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NIST IR 8600

Environmental Measurements

A Needs Assessment

Julia K. Marrs
David W. Allen
Gerald T. Fraser

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Environmental Measurements

A Needs Assessment

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Abstract

Reliable measurements are crucial to monitoring the environmental systems that support efficient food production, natural resource extraction, recreation, habitation, and many other economically important sectors. A summary is provided of the presentations, discussion, and findings from a two-and-a-half-day workshop on environmental measurements. The workshop focused on needs for new measurement science and measurement standards to support the characterization of terrestrial, aquatic, and atmospheric systems. The workshop consisted of formal talks and guided discussion sessions, during which overarching challenges within the field of environmental measurements were identified. These challenges included insufficient representativeness, measurement nonstationarity, obstacles to data continuity, and inconsistent or invalid reporting of measurement uncertainty. Suggestions on addressing these challenges focused on finding opportunities for collaboration between NIST and the environmental measurement community, which could support educational efforts on best practices for uncertainty quantification, sensor intercomparisons, and standardization efforts. Environmental measurements include many areas of study that are already of interest to NIST, and the findings of this workshop suggest that there are opportunities for collaborations between environmental researchers and the metrology community.

Keywords

Ecological measurements; Environmental measurements; Flux towers; Point measurements; Rain gauges; Satellite measurements; Sensor Networks; Sensors; Testbeds.

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1. Introduction

The National Institute of Standards and Technology (NIST) has a long history of collaborating with government agencies, academic and research institutions, companies, and national metrology institutes (NMIs) to provide the measurement science and standards for environmental measurements. The NIST role is to enable the traceability of environmental measurements to primary measurement or calibration standards that are based on realizations of the International System of Units (SI). Measurements relative to the SI are tied to fixed fundamental physical constants, such as the speed of light, the elementary unit of charge, and the Planck constant, that have been agreed to internationally through the operating procedures of the Treaty of the Meter [1]. That the SI is based on fundamental physical quantities enables SI-traceable measurements to be used to further the understanding of environmental processes, and to both develop and validate physics-based computer models for terrestrial, aquatic, and atmospheric applications.

Environmental research often involves efforts to quantify small changes in long-term trends, such as in cyclical or variable processes which may show a significant trend only at decadal and longer time scales. Earth-observing satellite and airborne instrumentation, environmental measurement networks, and *in situ* sensors are essential tools for automated environmental monitoring, but data on their connection to ecosystem function have high uncertainties, driven by the challenge of relating these disparate signals to real-world environmental processes and impacts SI traceability helps to confront this challenge by enabling the creation of reliable data records collected across instruments deployed at sites around the world, including by sensors that measure the same property but use a different physical principle. A broad range of environmental measurements require SI traceability, from tracking atmospheric pressure and temperature trends that are fundamental to biospheric activity to volumetric measurements of hydrological processes to radiometric scales that underpin spectral measurements of the Earth's surface. Additionally, the use of SI-traceable standards for ecological measurements enables the synthesis of data records from different organizations, sites, years, and sensor types. SI standards and traceability thus enable an enhanced ability to detect changes in environmental variables across spatiotemporal scales.

Measurement science is critical to the effective management of land resources for food production, natural resource extraction, recreation, habitation, and other needs that are important to the U.S. economy. For example, forest products account for approximately 4 % of the U.S. manufacturing Gross Domestic Product (GDP) [2], and agriculture and related industries contribute 5.5 % to the total U.S. GDP [3], suggesting that small improvements in agriculture or forestry productivity through the use of environmental measurements can have a major impact on U.S. economic growth and competitiveness. The market for sensors with environmental applications includes the precision agriculture community, a $6.5B industry in 2020 [4], which relies heavily on newly developed sensors to monitor water and nutrient inputs and productivity. The commercial SmallSat (compact satellite instruments) industry functions on the rapid deployment of constellations of multiple low-cost sensors, many of which are

aimed at monitoring agriculture, forests, and ecosystems; the SmallSat industry represented a $4.9B market in 2021 [5]. Recognition of the importance of robust SI traceability for both emerging and established environmental measurement technologies led NIST to organize a workshop to better understand community measurement and standards needs and possible solutions.

2. Workshop Announcement

Recognition of the importance of robust SI traceability of ecological measurements led NIST to organize a workshop to better understand the community's measurement and standards needs and possible solutions. A notice about an Environmental Measurement Workshop to be held on September 10 – 12, 2024 and a request for comments was published in the Federal Register on June 4, 2024 as "Earth and Space-Based Sensors for Environmental Measurements: Calibration, Standards, and Testbeds (Doc. 2024-12165)" [6]. Following this announcement, the workshop was advertised to the public using the following text, which captures the scope and objectives of this activity:

> *The National Institute of Standards and Technology (NIST) works to advance measurement science and is organizing a workshop to learn more about current limitations in making measurements of the environment, including terrestrial and aquatic ecosystems, agriculture, and managed urban areas. NIST is hosting a gaps analysis workshop to foster a community dialogue on needs related to sensors, measurement methods, and standards for ecosystem measurement. The goals of this workshop include:*
>
> - *Identification of specific measurement needs in local, national, and international efforts to quantify ecosystems.*
> - *Development of a clear path for NIST to support ecological measurement needs for improved human wellbeing, economic security, and ecosystem health.*
> - *Establishment of a community forum for ongoing discussion between NIST and the earth and environmental science communities.*

3. Specific Topics of Interest

The Federal Register Notice (FRN) highlighted specific topics of interest, as listed below:

- Are there sensors you use to make environmental measurements which have shortcomings, or which require improved standards?
- Which biological, chemical, and physical parameters are of greatest interest in making your environmental measurements?
- Whether the sensors you currently use are traceable to SI-traceable standards, including:
  - Whether you refer to NIST standards for radiometric quantities, temperature, pressure, gas concentration, or other quantities
  - If not directly traceable to the SI, whether you know how your environmental measurements compare to relevant SI-traceable standards (for example, by comparison against another sensor traceable to a NIST calibration).
- Feedback on challenges related to bridging spatial and/or temporal scales when making or analyzing measurements, and
  - Whether you see specific gaps in available sensor types that could alleviate these challenges
  - The scale(s) at which the measurements you use were collected (*e.g.* satellite remote sensing platforms, in situ environmental sensor networks, organismal scale, genomic or molecular scale)
- Whether measurements you currently make in field settings are limited or affected by temperature, humidity, or similar environmental fluctuations
- Gaps in data availability, including:
  - A need for novel sensors to capture environmental variables that are not currently measured
  - A need for greater reliability and comparability among existing sensors or sensor networks
- Feedback on your interest in environmental sensor testbeds, including:
  - Whether comparisons among particular types of sensors in a well-characterized setting would be of use to your work
  - Whether comparisons between sensors of the same type in a well-characterized setting would be useful to your work
  - Whether there are particular types of ecosystems that currently lack testbeds that could provide useful information for your work
- Current limitations to measuring small or incremental changes environmental parameters of interest over long time periods

4. Workshop Sessions

The workshop consisted of two and half days of presentations and open discussion, as well as focused discussion on the following topics:

1. Atmosphere and biosphere monitoring
2. Field instrumentation
3. Data and measurement accessibility
4. Data and measurement times series

Below we summarize the four group discussions that took place over the course of the workshop. The first two discussion sessions were held on Day 1, and the third and fourth sessions were held on Day 2. Questions intended to guide the discussion were generated in advance of the workshop. These questions were not intended to be comprehensive, nor to limit the subjects discussed; they were merely prompts and guiding topics to set the stage for discussion. In each section below, these discussion questions are reproduced, along with a table (Table 1 to Table 4) summarizing specific issues and potential solutions or resources brought up during each discussion section.

4.1. Atmosphere and Biosphere Monitoring

This session consisted of three presentations listed below with discussions after each presentation and at the end of the session.

- "Long-Term Environment Measurement (Through a Carbon Lens)," by Lucy Hutyra, Distinguished Professor and Chair, Earth & Environment, Boston University
- "Radiometry for Climate Metrology," by Michelle Stephens, group lead for Sources and Detectors Group, Physical Measurement Laboratory (PML), NIST
- "The National Ecological Observatory Network (NEON) Contributions to Environmental Measurement Stewardship," by Janae Csavina, Calibration, Validation, and Audit Laboratory Manager for NEON

The discussion was guided by a series of questions reproduced below:

1. What are the largest challenges you face in using measurements from currently deployed sensors?
    a. Are currently deployed sensors sufficiently accurate on an instantaneous measurement basis?
    b. Is there sufficient agreement and consistency across currently deployed sensors in the network for valid intercomparison across sites?
    c. Is there sufficient coherence /agreement throughout the historical measurement timeseries of your quantity of interest?
    d. Are there other gaps (technical, spatial, temporal) in current measurements of interest?

2. Are there quantities of interest to you which are not possible to measure with any instruments currently on the market?
3. What challenges do you face in attempting data fusion of complementary data streams?
    a. Are there barriers to combining measurements of the same quantity made using different sensors?
    b. Are there barriers to synthesizing data of different quantities of interest?
4. Do currently deployed sensors present any limitations for up- or downscaling data?
    a. Are there limitations to current sensors that prevent sufficient measurement density or spatial representativeness within networks?

A synthesis of workshop participants' responses to these questions is presented in Table 1, along with a summary of any resources or potential solutions mentioned during the discussion.

Table 1. Atmosphere and Biosphere Monitoring Challenges.

Challenge	Examples	Resources and Potential Solutions

Gaps in current measurement capabilities	• Water fluxes
	  ○ Soil moisture
	  ○ Soil matrix potential
	  ○ Leaf water potential
	  ○ Stomatal conductance
	• Precipitation during extreme weather events
	  ○ Current sensors may be insufficient to capture volume of precipitation (*e.g*. bucket overflows/tips before storm ends)
	  ○ High runoff leads to disconnect between extreme precipitation and soil moisture
	• Water quality and nutrients (particularly continuous timeseries, rather than point samples)
	• Belowground processes:
	  ○ Root biomass
	  ○ Soil chemical and physical properties
		• Studies in controlled or experimentally manipulated environments to develop improved monitoring strategies for difficult-to-measure signals
		  ○ Environmentally controlled growth chambers
		  ○ *In situ* nutrient additions
		• Measurements of multiple linked quantities of interest in order to leverage more precise measurements of one via known conversion factors; this is already done in atmospheric gas monitoring, and analogues could be developed for other applications.

