RESOURCES for the FUTURE

Opportunities for Increasing the Impact of NASA's Earth Observations along Environmental Justice Dimensions

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Working Paper 23-08
April 2023

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About RFF

About the Project

This research was supported in part through the NASA cooperative agreement number NNX17AD26A with RFF to estimate the value of information obtained from satellite-based remote sensing.

Sharing Our Work

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1. Introduction

Environmental justice (EJ) is an important social priority and has become a policy goal at the federal level. Executive Order 14008, Tackling the Climate Crisis at Home and Abroad, requires all federal agencies to develop programs, policies, and activities to address the disproportionately high adverse environmental impacts faced by marginalized communities. This raises the question of how NASA can increase the impact of its scientific outputs along EJ dimensions. How can the agency's existing data products be leveraged to enable progress on EJ-related questions? What new scientific information can NASA produce to help reduce environmental inequities?

Many of NASA's earth observations (EOs) offer complete geographic coverage and thus have strong potential to help systematically quantify the unequal burden of environmental harm and promote the equal enforcement of environmental law. For example, this report shows that using satellite-derived measures for monitoring compliance with environmental regulations could have potentially large equity implications. But despite recent efforts to increase the use of satellite data for such policy applications, satellite resources remain largely underutilized. While state and federal agencies are increasingly turning to satellite data for EJ research studies, these results often fall short of influencing decisionmaking (Holloway and Bratburd 2021). Barriers to use for EOs include difficulty in handling the native observations, a lack of trust in the accuracy of the data, and incompatibility of satellite-derived measures with legal compliance monitoring requirements (Prados et al. 2021).

Produced as part of the **VALUABLES Consortium**, this paper aims to outline ways that NASA can use its data products to promote EJ and overcome the barriers faced in the use of satellite data to influence decisionmaking. Importantly, the set of recommendations provided here is not intended to substitute for NASA's direct engagement with EJ communities to learn what would be of most value to them, but rather is meant to complement these efforts by providing a perspective from the environmental policy community. Specifically, the insights that this perspective can provide are based on environmental policy scholars' understanding of how scientific information, including remotely sensed information, plays a role in the formation of policy within a variety of economic, political, and social contexts. In addition, the recommendations here are informed by the literature on policy evaluation and knowledge of which kinds of policies have proven to be more effective than others, including those with EJ dimensions. This report focuses on four broad categories of opportunities for promoting EJ:

1. leveraging EOs to reduce the inequitable burden of environmental harm
2. making NASA's data products more accessible to EJ communities
3. developing new sensors and missions to fill EJ data gaps
4. contributing to the development of quantifiable metrics to measure progress toward EJ goals

This set of recommendations builds on existing efforts at NASA to increase the impact of satellite data along EJ dimensions. In particular, NASA's Health and Air Quality Applied Sciences Team (HAQAST) has a Tiger Team tasked with leveraging satellite data for EJ. HAQAST members are working with public stakeholders to identify communities disproportionately affected by environmental health risks, build capacity among EJ communities for using and interpreting satellite data sets, and increase the accessibility of satellite data for EJ applications. Additionally, in 2021, NASA announced a new funding opportunity providing an estimated $3 million in awards to advance progress on EJ domestically through the application of earth science, geospatial, and socioeconomic information. The aim of this document is to reinforce the need for this type of work at NASA and identify additional opportunities for advancing EJ using agency resources.

