CENTER FOR SPACE POLICY AND STRATEGY

AUGUST 2021

TOWARD ENVIRONMENTAL ACCOUNTABILITY: TRANSFORMING SATELLITE DATA INTO ACTION

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Summary

Over the past two decades, the proliferation of remote sensing satellites coupled with improved resolution has yielded vast amounts of new data for environmental monitoring and enforcement. Yet, the most significant advances go beyond space-based assets. They include modern information architecture, which offers new and predictive insights for environmental monitoring. Key use case scenarios suggest that environmental data that is open and shared across disciplinary and geographical silos builds greater transparency, trust, and accountability. This paper addresses how an environmental *data-to-action* strategy supports multidisciplinary users (e.g., industry, regulatory, nonprofit, and citizen) to encourage cooperation across local, regional, national, and international stakeholders. The paper also suggests a *data-to-action* framework, which includes a foundation of a modern data architecture and six key pillars for actionable environmental intelligence based on best practices demonstrated by existing programs for meeting environmental and sustainability goals.

Introduction

Scientists have historically focused on researching and understanding environmental and climate challenges facing the planet. While these studies are important, more could be done to bridge the gap from studying the problem to taking action. By leveraging successful practices demonstrated by environmental initiatives and programs, scientists, government agencies, and non-governmental organizations (NGOs) can transform research data into actionable information, or *data-to-action*. Best practices such as managing partnerships, proactive public engagement, using open and trusted data, leveraging domain experts, and optimizing timely alerts to reach stakeholders will contribute to the transformation of data into action. Scientists who manage various Earth observation programs have an opportunity to stretch beyond the detached language

> ***"Our goal is to make [the environmental impacts] obvious and accountable. Part of that is to show and tell the things that are happening through satellite images…and analysis that can't be easily explained away."***
>
> —John Amos
> Founder and President of SkyTruth[1]

of science to provide contextual information. Likewise, regulators, stakeholders, property owners, and industries could make informed decisions and respond through either mitigation or enforcement.

A satellite data-to-action strategy involves the sharing of space-based Earth observation (EO) data through open data formats and data fusion with other types of data (such as airborne and terrestrial-based remote sensing, in-situ sensors, and crowdsourced data from citizen scientists and social media). We can become better environmental stewards by leveraging the best available technologies across a range of terrestrial, air and space-based instruments, along with new techniques such as artificial intelligence and machine learning and shared data analytics platforms to enforce environmental regulations and various multilateral and bilateral environmental treaties. This paper also highlights technical, social, governance, and regulatory trends that encourage sustainability and environmental protection. A satellite data-to-action strategy will require a regulatory paradigm shift that underscores the need for broad, fair, and transparent monitoring using open data and modern information architectures. Moreover, a review of various international environmental monitoring programs reveals lessons learned that can be applied to future projects and international environmental protection agendas.

Space's Growing Role During a New Era of Environmental Cooperation

Common Goods and Diminishing Returns

The consequences of climate change can be seen daily, such as increasing wildfire incidence and intensities, public health concerns, decreasing arable land, depletion and contamination of drinking water, and mass climate-induced migrations of vulnerable human and wildlife populations.[2] While many countries attempt to improve their own situation through national level environmental protection legislation, the world continues to grapple with how to deal with "public goods," those nonexcludable and nonrivalrous resources that extend beyond national borders.[3] Examples of public goods include clean air and biodiversity because these resources cannot be excluded from use by an individual or group and consuming these goods does not benefit one nation at the expense of others.

Our planet may have reached a point of diminishing returns within the Tragedy of the Commons[*] architype whereby there are increasing costs for uncooperative behavior (e.g., over exploitation of resources or pollution of the global commons). In plain terms, the Earth's ecosystems face an existential threat. There are now greater incentives to mitigate pollution and avoid over-exploitation of resources. It is within this context that satellites offer a means to encourage cooperation and good behavior—despite the daunting challenges of working together at an international level with nonbinding incentives.

Agreements, Cooperation, and Commitment

According to the International Environmental Agreements Data Base (IEADB), there are over 3,000 multilateral and bilateral environmental agreements. Commitment levels for these International Environmental Agreements (IEAs) are nonenforceable because there is no international organization fully empowered to enforce the content of these agreements.[4] Despite the fact that these agreements are nonbinding, increased focus on common environmental monitoring assets, data

[*] Based on an 1833 essay by a British economist, which used a hypothetical example of the effects of unregulated grazing on common land. This concept became the basis for a more general economics problem in which every individual has an incentive to consume a shared resource at the collective expense of the larger population.

sharing, and analysis can work to create a harmonized view of an environmental scenario.

Sharing, validating, analyzing, and trusting information could go a long way toward solving some of the world's environmental problems. To meet an increasing need for global environmental intelligence, satellites generate imagery and data to uncover pollution sources, ecosystem destruction, and illegal exploitation of natural resources. Satellites can also contribute to improved situational awareness in the development of eco-conscious and sustainable infrastructure and supply chains.

Increasing Space Assets and Capabilities

By the end of 2020, there were about 890 EO satellites among the 3,372 operational satellites in space.[5] Euroconsult estimates that an additional 1,402 EO satellites (over 50 kg) and 1,600 smallsats (under 50 kg) dedicated to Earth observation will be launched from 2019 to 2028.[6] Moreover, about 73 countries operate satellites leveraging a range of commercial, nonprofit, civil, and military partnerships.[7] The resolution and types of sensors for EO continue to improve as the U.S. Department of Commerce has released new regulations to ensure that U.S. commercial space companies are not constrained compared to their international competitors.[8]

The increasing number of satellites and their improved resolution (temporal, spatial, and spectral) over the past two decades has generated a vast amount of remote sensing data.

Ultimately, the integration of data across multiple sensors and observation platforms could advance a broader and deeper understanding of the air, water, and land environments. Fortunately, recent and emergent technologies promise to offer transformational cooperative data fusion, sharing, and analytical capabilities. These modern data architectures combined with strategically located sensors powered by pervasive networks promise new cost-effective and efficient ways to fuse data from ground, air, and space from local to global scales (see Figure 1).

