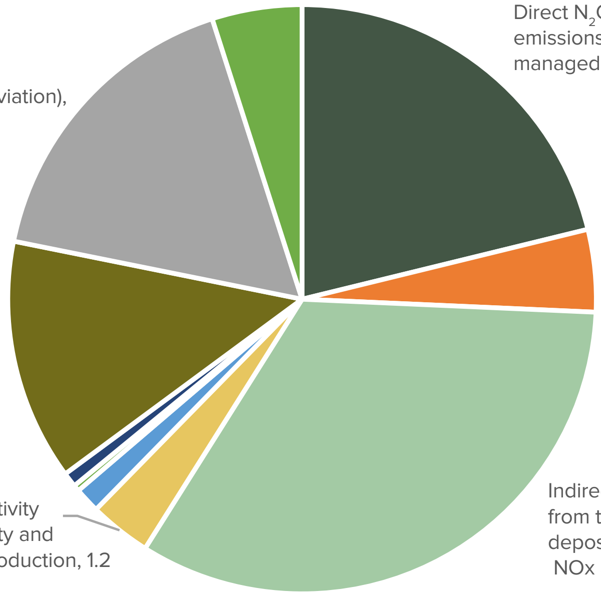
Another data source reporting KSA N_2O emissions by sector is EDGAR (2022). Regarding the total, EDGAR reported a similar amount for total N_2O emissions in 2016, with an estimate of 36.6 kilotons. However, there is a significant discrepancy in the sectoral breakdown between EDGAR (2022) and CDM-DNA (2022). Most notably, the direct and indirect N_2O emissions from soil management in EDGAR constitute only around 26% of the total, as opposed to 62% reported in CDM-DNA (2022). Figure 13 shows the N_2O emission breakdown as reported by EDGAR (2022).

Figure 12. N_2O emissions in kilotons by sectors and subsectors in 2016.



Source: CDM-DNA 2022.

Figure 13. N_2O emissions in kilotons by sectors and subsectors in 2016.

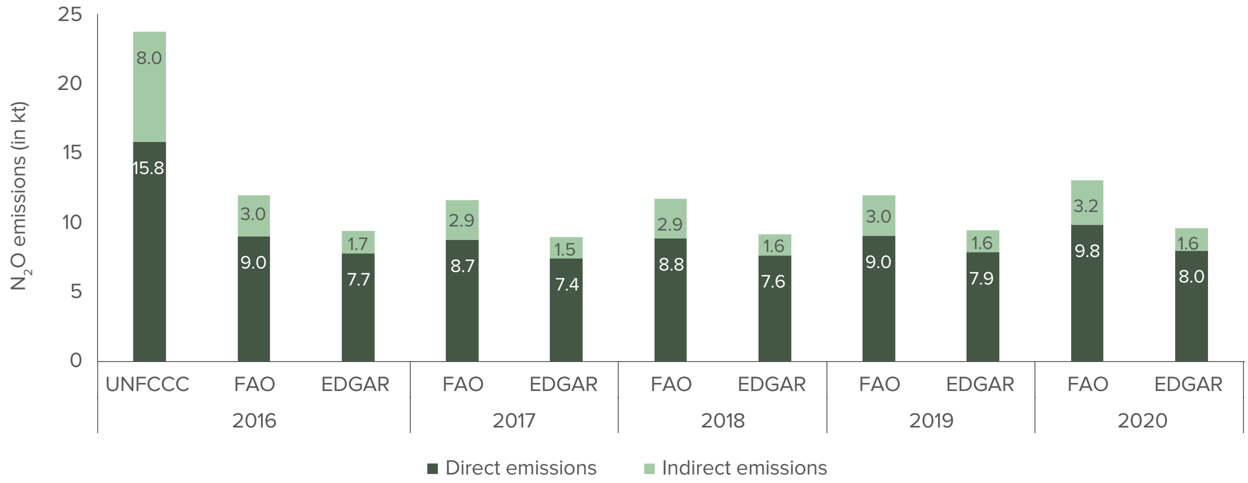


Source: EDGAR 2022.

The United Nations Food and Agriculture Organization (FAO) provides another estimate of N_2O emissions for Saudi Arabia. However, as indicated by the name, their estimate exclusively focuses on emissions stemming from the agricultural sector.

Figure 14 compares agricultural sector emissions in Saudi Arabia, specifically those originating from agricultural soils, between the three available estimates in CDM-DNA (2022), EDGAR (2022) and FAO (2023). All three estimates only include N_2O emissions from soil management activities. Figure 14 highlights some of the differences between the estimates, which are more pronounced than the differences observed between the various estimates of CO_2 emissions in the power sector but less stark than the striking disparities between the estimates of CH_4 emissions in the oil and gas sector. It is worth noting that these differences may be attributed to the distinct methodologies used to generate the estimates. Additionally, there is no standardized way to aggregate or classify the sources of emissions into sectors and subsectors, which could contribute to the variances observed in the N_2O estimates from different sources.

