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NORTH AMERICAN CARBON PROGRAM

Report for the

Carbon Dioxide Removal (CDR): Towards a Unified Monitoring, Measuring, Reporting and Verification (MMRV) Framework Workshop

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Pictured: In-person attendees for the workshop (left to right): Ning Zeng (UMD), Yiqi Luo (Cornell University), Yishen Lee (U.S. GCRP), Maoya Bassiouni (UC Berkeley), Aspen Reese (U.S. EPA, now at NIH), Gyami Shrestha (Lynker Corporation and formerly U.S. Carbon Cycle Science Program), Susan Crow (University of Hawaii), Libby Larson (NASA GSFC/SSAI, NACP Coordinator), Aditya Anil Bhandari (YouWeb), Patrick Duke (University of Victoria), Frenchy Morisette (USDA Forest Service)

Table of Contents

Workshop Background and Goals

Carbon Dioxide Removal (CDR) is any process, practice or technology removing CO2 from the atmosphere by enhancing existing natural processes or using chemical processes to capture CO2 directly from the ambient air to store it elsewhere (IPCC 2018). Widespread CDR is envisioned to remediate anthropogenic atmosphere CO2 that inhibits achieving Paris Agreement temperature targets, such as legacy (leftover) CO2 or the hardest-to-abate CO2 emitted even after ambitious mitigation efforts. Government and private-sector interest in mitigating climate change via CDR is growing quickly, but no unified monitoring, measurement, reporting, and verification (MMRV) framework exists yet to gauge the success of any CDR method. The U.S. Carbon Cycle Science Program (USCCSP) and its North American Carbon Program (NACP), as connectors and conveners of the U.S. carbon cycle expert community, hosted this workshop to help develop the foundation for a national unified CDR MMRV framework. Sponsored by the US Department of Energy and supported by multiple partners from the government and private sectors, participants included researchers, funders, and leaders from the public and private sectors. The workshop focused on what is needed right now to improve MMRV. The workshop connected people with a variety of different perspectives on CDR or CDR-relevant topics, and discussed what practices or information from different scientific domains can be applied to MMRV. Six groups were formed for breakout discussion in each key CDR sectors: Atmosphere and Direct Air Capture (DAC); Subsurface and Mineralization; Oceans and Coastal Regions; Croplands, Grasslands, and Soils; Forests; Governance, Policy, Society, and Economics. The workshop summarized opportunities, resources, and obstacles affecting the development of a unified national MMRV framework. The planned workshop outcomes include a more connected, coherent U.S. community that is focused on CDR MMRV across Earth system sectors, and a clearer path towards a U.S. MMRV framework that complements and builds upon present public and private investments, expertise, and initiatives.

Workshop Goals:

- Identify what information, assets, capacity, or enabling conditions are needed right now to advance CDR MMRV.
- Identify what knowledge exists from studies on both CDR and other topics, particularly carbon cycle science, that can be applied to advance CDR MMRV.

Workshop outputs:

- New connections among people from different organizations, specialties, locations, and perspectives who are working on CDR or CDR-relevant topics.

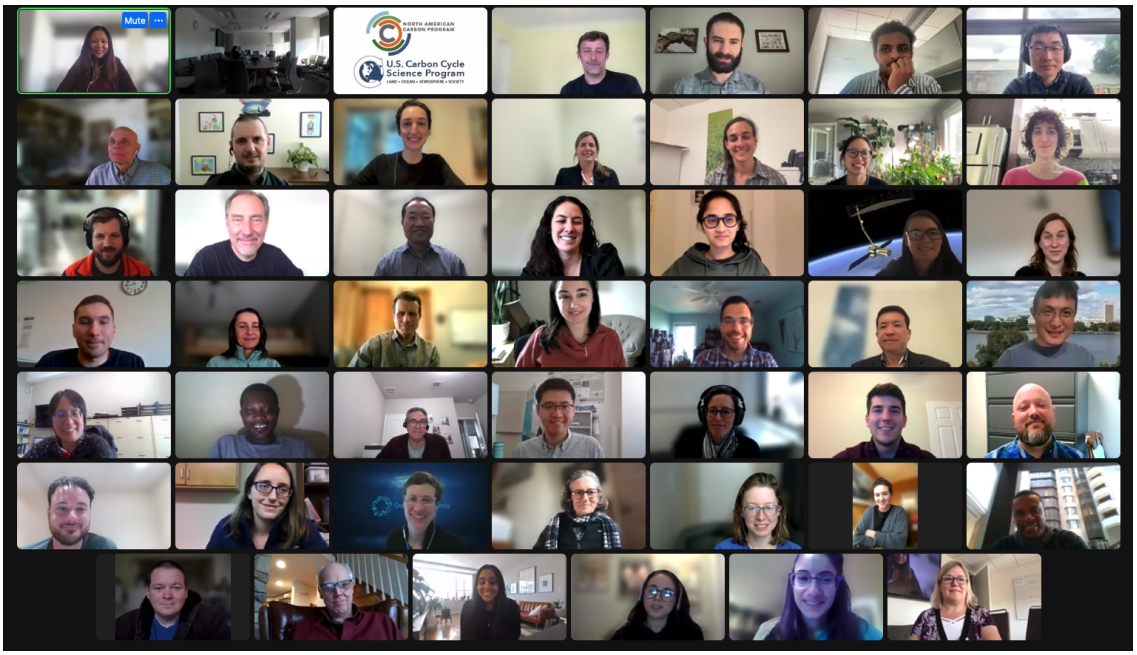
- Plan to create written product(s) that review(s) the opportunities, resources, and obstacles that participants identify as affecting the development of a unified national MMRV framework.
- Each attendee will plan one or more action items for themselves to support and extend their participation in this community.