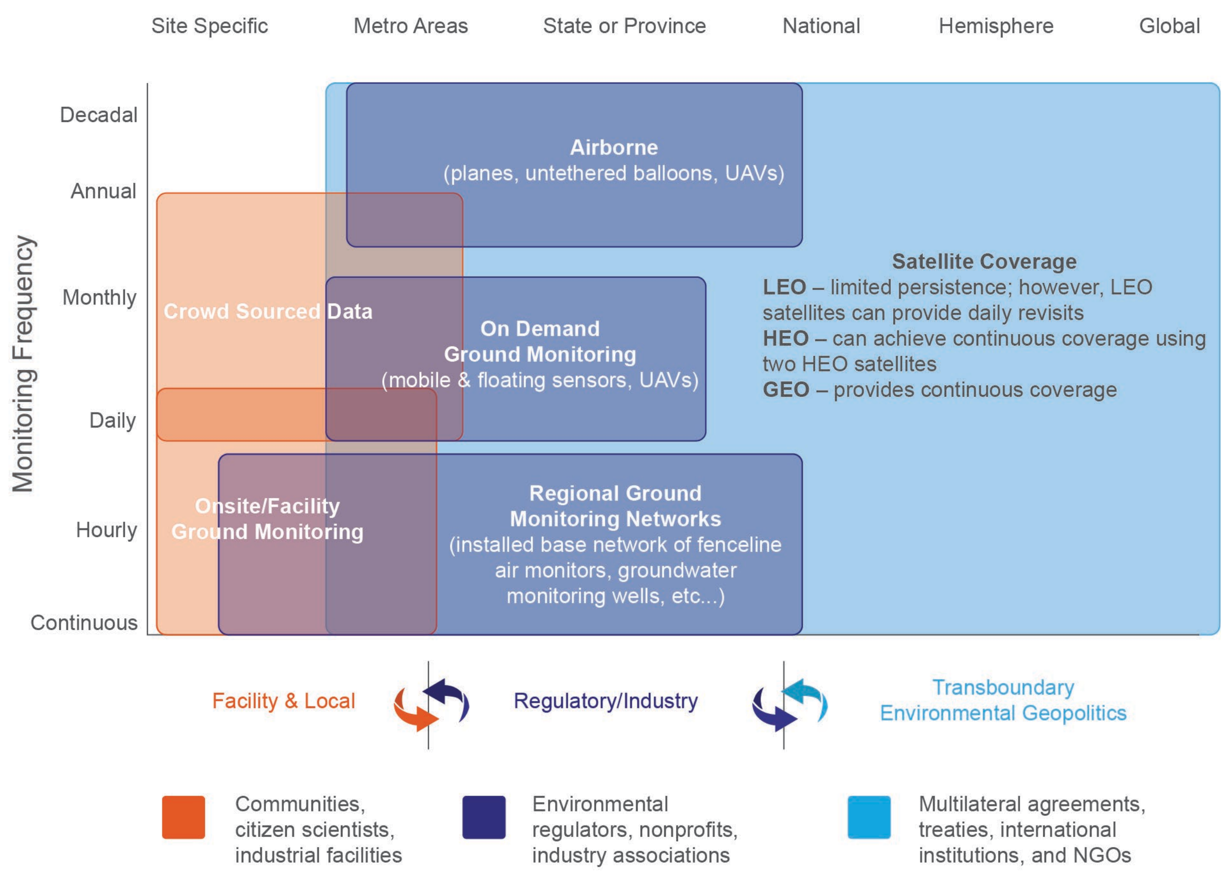

Figure 1: Multiscale and multitemporal monitoring for local, regional, or global missions. *Data users vary across spatial and temporal scales. Citizen scientists and industrial facilities provide onsite facility-and local-level data. Environmental regulators, nonprofits, and industry associations address pollution and natural resource issues at the state or national level. International bodies work environmental or natural resource issues across the globe, using multilateral and other types of transboundary agreements.*

Social and Legal Policies as a Foundation for Transparency

The Age of Increased Transparency

Remote sensing satellites can create transparency by revealing polluters and bad actors in an effort to establish accountability, which makes them useful tools for environmental treaty and regulatory compliance monitoring. Unfortunately, for many environmental or natural resource management scenarios, there are "free riders" or self-interested parties who benefit from certain group actions, but they do not participate or contribute to the efforts.

> ***"Sunlight is the best disinfectant, and that by staying vigilant and informed we can keep environmental policy on the right track."***
>
> —Environmental Law Institute[9]

Some countries, for example, will aggressively limit their carbon emissions to reduce global warming while other countries do not adopt these policies, and yet they still benefit from lower global emissions and ozone layer protection. Sustained and effective environmental stewardship often relies on holding all actors accountable.[10] Satellites can address the *free-rider problem* by collecting and sharing images and data across the globe to ensure fair accountability. Old-style command and control (CAC) regulatory approaches may not be as effective because there are more transparent ways to ensure overall compliance.[†]

Environmental transparency is rooted in the green movements of the 1960s and 1970s. Over the years, environmental groups, such as Greenpeace and Environmental Defense Fund, have become more proactive in transforming observational data into action. They do this through their own or partner environmental observation data collection and sharing efforts. For instance, Greenpeace now utilizes satellite data as evidence for legal actions to enforce environmental compliance.

Environmental observation, cooperation, and climate change-related initiatives are not limited to nonprofits and NGOs. For example, Kayrros (Paris, France), a venture capital-backed data analytics company founded in 2016, analyzes data across the energy sector. One of Kayrros's products, Methane Watch, collects data from the European Space Agency's (ESA) Sentinel remote sensing constellation, fusing this data with energy infrastructure geospatial information, and other datasets, to provide timely information to owners and operators. Methane Watch data products provide timely methane situational awareness and leak alerts to the energy industry using near-realtime measurements. ESA's Technical Officer for Methane Watch noted that the project "illustrates perfectly ESA's willingness to boost green commercialization."[11] Another venture-backed company, GHGSat (Montreal, Canada), measures greenhouse gas (CO_2 and CH_4) emissions from space using their three satellites. GHGSat's primary business model involves licensing imagery to commercial customers to better measure, control, and ultimately reduce industrial greenhouse gas (GHG) emissions.