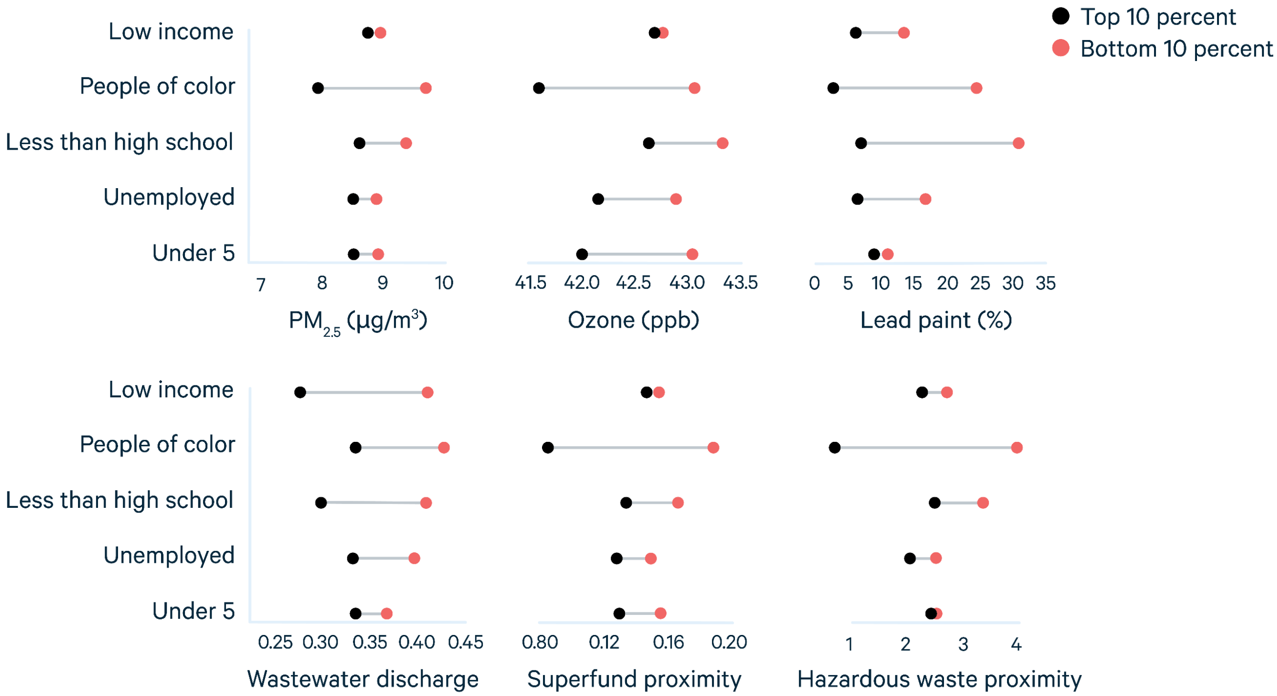
2. Information to reduce the inequitable burden of environmental harm

A large body of literature shows that the burden of environmental harm is not equally shared (Mohai et al. 2009). Communities of color, low-income communities, and those with less-educated residents face higher exposure to hazardous conditions such as pollution and toxic exposures (see Figure 1, for example). Historically marginalized communities also tend to experience greater sensitivity and vulnerability to such exposures (Landrigan et al. 2018; Carleton and Hsiang 2016; Hsu et al. 2021). NASA can leverage its satellite data products to help reduce this inequitable environmental burden through several channels, as outlined in the following subsections.

2.1. Expanding the monitoring and enforcement of environmental law

The ground-based systems currently used to monitor compliance with environmental regulations do not offer complete coverage over space and time. This creates the potential for inequitable enforcement, meaning that not all Americans benefit equally from environmental protections. NASA's EOs can help fill these data gaps, with potentially large equity implications. However, doing so will require increasing the compatibility of EOs with legislation.

Figure 1. Environmental inequities



Note: Comparison of census-tract-level exposures for the top 10% (orange) and bottom 10% (blue) along the dimensions of income, race/ethnicity, education, unemployment, and age. The distance between the two dots for each dimension indicates disparity in the exposure burden. Data on environmental exposures and EJ indicators are from EJScreen (Corrales 2016).