Figure 14. Direct and indirect N_2O emissions from soil management activities as reported by three data sources: UNFCCC (CDM-DNA, 2022), FAO (2023) and EDGAR (2022).



Methodology for N_2O Emissions

Unlike CH_4, the currently available public satellites do not possess the capabilities needed to directly measure emitted N_2O gas. Instead, satellites measure activities driving N_2O emissions, and these activity data are combined with other data sources to derive satellite-based emission estimates. Given the current capabilities of public satellite technology and the significant role the agricultural sector plays in N_2O emissions, we used satellite remote sensing techniques to infer the N_2O emissions associated with cultivating agricultural land.

The IPCC (2006) identified the nitrogen sources leading to direct and indirect N_2O emissions from agricultural soils. These include the application of synthetic fertilizers to the soil, in addition to animal manure, other organic fertilizers, crop residues and mineralization of soil organic matter. We focused on measuring N_2O emissions resulting from applying synthetic fertilizers to the soil and extrapolated the contributions of the remaining sources of N_2O emissions from agricultural soils. Our satellite-based synthetic fertilizer N_2O emissions were estimated through the following steps:

1. **Estimating annual total agricultural surface area:** We identified and monitored nine zones in the Kingdom exhibiting significant agricultural activity from 2015 to 2022, as shown in Figure 15. The total area covered by these zones amounts to over 70,000 km^2, constituting almost 80% of the total KSA agricultural land (GASTAT 2023). The Normalized Difference Vegetation Index (NDVI) was used to distinguish agricultural land from other land types and to monitor annual changes in agricultural land.

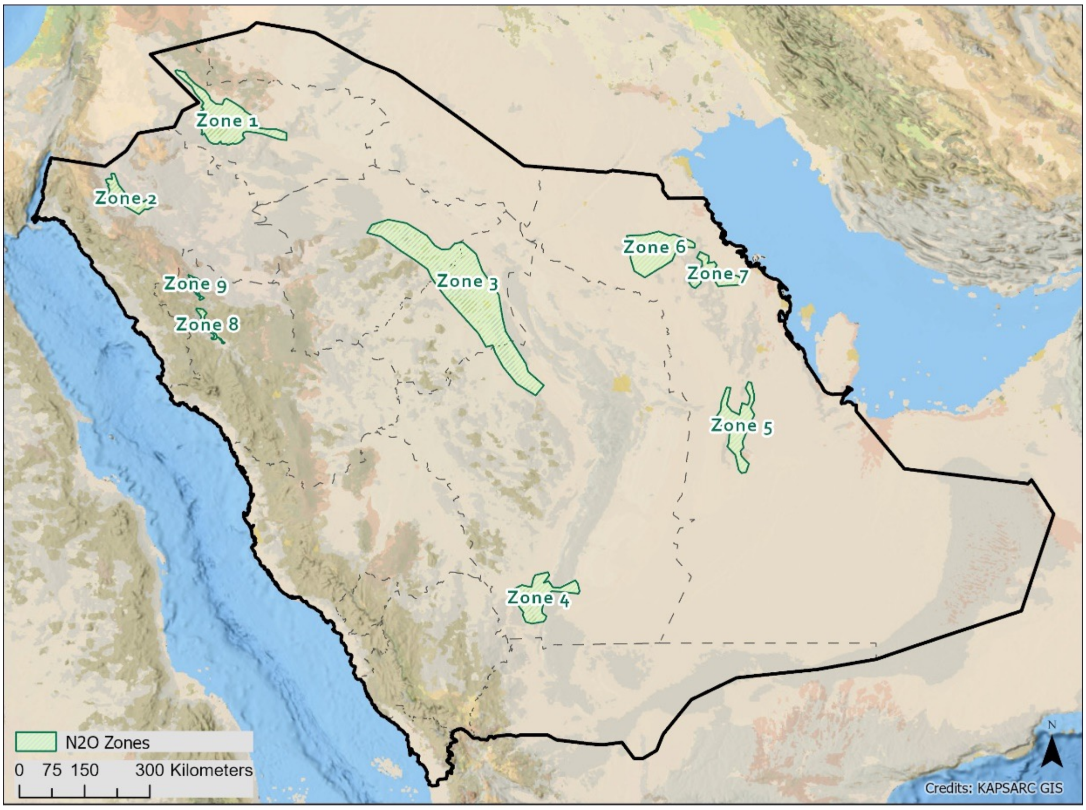
2. **Crop type assignment:** Different crop types vary in the amount of fertilizer they need, so it was necessary to assign crop types to the identified agricultural zones. This was achieved by identifying five distinct vegetation patterns covering the identified agricultural land based on monthly variations in the NDVI. The five vegetation patterns and associated crop types are listed in Appendix B.

