Examining the Value of Satellite Data in Halting Transmission of Polio in Nigeria: A Socioeconomic Analysis

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Abstract

In 2014, Nigeria halted transmission of wild polio virus[*] for the first time in its history. A critical enabling component in this historic achievement was the use of satellite data to produce more accurate maps and population estimates used in planning and implementing vaccination campaigns. This paper employs a value of information approach to estimate the net socioeconomic benefits associated with this use of satellite data. We calculate the increase in the likelihood of halting transmission of polio associated with the use of the satellite-based information compared to traditional data sources, and we consider the benefits associated with savings to the healthcare system as well as health benefits. Using a conservative approach focused on just one year of benefits, we estimate net socioeconomic benefits of between $46.0 million and $153.9 million. In addition to these quantified benefits, we also recognize qualitative benefits associated with improving human health, reaching marginalized communities, and building capacity among local populations. We also explore the substantial benefits associated with follow-on projects that have made use of the satellite-based data products and methodologies originally developed for the Nigeria polio eradication effort.

Introduction

In the 1980's, polio crippled an estimated 350,000 children a year and was rampant in 125 countries. Since the World Health Assembly called for eradication of the disease in 1988, more than 10 million people have been spared the lifelong disability attributed to polio, largely achieved through vaccination campaigns.[1] When a sufficient percent of a population receives the oral polio vaccine (OPV), transmission of polio is halted, and with persistent effort the disease can be eradicated.

The most recent country to successfully interrupt transmission of the disease was Nigeria, which was declared polio-free in August 2020.[2] This was an impressive achievement, given that just eight years earlier, Nigeria had accounted for more than half of all wild polio cases worldwide and was one of only three nations in the world – along with Pakistan and Afghanistan – where polio remained endemic.[3] Nigeria had been carrying out polio vaccine campaigns for decades, but the country reached a turning point due to a number of important interventions after 2012.

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[*] Wild polio virus is the original form of the virus and the primary focus of eradication efforts. When a community has relatively low levels of immunity, it is possible for the weakened form of the virus contained in the oral polio vaccine to revert to a vaccine-derived polio virus capable of causing paralysis. When the vaccine-derived virus circulates in the community, it is referred to as circulating vaccine-derived polio virus (cVDPV).

One element of these interventions – and a key ingredient in achieving this historic feat – relied on satellite data.[4]

Interrupting transmission of disease requires vaccination of a sufficient proportion of the population, and to ensure this, those planning vaccination campaigns must have an accurate understanding of the size and location of the population. However, in many places where these campaigns occur, detailed maps do not exist, official censuses are infrequently conducted, and the population is changing dynamically, with rapid urbanization and the rise of new settlements. Due to these trends, the traditional methods of planning vaccine campaigns and estimating populations result in inaccuracies, with whole settlements missed and misestimates of the resources needed to effectively eradicate the disease. Under these circumstances, an insufficient number of people receive vaccinations in the targeted area and disease transmission continues.

In the case of Nigeria, researchers were able to use satellite data to develop more accurate maps and population estimates. These resources proved essential to the polio eradication efforts in the country. In this paper, we review these efforts and provide an estimate of the socioeconomic benefits associated with the use of satellite data for this purpose.

We first discuss the importance of carrying out this type of socioeconomic valuation, particularly with regard to Earth observing satellites, and review approaches to doing so. We then move into the details of our case, summarizing the history of polio eradication efforts in Nigeria and providing a detailed discussion of how satellite data was used to inform and support these efforts. We explain the methodology used to place a quantitative value on these efforts. The following section provides information and background on the data used to carry out our analysis, including a discussion of definitions, sources, and any assumptions made. We then present the analysis and the estimated benefits. The paper ends with a discussion of the limitations of this approach, as well as the qualitative benefits associated with these efforts and the potential for future work in this area.

Estimating the Value of Satellite Data
Accurately quantifying socioeconomic benefits associated with the use of satellite data is important. Earth observing satellites are often developed by governments and paid for by taxpayers, and an individual Earth observation satellite typically costs tens or even hundreds of millions of dollars to build and operate.[5] Ensuring that the resulting data provides benefits that outweigh these costs is essential to making efficient investments in Earth observation technology now and in the future. Understanding and quantifying the value of satellite data is necessary for good decision-making.

This remains important even with regard to commercial satellite remote sensing data – which was the type of data used to support polio eradication efforts in Nigeria. Well-established satellite remote sensing companies, such as Maxar, rely on governments for the majority of their revenue, and many non-profits also find value in this data. We are currently seeing a wave of new commercial remote sensing companies aiming to bring new types of satellite data to the market, and it is likely that new companies will also see governments and non-profits as essential customers.[6] As the government makes decisions regarding whether to purchase this data, how

much to purchase, and at what price, it must have a good understanding of the types and total value of benefits that are likely to result from use of the data.

While there is general agreement that satellite data is valuable, placing a quantitative value on the data is challenging for a number of reasons. First, satellite data, like data in general, is non-rival. When one person uses the data, it does not reduce the amount available for others. Ideally, we'd like to understand all of the potential uses of a particular satellite data set to determine its total socioeconomic benefit. However, experience has shown that often the uses of the data cannot be determined in advance. Government agencies have found that a large portion of new applications and scientific publications rely on older satellite data made available through their archives.[7]

In addition, while satellite data is frequently used by private companies that generate revenue from its use, it is perhaps most often used by scientists, government agencies, and non-profit organizations to generate new scientific knowledge or to develop new applications. For example, satellite data is used by the U.S. Department of Agriculture to predict global agricultural production, by the U.S. Forest Service to track wild fires, and by non-profit organizations to monitor illegal forestry and detect potential human rights abuses.[8] These types of applications are clearly valuable, but placing a dollar value on these efforts is difficult because they do not result in revenue or other easily quantifiable benefits.