Two of the most significant and wide-reaching environmental regulations in the United States are the Clean Air Act (CAA) and Clean Water Act (CWA), which require that air and water quality meet national standards. In areas that do not meet these standards, state and local governments are required to develop implementation plans for reducing pollution levels. Compliance monitoring is done using a system of ground-based monitors. For example, the CAA uses a system of 974 National Ambient Air Quality Standards (NAAQS) monitors. Under the CWA, state and federal agencies monitor water quality at approximately 8,000 sites and use these measures to target local pollution control efforts. However, because ground-based monitoring systems do not offer continuous coverage over space and time, environmental hazards in some areas can exceed regulatory limits without consequence (Gray and Shimshack 2011). Most US counties have zero or one NAAQS monitor. This is troubling because air pollution levels can vary dramatically over short distances, especially for criteria air pollutants that have well-documented adverse health impacts (Monn 2001). Water quality monitoring is conducted by individual states, and investigations have found that state data reported to the US Environmental Protection Agency (EPA) for measuring CWA compliance do not reliably reflect the number of health-based violations that local water systems have committed (GAO 2021).

Leveraging EOs to fill gaps in monitoring networks could lead to significant changes in pollution levels and health outcomes. For example, two recent studies use satellite-derived estimates of PM2.5 to assess NAAQS compliance for the continental United States at 1 km resolution. These studies estimate that 24 million to 42 million Americans are living in areas with pollution levels higher than NAAQS, according to satellite measures, but they are not classified as nonattainment areas using the ground-based monitoring system (Sullivan and Krupnick 2018; Fowlie et al. 2019). Sullivan and Krupnick (2018) estimate that if these unmonitored areas were subject to the same level of enforcement as monitored areas, more than 5,400 premature deaths could have been avoided. EOs offer promise in water quality monitoring too. Remote-sensing data are currently used by EPA to detect harmful algal blooms in US freshwater systems and issue early warnings. These early warnings have been shown to reduce damages from adverse human health impacts caused by cyanobacteria (Stroming et al. 2020).

From an EJ perspective, using satellite data for regulatory enforcement would likely have large equity impacts. Indeed, evidence exists that local regulators avoid pollution hot spots in the placement of NAAQS monitors and disproportionately so where disadvantaged communities are concerned (Grainger and Schreiber 2019). To better understand these distributional impacts, I overlay average annual pollution concentrations and sociodemographic indicators across the United States with data on the location of NAAQS monitors (Figure 2). Doing so shows that areas with the highest air pollution levels and no NAAQS monitor within 1 km are disproportionately marginalized communities. These areas have significantly higher percentages of low-income, minority, unemployed, less-educated, and linguistically isolated people (Table 1). I also examine the demographic makeup of counties with misclassified air quality as defined by Sullivan and Krupnick (2018; i.e., those counties that are in nonattainment based on satellite-derived $PM_{2.5}$ measures but not on the ground-monitoring network).[1] I find that misclassified counties are disproportionately those with higher percentages of people of color, less-educated residents, and linguistically isolated individuals. These exercises suggest that the air quality benefits of expanding the geographic coverage of NAAQS monitoring and enforcement activities would disproportionately go toward marginalized communities.

Significant barriers remain to using satellite data products for regulatory enforcement because many EO measures of environmental quality are not compatible with existing legislation. Satellite-based sensors cannot directly measure most constituents of a polluted atmosphere, and the uncertainty inherent in satellite-derived estimates of ground-level pollution presents legal challenges. Additionally, some legislation explicitly requires monitoring at ground level, making EO-derived measures incompatible (Prados et al. 2021). Reducing these barriers would be one avenue for promoting EJ.

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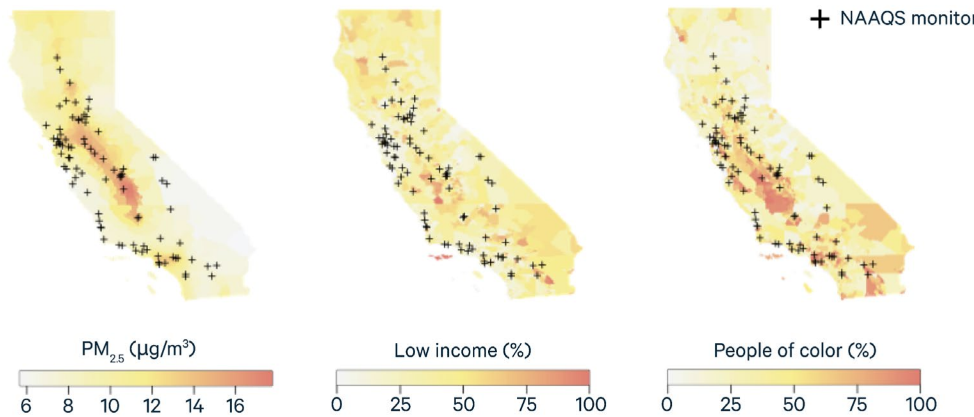
[1] Note that using county-level measures can obscure disparities as a result of spatial aggregation.