Notably, environmental, social, and (corporate) governance, referred to as ESG, is now an important movement for some investors. Investors who aim to incorporate their environmental values and concerns into investment portfolios seek both profitability and low environmental risk and sustainability attributes. The United Nations has also developed a collection of 17 interlinked global goals designed to be a "blueprint to achieve a better and more sustainable future for all." Specifically, *Sustainable Development Goal 16* calls for promotion of "effective, accountable and inclusive institutions at all levels" and supports the broader goal of transparency.[12]

Social and Legal Enablers

Logically, environmental transparency works best in countries with social and legal expedients to support and encourage accountability and enforcement, including:

- **Citizen and Civic Participation.** Active participation by citizens and society can add both value and trust for environmental causes and improve the perceived outcome of the activity.[13] Citizens can be encouraged to participate in community-based monitoring to satisfy both

[†] Environmental regulations have traditionally evolved in the United States and around the world as "command-and-control" (CAC) whereby specific standards are established for polluters. Along with standards, regulatory bodies, such as EPA or states, may mandate specific control technologies or production processes. While this approach has demonstrated significant successes over the last 50 years across Europe and North America, new performance-based and market incentives are now employed and considered to add more flexibility to the regulatory system.

altruistic and personal interests. Greater civic participation can be achieved through incentive programs that offer funding, learning opportunities, and recognition. For example, the EPA promotes citizen science and sponsors a number of air and water quality initiatives, one of which is partnering with indigenous communities to monitor the Great Lakes region for water quality and invasive species.[14] Citizen science also improves science, technology, engineering, and mathematics (STEM) learning and engages new, younger audiences, including students.[‡]

- **Environmental Justice.** In areas where poor and vulnerable communities are disproportionately affected by pollution and climate change, environmental justice could become a prominent issue. Fortunately, environmental impact assessments are already common in Organization for Economic Co-operation and Development (OECD) countries during the project decisionmaking process.[15] For those countries that may not apply environmental assessments to uncover potential impacts to communities, public decisionmaking systems and civic engagement can work to ensure that all voices are heard and provide the basis for litigation in the event of potential harm.

- **Right to Know.** Although over 120 countries have laws enabling right to know, it can still be quite difficult for citizens to access important government data.[16] Since 1967, the Freedom of Information Act (FOIA) has provided the U.S. public the right to request access to records from any federal agency. Even at the local level, open records laws can foster an informed citizenry to access and uncover important information as in the case of the Flint, Michigan, water crisis. Michigan has one of the lowest rates of public access to information and hid its poor water quality levels from EPA regulators.[17] Despite these barriers to information, various civic society organizations and journalists were able to invoke FOIA to obtain evidence needed to press charges against liable parties.[18]

- **Disclosure Requirements.** Industry and financial disclosure requirements can prompt companies, without compromising proprietary information, to be more transparent about their environmental footprint and to integrate this information into financial reports. Companies may also be required to provide targeted disclosure for specific environmental targets such as pollutant releases and facility level data. This could include an inventory of chemicals or pollutants released to air, water, and soil or transferred off-site for treatment.

Modern Information Architecture as a Platform

The confluence of rapidly increasing data volumes, accelerating data storage needs, low-cost processing capacity, and the evolution of advanced analytics has resulted in the modern data revolution, which offers a paradigm shift for environmental policymakers, justice advocates, regulators, and industry. In addition to specific mission-oriented remote sensing, various technological advances for data sharing, fusion, and advanced analytics have opened the door to data-driven discovery for which there is no prespecified hypothesis. Instead, the data leads to new and sometimes surprising conclusions.

Multiple datasets from various sources can be combined on cloud-based platforms to enable big data analytics, including deep learning algorithms.

[‡] An online searchable database, SciStarter, links to almost 1,600 citizen science projects and helps students and teachers find science projects appropriate for their interests and education level.

This new type of paradigm (see Figure 2) offers:

- Open data and related policies to enable usable and sharable data.
- Pervasive networks for connectivity so that users can access on demand or receive automated "push-based" information.
- Cloud platforms to enable data sharing, data fusion, and various shared applications.
- New opportunities for data discovery through advanced analytics and data verification. (See the predictive analytics sidebar.)

Resource Virtualization. The growth of large cloud platforms has further democratized computing capabilities by offering cloud-based apps and pay-as-you-go computing, storage, and networking capabilities. This virtualized model involves *out-of-the-box* functionality through applications for a subscriber fee, although some applications are free. By "virtualizing" IT resources to an outside cloud and IT service platform, an environmental organization can lower capital expenditures or "Capex" by shifting these expenses to operating expenses or "Opex." Resource virtualization can offer a distinct advantage, particularly when one considers elasticity or the ability to adapt, grow, or shrink infrastructure resources such as computer networks, processing, or storage capacity. Amazon Web Services defines this as "the ability to acquire resources as you need them and release resources when you no longer need them."[19]