One approach to improving our understanding of the value of satellite data is to undertake rigorous assessments of specific uses of satellite data to determine a dollar value associated with particular applications. By building a library of these examples, it is possible to get a more concrete understanding of the scope of the socioeconomic value of satellite data. The Europe Space Agency, in partnership with the European Association of Remote Sensing Companies, has undertaken a series of case studies that examine the value of data from its Copernicus Earth observation satellites, with examples ranging from winemaking in France (estimated value of satellite data: 1 to 2 million Euros per year) to pipeline infrastructure monitoring in the Netherlands (15.2 to 18.3 million Euros per year).[9] These projects use a value chain approach, in which researchers identify the role of satellite data in the creation of a product or service and then examine how that service drives benefits at multiple tiers in the value chain of a particular industry.[10]

Similarly, NASA, in partnership with the non-profit organization Resources for the Future, has created the Consortium for the Valuation of Applications Benefits Linked to Earth Science (VALUABLES), which funds projects that estimate the value of satellite data in a variety of areas.[†] VALUABLES projects, including this one, take a value of information (VOI) approach, focusing on the role of satellite data in a decision-making context. They examine how satellite data enabled an improvement in decision-making and determine the economic value of that improvement.[11]

To do this, projects typically examine a counterfactual, comparing the outcome that would result if action was taken based on information based on satellite data to the outcome that would result if action was taken based on information not informed by satellite data. The difference in the net

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socioeconomic benefits between these two outcomes represents the value of the satellite data.[12] Using this method, VALUABLES has generated a number of case studies, demonstrating, for example, that the use of satellite data as part of the federal Burn Area Emergency Response program resulted in savings of $35 million over a five-year period.[13] This project uses a similar methodology to examine the use of satellite data to help plan polio vaccination campaigns in Nigeria.

Polio Eradication in Nigeria and the Role of Satellite Data
In 1977, the World Health Organization created the Expanded Program on Immunization with the goal of worldwide eradication of six illnesses, including poliomyelitis, the viral disease which causes polio.[14] The program was introduced to Nigeria in coordination with the national government. Unfortunately, political and economic instability limited the progress of this effort, and less than ten percent of the population was immunized in the first five years of the program.[15]

The program was reinvigorated in 1988 with the creation of the Global Polio Eradication Initiative (GPEI), a public-private partnership with five partners: The World Health Organization, Rotary International, the U.S. Centers for Disease Control and Prevention, the United Nations Children's Fund, and the Bill & Melinda Gate's Foundation.[16] Nigeria implemented a number of national and sub-national immunization days with impressive success, reaching more then 50% of children under two within the first year. Unfortunately, a decrease in federal government support and a requirement that individual Nigerian states procure their own vaccines significantly slowed further progress. This policy was reversed in the mid-1990s with the creation of the National Program on Immunization, and Nigeria once again saw wild polio virus (WPV) cases begin to decrease.[17]

In 2003, Nigeria experienced a significant setback in its polio eradication efforts due to a loss of community trust. There were rumors that polio vaccination programs were part of an effort to decrease Muslim populations, and that vaccines were contaminated with anti-fertility agents or other harmful elements. Political and religious leaders of Kano, Zamfara, and Kaduna states, including the Kano state governor, called for a boycott of the vaccine. The boycott lasted for approximately a year, until a vaccine was procured from the predominantly-Muslim nation of Indonesia, at which point Kano and other states resumed immunization efforts.[18] The set-back associated with the boycott resulted in a significant increase in cases, which reached a peak of 1,144 cases in 2006.[19] The high level of cases in Nigeria affected the rest of the world, as well. Between 2003 and 2013, more than 26 previously polio-free countries experienced polio outbreaks that were traced back to northern Nigeria.[20] With renewed efforts, Nigeria was able to bring the number of WPV cases down to 56 by 2010.[21]

Introduction of Satellite Data to Polio Vaccination Campaign Planning
Cases began to increase once again in 2011, and a number of factors were identified that were hindering progress including security issues and lack of strong government support.[22] In addition to these challenges, there was a recognition that more mundane challenges – including inaccurate maps and lack of tracking and accountability – were also contributing to these difficulties and resulting in children being chronically missed by vaccinators. In December 2011, the National Primary Health Care Development Agency of Nigeria, along with GPEI partners and the Bill and

Melinda Gates Foundation, funded a project to create new maps for eight Nigerian states. Key aspects of the project are summarized here, and a full description can be found in Barau et al., 2014.[23]

Prior to this project, the vaccination teams had relied primarily on hand-drawn maps. This was necessary because official maps did not typically include boundaries for wards, the administrative level at which polio vaccination planning occurs. Unfortunately, these hand-drawn maps were often inaccurate and incomplete. They may be missing hamlets or the homes of nomadic individuals or have existing settlements placed inaccurately relative to each other. Methods for validating coverage after the fact relied on these same maps, so settlements missed in the initial campaign would also be missed when conducting post-campaign evaluations.[24]

New geospatial information system (GIS) maps were developed using recent high-resolution satellite imagery collected by DigitalGlobe (now Maxar). Researchers used manual feature extraction – clear, pre-determined definitions of various types of settlements – to identify hamlets, small settlements, and built-up areas. Field teams using a GPS-enabled phones added the settlement names and locations. The draft maps were then reviewed by ward leaders before being finalized. This resulted in more accurate, standardized maps. Initial use of the maps began in limited areas in mid-2012, and by December 2013, the GIS maps were distributed for use in all eight states, increasing efficiency and adding more than 3,000 previously unmapped settlements.[25]

The use of satellite-based maps also allowed geo-referencing that was not possible using the hand-drawn maps. Using this new capability, GPEI implemented a passive GPS tracking system for vaccination teams. A GPS-enabled phone was carried by each vaccination team, automatically logging a location every two minutes. The GPS tracks were then overlaid on the georeferenced maps to determine whether any areas were missed. Following the last day of the vaccine campaign, teams would use these maps to return to any settlements that had been skipped. Using this method, officials were also to verify that all settlements were now being visited.

A second satellite data-enabled project ran in parallel with these efforts. In addition to requiring knowledge of exactly where populations are located, officials planning vaccination campaigns must have an accurate estimate of the total population. This is necessary for ensuring adequate supplies, personnel, and time. When the goal is eradication, as is the case with the polio campaigns, accurate assessment of the total population is also essential for determining whether the percentage of the population that has been vaccinated is sufficient to provide herd immunity.[26]

One traditional source for these estimates is data collected in the national census. In the case of Nigeria, the most recent national census data comes from 2006. Estimates of population since 2006 typically rely on the application of constant growth rates that do not take into account differential changes in different geographic areas.[27]

As an alternative, researchers developed a novel census-independent method of estimating population using semi-automated analysis of satellite data. The full technical methodology is

described in Weber et al, 2018. The project used recent high-resolution satellite imagery of two Nigerian states – Kano and Kaduna – procured from DigitalGlobe (now Maxar) and Airbus. Analysts reviewed the imagery to identify settlements and classify settlement types. They trained a machine-learning model to analyze the imagery, and the results of the model were reviewed by a senior analyst to identify and fix any errors.