Figure 2. Spatial distribution of $PM_{2.5}$, NAAQS monitors, and EJ indicators in California



Note: This figure overlays satellite-derived measures of average annual PM2.5 concentrations at the census-tract level with the NAAQS ground-based monitoring network in California. This allows for the identification of areas with high pollution but no nearby monitor (left). We can then examine the sociodemographic characteristics of these communities (center, right).

Table 1. Unmonitored Areas with High Pollution

	Unmonitored tracts (1)	Misclassified Counties (2)	National Average (3)
Low income (%)	38.0	32.2	31.5
People of color (%)	43.7	55.9	39.7
Unemployed (%)	6.9	6.2	5.6
Less than high school (%)	14.6	16.2	4.6
Linguistically isolated (%)	5.7	8.5	5.4
Under 5 (%)	6.4	6.4	6.1
Over 64 (%)	14.2	13.9	15.7

Notes: High-pollution unmonitored tracts (column 1) are those identified with annual average $PM_{2.5}$ concentrations in the top percentile but no NAAQS monitor. Misclassified counties (column 2) are identified by Sullivan and Krupnick (2018) as those that are in NAAQS nonattainment as measured by satellite-derived estimates of $PM_{2.5}$ but not as measured by the ground-monitoring network due to sparse geographic coverage. Data on EJ indicators are from EJScreen.

NASA could increase the compatibility of EO data with environmental legislation through two primary channels. First, the agency could work with legal scholars to identify opportunities to incorporate EOs into regulation. This would require the development of a standard model for converting satellite measures into estimates of ground-level pollution. Alternatively, NASA could design EO sensors with the legal sector in mind. This would require consulting with legal scholars on what capabilities sensors need to have to be considered a valid measure of compliance. Either way, a first step could be to conduct an analysis of accuracy requirements of satellite data for regulatory purposes, since a lack of credibility is often cited as a barrier to use.

In the meantime, satellite data can be leveraged right now in several ways. One option is to use satellite-derived measures of air pollution to target the placement of additional ground-based monitors (Krupnick and Sullivan 2018). Priority could simply be given to areas with high satellite-monitored pollution levels but no nearby NAAQS monitor, or determining which areas to focus on could be a function of other social priorities. As another example, HAQAST members are already using EOs to help inform State Implementation Plans for reducing emissions and pollution and for exceptional event demonstrations, especially in the case of wildfires (Geigert 2018; Jin et al. 2018).

2.2. Facilitating cumulative impact analysis

Executive Order 14008 and the proposed Environmental Justice Act of 2021 call for the cumulative impacts of permitting decisions under the CAA and CWA to be considered before projects can move forward. Cumulative impact analysis is in its infancy, but EO data have a key role to play in advancing the field. “Cumulative impacts” refers to the total burden from environmental stressors and their interactions that affects the health and well-being of an individual or community (EPA 2022). Cumulative impact assessment requires accounting for the following:

- **Multiple environmental stressors.** Analyses should include multiple chemical and nonchemical stressors from the built, natural, and social environments.
- **Additivity.** The combined effect of two environmental exposures may be more damaging than either exposure alone as a result of their interaction.
- **Sensitivity.** Different groups of people have different responses to environmental harms. For example, young children and the elderly are more sensitive to pollution exposure than other adults.
- **Vulnerability.** Health disparities, economic insecurity, and other community-level factors often lead to different impacts of environmental exposures across communities.