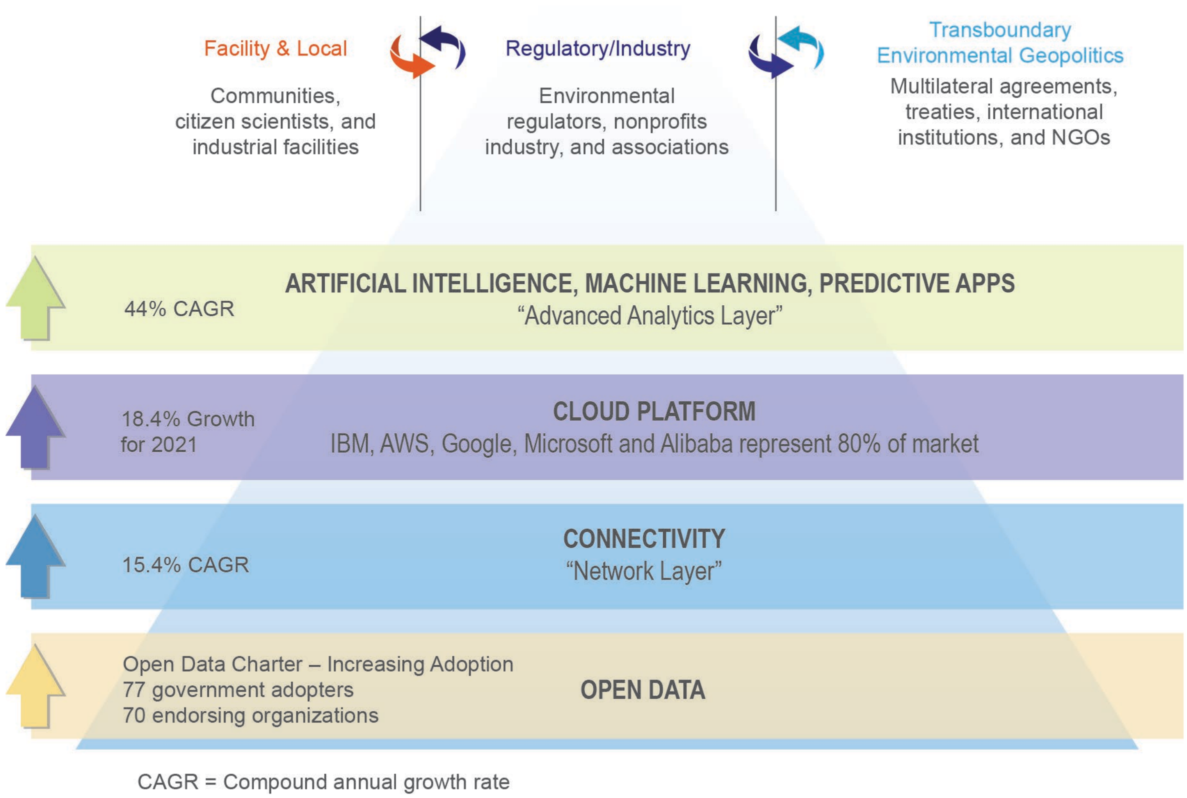

Figure 2: A modern information architecture underpins data-to-action environmental programs. *The goal is to provide interoperability from diverse open data sources, across a range of connectivity networks serving cloud platforms. A modern information architecture can support a range of applications to provide data-driven insight to stakeholders across local, regional, and international/transboundary levels.*

Predictive Analytics: Getting Ahead of the Problem

Emerging predictive analytic tools and platforms help governments, commercial companies, and others to integrate environmental and climate risks into their decisionmaking to "get ahead" of the problem. Both artificial intelligence (AI) and machine learning (ML) platforms offer data on climate risk and reveal patterns to predict future behavior. These tools can help develop systems that minimize environmental impacts. For example, an estimate has found that a third of GHG emissions can be reduced simply through better land management.[20] AI and ML can be applied to future economic development efforts enabling low-carbon electricity grids and transportation systems, sustainable land management, climate forecasting to evaluate long-term drought trends and storm frequencies, and biodiversity monitoring through detection of ecosystems at risk.

Simulation technologies can work in conjunction with AI and ML to allow for digital and physical processing simultaneously, improving their ability to absorb information, make decisions, and act more quickly. These include:

- **Virtual reality (VR) and augmented reality (AR).** Sensory simulations or superimposed digital information in real physical environments that model future architectures.
- **Digital twins.** Virtual replicas of physical systems that help envision future states of behavior, from modeling changes in the climate to designing green infrastructure and energy systems on a large scale. Countries and companies can better develop supply chains that integrate emissions data records with supply chain logistics and create systemwide control loops based on realtime data from in-situ and other sensors. For example, the European Union (EU) is launching its own project in 2021, called DestinE (see Appendix).

Six Pillars for Actionable Environmental Intelligence

Establishing an environmental program or initiative to leverage satellite data, fused with other types of data, into action involves many design elements to ensure success. All six best practices, outlined below, work alongside the two key principles of trust and accountability.

- **Trust.** Environmental programs bridge science and policy and require building trust among non-governmental organizations (NGOs); scientists and technologists in the academic community; local communities and indigenous people; workers and trade unions; community and environmental activists; industry associations and the commercial sector; and national, state, and local governments. This requires building partnerships between various stakeholders and establishing authoritative sources of truth based on domain expertise and credibility, trust in data sources, data management, and stewardship.

> ***"Good environmental governance takes into account the role of all actors that impact the environment. From governments to NGOs, the private sector and civil society, cooperation is critical to achieving effective governance that can help us move towards a more sustainable future."***
>
> —United Nations Environment Program[21]

- **Accountability.** While the concept of "environmental accountability" is closely associated with environmental enforcement programs, the meaning has broadened to encompass more than legal compliance to rules, regulations, and permitting. Environmental accountability now includes environmental behavior, public reporting of data, engaging with the community and stakeholders, and better environmental management systems.[22]

The six best practice pillars also rely on a foundation of modern information architecture and social and legal enablers (see Figure 3). In reviewing various environmental programs, the following common best practices emerged as critical to ensuring environmental program governance.

Pillar 1: Partnerships

Environmental programs often require coordinating across a range of technical disciplines, perspectives, and stakeholders. This could include, for instance, subject matter experts for air, water, or ecosystems along with regulatory experts who understand the compliance and legal implications. Industry is often a primary stakeholder, and they, too, are involved in providing insight and mitigation action. Partnership enables the alignment of environmental actions across different scales, for example, to fulfill pledges made in transnational agreements.[23]