To get data on population density, the team carried out a series of microcensus surveys. This involved identifying groups of 25-50 residences and visiting each one to get a population count for that building. A total of 167 such groups was identified and visited. With data on the number, type, location, and size of settlements, as well as data on the typical number of individuals within each type of settlement, researchers were able to estimate total population within specific wards.[28]

When carrying out polio vaccination campaigns, officials are specifically concerned with the number of children under five years old. Researchers involved in this project estimated the size of that sub-population based on rates identified in previous research that used household survey data. By applying those rates to the satellite-based total population estimates, they could determine the number of children under five residing in a given area. The resulting totals were validated using data collected during polio vaccination campaigns in Nigeria in late 2015 and early 2016.[29]

The Weber et al (2018) project demonstrated that the census-based population estimates had significantly underestimated the total population in the study areas. For example, in the Kano metropolitan area, the satellite-based estimates were higher than the census-based extrapolations by more than one million people. Comparing satellite data from 2006 and 2014 showed that the built-up area had increased at 4.37% per year, while UN census-based estimates had assumed population growth of just 2.1%.

These two projects developed satellite-based methods that detected settlements that would otherwise have been missed and more accurately estimated growth and current population. These data products and methodologies are a valuable tool for any effort in which population size is an important factor – and this value was clearly visible in the polio vaccination campaigns.

Methodology: Value of Information
As noted above, this project makes use of a value of information approach, estimating the difference in the magnitude of socioeconomic benefits associated with a scenario in which satellite-based information is used compared to a counterfactual scenario in which it is not. Specifically, this project measures the socioeconomic benefit related to the use of satellite-based maps and estimates of population for a polio vaccination campaign in Nigeria, compared to the counter-factual case of reliance on traditional hand-drawn maps and non-satellite-based population estimates. The magnitude of these benefits depends on the difference in the likelihood of halting transmission in each scenario.

Transmission of a disease is halted when sufficient vaccination coverage – the number of people vaccinated divided by the total population eligible – is achieved. This is the threshold vaccination coverage (V_{th}) required. In practice, programs aim to achieve full coverage –

vaccinating every eligible child – and this can result in an actual coverage level (V_{actual}) that is higher than the threshold coverage required. This "extra" coverage helps to account for uncertainties in population estimates as well as challenges of locating and visiting all settlements. Thus the number of people vaccinated as part of the campaign can be calculated with the following straightforward formula:

(Number of People Vaccinated) = (Population)*(Actual Vaccination Coverage Proportion)

This formula results in different estimates for the number of people vaccinated as part of the campaign depending on the estimate of the population. If the census-based population estimate (P_c) is used, then the number of people vaccinated would be $P_c* V_{actual}$. If the satellite-based population estimate (P_s) is used, then the number of people vaccinated would be $P_s* V_{actual}$.

To determine how likely either of these efforts would be to halt the transmission of polio, we need to know how they compare to the true population (P_{true}) multiplied by the threshold vaccination coverage required to halt transmission (V_{th}). To determine this value, we take advantage of the fact that the method developed by Weber et al (2018) makes it possible to generate prediction intervals for spatial population estimates, thus making it possible to generate a probability distribution to represent the true population of Nigeria. The probability distribution of the true number of people that needed to be vaccinated in order to halt transmission of polio in Nigeria is represented in Figure 1 as the probability distribution $P_{true}*V_{th}$.

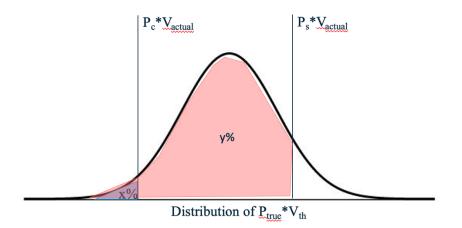**Figure 1. Using the Population Probability Distribution to Determine Likelihood of Eradicating Disease**

Figure 1 also shows the number of people that would have been vaccinated if a census-based estimate (P_c) or if a satellite-based estimate (P_s) was used, assuming an actual vaccination coverage of V_{actual}. The area under the curve to the left of P_s*V_{actual}, y%, represents the likelihood that disease spread would have been interrupted if a satellite-based estimate had been used. The area under the curve to the left of P_c*V_{actual}, x%, represents the likelihood that the true population was sufficiently low that disease spread would have been interrupted even if a census-based

estimate had been used. The increase in the likelihood of interrupting transmission of polio from using satellite-based maps and population estimates rather than hand-drawn maps and census-based estimates is y%-x%.

It is important to note that while this methodology relies on differences in the total population estimate, in reality, much of the benefit of the use of the satellite maps came from improved accuracy in determining the geographic location of settlements and the ability to identify and include settlements that had been systematically missed in the past. When threshold vaccination coverage levels are set, planners assume homogeneity and randomness – all individuals within the population are equally likely to be vaccinated and failure to vaccinate is essentially random (e.g. the family wasn't home because they were visiting relatives at the time of a particular campaign or the child happened to be sick that day). If some individuals are being systematically missed – because their settlement is never visited due to a lack of awareness among vaccinators that it exists – then this assumption doesn't hold. Under these conditions, it would be nearly impossible to halt transmission of the disease. The missed settlements would function as ongoing reservoirs of disease that could continue to re-infect surrounding areas.

This effect suggests that the benefits of using satellite data are underestimated by this analysis. Even in the event that the true population was sufficiently small that the threshold vaccination coverage was met even with lower estimates of population (such as those based on census data), it is unlikely that the effort would actually have halted transmission due to these missed settlements (e.g. rather than x%, the likelihood of halting transmission under these conditions would be essentially zero). The importance of geographic distribution and avoiding systematic errors also suggests that maps based on satellite data can provide significant benefits even in cases where the total population is being overestimated by traditional methods.

Once we've calculated the increase in the likelihood of halting transmission of polio associated with the use of satellite data compared to census data, we multiply this proportion by the total value of the socioeconomic benefits associated with halting transmission of polio. These benefits fall into two categories. The first is cost-savings to the health system. Intensive vaccination and surveillance efforts are expensive in terms of human effort and materials, and if these can be completed in a shorter period of time, significant savings are possible. The second outcome is better health for individuals within the population. If disease transmission is halted earlier, fewer people get infected. In the case of polio, this means fewer children are paralyzed.