Such a model has not yet been developed for regulatory analysis, but EO data can help build out the necessary components. For example, to appropriately account for sensitivity, the research community must first estimate heterogeneous effects of environmental harms on human health. Some work has been done on various demographic groups' sensitivity to air pollution and extreme heat, but more work is needed on mediating factors, such as access to healthcare, availability of air-conditioning, or distance to the nearest community center where vulnerable populations can shelter from hazardous conditions (Bell and Dominici 2008). Collaboration between EO providers and social scientists is required to link neighborhood-scale measures of environmental hazards with information on community resources to capture the influence of this type of modifying effect.

While much of the focus on additivity is centered around spatial overlaps in environmental risk, additivity also has a time dimension. Many of the most harmful events are ones in which two stressors (e.g., pollution and extreme heat) are coincident. This type of additivity is obscured in spatial maps that allow users to visualize average annual exposure to stressors within and across locations, because such maps can smooth out short-term spikes in exposure that drive adverse impacts.

EOs are already providing some of the native data required to conduct cumulative impact analysis, but to increase the utility of these resources, they should be converted into formats that researchers and EJ communities are accustomed to working with. In addition to the suggestions outlined in Section 2, one simple step NASA could take is to harmonize data on different environmental stressors over geographic space to facilitate research into additivity. This would involve producing neighborhood-scale maps of exposure to a multitude of environmental risks, such as pollution, extreme heat, and water scarcity. Ideally, these maps and the underlying data would also capture the time dimension of additivity, but no standard set of metrics exists for doing so. More research is needed into critical thresholds associated with the interactions of multiple environmental stressors.

2.3. Improving forecast accuracy for environmental hazards

Early detection and warning systems (EDWSs) are an important adaptive measure to environmental hazards, with the potential to save lives and prevent property damage. Because disadvantaged communities tend to be both more exposed and more sensitive to environmental hazards, EDWSs can improve EJ outcomes through informed decisionmaking by individuals or institutions (Rogers and Tsirkunov 2011; Kelly et al. 2012).

One avenue for strengthening EDWSs is to improve the accuracy of forecasting hazardous conditions by incorporating EOs into forecasting models (Kumar et al. 2019). Near real-time data from NASA's LANCE have already been shown to improve the predictive power of forecasts, especially for rare but high-cost events (Lee et al. 2022). NASA could take several actions to enhance the usefulness of its outputs for EDWSs, including the following:

- supporting research into methods for integrating satellite or in situ observations as a constraint on forecasting models (i.e., data assimilation), with a focus on environmental hazards that disproportionately affect vulnerable communities
- prioritizing the addition of near-real-time capabilities for upcoming missions such as TEMPO
- building capacity in public health and emergency departments in disadvantaged communities to facilitate the use of EOs in early warnings

One such effort is the ongoing collaboration between HAQAST members, NOAA, and EPA to develop satellite-derived hourly and daily PM2.5 estimates for integration into the AirNow system, an online resource providing real-time information on air quality (NASA 2021). This project provides a model for how EOs can enhance environmental monitoring by filling gaps in the ground-based monitoring network. A natural next step to this work would be to leverage these measurements in combination with EOs that measure atmospheric conditions affecting pollution transport to improve forecasts for use in EDWSs.

3. Making NASA's data more accessible to EJ communities

One takeaway from NASA's Equity and Environmental Justice Virtual Workshop in October 2021 was that the EJ communities and researchers who leverage the agency's data products to study EJ issues often find NASA's EOs difficult to engage with (NASA Earth Science Division 2022). NASA could take several actions to make EOs more accessible to the research and EJ communities.

For one, NASA could develop user-friendly interfaces that allow nonspecialists to easily engage with EOs. These dashboards could be designed to allow stakeholders to visualize environmental risks in their communities and easily understand temporal trends in exposure. Ideally, they would integrate multiple EJ concerns, such as air quality, extreme heat, limited access to food systems, and locally unwanted land use, into a single platform to provide a systematic perspective. The HAQAST Tiger Team on satellite data for EJ already has such an effort underway. It is developing a central warehouse for long-term satellite data on multiple environmental exposures that can be easily linked with health outcomes and socioeconomic characteristics at various geographic scales. The set of recommendations here echoes the need for such a product and provides additional suggestions for how NASA and affiliated scientists can increase the impact of satellite-derived data products.