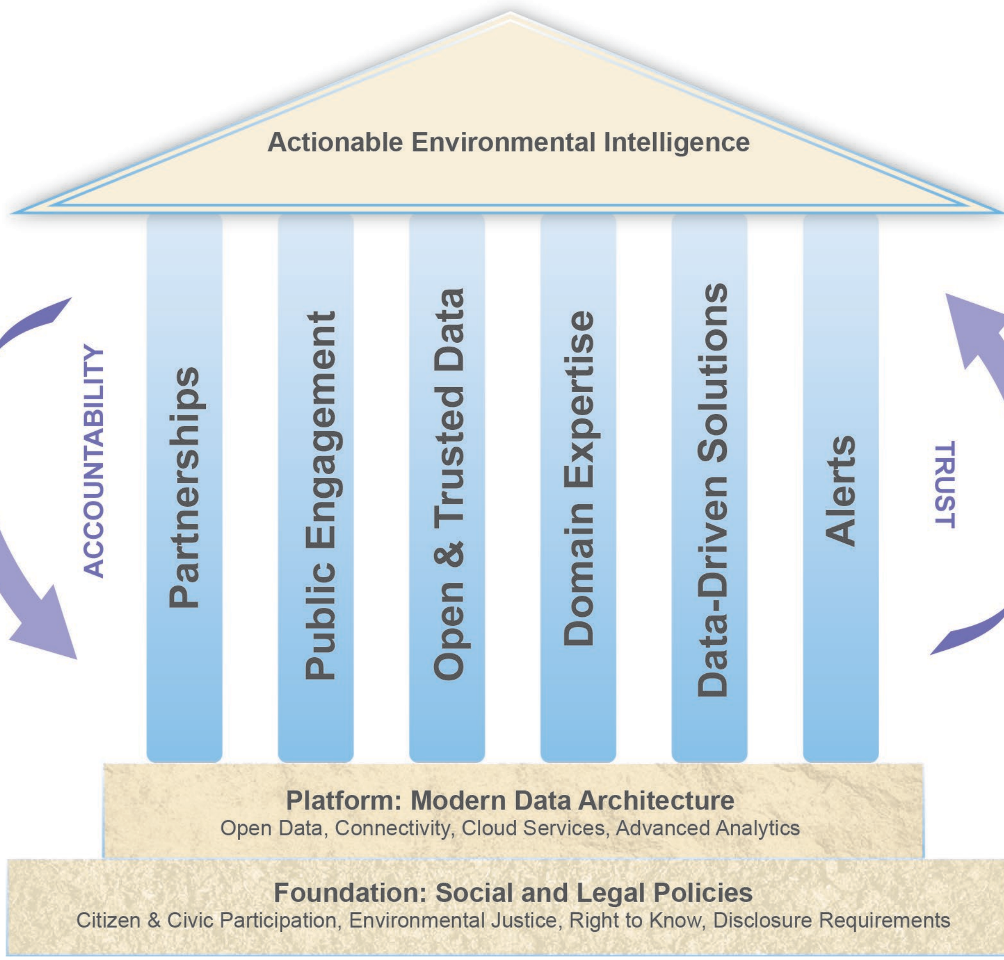

Figure 3: Data-to-action strategy: foundation, platform and six key pillars for actionable environmental intelligence.

Governments can also encourage partnerships with organizations that have a strong environmental focus. Bjorn Bergman, analyst with Global Fishing Watch, emphasized that "partnering with governments in a systematic way continues to remain a challenge."[24]

- **Group on Earth Observations (GEO).** The central characteristic of GEO is its partnership of more than 100 national governments and another 100 participating organizations (academia, data providers, businesses, scientists, etc.) that envision a future where decisions and actions are informed by coordinated, comprehensive, and sustained EO.[25] Partners come together to discuss and address environmental issues by theme and region in working groups, by project, and during conferences and summits.

- **Global Fishing Watch (GFW).** The GFW map currently displays Vessel Monitoring System (VMS) data from four countries (Indonesia, Peru, Panama, and Chile). There are plans to add data from additional countries in the near future, including Costa Rica, Ecuador, and Brazil.[26] GFW leverages such partnerships based on actionable commitment to verify and harmonize VMS data with its own commercially procured automatic identification system (AIS) data from companies like Spire Global (San Francisco, California). This allows GFW to create better analysis and monitoring of illegal fishing issues. It shares its analyses with partner countries who are concerned with illegal fishing so the countries can take action.[27]

Pillar 2: Public and Media Engagement

Environmental communication and engagement involve the ability to understand key environmental issues and convey them to the public, including the impact on society, public health, ecosystems, and natural resources. Environmental communication and journalism are growing fields and have become even more dynamic with the range of social media tools available and escalating concerns regarding environmental justice. Techniques for public and media engagement vary but could involve any combination of more subtle and gradual public education to more proactive "watchdog pressure." Sometimes tactics can escalate and may involve "naming and shaming" to ensure that accountable parties remediate or correct a specific situation.

> ***"We are all extremely aware that the expectations of normal scientific communication—couched in neutral, dry, dusty, dispassionate language—have had far too little effect on policymakers and captains of industry."***
>
> —Dr Phoebe Barnard
> Chief Science and Policy Officer, Washington's Conservation Biology Institute

- **Global Forestry Watch.** Provides universal access to imagery via a suite of tools, which reached over 1.5 million people in 2019 alone using the website and the *Forest Watcher* mobile application. The imagery can be easily used to support ongoing monitoring, investigation, advocacy, planning, and enforcement efforts.

- **SkyTruth.** Public and media engagement is critical to SkyTruth, which got its start opposing the U.S. government and British Petroleum's inaccurate, low estimates of the Deepwater Horizon spill damages.[28] SkyTruth's *FrackFinder* project is another example of engagement leading to legislative action. Its purpose is to crowdsource data to map and track all sites where hydraulic fracking is used to drill for natural gas.[29] The initiative was publicized in the *Washington Post* and ultimately led to the participation of 131 volunteers.[30] Scientists led by Dr. Brian Schwartz at Johns Hopkins University used the data to analyze the impact to public health. This study was then cited by Maryland Governor Larry Hogan to reinstate a fracking ban in the state.[31]

Pillar 3: Open and Trusted Data

Open data is data that can be accessible, machine readable, freely used, re-used, and redistributed by anyone—subject only, at most, to the requirement to attribute and share. Open data[§] policies play an integral role in encouraging access to data from Earth observation satellites. According to one study, data from less than half of the 458 satellites launched between 1957 and early 2016 were made available on a free and open basis.[33] In addition to satellite data, the Open Data Barometer, a nonprofit organization that tracks the impact of open data initiatives around the world and analyzes open data trends and progress, found only 7 percent of governmental data is fully open, only half of datasets are machine readable, and only one in four datasets has an open license. Of the datasets they assessed related to environmental management, only 6 percent of this data is truly open across all governments.[34]

> ***"Open-data has to start at the top, it has to start in the middle, and it has to start at the bottom."***
>
> —Sir Tim Berners-Lee
> Inventor of the World Wide Web[32]