The total socioeconomic benefits of using satellite-based population estimates (or costs of using traditional census-based estimates) would continue to grow with each additional year that transmission continues. In reality, program officials would likely adapt their approach and adopt new methods for planning, so we calculate a conservative estimate of benefits based on just one year of additional disease transmission. Therefore, the total benefits associated with the use of satellite data in this case will be calculated as the cost savings and health impacts associated with one year of continued transmission, adjusted to account for the possibility that transmission would have been interrupted in 2015, even using traditional methods (our counterfactual). We also take into account the costs associated with the development of the satellite-based maps and estimates of population. Thus the total socioeconomic benefit of satellite data in the Nigeria polio eradication effort is given by the following formula:

(y%-x%)*(total economic benefits)-(cost of generating satellite-based products)

In some ways, the methodology used here is relatively simple – comparing the results of vaccination campaigns immediately before and after a satellite-data based intervention and assuming an improvement in halting transmission of a single year. In reality, a wide variety of scenarios are possible. It is possible that if improvements weren't evident, planners would have added new approaches, such as even greater human resources, surveillance efforts, and community engagement that would also have led to positive results. By contrast, without satellite data, cases may have continued to grow after 2012. Some experts even voiced concerns that a failure to eradicate polio in Nigeria in this timeframe could have led to the abandonment of the eradication effort overall.[30] We believe that our analysis represents a conservative, but reasonable and straightforward approach to estimating benefits, without engaging in speculative scenarios.

Data
In gathering data to support this case, we rely on a wealth of information documenting the planning and conduct of the actual vaccination campaign, including the role of satellite-based population calculations. Polio vaccination campaigns had been conducted in Nigeria using traditional, non-satellite-based population estimates immediately prior to the transition to satellite-based estimates. This allowed us to gather detailed and highly relevant data on how vaccination campaigns would have been designed without satellite data.

Population Estimates and Vaccination Coverage
Our analysis of population estimates and vaccination coverage focuses on Kano state. Kano is the historical epicenter of polio in Nigeria and has long been a focus of GPEI efforts.[31] In early 2014, the Nigerian state of Kano was considered a key battleground in the fight for eradication of polio in Nigeria. Many campaigns had been conducted in Kano in the prior years, but those campaigns had failed to interrupt transmission of poliovirus.[32] Kano was one of the eight states for which satellite-based maps were first created, and it is one of the examples that Weber et al (2018) highlighted in their work.

Since the population estimates are associated with Kano state, the increase in the likelihood of halting transmission that we calculate is also specific to Kano state. However, we argue that because Kano state was so central to Nigerian eradication efforts, it is reasonable to use this percentage to represent the likelihood of halting transmission of polio in Nigeria as a whole. Thus, estimates of vaccination campaign costs and health benefits are computed for all of Nigeria, not just Kano state. Essentially, we are arguing that if you can successfully halt transmission in Kano, you can halt transmission for the country as a whole.

We recognize this is not a perfect assumption. In reality, after nearly two years with no polio cases detected, four children in the Nigerian state of Borno were determined to have wild polio virus, indicating that the interruption of transmission was incomplete in 2014. The appearance of the disease in Borno was widely attributed to security challenges that prevented access to children in that region, which was controlled by the violent terrorist group Boko Haram.[33] However, following this event, no further cases were detected (in Kano, Borno, or anywhere else in Nigeria), and Nigeria was officially certified as free of wild polio in 2020.[34] Also of note:

strategies such as security-escorted vaccinator visits and rapid campaigns to enable vaccination efforts in terrorist-held areas also relied on satellite-based maps and GPS tracking to ensure efficient access to the target population.[35] Researchers developed new satellite-based methods to distinguish between inhabited settlements and those that had been abandoned due to violence, increasing the efficiency and safety of vaccination efforts in insecure areas.[36]

Because the polio campaigns are focused on the population under five years old, the population estimates here will be specific to that subset of the population.

Probability distribution of the under-5 population of Kano state (P_{true}): As discussed above and demonstrated in the Weber et al (2018) paper, researchers used satellite data to produce estimates of the population that do not rely on census estimates, and they demonstrated the ability to use this method to determine the size of sub-populations, including children under five. The accuracy of those methods was validated by field work. Since that time, these efforts have continued to be refined and improved by the Geo-Referenced Infrastructure and Demographic Data for Development (GRID3) organization and its partner, WorldPop, a research program at the University of Southhampton. Based on this updated data and methodology, GRID3 provided the probability distribution for the under-5 population of Kano state, which is used in the calculations undertaken in this paper.[37]

Satellite-based population estimate of Kano state (P_s)‡: GRID3 also provided their mean estimates for the population of Kano State – 13,724,254 – as well as the under-5 population of Kano State – 2,678,826.

Census-based population estimate of Kano state in 2014 (P_c): The Nigerian National Bureau of Statistics released a demographic statistics bulletin in 2017 that estimated the population of Kano State in 2014 as 12,241,682. For the purposes of vaccination planning in Nigeria, it is typically assumed that a uniform 20% of the population is under 5 years of age.[38] This results in an estimate for the under-5 population of 2,448,336 children.

Although census-based estimates may be used for high-level planning, for the planning of individual campaigns – determining how many doses of vaccine to purchase and how many vaccination teams to employ – the GPEI program often uses estimates based on experience from previous years, specifically, the number of children that were reported to have been encountered by vaccination teams in the previous year adjusted to assume some growth. Over time, it appears that these estimates became significantly inflated, so that the population estimates used for planning were significantly larger than the true population. For example, in January 2014, the tally sheet summary stated that 4,270,792 children under five were vaccinated as part of that month's campaign in Kano state.[39] Eventually, due to a rigorous supervised enumeration completed by March 2014, combined with the satellite-based estimates, the tally-sheet estimates decreased.[40] The tally-sheet for the December 2014 campaign suggests that 2,570,295 children under five were vaccinated during that effort.[41]

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‡ The probability distribution and mean value for the satellite-based population estimates reflect data for 2016/2017. However, this data is very similar to the data for 2014 included in the Weber et. al. paper. That paper estimated the total population of Kano state to be 13,688,669.