3. **Estimating fertilizer quantity:** We relied on a study by Ludemann et al. (2022), which reported the amount of fertilizer required by each crop by country. Although this study included data from more than 60 countries, Saudi Arabia was not among them. Therefore, we used a global average to estimate the total amount of synthetic fertilizer applied per crop type in Saudi Arabia.

4. **Emission factoring:** After identifying the quantity of synthetic fertilizer applied, it was multiplied by the emission factor to obtain the direct and indirect N_2O emissions, following the 2006 IPCC guidelines (IPCC 2006).

For the remaining sources of emissions from agricultural soils (those not related to synthetic fertilizers), we extrapolated the direct and indirect N_2O emissions by leveraging the share of N_2O emissions due to synthetic fertilizers, as indicated by the FAO (2023).

Figure 15. Mapping of major agricultural zones in Saudi Arabia included in the satellite-based analysis.



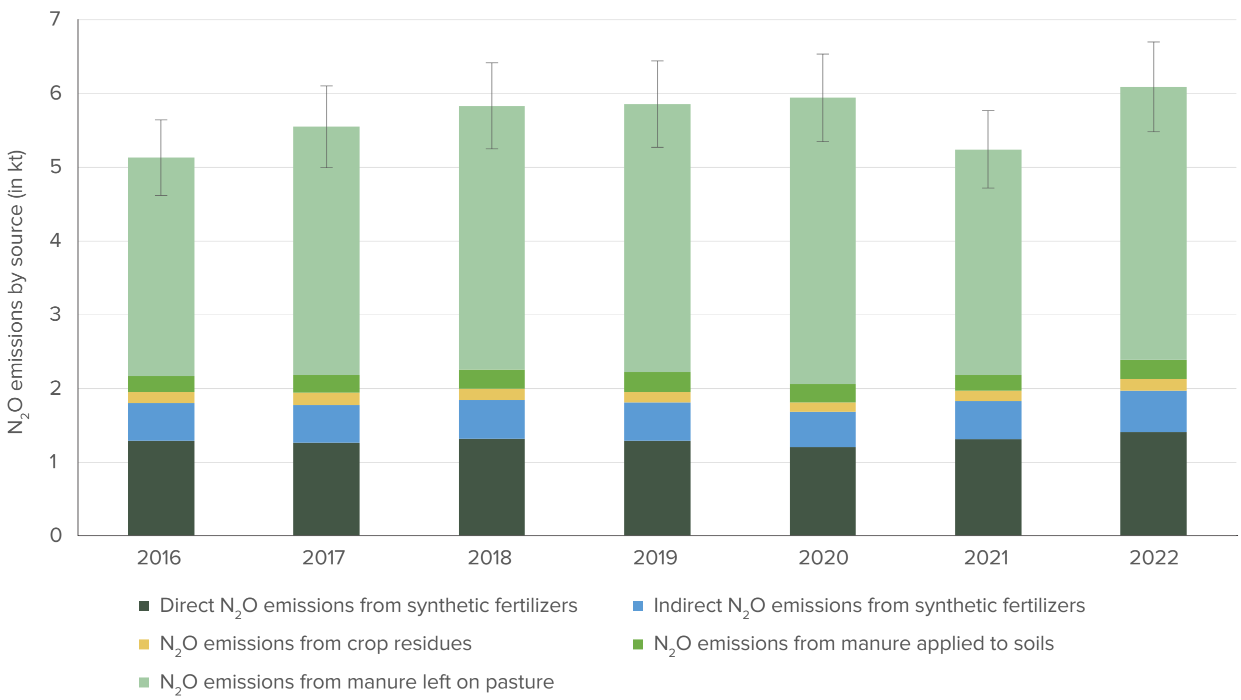
Sources: KAPSARC and Kayrros 2023.

Estimation Results

Figure 16 depicts the annual N_2O emission estimates associated with agricultural activity in the KSA, along with approximately 10% error margins. These margins account for spatial and clustering uncertainties related to agriculture land detection and vegetation pattern clustering (refer to the second column in Appendix B).

However, these approximate error margins do not capture uncertainties stemming from mapping crop types to vegetation patterns (see the third column in Appendix B), nor do they include uncertainties related to using global fertilizer use and emission factors, given the absence of Saudi-specific factors. Additionally, we found extensive variation in these factors between countries, which strongly influences our estimates but is not represented in our illustrated error bars.