Data continuity and interoperability	• Challenges in obtaining funding for continuing a long-running project compared to obtaining funding for a new project ○ Increased attention for existing projects often only occurs after there is a problem • Lack of standard protocols for ensuring data continuity during replacement of broken or obsolete sensors • Coordination among networks, including need for protocols for both measurement and reporting, to aid in consistent methods for data fusion	Synthesis and compromise needed. Existing examples include: • La Thuile synthesis eddy-covariance dataset [7] with consistent processing across sites • NOAA ObsPack synthesis of well-calibrated greenhouse gas data
Uncertainty estimation	Model uncertainty estimation challenges present barriers to fusing datasets	• Work needed on how measurement uncertainty propagates into model estimates and their uncertainties • Coordination among sensor networks to create protocols for consistent uncertainty reporting • Potential for development of NIST education program on uncertainty quantification and reporting

4.2. Field Instrumentation

This session consisted of three presentations listed below with discussions after each presentation and at the end of the session.

- "Dual-Comb Spectroscopy for Greenhouse Gas Sensing," by Kevin Cossel, Fiber Sources and Applications Group, PML, NIST
- "NIST Testbeds for Environmental Research," by David Allen, Remote Sensing Group, PML, NIST
- "Calibration Methods for Solar-Induced Fluorescence Monitoring Systems," by Julia Marrs, Greenhouse Gas Measurement Group, Special Programs Office (SPO), NIST
- "Integrating Airborne with Proximal Remote Sensing," by John Gamon, Professor, School of Natural Resources, University of Nebraska – Lincoln

The discussion was guided by a series of questions reproduced below:

1. Are there artifacts affecting your measurements which are specific to sensors deployed outdoors, *e.g.* temperature or atmospheric pressure artifacts, UV degradation of plastics?
2. What are your needs for, and interests in, testbed sites for sensor intercomparison and validation?
3. Do networking, internet connectivity, or data storage concerns pose barriers to your work?
    a. Are these concerns related to reliably measuring intermittent signals (*e.g.* variable point pollution sources, wildlife movement)?
    b. Are these concerns related to network access or speeds in remote areas?
    c. Are these concerns related to wirelessly transferring large data sets?
4. Are there quantities of interest which can be measured in laboratory settings but not in field settings?
5. What are your needs for standardization among existing field sites, including across different instruments used to measure the same quantity?
    a. Do you face challenges during data processing with metadata availability or formatting?

A synthesis of workshop participants' responses to these questions is presented in Table 2, along with a summary of any resources or potential solutions mentioned during the discussion.

Table 2. Field Instrumentation Challenges.

Challenge	Examples	Resources and Potential Solutions

Limitations to existing sensors	• Issues with drift in ethane sensors
	• Challenges of multi-species greenhouse gas measurements:
	  ○ Crosstalk across species
	  ○ Anticorrelation of different species of interest
	• Infrastructure supporting field-deployed instruments:
	  ○ Electrical outages at field buildings can lead to increased humidity in sensor enclosure, water infiltration, sensor failure
	  ○ Internet connectivity is still a challenge in some remote areas
	• Below ground processes:
	  ○ Instrumentation at field sites can be difficult to access if components fail
	  ○ Lack of discrete reporting on both data availability and reliability
		• Instrument intercomparison efforts could help to alleviate some of these challenges when using instruments in the field, though they are labor intensive and funding-limited
		• Satellite internet is currently being used to connect to remote sites within some national networks
		• Metrics on mean time between sensor or component failure would be useful for avoiding extended instrument downtime

Maximizing utility of testbed sites	• Funding limitations prevent even established sites from operating indefinitely • Lack of incentives for external researchers to travel outside their region or familiar sites • Challenge of representativeness and breadth when choosing testbed sites	Construct incentives for participation: • Opportunity to contribute to new measurement methods, sensor development, etc. open only to participants gas data
Standardization across measurement sites	Model uncertainty estimation challenges present barriers to fusing datasets	Controlled experiments, in which elements of a model are individually varied, can help to attribute source(s) of differences across models

4.3. Data and measurement accessibility

This session consisted of three presentations listed below with discussions after each presentation and at the end of the session.

- "Multi-Scale Study of Land-Atmosphere Interactions: Measurement Needs," by Kenneth Davis, Professor, Institute of Energy and the Environment, Pennsylvania State University
- "Utilizing Lower-Cost Indoor Air Quality Sensors for Environmental Monitoring," by Tyler Boyle, Greenhouse Gas Measurement Group, SPO, NIST
- "The NIST-on-a-Chip Program: Intrinsically Accurate Measurements and Sensors," by Jay Hendricks, Fundamental Thermodynamics Group, PML, NIST

The discussion was guided by a series of questions reproduced below:

1. Do you face challenges specific to making measurements in remote areas?
    a. What, if any, are the barriers to combining such measurements with additional data sources, such as satellite imagery?
2. How can local and Indigenous knowledge on environmental processes of interest be incorporated into measurement systems?
3. Would your measurement challenges benefit from the use of fit-for-purpose (*e.g.* moderate accuracy, low-cost) sensors?
    a. What are the current barriers to combining such data with additional measurements, for example from high-cost, high-accuracy sensors?
4. Is the need for real-time data reporting and/or analysis (*i.e.* for rapid decision-making or in response to disasters) important for your measurements?
    a. Do you face barriers to your work related to data availability lags or difficulties with data access for all stakeholders?
    a. A synthesis of workshop participants' responses to these questions is presented in Table 3, along with a summary of any resources or potential solutions mentioned during the discussion.

Table 3. Data and Measurement Accessibility Challenges.