I recommend designing a data portal that not only allows users to search and access NASA's data products but also facilitates their application to EJ issues by providing algorithms that allow for easy integration of satellite-derived data into existing workflows and offering world-class expertise on the strengths, limitations, and potential EJ applications of these data. The National Center for Atmospheric Research's Climate Data Guide could serve as a model for such a platform. Specifically, I recommend the following:

- Providing easy-to-digest descriptions of satellite-derived measures of environmental conditions and their accuracy. For example, what is aerosol optimal depth, and how can this measure be leveraged to estimate ground-level pollution levels? How have these measures been validated? What is the level of uncertainty associated with them?
- Providing analysis-ready data in a variety of file formats for easy integration into existing decision support systems.
- Developing tools that allow for easy regridding of data to facilitate their usage by the research and modeling communities. Where possible, satellite-derived measurements of ground-level conditions should also be calibrated at different spatial scales.
- Aggregating observations of environmental exposure to a range of administrative boundaries and temporal scales to facilitate linking measures of environmental exposure with EJ indicators. While aggregating data to census boundaries is already a common practice, a number of other geometries could also facilitate EJ analyses, such as those used for health surveys, school districts, and social services.
- Providing expert guidance on how to select from among off-the-shelf data products. For example, several different satellite-derived measures of $PM_{2.5}$ concentrations are available for researchers and community members to use, and different products may be better suited to different tasks. Those interested in the impact of pollution on urban populations may wish to choose products derived from models that are anchored to ground-based measurements, which tend to be more accurate in urban areas because of the density of monitors (e.g., Di et al. 2019). On the other hand, those interested in rural populations may prefer to use the output of approaches that combine satellite retrievals of aerosol optimal depth with chemical transport modeling, since these data have higher overall accuracy at greater distances from ground-based monitors (van Donkelaar et al. 2021).

4. Developing new sensors and missions to fill EJ data gaps

In recent years, NASA has increasingly recognized the need for application-oriented missions that provide satellite-derived measurements in support of human health and well-being (NRC 2007). The agency is making significant efforts not only to engage with public stakeholder users to increase the accessibility of its data products but also to integrate end-user needs into satellite mission planning. This strategy has proven highly successful in advancing climate change research. The potential exists to launch a similar effort in support of EJ. NASA could increase the value of its data for EJ by improving the spatial resolution, temporal coverage, and near-real-time capabilities of EOs. In addition, sensors that can directly measure many of the pollutants of most concern to EJ communities need to be developed. Following are some of the needs to fill EJ data gaps:

Spatial resolution. The native resolution of current satellites for monitoring air quality (3.5 × 5.5 km) can smooth out pollution (Anenberg et al. 2021). While postprocessing can yield surface concentration data sets with relatively high spatial resolution (e.g., 1 km), this sort of aggregation can obscure the most damaging events. Even more spatially granular data are required in densely populated urban areas (where census tracts are small) to discern which populations are benefiting from efforts to reduce pollution and track progress toward EJ initiatives such as Justice40. High-spatial-resolution data are also required for EJ priorities such as identifying pollution point sources, producing neighborhood-level flood maps, and mapping the characteristics of the built environment responsible for the urban heat island effect.

Temporal coverage. Polar-orbiting satellites offer limited temporal coverage (one measure per day) and are therefore unable to capture the full diurnal variation in environmental conditions. This is problematic because the adverse impacts of pollution, extreme heat, and other environmental stressors are highly nonlinear and largely driven by extremes. The upcoming NASA mission TEMPO will address this issue for pollution measures by taking hourly US air quality measurements throughout the daytime. New geostationary satellites could be developed for other environmental exposures.

Near-real-time capabilities. Prioritizing access to near-real-time data in future satellite missions would improve the accuracy of EDWSs, which have strong potential to improve EJ outcomes.