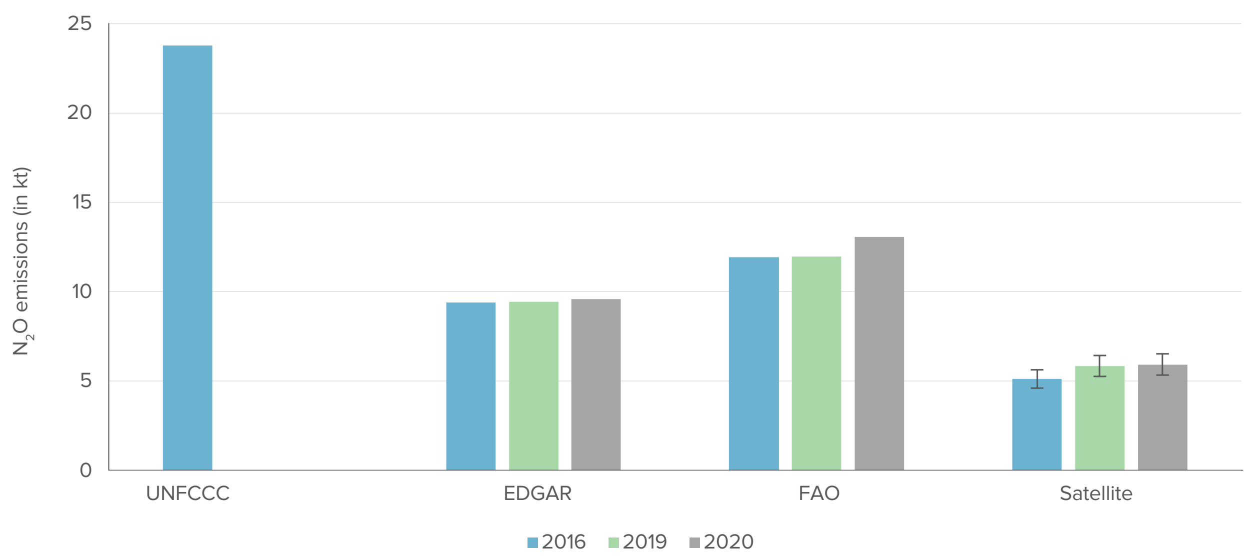
Figure 16. KSA N_2O emissions from agricultural activity in kilotons.



Source: Kayrros 2023.

Figure 17 compares our satellite-based estimates with other available estimates for N_2O emissions from soil management activities, including direct and indirect emissions, over three years. Figure 17 shows that our satellite-based estimates are consistently lower than those from other sources. For example, between 2016 and 2020, the FAO reported N_2O emissions from agricultural soils in the range of 11.94 to 13.07 kilotons, compared to our satellite-based estimates, which were in the range of 5.13 to 5.94 kilotons, or 1.3 to 1.6 million tons of CO_2e, using a GWP of 265.

Figure 17. Comparison between satellite-based estimates and other estimates of KSA N_2O emissions from agriculture activity in kilotons for the years 2016, 2019 and 2020.



Sources: CDM-DNA 2022; EDGAR 2022; FAO 2023; Kayrros 2023.

Limitations and the Future of Satellite Technology

There remain several limitations to the use of satellites for measuring GHG emissions. These limitations relate to the capabilities of satellites and their sensors, resolutions, revisit times and various other factors. For example, cloud cover is a major impediment to detecting GHGs in the atmosphere because it hinders or prevents light transmission. Satellites rely on sunlight reflected off the Earth's surface. Some of these limitations also vary by GHG, depending on factors such as the ease with which each GHG can be detected through imagery and the ability to separate anthropogenic emissions from background or natural emissions.

Although satellites seem particularly useful for measuring CH_4 emissions, which are detected directly through satellite imagery, there are some CH_4-specific limitations. For example, Sentinel-5P experiences difficulty with water surfaces and snowy environments. Sunlight is reflected at different intensities and directions on water surfaces. When sunlight is reflected directly into the sensor, water is perceived as a bright surface, which can be misinterpreted as cloud cover (Latsch et al. 2022). It has recently been shown that Sentinel-5P overestimated CH_4 emissions in such cases (Latsch et al. 2022). In our study of the Saudi oil and gas sector, we were unable to use satellites for any offshore assets, compelling us to use extrapolations to ensure full coverage of the sector's emissions, thereby introducing additional uncertainty into our estimates. However, developments for detecting CH_4 above water and at night have been noted (Jacob et al. 2022), but uncertainties remain relatively larger for offshore assets. For urban areas, estimating CH_4 emissions above coastal urban regions with mountainous topographies, a description fitting much of Saudi Arabia's western coast, proved challenging (Lorente et al. 2021). Mountainous terrain poses challenges due to light reflection anomalies that produce significant uncertainties (Cooper, Dubey, and Hawkes 2022).