Workshop outcome:

- A diverse, growing US community of practice focused on advancing a national MMRV framework relevant for public and private land-, atmosphere-, and ocean-based CDR activities.

The February 2023 CDR workshop was intended to be an active, discussion-based activity, requiring that attendees share a common understanding of the basics of CDR across multiple contexts. Therefore, the USCCSP and NACP developed a CDR Academy in the Fall of 2022. The CDR Academy & CDR 101 materials were presented to all the CDR MMRV workshop participants as background preparatory materials. The introductory materials on the basics of CDR in different Earth systems, include: (i) curated list of introductory resources (ii) a series of 1-hour webinars on CDR in different ecosystems/contexts, such as oceans and coasts, geological reservoirs, natural and working lands, and the atmosphere; (iii) a panel discussion with webinar presenters discussing cross-cutting themes, research needs, and potential opportunities for collaboration.

The workshop spanned 3 afternoons and featured a combination of discussions in plenary and more focused topical breakout sessions for small-group interactions. In this workshop report, we present brief synopses of both the plenary and breakout sessions. Individual panels and plenary discussion sessions are described. Readers are encouraged to view the workshop website for the detailed agenda and access to videos of all sessions and breakout group discussions.



Pictured: Subset of the virtual participants in the workshop.

Introduction of the Workshop

The workshop began with a brief introduction of the two organizations responsible for overseeing the workshop. The US Carbon Cycle Science Program, associated with the US Global Change Research Program, works closely with the scientific community and organizes meetings. Two programs, the North American Carbon Program and the Ocean Carbon and Biogeochemistry Program (OCB), operate under the Carbon Cycle Science Program's umbrella. NACP Coordinator Dr. Libby Larson mentioned that OCB had recently hosted a workshop on marine CDR and hoped for synergistic activities to follow. She also referred participants to three significant documents, the 2011 Carbon Cycle Science Plan, Second State of the Carbon Cycle Report (2018), and the 2022 NACP Science Implementation Plan. These foundational documents are representative of the U.S. carbon cycle science community's overall history, knowledge, and future research goals, all of which inform the approach and perspectives of the CDR Workshop.

Dr. Sarah Cooley, the director of Climate Science at the Ocean Conservancy and the meeting chair, introduced herself and mentioned the workshop's sponsorship by the Department of Energy's Office of Fossil Energy and Carbon Management. She referred to previous CDR convenings and workshops and explained that the current workshop aimed to build a diverse and growing US community of practice focused on developing a national MMRV (Measure, Monitor, Report, and Verify) framework for carbon dioxide removal (CDR) activities.

Dr. Cooley emphasized the goal of identifying the necessary information, assets, capacity, and enabling conditions for advancing CDR, highlighting the importance of leveraging existing knowledge from studies on CDR and other carbon cycle science topics. Dr. Cooley expressed hope for creating new connections among participants from different organizations, specialties, locations, and perspectives. Dr. Cooley presented the workshop's aim to produce a report or other products that would review the opportunities, resources, and obstacles affecting the development of a unified national MMRV framework.

Before the first plenary session, there was a brief breakout session for participants to meet and learn about each other. This breakout session, along with the other small group discussions in the workshop, was crucial for connecting with others in this virtual setting. Many participants expressed interest in advancing their knowledge and understanding and were curious about CDR systems outside their usual scope of work. They noted that there are complex questions regarding interoperability mapping and unified frameworks for CDR. Participants were located across the lower 48 states, with some also representing Hawaii and other parts of the world. The organizers expressed gratitude for everyone's presence and encouraged continued virtual interactions during the workshop and beyond to foster community-building.

Panel 1: Current State of CDR

The first panel discussion provided an overview of the current state of CDR and was led by Dr. Pam Chu (NIST). Panelists included Dr. Kevin Kroeger (USGS), Dr. Kim Novick (Indiana University), Dr. David Ho (University of Hawaii), and Dr. Tony Feric (DOE FECM). Kevin began by discussing his participation in CDR task forces and his research on blue carbon and enhanced weathering. Dr. Novick gave her perspective on terrestrial ecosystem carbon cycling and the need for science-based nature-based climate solutions. Dr. Ho described the current understanding of CO2 uptake by the ocean and provided scientific advice on ocean CDR methods. Dr. Feric focused on direct air capture and enhanced weathering, as well as providing input on various CDR activities.