Challenge	Examples	Resources and Potential Solutions
Measurement representativeness	• Lack of rules on how much on-the-ground sampling is necessary for ground truthing data for large satellite pixels ○ This is dependent on spatial heterogeneity • Costs of high-precision sensors often limit monitoring network size and coverage • Even low-cost sensors are not evenly adopted by the public (*e.g*. Internet of Things (IoT) air-quality sensor locations closely resemble maps of wealth distribution)	• Consider using low-cost, moderate-accuracy sensors to capture spatial variability. May require tradeoffs in measurement accuracy • Consider network calibration approaches to remove bias/drift in networked sensors
Measurements in remote areas	• Power/internet connectivity challenges at remote sites • Even fiber internet connections need periodic repair • Difficulties of selecting methods for data communication infrastructure that are well suited to field settings	• SmartCities Connect offers help with low-cost power hookups to existing streetlights or other infrastructure and wireless internet access • NIST guidance on communication approaches and hardware reliability would be useful • Institute of Electrical and Electronics Engineers (IEEE) produces standards on interfacing sensors and wireless networks
Local and indigenous knowledge	• Concerns surrounding data sharing ○ For example, data on urban temperature or pollution rates could lower property value • Establishing long-term connections and providing valuable tools or knowledge to communities on whose land we work • Fatigue from local communities who are repeatedly asked for short-term input on new research projects	• Clear communication with communities is key. Some will want rapid insight into local hazards or phenomena, and others will feel the opposite • Local scientists and advisors should be authors on resulting publications, but scientific publications alone will not suffice as a valuable end result in most cases • Experience of archaeology research community may help here • Ensure sufficient long-term funding before starting a project to help avoid the frustration of projects ending before useful information is obtained

Data availability challenges	• Natural disaster monitoring and forecasting
	  ○ Monitoring networks receive frequent requests for data which typically have a lag period for QA/QC
	• Highly localized events, especially in urban areas
	  ○ Street and basement flooding are important for human safety and research on water fluxes, but are often only tracked by voluntary reporting (*e.g*. 311 calls)
		Private companies or state/local governmental agencies may already provide useful information on flooding and wildfire risks

4.4. Data and Measurement Timeseries

This session consisted of three presentations listed below with discussions after each presentation and at the end of the session.

- "Closing the Earth Observation Traceability Loop: From Remote Sensor Development to Analysis -Ready Data," by Christopher Crawford, Earth Resources Observation and Science Center, U.S. Geological Survey
- "Translating CO2 Measurement Uncertainty to Modeling," by Kimberly Mueller, Greenhouse Gas Measurement Group, SPO, NIST
- "Far-InfraRed Virtually Imaged Radiometry (FIRVIR) for Climate Metrology and Spectral Reference Data for GHGs," by Adam Fleisher, Optical Measurements Group, Materials Measurement Laboratory, NIST
- "Direct Measurement of Whole-Ecosystem Carbon Sequestration Through Eddy-Covariance Networks," by Trevor Keenan, Associate Professor, Department of Environmental Science, Policy, and Management, University of California Berkeley

The discussion was guided by a series of questions reproduced below:

1. What are the measurement uncertainty needs for long-term time series of your variables of interest?
    a. What is the current uncertainty threshold needed for your applications?
    b. As your analyses progress in the future, do you anticipate that acceptable uncertainty ranges will narrow?
    c. What practices are needed to maintain measurement consistency over long temporal scales?
2. What are your needs for uncertainty propagation (*i.e.* appropriately accounting for measurement uncertainty during later analysis and/or modeling work)?
3. How do we effectively weigh the costs and benefits of greater measurement accuracy (*e.g*. higher cost of sensors, more frequent recalibrations)?
4. What do you foresee as needs for continuity of data collection and analysis?
    a. What practices are needed for institutional knowledge transfer when researchers leave or retire?
    b. What are the environmental measurement community's needs for data archiving?
    c. What are the practical needs for keeping databases going and relevant / updated (High-Resolution Transmission Molecular Absorption Database (HITRAN) as example)?
5. Which online portals or other repositories do you go for long-term data (*e.g.* data.gov geospatial page, DOE data explorer, others))?

A synthesis of workshop participants' responses to these questions is presented in Table 4, along with a summary of any resources or potential solutions mentioned during the discussion.

Table 4. Data and Measurement Timeseries Challenges.

Challenge	Examples	Resources and Potential Solutions

Data continuity over long timescales	• Changes in PI can lead to legacy issues with data sharing policies
	• Data archiving needs
	  ○ Documentation requirements: level of detail needed for future researchers may be different on short- and long-term timescales
	  ○ Completeness of documentation is difficult to enforce
	• Obsolescence of data formats and coding languages present risks to data continuity
	• Data quality challenges
	  ○ Recalibration frequency: sensor drift can be corrected if checked frequently, but longer waits between revisits pose a challenge
	  ○ Intercomparability among sites
		• Contracts covering change of PI are needed
		  ○ Early career support is crucial to resolving these issues in the long term
		• Some data repositories (*e.g.* Landsat archive, FLUXNET data portal) have strict documentation requirements, which could serve as models
		• NIST and Physikalisch-Technische Bundesanstalt (PTB) are working on a standard format for some calibration report types
		• Cost-benefit analysis of more frequent recalibrations is typically necessary
		• This depends on sensor type, site remoteness, environmental variability, calibration materials costs, etc.