For CO_2 emissions from the power sector, the current capabilities of publicly available satellites make it very difficult to measure the gas directly, which is why we used satellites to measure an activity driving the emissions. Nevertheless, even with our indirect approach, which relied on imaging fumes or thermal signatures from power plants, we encountered difficulties measuring emissions from gas-powered steam turbines and combined-cycle power plants. It is possible that these types of plants are more efficient or constructed in a way that limits detectable fumes or thermal signatures. As Saudi Arabia moves closer to its target of generating 50% of its electricity from renewables and 50% from gas — mainly from energy-efficient combined-cycle power plants — the use of our approach will become even more challenging unless there are developments in optical or thermal imagery that make it possible to detect signals from combined cycle plants more easily. Furthermore, current revisit rates introduce significant uncertainties, requiring the interpolation of power plant activity between satellite revisits. Higher temporal resolutions will be needed to reduce the uncertainty in these estimates, a requirement that also applies to the other GHGs.

For N_2O emissions from the agricultural sector, the current capabilities for directly measuring the gas are limited, prompting us to use satellites to measure activities driving the emissions. Nevertheless, even with our indirect approach, which relied on detecting the areas of agricultural zones and mapping crop types, we encountered difficulties detecting agricultural zones in the mountainous regions of southwest Saudi Arabia, such as in Jazan province. Moreover, the resolution was not high enough to detect specific crop types, necessitating the use of an index to indirectly determine them, which introduced further uncertainty.

In conclusion, satellite technology for measuring GHG emissions continues to evolve rapidly. A plethora of new satellites and sensors are expected to be launched in the coming years, with the hope of overcoming many of these limitations.

Policy Recommendations

Meeting the goals of the Paris Agreement necessitates comprehensive, transparent, timely and accurate measurement of emissions. Parties to the Paris Agreement are required to regularly submit a bottom-up national inventory of GHG emissions following IPCC guidelines. However, such an approach promotes comprehensiveness at the expense of timeliness. Satellite technology enables near-real-time measurement of emissions, addressing the issue of timeliness but sacrificing comprehensiveness. Therefore, employing different methods to measure GHG emissions can help overcome such trade-offs. Ultimately, there is no one-size-fits-all solution to emission measurement. Employing a combination of bottom-up methods, ground-based remote sensing platforms and top-down airborne and satellite methods will optimize comprehensiveness, transparency, accuracy and timeliness.

Regarding accuracy, conflicting estimates of GHG emissions, particularly for CH_4, make it challenging to ascertain the current standings of countries and their progress toward achieving their goals. For example, over 150 countries signed the Global Methane Pledge, a non-binding agreement to collectively reduce global CH_4 emissions by at least 30% below 2020 levels by 2030 (Climate & Clean Air Coalition 2021). Without a clear understanding of the actual level of CH_4 emissions in 2020, it will be difficult for countries to take the necessary actions to achieve this goal, as the lack of accuracy makes it unclear how close or far that goal really is. Consequently, countries would benefit from regularly using satellite technology to measure CH_4 emissions and employing the information to refine their bottom-up estimates. Global providers of emission data, such as the IEA and EDGAR, could also enhance their GHG emission data through satellite measurements. For example, IEA (2022) provided data on national CH_4 emissions for countries globally based on a granular measurement of CH_4 emissions for the U.S. oil and gas sector, which was then scaled to other countries using scaling factors. Our satellite-based estimates suggest that the assumptions used by the IEA to scale their estimate of CH_4 emissions for Saudi Arabia were inaccurate. By incorporating satellite measurements, such global data providers could refine their assumptions. Improved data quality from these providers would yield higher-quality outputs from various analyses and models that rely on their data as inputs.

Satellites play a pivotal role in promoting transparency, offering a non-intrusive solution for quantifying and verifying GHG emissions globally through measurements that are universal and consistent. Transparency is a foundational element of the Paris Agreement, as articulated in Article 13, which focuses on the ETF. Hence, utilizing satellites to measure GHG emissions can foster trust, a critical component in achieving global climate goals. However, the current IPCC guidelines do not encourage countries to explore or utilize satellite technology in their emission measurements. There is a need for developments in IPCC guidelines to encourage countries to utilize satellites in their national GHG inventory submissions, thereby achieving the transparency outlined in the Paris Agreement's ETF. For example, the IPCC could refine its inventory guidelines, encouraging countries to test or use satellite technology to validate their emission estimates or to identify potentially overlooked emissions.

Despite the advantages of satellite technology, several challenges exist. First, handling raw remote sensing data on a national scale is technically demanding and resource-intensive. Some developing countries might lack the necessary resources to generate satellite-based estimates. Second, relatively large uncertainties are associated with satellite-based estimates, as discussed in this paper. More efforts are needed to fully understand and quantify these uncertainties. Third, the technology does not yet possess the capability to comprehensively cover all sources of emissions across all sectors.

Political challenges also surround the adoption of satellite technology for measuring national GHG emissions. For example, satellite-based estimates might be favorable for one country, revealing lower-than-expected GHG emissions, and unfavorable for another, revealing higher-than-expected emissions. In such cases, countries receiving unfavorable results might resist using satellite technology for measurement through the negotiation process under the UNFCCC. Even in the relatively less politicized IPCC, political interests can influence its processes and outcomes (Lucas 2021). Therefore, encouraging the use of satellite technology through both the IPCC and UNFCCC processes might be time-consuming. Nevertheless, it is possible that research institutions, intergovernmental organizations or non-governmental organizations will take the lead in using satellites to produce standardized and transparent national emission estimates for parties to the Paris Agreement. This could potentially influence the global stocktake and the climate actions required to achieve global climate goals.