Paradoxically, this means that while the satellite-based maps and population estimates resulted in new settlements being discovered and more individuals being vaccinated, as well as significant increases to total population estimates compared to census-based estimates, they also resulted in a reduction of the population estimates used most directly in vaccination campaign planning and thus savings in terms of the number of vaccine doses purchased and vaccination teams employed.[42] Although we are noting the effect here, we do not incorporate these savings into our analysis.

Population represented on hand-drawn maps for Kano state in 2014 (P_h): To account for this situation – that an artificially inflated over-estimate of population was used for campaign planning while at the same time that the population being served during the campaigns was lower than the true population (because whole settlements were not included on planning maps and thus not being visited) – we introduce one additional method for estimating the total population included in polio vaccination campaigns prior to the creation of the satellite-data maps. This method takes into account an estimate of the proportion of the total population that was present in the missing settlements. Researchers estimated that approximately 5% of all settlements were chronically missed before the satellite-based maps and GPS-tracking systems were implemented.[43] This would suggest a total population for Kano State of 13,038,041 and a total for the under-5 population of 2,325,919.[§]

Threshold Vaccination Coverage Required to Halt Transmission (V_{th}): The target that was set for Nigeria in 2014 by the GPEI program to interrupt transmission was >80% coverage in high-risk areas as confirmed by lot-quality assurance sampling methodology (LQAS).[44] To carry out LQAS, a particular district or sub-district area (a "lot") is selected and 10 children from six different settlements (60 children total) are included in the survey. If three or fewer of the 60 children are found to be unvaccinated, then the area is assumed to have higher than 80% coverage. If 9 or more children are unvaccinated, it is assumed that the 80% coverage level was not reached. (Findings between 4 and 8 children require additional indictors be examined.) [45]

Actual Vaccination Coverage without Satellite Maps ($V_{actual-nosat}$): As noted above, vaccination campaigns aim to vaccinate every eligible child, but the actual vaccination rate can vary significantly from both the threshold and this goal. Therefore, it is important to take into account the actual vaccination coverage achieved. In 2011, before the first satellite-based maps were created, the vaccination coverage rate in Kano was typically 60% or lower.[46] This suggests a very low likelihood that transmission would have been successfully halted without the use of satellite-based maps. Use of the satellite maps began in 2012, but was not fully implemented until December 2013. In 2013, the average vaccination coverage rate in Kano was about 83%, on average, and by 2014 it rose to 89%. Although these improvements are likely due primarily to the increasing use of satellite-based maps and the GPS tracking they enabled, we will consider the full range of 60% to 89% in this analysis.

Even the relatively low vaccination coverage measured in 2011 may have been over-estimating true vaccination coverage. When using choosing lots for LQAS, evaluators would have access to the same maps as those carrying out the campaigns. The same settlements that were absent from

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[§] These estimates are calculated by decreasing the mean population estimate based on satellite data by 5%.

the hand-drawn maps and excluded from vaccination when planning the campaign would also be absent from the maps and excluded when evaluating the campaign.[47]

Actual Vaccination Coverage with Satellite Maps ($V_{actual-sat}$): The first maps based on satellite data were completed in July 2012. These added missing settlements into the plan and enabled the first GPS-tracking of vaccination teams.[48] The improved maps, along with the GPS tracking to ensure all settlements were visited, were expanded over the following two years. This change was associated with a steady increase in vaccination coverage as determined by LQAS. By 2014, Kano state had an average vaccination coverage across campaigns of 89%.[49]

Table 1. Definition of key variables and their values

Variable	Description	Value	Source
V_{th}	Threshold coverage needed to achieve interruption of transmission	0.8	Annex B of GPEI 2013-2018 Polio Eradication and Endgame Strategic Plan
$V_{actual-nosat}$	Actual vaccination coverage achieved in 2011 based on LQAS (prior to implementation of satellite-based maps)	0.6 to 0.89	GPEI/ BMGF/ LQAS Presentation
$V_{actual-sat}$	Actual vaccination coverage achieved in 2014 based on LQAS (after implementation of satellite-based maps)	0.89	GPEI/ BMGF/ GIS Impact Report Presentation
P_s	Satellite-based estimate of under-five population in Kano state	2,678,826	GRID3/ WorldPop
P_c	Census-based estimate of under-five population in Kano state in 2014	2,448,336	Nigerian National Bureau of Statistics, 2017 Demographic Statistics Bulletin; Assuming 20% Under-5 Population
P_h	Estimate of under-five population in Kano state in 2014 based on hand-drawn maps	2,325,919	Origins of Grid3 Presenation; GRID3/ WorldPop

Campaign Cost Savings

The socioeconomic benefits of halting transmission of polio in 2014 are directly related to the costs of maintaining the large-scale vaccination campaign efforts necessary to halt transmission in a country where polio is endemic – in this case, Nigeria. Therefore, in this section, we identify and enumerate those costs. GPEI organizes polio eradication costs into four categories: immunization activities (e.g. the vaccine campaigns themselves), surveillance and response capacity, containment and certification, and core functions and infrastructure.

The total cost of immunization activities is heavily influenced by the number and quality of vaccination campaigns.[50] Each of these campaigns is complex and expensive. The goal of a polio vaccination campaign is to give two drops of oral polio vaccine to every child under five years old residing in the target areas over the course of the four-day campaign.[51] To enable this, the program must purchase a sufficient number of oral polio vaccines and cover operational costs. They must also account for campaign-related social mobilization costs and communication efforts to ensure there are high levels of awareness and demand for the vaccine within the community.[52]

Planning for these campaigns requires significant operational and managerial efforts to facilitate national, international, and local coordination, supervision, and performance evaluation. Carrying out the campaign requires a large number of vaccinators, engagement of local community-based educators, and technical assistance from experts. These individuals require access to adequate transportation and communication capabilities to reach inaccessible and sometimes insecure areas, as well as adequate vaccines and cold-chain storage.[53] In Nigeria, each campaign involves visiting hundreds of wards and managing thousands of vaccination teams operating during each campaign.[54]

In addition to the campaigns themselves, funding is also required to support surveillance and emergency response. This includes a surveillance network to detect and investigate acute flaccid paralysis cases and maintain laboratories able to do this analysis. Emergency response efforts are undertaken in response to outbreaks, and thus are especially relevant in countries where polio is still endemic. Emergency response is also required when outbreaks occur in countries where polio is not endemic, but is imported from an endemic country.[55] Accordingly, funds needed to support these activities will decrease when transmission of polio is halted in an endemic country like Nigeria.