Uncertainty quantification	• Uncertainty propagation through models is challenging
	  ○ Input datasets have their own measurement error and uncertainty, in addition to model uncertainties
	• Uncertainty propagation during data fusion efforts
	  ○ Uncertainties from data products with different uncertainty magnitudes should be weighted proportionally when calculating the uncertainty of the merged product. No accepted method to do this
	• Need for clear communication of uncertainties in GHG assessments
	  ○ Important for assessments that will become part of carbon markets
	  ○ Actionable information (*e.g*. air quality, water quality, temperature disparity) for communities living in areas of study
		• Performing multiple model runs with different input data and model settings can help identify sources of uncertainty. It is difficult to get a whole community to do this consistently
		• European Association of National Metrology Institutes (EURAMET) may be working on this problem
		• Baltimore Social and Environmental Collective (BSEC) is concerned with informing community of their measurements, but have faced challenges with large uncertainties that make it difficult to give clear advice

Spatial representativeness	• Challenge of addressing spatial gaps ○ Often, a region is underrepresented because there is no pre-existing capacity to instrument new sites • Network design	Capacity-building efforts can address these challenges, although this is dependent on funding

5. Needs and Challenges

Following the above-described group discussions, a final summary session was held to discuss the overarching challenges, needs, and potential solutions in ecosystem measurements. Overarching challenges, described in section 5.1, included insufficient representativeness, measurement nonstationarity, full consideration of data continuity needs, and barriers to consistent and meaningful uncertainty quantification. Section 5.2 describes specific measurement needs identified by workshop participants as areas where NIST involvement in advancing the measurement technology could be of great use to the environmental science community.

5.1. Overarching Challenges

The representativeness of a network of sensors or field measurement plots indicates whether it under-samples any key regions or parameters of interest. A more representative network will have sufficient coverage, whereas a less representative one will contain gaps. In this case, workshop participants highlighted a lack of spatial representativeness of many ecological measurement networks, with gaps being particularly prevalent within the tropics. Some key ecological parameters, such as the allometric equations used to estimate forest carbon stocks from tree trunk diameter at breast height (DBH) measurements, were also noted to have shortcomings. Allometric equations are defined on a species-specific basis, and are often valid for only a certain range of tree height and diameter. While these equations are fit for purpose for many commercial forestry applications, many tropical forests, and even some temperate ones, contain species not covered by existing equations, or trees whose size far exceeds the equations' valid ranges. Similar concerns were raised regarding wood density conversion factors also used on forest carbon stock estimation. Finally, participants highlighted issues with the exclusion of some land cover types from carbon modeling and carbon budget activities. For example, the exclusion of landscape-scale anthropogenic changes, such as urbanization and forest fragmentation, would mean omitting the important effects of these processes on vegetation productivity.

Several discussions touched on the difficulties presented by nonstationarity, a term describing a continual change in the mean or variance of a quantity of interest over time. In environmental measurements, nonstationarity can result in significant difficulties in interpreting trends and attributing sources of measured changes when both a quantity of interest and its drivers are changing in magnitude and variance over time. Similar phenomena can also present as challenges for measurement infrastructure. Participants highlighted one example of an eddy-covariance flux tower built to hold sensors at a minimum distance above the top of a forest canopy. The longest-running eddy-covariance flux towers are now encountering issues of canopy height increase due to several decades of forest growth, necessitating infrastructure replacement and resulting in measurement gaps.

Workshop participants emphasized the importance of data continuity while identifying several common barriers. Long-term time series measurements often represent crucial records that underpin many projects or analyses. Nonetheless, there are often funding challenges to

maintaining these timeseries, simply due to the fact that new initiatives may seem more exciting and thus outcompete proposals to continue an existing project. This point led to a further discussion of the need for improved archiving of environmental data, as well as for clear identification of crucial datasets to be maintained in the long term. Participants shared concerns that any sufficiently long-running project will eventually encounter researchers who leave or retire from their institution, resulting in the loss of institutional knowledge that can affect the quality of data collected as the project continues. Finally, the need for best practices for maintaining calibrations along the life of a project was highlighted as a priority area of work. Guidance on how often instrumentation should be recalibrated in lab settings was requested, as was the development of field calibration techniques to reduce downtime and gaps in measurement timeseries.

A final theme covered throughout the workshop discussions was uncertainty estimation. Participants highlighted that there are currently issues with interoperability when examining reported uncertainties in environmental measurements; not everyone is calculating uncertainty the same way, or even reporting it at all. The discussions highlighted that this is driven by a lack of established methods for quantifying uncertainty in environmental measurement systems, and a lack of knowledge within the community even when methods exist.

5.2. Specific Needs

In addition to the overarching challenges summarized above, several specific data gaps and community needs were mentioned during the discussion sections.

Several participants emphasized the need for better belowground measurements, including soil characteristics such as soil moisture, soil matric potential (a metric of water availability to plants), and other soil physical properties. Root biomass was also highlighted as a parameter with high uncertainty.

During a discussion on flux tower networks, several gas fluxes were highlighted as being of interest for the future. These included methane (CH_4), which is becoming more commonly measured using eddy flux covariance techniques, but for which measurement methods are not as developed as for CO_2. Additional gas species of interest included nitrous oxide (N_2O), carbon monoxide (CO), ethane (C_2H_6), and isotopic measurements of ^{14}C. Generally, participants emphasized that measurements of pollutants and gas species relevant to air quality, which aid in understanding of anthropogenic contributions to atmospheric composition, are of great interest. A further point of discussion centered around the need for improved surface energy balance closure. Specifically, it was noted that improved vertical wind measurements are needed to capture the effects of large atmospheric eddies, which are not currently well characterized.