The panel opened with a brief discussion of some of the key issues facing CDR efforts in different sectors. Dr. Novick outlined criteria for successful nature-based climate solutions, referring to a recent white paper. The strategies employed should: 1) be enhancements in carbon uptake or reductions in emissions that are additional to the baseline scenario, 2) lead to net cooling, 3) have durability (though the definition of this is debatable), and 4) account for leakage. Dr. Kroeger noted that durability poses a challenge in projecting long-term carbon fate, particularly for new technologies, while geological storage provided some confidence in long-term durability. Dr. Novick expanded on this to describe two categories of risk to durability:

physical (wildfires, droughts, insect outbreaks) and social (landowners reversing decisions). Dr. Ho described CDR approaches in oceans, which consist of two steps: reducing surface pCO2 in the water via some means (e.g. fertilization), and then allowing for equilibration of the ocean with the atmosphere, which is not 100% equal to the pCO2 reduction. Quantifying both of these steps requires rigorous MMRV. He also noted that the ocean is not subject to the same threats to durability as land-based approaches.

The panel then addressed the question of additionality, which relies on evaluating dynamic baselines and counterfactuals (what would have occurred if no action had been taken). Dr. Novick noted that for many land-based market systems, the programs do not reserve areas to serve as controls against which to measure their CDR efforts. One possible way to address this involves pairing project areas with similar areas in the landscape nearby. For oceans, there is still much to be learned about basic carbon cycling, so establishing baselines is especially difficult. Dr. Ho noted that the data and models used by the Global Carbon Project to estimate ocean CO2 uptake currently disagree by approximately 1 Pg/year, which is much more than any of the proposed marine CDR projects propose to accomplish. More observations and improvements to models are needed to better constrain our understanding of the ocean carbon cycle. The uncertainty of natural ocean dynamics therefore makes it difficult to verify the effects of any perturbations for CDR. Dr. Feric noted that there are some methods for evaluating additionality in engineered systems. Metrics include: looking at the internal rate of return with and without credit generation; market penetration of the technology; and differences between project and local activities within the region.

What level of abstraction is acceptable? How do we not let the perfect be the enemy of the good? Dr. Novick noted that part of the difficulty currently is that our understanding of the carbon cycle remains data-limited, and called for investments in measurement and monitoring networks, both to monitor CDR efforts, but also to help evaluate which locations and methods are most likely to succeed. Dr. Feric agreed and gave an example for enhanced weathering CDR activities. He noted that there are three main approaches to quantify carbon dioxide removal: measuring gas fluxes at the soil-atmosphere interface, analyzing mineral content in soils through soil sample cores, and conducting water analysis for bicarbonates. However, there is still uncertainty associated with these quantification tools. Long-term field studies, as well as laboratory and mesocosm experiments are needed, and it will be important to couple this experimental work with life cycle analysis (LCA) and techno-economic analysis (TEA) to maximize efficiency of CDR and reduce costs in the long term. Dr. Ho noted that ocean MMRV will always need to rely on calibrated models due to the time and space scales involved – it would be cost-prohibitive and logistically impossible to deploy sensors everywhere. He said it is important to monitor initial perturbation monitoring, but it is unlikely to be financially possible to do so for all marine CDR activities (e.g., ship time for a 20-day monitoring cruise is easily $1

million), so the community will ultimately have to rely on models. Dr. Kroeger brought up data and modeling considerations for coastal wetlands noting that land cover maps do not capture management condition and potential vulnerability of the landscapes. Dr. Novick noted also that in terrestrial systems, the focus is often on measuring tree carbon change and soil carbon change, which may overlook other important carbon sinks, the influence of greenhouse gasses like nitrous oxide and methane, and possible changes to albedo. She referred attendees again to the white paper, which calls for developing gold standard datasets by measuring everything at paired sites and making the data open and accessible to evaluate emerging approaches for MMRV and mitigation. Key knowledge gaps include methods to measure net carbon uptake from space, and national soil carbon monitoring system for consistent, representative measurements across time and space.

The panel acknowledged the challenges in governance and coordination for developing such datasets and emphasized the need for economically scalable approaches. The discussion touched upon the need for methodologies to credit nature-based climate solutions and the challenge of unifying consistent crediting across different technologies and systems. The durability, uncertainty, and value of carbon storage and the consideration of discount rates were mentioned. The speakers expressed the need for knowledge-specific expertise in ocean MMRV and cautioned against profit-oriented verification. They discussed the role of governments and the challenges associated with potentially being both buyers and verifiers, creating a conflict.