At the national level, our analysis yields several policy recommendations for decision-makers in Saudi Arabia. In the case of CH_4, we demonstrated how satellite technology can be used to measure super-emitting events, which would likely go undetected by conventional bottom-up methods. Defined as a facility emitting CH_4 at abnormally high rates, our estimates revealed that super-emitters in Saudi Arabia accounted for less than 0.5% of total CH_4 emissions in the Saudi oil and gas industry over our study period. We also detected several super-emitting events originating from urban activities. In fact, we measured relatively larger super-emitting events from urban activities when compared with the oil and gas sector. These urban activity super-emitting events were likely attributable to landfills or industrial wastewater, highlighting the significant potential for reducing those emissions. Monitoring such super-emitting events enables regulators to respond promptly, thereby achieving significant abatement. Satellite remote sensing could thus offer Saudi ministries and regulators a proven and timely method to track and regulate super-emitters in the Kingdom. For example, satellite monitoring could be assigned to a new unit within the Ministry of Energy tasked with overseeing and monitoring CH_4 super-emitters. With appropriate regulations in place, upon detection of a super-emitter, the Ministry of Energy could inform the responsible entity to act, and regulations imposing financial penalties on super-emitters that do not respond promptly could be enforced.

Direct satellite measurements could contribute to the CDM-DNA's national inventory submissions to the UNFCCC. Currently, CDM-DNA employs Tier 1 equations for estimating emissions, relying on average emission factors. Utilizing satellites to measure emissions could provide CDM-DNA with a better understanding of potential errors in these emission factors. As noted by Chen et al. (2022), IPCC emission factors for the oil and gas sector can be inaccurate by several orders of magnitude.

Looking to the future of Saudi Arabia, numerous ongoing projects aim to plant trees, with the goal of planting 10 billion trees by 2050 (Saudi Green Initiative, 2023). Satellites can help in gauging not only the removal of emissions from the atmosphere but also any potential increases in N_2O emissions that might result from increased fertilizer use due to the greening initiative.

However, limitations persist around the use of satellite technology to directly measure GHGs, including CO_2, which is the gas accounting for the largest share of global GHG emissions. Further investment is still needed to develop satellite technology and improve its accuracy. Ultimately, using a combination of bottom-up methods, ground-based remote sensing platforms and top-down airborne and satellite methods will aid in maximizing the comprehensiveness, transparency, accuracy and timeliness of GHG emission estimates.

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Endnotes

[1] The abbreviations of satellite missions and their respective instruments are listed as: Sentinel-5P is Sentinel-5 Precursor, TROPOMI is Tropospheric Monitoring Instrument, Landsat is Land Satellite, OLI is Operational Land Imager, OLI-2 is Operational Land Imager-2, MSI is Multispectral Instrument, EMIT is Earth Surface Mineral Dust Source Investigation, ISS is International Space Station, PRISMA is Hyperspectral Precursor of the Application of Remote Sensing Mission, HYC is Hyperspectral Infrared Imager, OCO-2 is Orbiting Carbon Observatory-2, OCO-3 is Orbiting Carbon Observatory-3, Metop-A/B/C is Meteorological Operational Satellite Program-A/B/C, IASI is Infrared Atmospheric Sounding Interferometer.

[2] Organizations' abbreviations are defined as follows: ESA stands for European Space Agency, USGS is United States Geological Survey, NASA is National Aeronautics and Space Administration, ASI is Italian Space Agency, and EUMETSAT is European Organization for the Exploitation of Meteorological Satellites.

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Appendix A

It is useful to explore how the IPCC guidelines address remote sensing and satellite technology. In the 2006 IPCC guidelines, the mention of such technologies and approaches is quite limited. The few instances where remote sensing or satellite technology is discussed in the 2006 IPCC guidelines include the following (IPCC 2006):

- Volume 1, Chapter 5: The guidelines discuss how "in the future, new inventory methods may be developed that take advantage of new technologies or improved scientific understanding. For example, remote-sensing technology improvements in emission monitoring technology may make it possible to monitor directly more types of emission sources" (page 5.6).

- Volume 1, Chapter 6: The guidelines delve into the use of "atmospheric measurements" to independently verify national GHG inventories. They specifically state that "even the availability of satellite-borne sensors for greenhouse gas concentration measurements (see Bergamaschi et al., 2004) will not fully resolve" challenges pertaining to complexity, the need for specialized modeling skills and comprehensiveness due to the "limitations in spatial, vertical and temporal resolution" of satellites (page 6.21). Nonetheless, the guidelines acknowledge the growing scientific recognition of the potential of these techniques for both level and trend verification of national inventories.