However, growth in open data sharing is rapidly gaining momentum. As of February 2021, the Open Data Charter has been adopted by 78 national and local governments[35] and endorsed by 71 non-state institutions.[36] Promotion of open data sharing coupled with open source software policies can have a positive feedback loop, enabling better data fusion and analytics. The Open Data Barometer suggests that governments must prioritize and invest in open data governance "to support the substantial changes needed to embed an open approach across agencies and departments."[37] Expanding beyond open data, there is now increasing emphasis on peer-to-peer mechanisms, which can help to realize the full potential of open data. As an example, the Pangeo project is partially funded by NASA's Advancing Collaborative Connections for Earth System Science (ACCESS) program and hosts an open-source ecosystem of tools and analytics to allow researchers from across the world to engage in data-intensive Earth and environmental science analytics. Although this project is still in beta phase, it has hosted thousands of scientists working collaboratively to develop software and infrastructure to enable big data geoscience research.[38]

The Memorandum on Transparency and Open Government signed by President Obama helped to usher in a new era of open and accountable government and led to several intergovernmental open data platforms such as GeoPlatform (see

[§] In 2013, G8 leaders signed the G8 Open Data Charter, which set five main principles for open data: (1) "Open Data by Default," (2) "Quality and Quantity," (3) "Useable by All," (4) "Releasing Data for Improved Governance," and (5) "Releasing Data for Innovation." (Source: Cabinet Office – Policy Paper, *G8 Open Data Charter and Technical Annex*, June 18, 2013. https://www.gov.uk/government/publications/open-data-charter/g8-open-data-charter-and-technical-annex)

Appendix).[39] Beyond the United States, there are now many worldwide platforms and emerging nonprofits with robust open data policies. These include the Group on Earth Observations (GEO), the World Meteorological Organization (WMO), International Oceanographic Commission, U.S. Global Change Research Program, and United Nations Office for Outer Space Affairs' new Open Universe Initiative to make all aspects of space, including data sharing, more accessible.

Reid Lifset at the Yale University Center for Industrial Ecology notes that there are sometimes economic barriers to open and free data and that "some important datasets reside behind pay walls. For environmental data it is often a matter of who pays. Datasets need to be created, managed, and curated, and this costs money. If it is not the end user that pays, the creator or a third-party must. Other databases are not public because of privacy issues or because the data is proprietary."[40]

- **GeoPlatform.** This U.S. government initiative provides environmental information to the public for free. For example, the environmental open data catalog on GeoPlatform's online portal offers a range of tools, maps, and online services. It has registered over 173 National Geospatial Data Assets across 18 themes, including topics such as the Arctic, coastal flooding, ecosystem vulnerability, energy infrastructure, transportation, tribal nations, food resilience, health, and water. The goal is to provide data for better climate resilience. These datasets are managed according to the FAIR Data Principles[**] and provided by various federal agencies and state, local, tribal, and regional partners.[41]
- **Group on Earth Observations System of Systems (GEOSS).** One of the main goals of this initiative launched by GEO is to better integrate existing systems and share data by connecting existing infrastructures using common standards. GEOSS provides a portal that houses more than 400 million open data resources from more than 150 national and regional partners and international organizations like WMO and commercial partners like DigitalGlobe. GEOSS's global standards ensure that "data are accessible, of identified quality and provenance, and interoperable to support the development of tools and delivery of information services."[42]

Pillar 4: Domain Expertise

While advances in artificial intelligence (AI) and machine learning (ML) have improved our ability to monitor Earth's surface and the various changes that are occurring, domain expertise for specific industries, regions, or applications remains invaluable. In fact, the volume of data and automated change detection has created even greater and more enduring opportunities for domain experts such as industry experts, intelligence analysts, land use specialists, and a variety of scientists to weigh in to add further context and meaning.

- **Circulo de Politicos Ambientales.** Milko Schvartzman, a senior oceans campaigner, has worked for a variety of organizations including Greenpeace Argentina to improve access to satellite imagery. Schvartzman recognized that the ability to protect a country's exclusive economic zone (EEZ) depended in part on understanding what was happening beyond a country's EEZ in international waters.[††] Using

[**] Principles require data to be Findable, Accessible, Interoperable, and Reusable (FAIR) as set forth by the international organization GO FAIR and endorsed by G20 leaders.

[††] An EEZ extends up to 200 miles from shore, as prescribed by the 1982 United Nations Convention on the Law of the Sea. Within each nation's EEZ, a nation has jurisdiction to govern the use of its marine resources, including licenses, catch limits, or even fishing bans.

the Global Fishing Watch (GFW) data platform, he combined his knowledge of illegal shipping, fishing, and human rights abuses with his legal and regulatory knowledge and access to local and regional policymakers in Montevideo, Uruguay, to encourage better port controls and monitoring.

- **SkyTruth.** John Amos, president of SkyTruth, a nonprofit company dedicated to using satellite imagery to illuminate environmental problems, noted that domain expertise is key, underscoring that "we build towards the truth by finding our own domain experts with highly specialized knowledge and on-ground experience." Amos added that these domain experts work with satellite imagery to interpret what might be occurring on the ground, such as natural gas flaring, petroleum industry well fracking, illegal small-scale mining, mountaintop mining, and oil pollution at sea.[43]

Pillar 5: Data-Driven Decisions

A modern information architecture may provide the opportunity for various stakeholders to interface with the data in a way that allows for evidence-based policymaking. Platforms can support tools for discovery of undetected problems within ecosystems (high rates of emissions, overfishing, etc.). Customizable modeling tools can also answer specific concerns at different scales of use. Most environmental data platforms described in this paper utilize ML to interrogate large amounts of information, such as vessel monitoring data for Global Fishing Watch or sudden hyperspectral imagery changes over oil production sites (e.g., Kayrros).