Plenary Discussion 1: Breakout session reports on CDR needs

The reports from the first breakout group discussion dove into the current state and needs of CDR in six key sectors: Atmosphere and direct air capture (DAC); Subsurface and Mineralization; Oceans and Coastal Regions; Croplands, Grasslands, and Soils; Forests; Governance, Policy, Society, and Economics. Questions guiding each discussion included:

- What is the “state of play” regarding CDR in this sector (e.g., maturity, obstacles, enabling conditions?)
- What CDR-related uncertainties are greatest in this sector and might influence MMRV? (e.g., uncertainty in measurements, quantification, biological systems, authority, timescales)
- What needs to be known about CDR for this sector to begin moving towards MMRV?
- What advantages does this sector have? Can these address challenges faced by other sectors?
- Who’s involved? How does that influence what’s happening now?

- What kinds of community products could help steer research progress?

Dr. Gyami Shrestha, from Lynker Corporation, and formerly US Carbon Cycle Science Program Office Director, moderated the breakout reports and asked each of the six groups, representing the six key CDR sectors, to provide a summary.

The *Atmosphere and DAC* breakout group highlighted scalability and efficient capture systems as major challenges in DAC. They emphasized the need for engineering advancements to reduce operational and capital costs. They also noted that DAC offers better measurement and reporting capabilities compared to nature-based solutions. However, the group identified gaps in the market, particularly the absence of guidelines for life cycle assessment (LCA) and deployment decisions. They suggested that government organizations, such as the Department of Energy, could develop guidelines for deploying DAC units and conducting life cycle analysis.

The *Subsurface and Mineralization* group discussed topics such as geologic CO2 storage, mineralization in different regions (e.g., exposed mine tailings or reactive rocks, introduction of olivine in wetlands), enhanced biomass burial, and utilizing ocean basalt for injection. The group acknowledged the advanced state of CO2 injection in subsurface reservoirs but highlighted the lack of guidelines for location selection. They emphasized the importance of understanding basic chemistry, establishing verification methods, and monitoring systems to address leakage concerns. The group concluded that more research is needed in these areas.

The *Oceans and Coastal Area*s breakout group mentioned that the recent Ocean MMRV workshop would provide valuable insights into the current state of play. They noted that many CDR techniques in this sector have been tested on a lab scale but require large-scale deployments for real-world efficacy. There is a policy gap related to implementation, and impact assessments (both ecological and social/cultural), improved modeling, data standards, and social acceptability were identified as important considerations. The group highlighted that the ocean has the advantage of huge capacity for storage, even from other sectors, and potentially very long durability. There is a need for greater involvement from the Federal Government, as most of the work to date has been done by the private sector. Since projects may occur in international waters, intergovernmental cooperation is crucial.

The *Croplands, Grasslands, and Soils* group discussed various technologies and practices for carbon sequestration, such as regenerative farming, cover cropping, grassland restoration, enhanced weather, and biochar. The group acknowledged the potential of these practices in mitigating climate change but raised concerns about monitoring soil carbon and understanding deeper soil carbon. They mentioned the challenges of upscaling small demonstrations to commercial-scale projects. Beyond data needs, they highlighted the need to align incentives,

provide better outreach and education to farmers, and address the time-scale and cost issues associated with implementing regenerative agriculture.

The *Forests* group reported that their conversations were informed by the diversity of their participants from both the private and public sector, spanning across career stages and from all 3 North American countries. While CDR in the forest sector is perhaps the most mature, there are still some important gaps: the work is still data-constrained and would benefit from greater coordination, consistency, and communication. It is important to consider how forest CDR projects are with other sectors, across system boundaries. For consistency, there are multiple registries that may not always be comparable, thus standards for MMRV are needed. For communication, developers, scientists, users and regulators need to have more conversations about the current state, potential capacities, and reasonable expectations for implementation. The group also discussed leakage and durability concerns, which are likely to become worse over the coming decades, as forests are particularly susceptible to degradation and decline due to climate change.

The *Governance, Policy, Society, and Economics* group focused on the “who”, “what”, and “how” of CDR activities. For the “who”, the group called for improved coordination across different levels of government to create standardized, universal protocols and methodology, and suggested dedicated governance roles for each CDR sector. For the “what,” the group highlighted the importance of MMRV for establishing trust, transparency, efficacy, and equity for CDR implementation.They identified 4 elements to support these outcomes: establishing independent/third party oversight and accounting; creating shared benchmarks, traveling standards, and interoperability mapping across different sectors; enhancing the feedback between research and CDR operations; and leveraging tax incentives and other financial tools to achieve these goals. For the “how”, the group focused on the need to resolve scientific uncertainties in order to establish MMRV protocols, suggesting that existing observations and data can be used more completely. One participant, Dr. Caroline Normile, reported that concerns about data privacy may be barriers to participation by various stakeholders and should be considered in policy applications.

Panel 2: Focus on MMRV

The second day of the workshop began with three presentations describing activities and perspectives on MMRV, recognizing its varying stages of advancement across different sectors. This session was moderated by Dr. Pam Chu (NIST).