- Volume 2, Chapter 5: Satellites are mentioned as a potential means for providing "proxy measurements to detect leakage from geological CO_2 storage sites." While satellite technology is considered for this purpose, the guidelines note that it is still "at the research stage" (page 5.29).

- Volume 4, Chapter 2: Remote sensing is listed as an option for collecting activity data in the AFOLU sector.

- Volume 4, Chapter 3: The guidelines examine the use of national versus international land-use databases for constructing GHG inventories and cite examples of international databases generated using satellite data. Importantly, remote sensing is explicitly discussed as a data collection tool: "Remotely sensed data, as discussed here, are those acquired by sensors (optical, radar, or lidar) onboard satellites, or by cameras equipped with optical or infrared films, installed in aircraft. These data are usually classified to provide estimates of the land cover and its corresponding area, and usually require ground survey data to provide an estimate of the classification accuracy" (page 3.26).

- Volume 4, Chapters 4–6, 8 and 9: The guidelines discuss the use of satellites/remote sensing for detecting areas and changes in forest land, cropland, grassland and settlements. They also address the use of remote sensing imagery to estimate changes in land-use categories and discuss how combining ground-based surveys with remote sensing can enhance coverage and improve the precision of land-use activity data.

In summary, the 2006 IPCC guidelines mention satellite technology and remote sensing as tools for measuring land-use activity data in the AFOLU sector and as potential tools for verifying emissions or removals, albeit highlighting that the technology was still in its nascent stages at that time. However, it is worth noting that these guidelines were published nearly two decades ago, and there have been substantial advancements in satellite technology, sensors and image-processing capabilities since 2006.

The most recent update to the 2006 IPCC guidelines is encapsulated in the 2019 refinement to the 2006 IPCC guidelines (IPCC 2019). As articulated by the IPCC (2019), the “2019 Refinement does not supersede the 2006 IPCC Guidelines, but rather updates, supplements and/or elaborates on them where gaps or outdated science have been identified.” Given the advancements in satellite technology since 2006, we also investigated how the 2019 Refinement addresses remote sensing and satellite technology. We found the same references as in the 2006 IPCC guidelines, along with tzhe following new references to the use of remote sensing and satellite technology:

- Volume 1, Chapter 2: The 2019 Refinement adds that when compiling an inventory, it is good practice to start by using existing data, which could be sourced from national statistics, international statistics or other data sources, including remote sensing.

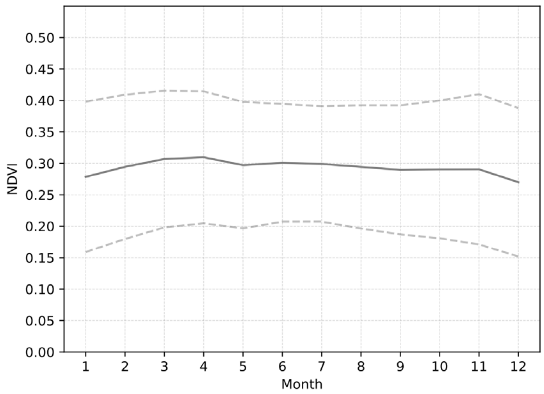
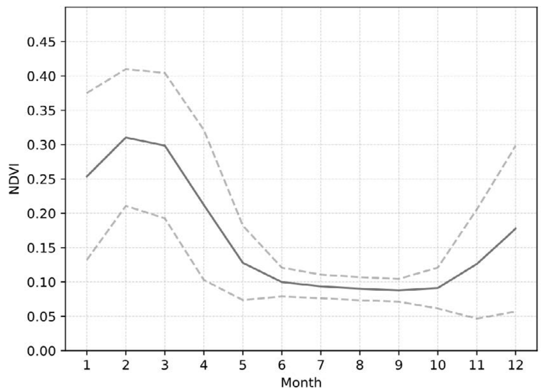
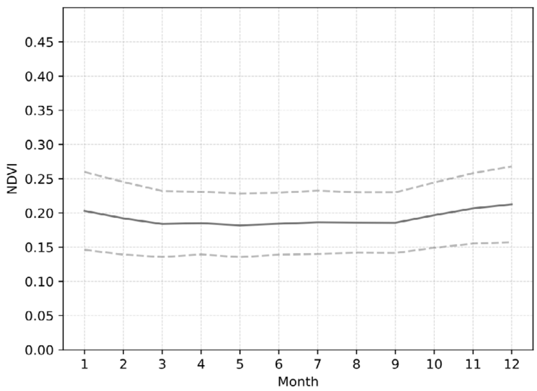
- Volume 1, Chapter 6: The 2019 Refinement provides a more in-depth discussion of using satellites to verify inventories, stating: “While in situ [satellite] measurements have the advantage of directly measuring concentrations within the boundary layer, providing strong constraints on regional emissions, satellite retrievals are … subject to biases.” It continues to discuss the strengths and weaknesses of using atmospheric measurements to verify national inventories, asserting that satellite observations are “expected to contribute” and “are expanding” in the future. The document also discusses how satellite observations can complement national inventories, citing several examples of satellite usage for measuring CH_4 emissions in India and the U.S. It notes that the “use of satellite observations … is still in the experimental stage” and highlights some of the latest developments of the time: “With the expected availability of GHG observations from new satellite sensors, such as TROPOMI, …, the limitations of observation numbers will be relaxed, and national scale emission estimates by hot-spot emission data analysis are expected to become possible. Multiple new satellite missions with enhanced capabilities for GHG observations are in preparation, such as listed in CEOS database, so the emission estimates using satellite data will steadily improve” (pages 6.14-6.18).