Containment and certification of wild polio virus requires not only highly sensitive surveillance, but also full application of bio-containment requirements across the entire world. These efforts continue even in regions of the world certified to be polio-free. GPEI also supports countries with their core infrastructure, including technical assistance, efforts to improve the efficacy of immunization campaigns, community engagement, and research and development. In some high priority countries this also involves supporting efforts to improve routine immunization systems.

GPEI provides annual expenditure documents with high-level summaries of expenditures for the GPEI program as a whole. Table 2 shows total annual expenditures as well as the portion of expenditures spent directly on immunization activities. Immunization activities represent a very large proportion of overall GPEI expenditures, although spending in this area decreased notably after Nigeria halted transmission of wild polio virus in 2014.

Table 2. GPEI Annual Expenditures (US$ Millions)

	2012	2013	2014	2015	2016	2017	2018	2019
GPEI Total Expenditures	Not Available	$932.05	$952	$1,043	$1,105	$1,004	$939	$866
GPEI Expenditures on Immunization Activities	Not Available	$575.02 (61.7%)	$651 (68.4%)	$639 (61.3%)	$558* (50.1%)	$472* (47.0%)	$442* (47.1%)	$303* (35.0%)

*The organization of costs in the annual expenditure report changed in 2016 compared to earlier years. This number represents the cost of "Campaigns" and "Other Immunization Activities."

Financial Resource Requirements (FRR) reports (GPEI's budget planning documents) from the period 2013-2018 were released approximately bi-annually from 2012-2014 and provide significantly greater detail, including a breakdown of costs in Nigeria. These documents show that costs associated with GPEI activities in endemic countries account for nearly half of the total

costs for the program, with efforts in Nigeria being particularly costly. As of 2014, GPEI efforts in Nigeria alone were expected to account for more than a quarter of all GPEI costs from 2013-2018. Estimated total costs for GPEI activities in Nigeria based on these documents are shown in Table 3. As of 2017, GPEI moved to an interactive online tool to provide budget information and the categories used to breakdown funding areas changed.[56] Total budget estimates for Nigeria for 2017-2020 based on this tool are shown in Table 4.

As noted above, these costs are significantly impacted by the number and extent of vaccination campaigns required, which decreases when interruption of transmission is achieved. These charts show that while costs don't go down immediately, due to the need to continue intense immunization efforts until the elimination of wild polio virus is confirmed, costs decrease significantly within a few years. Funding needed during these "ramp down years" would remain similar regardless of the year transmission was halted. Therefore, for the purpose of this analysis we will use 2014 and 2020 as representative years.

If transmission of wild polio virus had not been achieved in 2014, then GPEI could have expected to face an additional year with costs of approximately $281.18 million in place of an additional year with low-cost, post-certification costs similar to those faced in 2020, of approximately $110.331 million. Therefore, the cost of not halting transmission in 2014 are estimated at $170.85 million.

Table 3. GPEI Budget Estimates for Nigeria 2012-2017 (US$ Millions)

	2012	2013	2014	2015	2016	2017
OPV	39.70	58.72	55.83	55.89	43.00	24.90
Operational Costs	63.41	128.88	102.85	101.89	78.80	51.77
Surveillance	12.50	14.94	15.44	16.32	14.72	14.72
Technical Assistance	52.52	60.95	67.70	74.84	39.50	39.47
Special Polio Vaccination Activities	--	--	11.82	12.52	7.96	0.00
Social Mobilization	4.22	23.17	27.54	26.56	26.82	26.82
Total	172.35	286.66	281.18	288.02	247.42	157.68
Assumed Number of National Immunization Days	2	2	2	2	2	2
Assumed Number of Sub-National Immunization Days	5	7	7	6	4	1
Source	October 2012 FRR	June 2013 FRR	July 2014 FRR	December 2014 FRR	December 2014 FRR	December 2014 FRR

Table 4. GPEI Budget Estimates for Nigeria 2017-2020 (US$ Millions)

	2017	2018	2019	2020
Campaigns	90.978	74.233	64.882	45.302
Core Functions and Infrastructure	61.999	26.108	26.201	20.715
Other Immunization Activities	17.159	12.476	9.277	1.744
Surveillance	13.360	36.101	37.616	42.550
Total	183.496	148.958	137.976	110.311
Last Budget Revision	June 2017	October 2018	October 2018	December 2019

*These budget estimates are based on the GPEI interactive online budgeting tool.[57]

Improved health

Perhaps the most salient benefit of halting transmission of polio is the decrease in the number of children that become ill with the disease. We look at both wild polio cases in Nigeria as well as instances of outbreak polio – cases outside Nigeria caused by ongoing polio in Nigeria.[**] Based on this data, we make rough estimates of the number of polio cases that may have occurred if satellite-based maps and population estimates had not been used. We also translate this reduction of disease into socioeconomic costs using widely-accepted values from the global health literature.

Table 5. Polio cases in Nigeria 2011-2020

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
WPV	62	122	53	6	0	4	0	0	0	0

Source: Progress Toward Poliomyelitis Eradication – Nigeria, January 2014-July 2015

Wild Polio Cases: Although polio is a highly contagious disease, with a high risk of serious complications, cases typically decrease significantly in the years prior to interrupting transmission due to the ubiquity of vaccination campaigns. WPV cases in Nigeria steadily decreased from 122 in 2012 to just 6 in 2014 (five of which were in Kano state).[58] The decrease in the number of infections is likely related to the increase in vaccination coverage, discussed above, which was influenced significantly by the introduction and expansion of the satellite-based maps and GPS-tracking that began in mid-2012 and were fully implemented in 2014. Therefore, we will consider a range from 6 cases to 122 cases to represent the likely number of additional cases that would have occurred in the absence of the satellite-based maps and population estimates. Duintjer Tebbens et al. (2015) suggest that the socioeconomic costs per paralytic polio case are approximately $27,000 in a lower middle-income country like Nigeria,