Presentation 1: Federal Approaches to GHG Measurement and Monitoring

Speakers Dr. Phil Duffy and Dr. James Whetstone first presented on Federal Approaches to GHG Measurement and Monitoring. Dr. Duffy served as the climate science advisor at the White House Office of Science and Technology Policy (OSTP), while Dr. Whetstone leads the NIST-wide greenhouse gas measurements program and participated in the greenhouse gas monitoring and measurement interagency working group. Due to illness, Dr. Duffy couldn't attend, so Dr. Whetstone began with Dr. Duffy's presentation titled “Toward an Integrated U.S. Greenhouse Gas Measurement & Monitoring Information System.” These slides outlined the Administration's planned actions to achieve aggressive reduction goals by tracking progress, assessing mitigation policies, fostering innovation, and supporting the use of advanced greenhouse gas measurement and monitoring technologies. The Office of Management and Budget (OMB), along with the White House’s OSTP and Climate Policy Office convened an interagency working group consisting of representatives from 10 U.S. Federal agencies. Within this group, two technical sub-groups were formed: one to assess agricultural and forestry needs and approaches, and the other to plan the development of an integrated U.S. monitoring and information system. Dr. Whetstone focused on the latter, outlining the information system's goals, concepts, objectives, and approaches.

The new system will enhance and expand current federal agency capabilities with accelerated research investments in advancing measurement/monitoring as well as improved information delivery. The seven proposed system performance goals include 1) reconciling activity-based estimates with observed atmospheric measurements; 2) transforming atmospheric concentration data into emission and removal flux estimates across spatial scales and economic sectors; 3) providing these emission and removal flux data to decision-makers to enhance mitigation efforts; 4) promoting the availability and use of international references and standards; 5) increasing the amount of observations feeding into the system via partnerships and technology development; 6) adding testbeds (demonstration projects) to improve capabilities; and 7) enhancing consistent measurement methodology for stakeholders. The system components include a combination of atmospheric and activity-based methods, an information repository, and various strategies to enhance measurement capabilities and data products. Dr. Whetstone noted that near-term strategies for this effort include expanding measurement networks in a multi-tiered approach, accelerating the transition to sustained use in operations, and exploring how to enhance coordination across multiple internal and external actors. He mentioned demonstration projects related to oil and gas methane measurements, urban and rural area measurements, landfill demonstrations, and advances in satellite data analysis.

Presentation 2: Terrestrial CDR MMRV

Dr. Yiqi Luo (Cornell University) and Dr. Jeffrey “Frenchy” Morisette (USDA Forest Service) each gave brief presentations on MMRV concerns in terrestrial ecosystems. Dr. Luo began with a description of the main categories of approaches to terrestrial CDR, all of which rely on carbon sequestration in either the plant biomass or soil carbon pools. He noted that estimating changes in soil carbon over time is more difficult than calculations for aboveground biomass, mentioning several different models which largely depend on long-term measurements. Different models are primarily used in different countries (e.g. DayCent in the U.S., Century in Canada, C-TOOL in Denmark, etc.). There are issues with the accuracy and integration of measurements and models, and in many cases the uncertainty has not been quantified, limiting the development of MMRV metrics and protocols. Dr. Luo pointed out that some CDR approaches that increase plant biomass can also result in decreasing soil carbon. He highlighted the need for new CDR techniques that can be easily measured, reported, and verified, as well as the importance of improving MMRV methods and quantifying uncertainty. One example of an easily quantifiable CDR technique is biomass burial, which can be enhanced by increasing both carbon input and residence time. Based on Dr. Luo’s analysis, the amount of carbon input is relatively inelastic, and CDR approaches can have a greater impact by increasing residence time. He provided estimates of possible ranges for increased residence time for several different techniques, such as afforestation/reforestation, biochar, litter under anaerobic conditions, etc. Additionally, he mentioned the use of data simulation, deep learning, and machine learning to improve prediction accuracy.

Next, Dr. Morisette expanded on Dr. Luo’s presentation by giving a federal land management perspective focused on biochar. He noted that the USDA Forest Service explicitly has a priority of carbon stewardship, and biochar production is one area that is expanding because traditionally the Forest Service has produced more slash piles (branches, tops and other woody material left behind after logging and/or other forest treatments) than they can manage. While there are some uncertainties still with biochar implementation and monitoring, it offers high potential with careful design. He presented some of the barriers identified to biochar implementation, including administration and permitting, funding, and public support, but noted that there are several co-benefits such as job creation, water purification, mine soil remediation, and cropland soil amendments. He estimates that biochar applications in the U.S. have the potential to sequester 98 million tons of CO2e/year, which equates to approximately 1.6% of U.S. carbon emissions and ~15% of U.S. agricultural emissions. Despite these promising results, there is currently no mandate or target for the Forest Service for stabilizing carbon, which he sees as a policy gap. In response to questions from participants, Dr. Morisette noted that more work needs to be done on LCA for biochar, but that compared to business as usual,

where slash piles are typically burnt, biochar is a better alternative for sequestering carbon and diminishing air pollution.