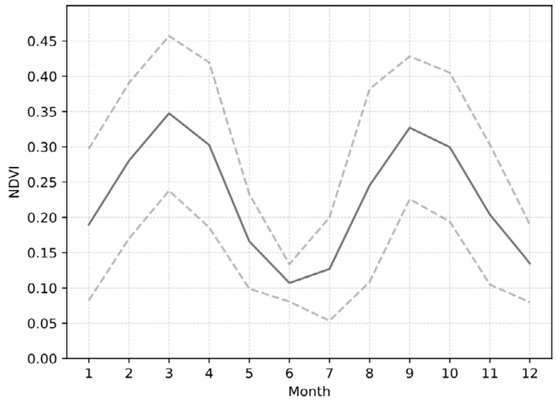
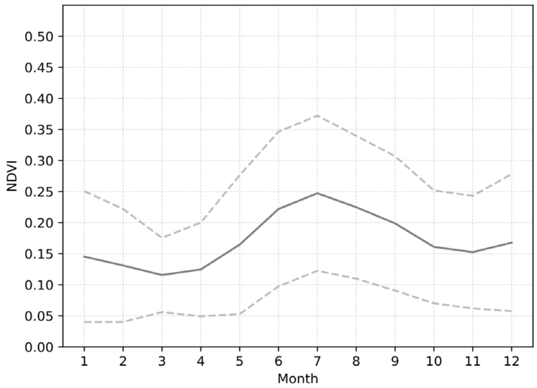
- Volume 4, Chapter 2: The 2019 Refinement elaborates on the use of remote sensing satellite technology for measuring the heights or volumes of woody plants and trees, which are essential for estimating changes in biomass. The guidelines underscore the “evolving approaches that monitor changes in biomass density through time directly from remotely sensed data,” mentioning that they “require consistent measurements and estimates, and such consistency can be challenging when different satellite data sources and different ways of processing and analysing the data are used.” The 2019 Refinement goes on to state that “the sensitivity of the remotely sensed data to subtle biomass changes needs to be carefully evaluated” (page 2.18).

- Volume 4, Chapter 3: The 2019 Refinement mentions satellites a total of 39 times, compared to only 12 times in the same volume and chapter of the 2006 IPCC guidelines. It expands on the use of satellites to estimate land-use changes from repeated samples and their role in validating data. Regarding the use of remote sensing techniques for data collection, the 2019 Refinement acknowledges the “increasingly remarkable array of remote sensing and other geospatial data, methods, and tools have become available in the last decade for consistent country-specific representation of land-use and land-use change” (page 3.38).

In summary, the 2019 Refinement to the IPCC guidelines (IPCC 2019) discusses and elaborates on the use of satellite technology and remote sensing, acknowledging advancements in the technology since 2006. Nonetheless, the technology is still characterized as being in the experimental stage and is primarily showcased as a tool for measuring land-use activity data in the AFOLU sector and for verifying emissions or removals. However, since the 2019 Refinement, remote sensing and satellite technology has continued to develop rapidly.

Appendix B

Vegetation pattern name	NDVI pattern cluster	Associated crop(s)
High-frequency permanent		Alfalfa (other cereals)
Single peak in March		Wheat
Stable permanent		Olives or dates

Vegetation pattern name	NDVI pattern cluster	Associated crop(s)
Double peaks		Barley (other cereals)
Single peak mid-year		Wheat and sorghum

Source: Kayrros 2023.

About the Authors

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About the Project

This paper is also part of the Knowledge & Analysis project titled "Measuring Greenhouse Gas Emissions in Saudi Arabia: Inventories, Tracking Progress, and Baselines." This project contributes to the development and improvement of greenhouse gas emission measurement, with the goal of obtaining comprehensive, accurate, transparent, and timely information on GHG emissions. As part of this project, different approaches and methods for measuring greenhouse gas emissions are compared and contrasted, including unconventional top-down satellite-based methods.

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