Measurement of pollutants of concern for EJ communities. Currently, satellites cannot directly observe black carbon or hazardous air pollutants, which are of great concern to EJ communities. These pollutants not only disproportionately affect EJ communities but also are highly localized, making remotely sensed measures that offer continuous coverage over geographic space particularly important. Satellite-derived NO_2 concentrations could potentially be used as a proxy for these spatially heterogeneous pollutants from fuel combustion, but methods have not yet been developed to do this (Anenberg et al. 2021). I recommend that NASA systematically evaluate which pollutants are of highest priority to the EJ communities and then either invest in new sensors to enable the measurement of such pollutants or prioritize the development of models to estimate concentrations from satellite-derived NO_2 measures, or both.

Spatial-temporal modeling of nonpoint-source water pollution. Sensors and modeling capabilities that allow for spatial-temporal mapping of nonpoint-source water pollution are also needed. Nonpoint-source pollution includes pollutants such as excess fertilizers or insecticides from agricultural lands, oil and toxic chemicals from urban runoff, and sediment from improperly managed construction sites. It is considered the leading cause of water quality problems in the United States today. Better spatial-temporal modeling of nonpoint-source pollution is a prerequisite for improving water quality and guiding control efforts.

5. Using metrics to measure progress toward EJ goals

One barrier to tracking progress toward EJ goals is that accountability metrics and the scale at which equity effects should be measured are not well established. While the ultimate goal of many EJ initiatives is to reduce disparities in environmental impacts in disadvantaged communities, data limitations often lead to the use of proxy measures to track progress toward this goal. For example, it is more straightforward to measure what share of environmental investments goes toward vulnerable communities than what share of benefits is delivered to these communities. It is also easier to measure disparities in pollution and toxin concentrations than disparities in impacts. Consider, for example, the cleanup of hazardous waste sites. An evaluation criterion based on effort level could track how many sites qualify for federal cleanup funds based on Superfund listings. An evaluation criterion based on concentration levels might go one step further and measure the impact of site cleanup on soil, air, or water quality. But the ultimate goal is to reduce disparities in adverse impacts, which requires measuring changes in health or quality of life, as well as broader economic and structural changes to the area. Another open question is whether the appropriate scale for measurement is at the societal, community, neighborhood, or even household level. There is a risk that community- or neighborhood-level EJ impact assessments can be misleading if improvements in environmental quality displace marginalized groups through gentrification (Melstrom and Mohammadi 2022; Pearsall 2012).

As federal, state, and local governments continue to develop accountability metrics for EJ initiatives such as Justice40, they will need input on what metrics are feasible to measure with existing data sources. NASA can play an important role in informing these discussions. The agency's data products provide unique opportunities to measure EJ at highly local scales because of the spatial granularity and geographic coverage of remotely sensed data. For example, for some pollutants, such as PM2.5 and NO2, NASA's data products already enable us to quantify disparities in exposure across sociodemographic groups at the neighborhood level by linking high-spatial-resolution estimates of surface-level concentrations derived from satellite measurements with administrative data. But for other pollutants, such as black carbon, data scarcity makes it more appropriate to measure accountability by focusing on investment dollars rather than impacts. Collaborating with other government agencies to trace out where data allow for measuring outcomes rather than just investment dollars is an important first step toward developing a set of accountability metrics that add teeth to EJ initiatives.

Another area of concern is that even where we can measure exposure to environmental risk at the neighborhood level, the same level of exposure does not lead to the same level of adverse impacts across communities. Indeed, we need to understand a community's cumulative burden to quantify impacts, since environmental, health, and socioeconomic factors often combine to create a much heavier burden on a community than each environmental risk factor alone may suggest. One way to make progress toward this goal would be the establishment of an interagency initiative tasked with producing new measures of environmental burdens that capture cumulative exposure and estimating exposure-health response functions that can be used to inform where resources should be directed to have the greatest impact on reducing adverse environmental impacts and inequities.

It is my recommendation that NASA collaborate with NGOs, academia, and state and federal agencies to identify EOs that can be integrated with social science data sets to enable transdisciplinary science and track progress toward the EJ initiatives. It is critical to partner with EJ organizations from the beginning phases of this work to ensure that the data products NASA and others develop closely reflect community priorities.

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