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[**] Typically, the increased vaccination levels associated with the efforts to halt the transmission of Wild Polio Virus will also decrease the amount of circulating vaccine-derived Polio Virus (cVDPV). However, the impact also depends on the particular form of the vaccine that is used. In Nigeria, officials used a form of the vaccine that is particularly effective against WPV but less effective against cVDPV, leading to an increase in cases from 2013 to 2014. A switch to a different form of the vaccine helped to bring this down, but cVDPV outbreaks have remained an issue as recently as 2020. Due to the complexities related to decisions on the form of vaccine, we have not included this element in our analysis.

which would suggest a socioeconomic cost of between $162,000 and $3,294,000 associated with these cases.[59]

Polio Outbreak: Wild polio infections can occur in non-endemic countries due to importation of the virus from endemic countries – a phenomenon referred to as outbreak. In 2013 and 2014, WPV imported from Nigeria caused outbreaks in Somalia and Cameroon, resulting in a combined 108 cases in these countries.[60] Following the initial halt of transmission of WPV in Nigeria in 2014, no further WPV outbreaks have been linked to the country.[61] The number of cases associated with WPV outbreaks is unpredictable, since it depends significantly on the immunization levels in other countries, however, based on the experience in 2013-2014, we will use a rough estimate of 50 cases to represent the likely number of additional cases that would have occurred in the absence of the satellite-based maps and population estimates. The socioeconomic cost associated with these cases would be approximately $1,350,000.[62]

In addition, when outbreaks occur, rapid large-scale responses are required to address them, including special vaccination campaigns and enhanced surveillance, which, as noted above, typically cost millions of dollars to plan and implement.[63] We do not include an estimate of these costs in our analysis due to wide variation possible, so the estimates associated with outbreak likely underestimate true costs.

Cost of Generating Satellite-based Estimates
Finally, we account for the costs of generating satellite-based estimates. Gates Foundation officials estimated the top-line number for this activity is estimated at approximately $5.75 million. This estimate includes not only the cost of the satellite data itself (about $1.5 million), but also the effort required to analyze the data and create the data products, as well as validation activities on the ground in Nigeria and training and capacity building activities to enable local actors to use the products.[64] While some additional funds have been spent to maintain, update, and improve these capabilities, the maps themselves as well as the approach developed can be, and has been, leveraged and applied in additional situations and products for significantly lower cost. The conclusion section identifies some of the broader applications that have come from this work.

Analysis
Bringing all of this data together and following the methodology laid out above, we now calculate the total socioeconomic benefits associated with the use of satellite data to support the polio eradication effort in Nigeria.

Probability of Halting Transmission: Using the probability distribution of the under-five population of Kano state presented above, we examine the probability of halting transmission of polio (i.e. achieving 80% vaccination coverage or more) under various scenarios. Using the mean satellite population estimate and the actual vaccination coverage achieved in 2014 of 89%, the probability of halting transmission is 91%. Using either the census-based population estimate or the estimate based on hand-drawn maps, if the actual vaccination coverage was 60%, the distribution suggested there was zero chance of halting transmission. This is not surprising, as both of these population estimates likely underestimate the true population and the vaccination coverage rate is lower than that needed to halt transmission. If we assume that even without the

satellite-based maps, vaccine campaigns would have achieved 89% coverage, then the probability of halting transmission with census-based estimates or estimates based on hand-drawn maps would have been 61% and 36%, respectively. Overall, this suggests that the satellite-based maps and population estimates increased the likelihood of halting transmission in the range of 30% to 91%, a range generated by comparing the difference between satellite-based population estimates and any of the other potential counterfactuals.[††]

Table 6. Probability of Halting Transmission Under Different Scenarios

	Under-five Population	Actual Vaccination Coverage	Probability of Halting Transmission of Polio in 2014
Satellite-based Population Estimate	2,678,826	0.89	91%
Census-based Population Estimate and 2011 Vaccination Coverage	2,448,336	0.6	0%
Census-based Population and 2014 Vaccination Coverage	2,448,336	0.89	61%
Hand-drawn map-based Population and 2011 Vaccination Coverage	2,325,919	0.6	0%
Hand-drawn map-based Population and 2014 Vaccination Coverage	2,325,919	0.89	36%

Socioeconomic Benefits: The estimated benefits of halting transmission of polio in 2014 associated with vaccine campaign and other programmatic cost savings were determined to be $170,850,000. The socioeconomic benefits associated with the decrease in wild polio virus cases resulting from halting transmission in 2014 were estimated to fall with the range of $162,000 to $3,294,000, and those associated with the decrease in outbreak polio were $1,350,000.[‡‡] Added together, this suggests a total socioeconomic benefit of between $172,362,000 and $175,494,000.

Total Socioeconomic Value of Using Satellite Data for Polio Eradication in Nigeria: For this analysis, we want to take into account the fact that the use of satellite maps was not associated with certainty in halting transmission and that there was a possibility that the transmission of wild polio virus would have been halted in 2014 even if satellite data had not been used. Accordingly, the value attributed to the use of satellite data is between 30% and 91% of these values, resulting in an estimates of between $51.7 million and $159.7 million. Lastly, we factor in the cost of generating and using the satellite-based maps of $5.75 million. Considering all of these factors, we estimate that the net socioeconomic benefit associated with the use of satellite data to assist in halting the transmission of polio in Nigeria in 2014 are between $46.0 million and $153.9 million.

Findings and Discussion

[††] Calculated by looking at the difference in the probability of halting transmission under various scenarios, (e.g. 0.91-0.61=0.30 and 0.91-0=0.91).

[‡‡] Cost savings related to campaigns are significantly higher than the benefits from reduced health impacts. As noted above, this is due to the fact that there are typically very few Polio cases in the years immediately preceding a halt in transmission. Expending large sums to continue vaccination campaigns when only a handful of cases occur each year may seem counterintuitive. However, other research shows that the long-term benefits of Polio eradication make this expenditure worthwhile.

Based on the information and analysis above, we find that the use of satellite data in the 2014 polio vaccination campaign in Nigeria resulted in net socioeconomic benefits of between $46.0 million and $153.9 million. This contribution is impressive, and yet these estimates likely under-estimate the total benefits of using satellite data, both qualitatively and quantitatively. With respect to qualitative issues, these totals include monetary estimates accounting for the value of avoiding between 56 and 172 cases of polio, but it is worth acknowledging that the benefits of these avoided cases – and the associated decrease in human strife associated with the possible paralysis or death of the affected children – goes far deeper than the monetary estimate used for quantification purposes.