Finally, participants highlighted unexpected challenges while using rain gauges to monitor precipitation. In part, these challenges arise from mechanical shortcomings of current rain gauges, including temperature-dependent problems with the springs that regulate the self-emptying functions of some tipping rainwater buckets. Some participants also noted that the unpredictability of rainfall events in their study areas has led to unanticipated overflow from

rainwater buckets and flasks, and subsequent underestimation of precipitation. Even if these mechanical issues could be corrected, this discussion also emphasized that rainfall is highly heterogeneous on a regional scale, meaning that point measurements from individual rain gauges may not capture the magnitude of rainfall events. This topic was raised as part of the overall discussion of measurement representativeness, and serves as an illustrative example of this challenge. Often, rain gauges are deployed in convenient locations or at the site of other instrumentation. A sparse network of sensors or one where sensor locations are not optimized to capture landscape-scale variability can lead to increased uncertainty when interpolating point measurements across a region or large domain. While no comprehensive solutions to this challenge currently exist, some emerging technologies could help to improve precipitation monitoring networks. For example, cosmic-ray neutron sensors (CRNS), which can be used to monitor soil water content over footprints spanning multiple square kilometers, could also be employed in future precipitation monitoring networks [8]. As with any emerging technology, calibration methodologies would need to be developed and validated before incorporating CRNS into large-scale monitoring efforts, but they serve as an illustrative example of the potential for new technologies to address environmental measurement needs.

6. Potential Solutions

6.1. Intercomparisons and Field-Deployable Standards

During the final discussion, resources and potential solutions to some of the above-listed challenges were identified.

NIST participants at the workshop suggested that instrument intercomparisons and field-deployable standards could help to address some environmental measurement challenges. Intercomparisons among NMIs are crucial for establishing reliability and traceability of measurements, and intercomparisons from testbed field sites could be used for a similar purpose for environmental measurements. It was noted in the discussion, however, that there are likely diminishing returns for establishing more and more testbed sites, due to the difficulty of convening sufficiently large groups at a multitude of different locations. Thus, this work should prioritize the use of existing testbeds. Testbed field sites for shared use can support intercomparisons and help to address issues of representativeness. In keeping with the point above, effort should be focused on finding an optimal number and distribution of such testbed sites before new sites are established.

Increased development and availability of field-deployable reference standards would also support testbed sites and intercomparison activities. These could include reference lamps, reference sensors, reference materials, and reference systems. Some existing reference standards might serve as useful models when developing field-deployable standards for new applications. As an example relevant to atmospheric measurements, NIST maintains traceability of reference gases via the distribution of high-purity, stable Standard Reference Material (SRM) calibration gases, and by certifying NIST Traceable Reference Material (NTRM) gases prepared by specialty gas companies. Additionally, NOAA currently maintains reference gases for a variety of environmental applications, and has published public, standardized procedures for their use to create secondary standards for field use. This work could serve as a blueprint for distributing other reference materials. AmeriFlux maintains flux tower systems that can travel for *in situ* intercomparisons. The development of additional portable reference systems would help to support intercomparison activities and avoid data gaps.

6.2. Fit-for-Purpose Sensors

In the interest of expanding the spatial coverage and representativeness of environmental sensor networks, the inclusion of lower-cost, fit-for-purpose sensors would likely be advantageous. In addition to enabling a greater density of sensor sites, fit-for-purpose sensors also offer potential for ameliorating field calibration challenges. For example, some sensor networks perform network calibrations or intercomparisons of all in-network sensors to reduce effects of individual sensor bias and/or drift. Participants highlighted that guidance on sensor deployment, including data transmission methods and data collection infrastructure, is still

needed in many applications. Additionally, guidance on fusing high-accuracy data with a network of fit-for-purpose sensors is also still needed. This is particularly true in cases where the same quantity is being measured by sensors based on different physical principles.

6.3. Community Standards Development

Discussions highlighted the potential benefits of standardization efforts concerning tiered field site or laboratory structures, including requirements for data quality, expectations for regular sensor or system intercomparisons, and the development of documentary standards through national standards bodies. Participants also discussed the potential for certification of commercial data networks, particularly those whose data products support economic activities. Organizations such as the National Conference of Standards Laboratories International (NCSLI) could also potentially assist with this work. The importance of linking to existing frameworks was emphasized, in the interest of incentivizing community participation and avoiding redundancy. A sample, non-exhaustive list of existing standards and guidelines that could be considered is shown in Table 5.

Table 5. Example Standards, Guidelines, and Best Practices.

Resource	Location
International Organization for Standardization (ISO) 17025 General requirements for the competence of testing and calibration laboratories	https://www.iso.org/standard/66912.html
ISO 17043 Conformity assessment — General requirements for proficiency testing	https://www.iso.org/standard/80864.html
ISO 9001 Quality management systems — Requirements	https://www.iso.org/standard/62085.html
IG3IS Urban Greenhouse Gas Emission Observation and Monitoring Best Research Practices	https://community.wmo.int/en/meetings/revision-ig3is-urban-good-practices

6.4. Educational Resources on Uncertainty Quantification

Workshop participants requested more educational resources on uncertainty quantification in support of clear and consistent uncertainty reporting across the field. Transparency in reporting uncertainty benefits the entire research community. The final discussion included requests for NIST to develop guides and/or courses aimed at uncertainty quantification for environmental measurements. Within this suggestion, there were several specific requests for what this guidance could contain.

Guidance on best practices for site configuration, including coverage of how to avoid biases due to data collection location, was requested. Participants suggested that a system of periodic audits of field sites to evaluate sensor deployment or experimental design could support the widespread and continued use of such guidance. Specific requests for educational resources also included protocols for propagating uncertainty associated with individual sensors, concise

graphical or video documentation to support institutional knowledge transfer over the long term, and workshops to demonstrate uncertainty estimation practices to attendees.