- **Destination Earth Project (DestinE).** DestinE will provide the European Union (EU) with digital replicas or "twins" to monitor and predict environmental changes to Earth's systems, including land, marine, atmosphere, and biosphere. This open system platform is designed for multilevel use so that national, regional, and even local actors can "nest" their own models and activities into the larger information system produced at the European level. The models will leverage EU satellite data, and various stakeholders can plan infrastructure projects with an eye toward reaching EU's Green Deal twin goals of net zero emissions by 2050 and a sustainable EU economy.[44]

- **GEO.** According to Dr. Gilberto Camara, Director of the Secretariat, access to and analysis of large volumes of Earth observation data is challenging for many of GEO's members, particularly in developing countries where resources are limited, and Internet connectivity is poor or unreliable. To help address some of these challenges, GEO has engaged with cloud solutions providers such as Amazon Web Services (AWS), Google, and Microsoft to organize Cloud Credits Programs that offer developing countries access to complimentary cloud services to help with the hosting, processing, and analysis of big data in the field of EO. [45] GEO is also focused on implementing an open source directory of data applications for partner organizations.[46]

Pillar 6: Alerts

Timely messages are automatically directed to relevant parties (e.g., subscribers, stakeholders, citizens, or areas) when specific environmental conditions trigger an alert. AI and ML and other platform-based applications provide location-relevant information to civil organizations, including regulators, nonprofits, and citizen scientists, who can then verify and validate the information. A move toward integrated architectures to push alerts to receptive stakeholders is growing.

A recent example is a new consortium called *Carbon Mapper*, which combines public and private sector capabilities. This project includes the State of

California, NASA's Jet Propulsion Laboratory, Planet Labs Inc., Arizona State University, and the University of Arizona. Carbon Mapper plans to launch the first two remote sensing satellites in 2023 and will focus on monitoring GHGs, including methane and CO_2, by delivering timely and actionable information to stakeholders. Carbon Mapper is collaborating with the California Air Resources Board (CARB) to make the data available to find and expedite repair of leaks and support disaster response.

- **Global Forestry Watch (GFW).** Satellite imagery is combined with ground-based crowdsourcing tools for ground verification, and universal access to allow relevant stakeholders, such as analysts, policymakers, conservationists, and others to track forestland conservation progress and verify and prioritize deforestation alerts. GFW provides universal access to the imagery and reached over 1.5 million people in 2019 alone using the website and the Forest Watcher mobile app. The imagery can be easily used to support ongoing monitoring, investigation, advocacy, planning, and enforcement efforts.[47]

Conclusion: Implications for Environmental Mission Success

The environmental health of the planet continues to deteriorate as scientists study the problem. Meanwhile, regulators and stakeholders continue to be confounded by how to access trusted and actionable environmental information. Changing this dire trajectory will depend on well-organized and skillfully executed environmental agendas. Program managers can work across local, regional, and national levels to integrate data across multiple sensors and observation platforms to advance an understanding of the air, water, and land environments. Successfully transforming data into action will require a range of best practices such as managing partnerships, public engagement, using open and trusted data, leveraging domain experts, and optimizing alerts to reach stakeholders on a timely basis. Underpinning these environmental programs, modern information architecture will provide transformative capabilities and generate actionable environmental intelligence for industry, regulators, concerned citizens, environmental organizations, and the various environmental initiatives and programs that aim to cross geographies and disciplines.

What does the next successful environmental initiative look like, and where will it come from? Data-to-action examples provided in this paper demonstrate that NGOs, governments, academia, the private sector, and even smaller nonprofits operating on miniscule budgets can be successful. The organizations that tend to make a difference are the ones that move beyond studying the problem. Instead, they rely on a cross-disciplinary understanding of environmental intelligence to realize lower environmental risk, improved sustainability, and appropriate compliance or corrective action. Yet some institutional challenges persist such as how to encourage greater sharing of information and how to build trust among the public and other stakeholders. But the genie is out of the bottle and satellite-derived data continues to proliferate and will play a central role in generating actionable environmental intelligence. The future of our planet depends on it.

Acknowledgments

The authors are grateful for the insight and expertise of the following subject matter experts:

- John Amos, president of SkyTruth
- Bjorn Bergman, analyst with Global Fishing Watch and project manager at SkyTruth
- Dr. Gilberto Camara, director of GEO Secretariat
- Reid Lifset, Yale University, Resident Fellow in Industrial Ecology
- Milko Schvartzman, senior oceans campaigner, Circulo de Politicas Ambientales

The paper also benefited from careful review and suggestions from our colleague, Dr. James A. Vedda.

Appendix: Project Profiles – Mission, Background, and Description

The following nine projects are useful to study to understand the technologies, methodologies, best practices that are applied toward a range of environmental goals and missions.

1 Carbon Mapper

Greenbrae, California

https://carbonmapper.org/

Mission: Accelerate mitigation of methane super-emitters, to independently verify power plant CO2 emissions globally, and to deliver other hyperspectral indicators for carbon and ecosystem management.

Background: A non-profit (501c3) entity, Carbon Mapper was founded during 2021 by a coalition of private and public-sector actors, including Planet, NASA's Jet Propulsion Laboratory, the State of California, the University of Arizona, Arizona State University, RMI, and philanthropic sponsors.

Description: Carbon Mapper will rely on satellites built and managed by Planet, a California company that already operates a constellation of Earth-imaging satellites. The spacecraft will rely on "hyperspectral" imaging spectrometers developed by NASA's Jet Propulsion Laboratory (JPL).

2 Destination Earth Project (DestinE)

Greenbrae, California

https://ec.europa.eu/digital-single-market/en/destination-earth-destine

Mission: Develop a high-precision digital model of Earth to:

- Simulate test scenarios of sustainable development, climate change, and weather.
- Spur innovation and enable the benchmarking of models and data.

Background: This project will develop gradually and will be implemented over the next 7 to 10 years. In 2023, DestinE will launch an operational cloud-based platform and the first two digital twins. DestinE is being developed as part of the European Commission's Digital Europe program. Also, Horizon Europe will provide research and innovation opportunities that will support the further development of DestinE.

Description: The DestinE project aims to "create a crucial tool for everyone from politicians and city planners to energy companies to simulate in detail, using how human and physical systems will change in a warming world." DestinE uses a range of technologies and methodologies, including AI and ML algorithms, digital twins and simulations, predictive analytics, and modelling. Initially, DestinE will serve public authorities and will gradually grow to serve scientific and industrial users.

Leveraging European Space Agency and EU's Copernicus satellite and other field data, DestinE will include three high-precision digital Earth models or "twins," which are meant to be detailed representations of reality.[48] DestinE will provide digital replicas of various aspects of the Earth system such as weather forecasting and climate change, food and water security, and global ocean circulation. DestinE is meant for multilevel use so that national, regional, and even local actors can "nest" their own models and activities into the larger information system produced at the European level.