Another important, but difficult to quantify benefit is the role of satellite data in helping to address not only inaccuracies, but also inequities. Notably, the populations that are missing from the traditional census and discovered through satellite images are typically poorer and more vulnerable than those captured by the census. The same forces that drive these individuals to the margin of society also systematically exclude them from official records like the census and the social services that census status dictates. There is socioeconomic value in literally "putting on the map" these traditionally marginalized populations.

Our analysis also does not factor in the long-term benefits associated with capacity building within the local population. As part of the initial effort to create GIS maps in 2011, thousands of Nigerian health workers were trained to read and work with GIS-based maps. This has allowed them to recognize the potential applicability and value of this tool in other areas, including routine immunization activities, logistics support, broader health efforts, and even non-health-related projects with a geographic component.[65] In January 2021, the Nigerian government took over management and maintenance of a national database originally developed in coordination with these efforts.[66]

Completing a campaign more quickly can also help to avoid vaccine hesitancy. With frequent campaigns, some children may be vaccinated many times, which can lead to confusion or even suspicion among the families involved, particularly given the lack of access to other, seemingly more immediate healthcare needs.[67] Efficient campaigns that result in clear results in a timely manner can help to improve community trust in vaccines more generally.

On the more quantitative side, it is worth reiterating that the benefits calculated here represent just one year of socioeconomic benefits. As noted above, our methodology assumes that even without satellite data, national planners would have adjusted their approach and halted transmission of polio just one year later. However, given the many reports regarding the large impact of the use of satellite-based maps and population estimates, as well as the trends in vaccination coverage and cases associated with the introduction of these methods, it seems likely efforts to halt transmission would have taken significantly more time. This would suggest a true socioeconomic benefit associated with the use of satellite data many times the estimate provided here.

The experiences in the two remaining countries in which polio remains endemic as of 2021 – Afghanistan and Pakistan – seem to reinforce this understanding. Neither of these countries has made extensive use of satellite-based mapping, in part due to local government sensitivity to

potential security issues. However, both face unique challenges that limit the ability to directly compare them to the Nigerian case. Even in Nigeria, we recognize that the satellite-based innovations were not the only interventions made, nor the only ones needed. Satellite data-related efforts coincided with high-level political support for polio vaccination efforts, significant funding and logistical support from the international community, broad support among local community leaders, a significant increase in human resources, and innovative approaches to reaching children in insecure areas.

The socioeconomic benefits calculated here account only for the benefits of the use of satellite data in the particular case of halting transmission of polio in Nigeria. However, one of the hallmarks of satellite data (and of value-added products generated using that data) is that the use of the data for one purpose does not reduce the value of that data for other purposes. In fact, not only the maps and estimates themselves, but also the methodology used in the Nigeria case in 2014 has already led to significant benefits in other cases. As noted above, researchers built on this work to create maps that helped vaccinators to reach children in terrorist-held areas in Borno, ensuring that the 2014 benefits associated with halting transmission were not lost due to security challenges.[68] Satellite-maps and population estimates originally developed for the Nigeria case have also been used to support vaccination campaigns related to measles and yellow fever.[69]

Perhaps most illustrative of the broad benefits arising from this work is the 2018 creation of GRID3, which was formed as a direct result of the experiences using satellite-based maps and population estimates in Nigeria. The organization aims to work with countries to apply these techniques to support a wide array of humanitarian decision making.[70] In 2021, GRID3 was active in 10 countries in Africa, including Nigeria, and was engaged in projects that included supporting vaccination and other health efforts, helping to examine where new schools are most needed to improve access to education, and supporting sustainable development overall.[71] GRID3 has also worked closely with governments in Africa to use their satellite-based resources and capabilities to monitor and address COVID-19, including helping to develop vaccination plans.[72]

Clearly, satellite data has immense current and potential value for the global health sector as a whole. This is also true in other sectors in which satellite data has not traditional been used, particularly when accurate population estimation or geographic distribution is a key input. Weber et al. note that more than one-third of the indicators established to measure progress on the United Nations (UN) Sustainable Development Goals (SDGs) are defined in terms of total population or subpopulation.[73] More accurate estimates of population across these metrics could have a substantial effect on our ability to understand and address a wide range of critical sustainable development issues.

Conclusions
This article used a value-of-information approach to estimate the net socioeconomic value associated with the use of satellite data in efforts to halt transmission of polio in Nigeria. Satellite data enabled the creation of more accurate maps and resulted in the identification of thousands of settlements that had previously been systematically missed by vaccination teams. These satellite-based maps also enabled GPS tracking of vaccination teams that made it possible for officials to

ensure that all areas were visited during the campaign, further decreasing the number of children missed. Population estimates enabled by satellite data proved more accurate than traditional census-based estimates, ensuring that planners had an accurate understanding of the total number of children that needed to be vaccinated. The implementation of these satellite data-enabled interventions was associated with increased vaccination coverage and decreased incidence of wild polio virus. These trends, along with expert evaluations, suggest that satellite data played a critical role in the ability of Nigeria to halt the transmission of wild polio virus in 2014.

The net socioeconomic benefits of these activities were estimated using a counterfactual approach that compared the impact of decisions made based on satellite data to the alternative of decision-making based on vaccination campaign planning methods not informed by satellite data. We calculated the likelihood that transmission of wild polio virus would have been halted in 2014 under each of these conditions. These probabilities were then applied to estimates of the programmatic cost savings resulting from the decrease in human effort and materials associated with halting transmission one year sooner than otherwise, as well as the benefits associated with the decrease in wild polio virus cases. This analysis suggested that the interventions enabled by satellite-data resulted net socioeconomic benefits of between $46.0 million and $153.9 million.

The monetary benefits listed here are only part of the story. We also acknowledge and describe the difficult-to-quantify benefits associated with improvements in human health, increased attention to marginalized communities, and support for capacity building within the local community. It is also important to acknowledge that both the satellite-data products and the methodology associated with this project have found broad applications that continue to generate further socioeconomic benefits. New applications continue to be developed and many more show potential, suggesting there is much more value that can and will be generated in this area.

We hope that awareness of these benefits will encourage further collaboration between experts in Earth observation, satellite data analysis, and global health, prompting greater uptake of these methods within the global health and international development sectors that fuel productive research and advancements in health-related satellite product development. We believe these developments can and will translate into global socioeconomic benefits, reduction of inequities, and tangible improvements in the lives of people around the world.

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