6.5. Environmental Data Resources

The discussion highlighted the importance of identifying critical resources to be maintained and archived. Workshop participants discussed organizations, data portals, and online repositories as important data sources. Those that were mentioned by name during the discussion are provided below (Table 6); this list is non-exhaustive, and includes just a sample of the many data sources that are used for environmental measurement applications.

Table 6. Environmental Data Sources.

Resource	Link(s)
NIST Science Data Portal	https://data.nist.gov
NEON Data Portal	https://data.neonscience.org/
Department of Energy	https://ess.science.energy.gov/
Data.gov	https://data.gov/
National Aeronautics and Space Administration Distributed Active Archive Centers (NASA DAACs)	https://www.earthdata.nasa.gov/centers
AmeriFlux	https://ameriflux.lbl.gov/data/badm/ https://ameriflux.lbl.gov/data/flux-data-products/
NOAA ObsPacks	https://gml.noaa.gov/ccgg/obspack/

Participants provided several recommendations for data collection and accessibility. They highlighted that the Findability, Accessibility, Interoperability, and Reusability (FAIR) principles [9] offer a useful framework for long-term data use and stewardship. Open data policies and easy accessibility (especially of data processed to a readily useable level) act as an incentive to continue programs, increase usership, and maintain data processing consistency. Participants highlighted that consistent handling of data gaps and anomalies are key to data continuity, and that this should be considered at the beginning of any projects projected to have a long lifespan. Finally, it was noted that cloud computing platforms may be able to help address challenges of storage and processing large data volumes, although participants also cautioned that commercial archives could pose a risk for loss of access to critical data.

Workshop participants requested additional guidance on denoting data quality and reliability, highlighting that this guidance would be broadly useful to the environmental measurement community. It was noted that peer-reviewed journals increasingly require data archiving, but may not be equipped to perform a data quality assurance role. Some grant funding processes require statements on uncertainty assessment in submitted proposals, and it was suggested that the development of incentives for better uncertainty quantification could fit into this process. Finally, it was noted that processes to certify data not obtained from official sources (*e.g.* redistribution of satellite data) are needed throughout the ecological measurement community.

7. Conclusions and Next Steps

The final workshop session featured a discussion among organizers and participants on how to sustain the activities started at the workshop, as well as on listing tangible actions to prioritize going forward.

Participants suggested that a follow-up workshop or conference session, perhaps at a future American Geophysical Union (AGU) annual meeting, would be a useful way to revisit the prior discussions and potentially involve new participants. Until that time, a number of suggestions on available training and resources pertaining to the topics covered in this workshop were collected (Table 7); this list is non-exhaustive and includes those resources that were mentioned by name during the final discussion.

Table 7. Training Opportunities and Resources.

Resource	Topic(s)	Link(s)
NCSLI	Information on quality systems and professional network of metrologists	https://ncsli.org/
Measurement Science Conferences (MSC)	Annual conference for professionals in the measurement technology community	
NIST Office of Weights and Measures	Professional development and skill building for metrologists	https://www.nist.gov/pml/owm/owm-training-and-events
SPIE	Meetings and courses, with a focus on sensor calibration, particularly for optical sensors	https://spie.org/
AmeriFlux	Annual meetings on water and C fluxes, plus specialized courses	https://www.ametsoc.org/index.cfm/ams/meetings-events/
International Bureau of Weights and Measures (BIPM) Sectorial Task Group on Climate Change and Environment	Task group on metrology for climate change and environment; recent meeting report	https://bipm-cenv2024.org https://www.bipm.org/en/doi/10.59161/Rapport202501
Methane Emissions Technology Evaluation Center (METEC)	Test facility for methane emission quantification	https://metec.colostate.edu/
NEON	Workshops and self-guided trainings on NEON datasets and ecological processes	https://www.neonscience.org/resources/learning-hub/workshops-courses https://www.neonscience.org/resources/learning-hub

Workshop attendees identified the need to identify and recruit additional participants in this work. Suggestions for how to achieve this goal included involving the international community, encouraging NIST staff attendance at Earth and environmental science conferences, and the creation of demonstrations or lessons on uncertainty quantification for the environmental science community. Additionally, the FAIR principles were proposed as guidance for producing and publishing data that could be used in the environmental measurement community.

Attendees felt that NIST could facilitate such improved measurements through the organization of sensor intercomparisons, data processing method intercomparisons, the development of field-deployable standards, evaluation of existing environmental testbeds, and by providing guidance on uncertainty quantification for the environmental measurement community. Reliable measurements are needed to guide responses to changes and trends in environmental conditions that could affect crucial economic interests such as efficient food production, natural resource extraction, recreation, and habitation. Environmental measurements touch on topics of interest across numerous ecological, biogeochemical, and meteorological fields of study, and insights from this workshop suggest that there are promising opportunities for productive collaboration between NIST metrologists and the environmental measurement community.