3 GeoPlatform
United States
www.geoplatform.gov

Mission: Provide access to federally maintained geospatial data, services, and applications through a national geospatial information system (GIS) platform. It makes federal geodata Findable, Accessible, Interoperable, and Reusable in accordance with the FAIR principles.

Background: Developed by the Federal Geographic Data Committee, GeoPlatform is organized under the Department of Interior (USGS) and partners with NASA, NOAA, EPA, and 32 federal agencies to make datasets (satellite, air, and ground-based data) open to the public. It offers a comprehensive list of states, cities and counties, and international countries and regions which provide open datasets.

Description: Environmental open data catalog on GeoPlatform, an online portal with a range of tools, maps, and online services covering a series of topics such as the Arctic, coastal flooding, ecosystem vulnerability, energy infrastructure, transportation, tribal nations, food resilience, health, and water.

4 GHGSat
Montreal, Canada
https://www.ghgsat.com/

Mission: Detect and measure sources of greenhouse gas (GHG), air quality gas, and other trace gas emissions in the atmosphere at high-resolution, enabling industries to improve operations and reduce emissions.

Background: GHGSat was founded in 2011 as a commercial startup.

Description: GHGSat's orbiting satellites monitor emissions at the facility level, giving companies near realtime data about their global operations. GHGSat currently operates three high-resolution demonstration satellites: GHGSat-D, GHGSat-C1, and GHGSat-C2. New high-resolution aircraft platforms (GHGSat-AV) are also being built for operation. They also provide in-house datasets (DATA.SAT and DATA.AIR), data archive, analytics platform, and alerts to their customers.

5 Group on Earth Observations (GEO)
Geneva, Switzerland
www.earthobservations.org

Mission: Build the Global Earth Observation System of Systems (GEOSS), a set of coordinated, independent Earth observation, information and processing systems that interact and provide access to diverse information for a broad range of users in both public and private sectors. GEOSS links these systems to strengthen monitoring of the state of Earth.[49]

Background: GEO was established in 2005 at the Third Earth Observation Summit to carry out *The Global Earth Observation System of Systems (GEOSS) 10-Year Implementation Plan*.

Description: An intergovernmental partnership working to improve the availability, access, and use of open Earth observations, including satellite imagery, remote sensing, and in-situ data to affect policy and decisionmaking in a wide range of sectors.

6 Global Fishing Watch (GFW)

Washington, D.C.

https://globalfishingwatch.org

Mission: Create transparency for commercial fishing activities and address fisheries compliance and ocean sustainability.

Background: GFW was founded in 2017 by Google, with partners Oceana and SkyTruth. Terrestrial and satellite AIS signals trackers, vessel registries, other related GIS data. It uses the Google data sharing platform and cloud computing, GitHub for open source algorithms, ML for pattern detection and visualization models such as online and downloadable maps and datasets.

Description: GFW makes maritime vessel data public by processing and publishing Vessel Monitoring System (VMS) data. According to GFW, most fishing nations collect VMS data to track commercial fishing activity in their nation's waters but typically do not make that information public. This data is owned by the national government and includes information on the country's commercial fishing fleet and foreign vessels registered to fish in their waters. GFW is now working to partner with 20 countries within the next 5 years to make its VMS data public and receive the support of the platform.

7 Global Forest Watch

Washington, D.C.

www.globalforestwatch.org

Mission: Monitor global forests in near realtime. Focused on compliance, enforcement, empowering local communities, and build greener supply chains.

Background: Global Forest Watch is an open source web application launched by the World Resources Institute in 1997 to monitor global forests in near realtime.

Description: Global Forest Watch provides change detection analyses of tree canopies, looking for indicators related to deforestation, harvesting of tree plantations, fire damage, and forest die-off from disease and pests. As such, analysts, policymakers, conservationists, and others can track forestland conservation progress and verify and prioritize deforestation alerts.

Global Forest Watch collects satellite data (Landsat, MODIS, etc.), governmental standards and inventories, ground-based monitoring networks, and other GIS data. It uses an open data portal, Google Earth Engine (cloud computing), mapping and computing, ML and AI algorithms, mobile applications and alerts, and crowdsourcing information to spot signs of impending deforestation and trends in illegal logging to help predict future problems. GFW provides universal access to the imagery via a suite of tools, which reached over 1.5 million people in 2019 alone using the website and the Forest Watcher mobile app. The imagery can be easily used to support ongoing monitoring, investigation, advocacy, planning, and enforcement efforts.[50]

Several companies, such as the producers of palm oil, a product that has led to widespread deforestation in Southeast Asia, are beginning to assess risks of deforestation in their supply chains in efforts to achieve net zero deforestation using these AI methods.[51]

8 Kayrros

Paris, France

https://www.kayrros.com/

Mission: Help traders, investors, operators, and governments make better decisions. Deliver industry- and domain-specific insight into climate risk and extract value from the integration of alternative and market data to effect solutions and product offerings.

Background: Kayrros was founded in 2016, venture capital backed.

Description: Kayrros is a leading global asset observation platform that provides transparency to energy markets. This advanced data analytics company monitors and measures energy and natural resource activity worldwide. It has access to data on more than 200,000 industry assets. Kayrros customers track individual or multiple assets in configurable proprietary or collaborative workflows to analyze industrial and environmental performance, optimizing business and operational decisions.

Methane Watch data products provide timely methane situational awareness and leak alerts to the energy industry, using near realtime measurements.

9 SkyTruth

Shepardstown, West Virginia

https://skytruth.org/

Mission: Stated mission is to "use the view from space to inspire people to protect the environment."

Background: SkyTruth was founded in 2000 by John Amos, and, as a nonprofit organization, it relies on donations.

Description: SkyTruth monitors a range of industrial activities, including mining, oil and gas drilling, hydraulic fracturing or "fracking," fishing, and land development. It serves as a watchdog and seeks to connect communities with accurate information that might not be provided by industry or government regarding industry emissions, oil and chemical spills, bilge dumping, ocean pollution, and illegal exploitation of natural resources and their environmental consequences. SkyTruth transfers and utilizes satellite and aerial datasets in Google Earth Engine and connects those to GIS and ML platforms to visualize the data and analyze it further. SkyTruth also provides timely alerts to communities and subscribers.

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