Presentation 3: Governance, Regulation, and Markets

During the next presentation, Julie Suarez (Cornell University) discussed several issues related to climate change and the challenges and opportunities faced by New York State. Having served as a member of the agricultural and forestry committee that helped design the agriculture and forestry chapters of the New York State Climate Act, she is deeply familiar with the issues at hand. She is hopeful that states can serve as laboratories for climate action, and ultimately help inform federal efforts as well. In developing implementation plans for the NY Climate Act, analysis showed that achieving its goals only possible by pairing steep reductions in emissions with enhanced carbon sequestration.

Ms. Suarez identified several barriers, challenges, and opportunities for the plan. She acknowledged the substantial financial resources required for compliance and emphasized the need for incentives, such as low-carbon procurement policies. She highlighted the collaboration enabled by the USDA's Climate Connects Grant, which brought together state agencies and academic institutions to provide incentives for farmers and foresters. Ms. Suarez emphasized the role of social sciences in the climate debate, addressing climate disinformation, and the need for effective communication strategies. Regarding governance, Ms. Suarez noted that land use conflicts are a significant challenge, and the private sector's decisions regarding land use will impact compliance with climate goals. Additionally, there are unresolved tradeoffs embedded in the climate plan, where goals require both forest conservation and the promotion of a bioeconomy using wood products. Similarly the push for large-scale renewable energy deployment could lead to the substantial loss of farmland.

Ms. Suarez also discussed the regulatory framework in New York State, particularly methane accounting and mitigation. There are challenges related to quantifying methane emissions from food waste and livestock and thus there is a need for further research and development. Additionally, she mentioned the need for clarity on carbon markets and incentives for sustainable practices in the agriculture and forestry sectors. The climate plan allows for people to buy credits for hard-to-decarbonize industries, but explicitly excludes biochar and biofuels due to environmental justice concerns. She noted also that there remains confusion among stakeholders about how carbon markets work – are credits paying for emissions? Paying for sequestration? And how can people receive credit for sustainable technologies they've been using for a long time? Lastly, Ms. Suarez touched on the importance of translating lab research into commercialization, particularly in the bioeconomy sector. She cited examples of innovative technologies and the challenges associated with supply chain dynamics.

While New York State is just one actor on the global stage of climate mitigation, she hopes that by serving as a laboratory and demonstrating success, action under the state climate plan can improve both the lives of New Yorkers and the global community. She noted the need for working together to drive innovation in meeting climate mitigation goals. In response to a question about identifying and engaging with stakeholders, she suggested that intermediaries, such as Cooperative Extensions, can serve a vital role.

Plenary Discussion 2: Top Solvable Obstacles to MMRV and Needs

The reports from the second breakout group discussions evaluated solutions for obstacles to MMRV associated with each of the six CDR sectors. Questions guiding each discussion included:

- For which types of CDR in this sector does MMRV work right now?
- What are the top MMRV obstacles as of today for this sector?
- What are practical or aspirational solutions for these obstacles?
- What's needed to develop or implement the solutions we just identified?

Dr. Shrestha once again reconvened everyone in plenary to report back on breakout discussions.

The *Subsurface and Mineralization* group noted that in this sector there are examples of well developed MMRV for carbon storage underground, as there are EPA guidelines for monitoring and verification. For other mineralization CDR activities, such as enhanced weathering, there are draft plans for MMRV, but none have been implemented to date. For obstacles to implementation, the group mentioned that the timeline for permitting can be long, and that there may be social opposition to proposed activities. The solutions to these issues include streamlining permitting and further research on less-developed approaches. The group felt that demonstration projects would be particularly useful in this arena. They recognized the value of incentives that may help speed these processes.

The *Atmosphere and DAC* group reported that MMRV on the capture side is relatively straightforward, but the MMRV on the utilization and sequestration side still needs research and standardization. They noted that most current technologies operate on the 1,000 ton scale, and more work needs to be done regarding sink capacities for scaling to the needed gigaton scale. They suggested that a 3rd party or non-governmental organization would be appropriate for mapping avenues for storage and utilization of captured CO2, providing verification of storage amount and durability. Acknowledging that MMRV will likely need to be defined for each

technique/approach and given that DAC can be placed in multiple environments, they recommended that for DAC it would be appropriate to have international standards. Finally, they emphasized that all DAC project owners should have clear communication with communities where facilities are located about the progress, benefits, and results of the local work.

The *Oceans and Coastal Regions* group reported that MMRV in ocean systems are quite nascent, with work occurring both in organic and inorganic systems. Their discussion focused primarily on obstacles, which include the need for standardization of parameters and protocols, innovations needed for scaling up, and ensuring that stakeholders are involved. They noted that it is particularly difficult to measure ocean uptake of carbon, and so projects will need to rely heavily on modeling efforts. They discussed how to assess when models are sufficient for moving forward with implementation. One theme that occurred throughout their session was the need for coordination among governments, private sector, and researchers. They highlighted the need to evaluate, reduce, and communicate uncertainties to all involved.