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Appendix A. Workshop Agenda

Day 1: Tuesday, September 10, 2024

9:00 – 9:20	Arrival and networking
9:20 – 9:40	"Workshop on Environmental Measurements" - Overview Talk, Gerald Fraser (15 min talk, 5 min Q&A)
9:40 – 10:25	"Long-Term Environment Measurement (Through a Carbon Lens)" - Lucy Hutyra, Boston University (30 min talk, 15 min Q&A)
10:25 – 10:40	Coffee Break
10:40 – 11:10	"Radiometry for Climate Metrology" - Michelle Stephens (20 min talk, 10 min Q&A)
11:10 – 11:40	"The National Ecological Observatory Network (NEON) Contributions to Environmental Measurement Stewardship" - Janae Csavina (20 min talk, 10 min Q&A)
11:40 – 12:40	Lunch
12:40 – 1:40	Discussion: biosphere monitoring • Data fusion challenges (combining complementary data streams) • Challenges with measurement types – networks too sparse? Not sufficiently representative? • Barriers to up- and downscaling • Different requirements for *in situ* vs. remote measurements
1:40 – 2:10	"Dual-Comb Spectroscopy for Greenhouse Gas Sensing" - Kevin Cossel (20 min talk, 10 min Q&A)
2:10 – 2:20	"NIST Testbeds for Environmental Research" - David Allen (10 min talk)
2:20 – 2:30	"Calibration Methods for Solar-Induced Fluorescence Monitoring Systems" - Julia Marrs (10 min talk)
2:30 – 2:40	10 min combined Q&A for D. Allen and J. Marrs
2:40 – 3:10	"Integrating Airborne with Proximal Remote Sensing" - John Gamon (20 min talk, 10 min Q&A)
3:10 - 3:25	Coffee break
3:25 – 4:25	Discussion: field instrumentation challenges • Artifacts specific to outdoor measurements (*e.g.* temperature and atmospheric pressure, UV degradation of plastics) • Networking, internet connectivity, and data storage challenges • Metadata collection and standardization across sites and instrument types
4:25 – 5:00	Group discussion to summarize main points of the day

Day 2: Wednesday, September 11, 2024

9:00 – 9:15	Arrival and networking
9:15 – 9:45	"Multi-Scale Study of Land-Atmosphere Interactions: Measurement Needs" - Ken Davis (20 min talk, 10 min Q&A)
9:45 – 10:15	"Utilizing Lower-Cost Indoor Air Quality Sensors for Environmental Monitoring" - Tyler Boyle (20 min talk, 10 min Q&A)
10:15 – 10:30	Coffee Break
10:30 – 11:00	"The NIST-on-a-Chip Program: Intrinsically Accurate Measurements and Sensors" - Jay Hendricks (20 min talk, 10 min Q&A)
11:00 – 12:00	Discussion: accessibility • Making measurements in remote areas • Incorporating local and Indigenous knowledge • Resolving challenges of high-cost, high-accuracy sensors • Accessibility of data collection and data analysis/use
12:00 – 1:00	Lunch
1:00 - 1:30	"Closing the Earth Observation Traceability Loop: From Remote Sensor Development to Analysis Ready Data" - Christopher Crawford (20 min talk, 10 min Q&A)
1:30 – 2:00	"Translating CO_2 Measurement Uncertainty to Modeling" - Kimberly Mueller (20 min talk, 10 min Q&A)
2:00 – 2:30	"FIRVIR for Climate Metrology and Spectral Reference Data for GHGs" - Adam Fleisher (20 min talk, 10 min Q&A)
2:30 – 3:15	"Direct Measurement of Whole-Ecosystem Carbon Sequestration Through Eddy-Covariance Networks" - Trevor Keenan (30 min talk, 15 min Q&A)
3:15 - 3:30	Coffee Break
3:30 – 4:30	Discussion: Timeseries • Uncertainty needs for long-term time series • Consistency over temporal scales • Measurement uncertainty thresholds • Uncertainty propagation
4:30 – 5:00	Group discussion to summarize main points of the day

Day 3: Thursday, September 12, 2024

9:00 – 9:15	Arrival and networking
9:15 – 11:00	Discussion on connections among sessions, shared and related gaps in measurement capabilities, priority setting
11:00 – 11:15	Coffee Break
11:15 – 12:00	Final wrap-up, summary, and identification of next steps

Appendix B. List of Symbols, Abbreviations, and Acronyms

AGU
American Geophysical Union

BIPM
Bureau International des Poids et Measures (International Bureau for Weights and Measures)

C_2H_6
Ethane

CH_4
Methane

CO
Carbon monoxide

CO_2
Carbon dioxide

DAAC
Data Analysis and Assessment Center

DBH
Diameter at breast height; the standard measurement for the size of a tree trunk

DOE
Department of Energy

EURAMET
European Association of National Metrology Institutes

FAIR
Findability, Accessibility, Interoperability, and Reuse

FIRVIR
Far-InfraRed Virtually Imaged Radiometry

FRN
Federal Register Notice

GDP
Gross domestic product

GHG
Greenhouse gas

HITRAN
High-Resolution Transmission Molecular Absorption Database

IEEE
Institute of Electrical and Electronics Engineers

IG3IS
Integrated Global Greennouse Gas Information System

IoT
Internet of Things

ISO
International Organization for Standardization

MSC
Measurement Science Conferences

N_2O
Nitrous oxide

NASA
National Aeronautics and Space Administration

NCSLI
Formerly the National Conference of Standards Laboratories; now called NCSL International

NEON
National Ecological Observatory Network

NIST
National Institute of Standards and Technology

NMI
National Metrology Institute

NOAA
National Oceanic and Atmospheric Administration

NVLAP
National Voluntary Laboratory Accreditation Program

ObsPack
Observation Package data product format distributed by NOAA

PML
NIST Physical Measurement Laboratory

PTB
Physikalisch-Technische Bundesanstalt

SI
Système International d'Unités (International System of Units)

SPIE
No longer an abbreviation; formerly Society of Photographic Instrumentation Engineers and Society of Photo-Optical Instrumentation Engineers

SPO
NIST Special Programs Office

UV
Ultraviolet