The *Croplands, Grasslands and Soils* group began by acknowledging that MMRV for soil-based sequestration is either too-expensive because it requires lots of sampling, or inaccurate because the models are not sufficiently developed. They suggested that greater on-the-ground sampling could improve both models and remote sensing capabilities. Additionally the group discussed the viability and appropriateness of using soil carbon as a metric, and explored other approaches such as carbon dating or assessing radiative forcing outcomes of CDR activities. They reaffirmed the importance of evaluating durability for any approach.

The *Forests* group noted that current methods for estimating CDR in forests are well developed, but monitoring activities are not likely to be widely distributed enough to assess efficacy. In the future, approaches that can harmonize across data streams of various sources may help with this, but it will be important to also consider other ecosystems components (e.g. soil) and leakages. They noted that in addition to the need for technological improvements, there are social and institutional advancements as well. There may be a disconnect between forest management and CDR approaches on private vs. public lands, and it will be important to ensure that MMRV is accessible and appropriate for each context. They discussed that there are currently multiple standards and suggested a “standardization of standards” to assess if CDR activities are meeting climate goals.

The *Governance, Policy, Society, and Economics* group had four take-home messages from their discussion. First, closed systems are easier to track, and highly engineered systems like underground injection wells already have published EPA guidelines. Second, obstacles to achieving further success include detecting changes from shifting baselines, standardization of MMRV approaches across sectors, existing technical capacity, data interoperability and knowledge integration across sectors. They noted the need for balancing voluntary bottom-up

vs. governmental top-down approaches, especially with respect to equity concerns. Third, solutions to these obstacles could be achieved by advancing market commitments and building more financial and policy incentives. They acknowledged that there will likely be a diversity of standards for different sectors/systems, depending on complexity, and highlighted the need to reconcile atmospheric data with ground-based measurements to improve MMRV. Finally, they noted that success for CDR activities will need to build societal trust by ensuring safety and transparency. A key component of this will be establishing clear, easy-to-follow standards and benchmarks for interoperability across sectors.

Plenary Discussion 3: Review and highlights

Dr. Cooley opened the third and final workshop day with a review of the prior activities, recalling that on Day 1 we reviewed the state of play on CDR knowledge across sectors/domains. On the second day the panels and discussions dove into the specifics of MMRV with deeper breakout groups focusing on *Atmosphere and DAC*, *Subsurface and Mineralization, Crops, Grasslands and Soils, Forests,* and *Governance, Policy, Society, and Economics*. She encouraged the day's attendees to dig in further on the remaining challenges, both those that are sector-specific and those that span across several or all sectors. She also suggested that the breakout groups consider how the workshop participants, as part of an emerging community of practice, could help address these challenges.

Before commencing the breakout sessions, Dr. Cooley summarized the results from the workshop's Mural board, and reminded attendees to both continue adding observations and use it as a basis for prompting breakout group discussions. In her review of the Mural board's postings from Day 1, she categorized the posts on obstacles to progress with CDR generally into two groups: scientific or technical issues and people or structural issues, noting that many of the topics were interconnected. She then focused on Mural posts related to potential products or activities that may address the challenges reported by the breakout groups. Across many of the sectors, the underlying research is not yet mature, and many activities do not have adequate monitoring. So much work is needed in the development of approaches and evaluation of outcomes, especially considering the climatic, environmental, or human development changes already underway. Other factors contributing to enabling CDR efforts include better governance, development of regulatory approaches, better outreach and clarity in communication among all researchers, practitioners, etc. She mentioned that there are some bright spots where specific sectors are more advanced across one or more of these topics.

The Mural board postings from Day 2 focused more specifically on MMRV. In reviewing the posts from that day, Dr. Cooley noted that many of the "solvable obstacles" identified were of a

technical nature, rather than related to the societal or governance issues, however that may be due in part to the backgrounds of the workshop participants. The proposed solutions posted to the board included permitting, targeted research, demonstration projects, and incentives. In order to implement these solutions, there were clusters of ideas around trust, coordination, and communication, as well as some suggestions for specific activities such as modeling, metrics, and workforce development. She encouraged participants to look for approaches that might apply broadly across sectors during their conversations on Day 3.

Plenary Discussion 4: Next steps

Dr. Shrestha then moderated a plenary discussion about possible products and outcomes for the workshop. Yishen Li (U.S. Global Change Research Program) suggested that a short video or other media such as podcasts may be accessible and useful. He referenced a NOAA podcast series that has been successful in increasing audience communication. Guy Michelin proposed creating an online space for ongoing communication and collaboration. Dr. Cooley mentioned a couple of existing platforms, sometimes sector specific, that may serve this purpose, although there may be a benefit to creating something specific for the workshop participants. Dr. Cooley asked Ben Rubin (Carbon Business Council) about the possibility of linking across groups as well. Mr. Rubin agreed, mentioning an existing Slack channel they manage that may be interesting in connecting with others. Dr. Chase Dwell (Fix6) suggested creating a list, perhaps from workshop participants, of carbon exports who could help serve as protocol reviewers and CDR experts. Dr. Shrestha was encouraging of this idea of creating an expert database, however Dr. Meg Chadsey (Washington Sea Grant & NOAA PMEL) noted that measures would need to be taken to balance, manage, and remunerate the amount of work any experts in such a database would likely be asked to do. Dr. Maoya Bassiouni (UC Berkeley) proposed combining a couple of the ideas by having podcast episodes or videos where a practitioner is paired with a researcher to address a particular problem or issue or topic. Dr. Chu proposed developing a summary of the issues and next steps, based on the CDR Academy and this workshop, that could be useful for agencies as they move forward with their federal-level planning.

Plenary Discussion 5: Developing a plan and final breakout group reports

For the reports from the final breakout session of the workshop, groups were tasked to outline a prioritized plan for enabling activities, research, and conditions for MMRV development and implementation in the six key sectors. Questions guiding each discussion included:

- Is MMRV development hampered by some aspect of CDR research that's incomplete?
- What are the greatest MMRV research needs in this sector? Technology development?
- Environmental or carbon cycle baseline understanding? Scaling concerns? Uncertainty?
- Can we identify the enabling conditions for MMRV development? Such as funding, human capacity, unusual partnerships, coordination, regulatory targets or a mandate, market development etc.?
- Are the "right people" involved now?
- What uncertainties/obstacles are most in the way of MMRV development?

Dr. Shrestha once again reconvened everyone in plenary to report back on breakout discussions.

The *Subsurface and Mineralization* group discussed two CDR approaches in depth: biomass burial and enhanced geothermal with CO2 storage. The latter is a new area of research that has had some designs and demonstration projects but is overall still in its infancy. For biomass burial, the group noted that in addition to the research needs to develop the technology, there remain questions around permitting and public acceptance. The group discussed durability for many approaches, and also highlighted that many parts of the world have not been adequately evaluated for geologic CO2 storage. For mineralization approaches, the group referenced an existing document, the Carbon Mineralization Roadmap (2021), that summarizes the research gaps nicely. For MMRV specifically, the group noted that baseline observations and approaches to scaling are common needs across all techniques. They emphasized the need for regulation, governance, communication, and capacity building.

The *Atmosphere and DAC* group summarized a few obstacles in the general CDR space. They noted that there is low knowledge about the state of CDR across sectors, and proposed a knowledge hub that summarizes MMRV technology for different CDR techniques, with level of readiness, funding opportunities, and perhaps even reporting of companies' MMRV statistics. Another obstacle is lack of measurement instrumentation and standards, which could be addressed not only by increased funding, but also by inclusion of MMRV as a core component of CDR development right from the get-go, and voluntary consensus from all stakeholders. The group also highlighted issues about verification, noting the current lack of third-party verifiers

and safeguards against double-counting. Increasing verification by trusted groups can also increase community awareness and support for CDR activities.

The *Oceans and Coastal Regions* group also discussed regulatory issues such as permitting and third-party verification, and suggested forming an advisory group to help guide policy-makers on structures, processes, and protocols. In order to scale-up field trials, they noted the need not only for research but also standardization and oversight, requiring participation of funders, governments, and independent verifiers, and possibly an international governing body. They highlighted the gaps in scientific understanding of carbon cycle baselines and natural variability in these systems. Finally, they discussed equitability and acceptability of known or potential impacts to humans and communities, and encouraged the continued creation of best practices for projects to ensure engagement and co-development of projects, such as those that have already begun to be developed like the Aspen Institute Code of Conduct for mCDR Research and the Guide to Best Practices in Ocean Alkalinity Enhancement Research. Overall, they felt that an independent governmental institution (possibly a government agency, an advisory board, or some other form to be determined) was appropriate for overseeing field trials, standardization, oversight, baseline understanding, and acceptability/equity.

The *Croplands, Grasslands, and Soils* group discussed several topics, including planned research and activities to address variable effects of CDR activities across locations, improving model predictions, uncertainties and decision-making under uncertainty. They suggested collaborating with state and federal agencies, practitioners, and parties to carbon trading. The group noted that managed lands are highly complex, and that climate-smart practices in addition to CDR (e.g. avoided emissions, other conservation practices) may need to be "stacked" to achieve desired outcomes and co-benefits. They suggested that system-level MMRV protocols may be more appropriate for these activities. They gave the example of biochar within the larger agricultural and forested systems context for considering the actualization of real climate benefits.

The *Forests* group similarly identified the need for landscape-level perspectives that include belowground and horizontal transport for MMRV in forests. They emphasized the importance of including land managers as a source of best practices within a given context, and the need for mechanisms of incorporating new experimental results into both protocols and the knowledge base. They envisioned a resource similar to those that the USDA creates for soil management that would enable private forest owners to make management decisions for carbon. Lastly, they discussed mandates or incentives that would ensure better quality for carbon offers in forests. The group noted the need for advocacy for standards, monitoring, and reporting outcomes rather than the sole focus remaining on initial implementation.

The *Governance, Policy, Society, and Economics* group reported many of the same cross-cutting issues, such as using existing data, identifying knowledge gaps, establishing clear standards and frameworks for MRV and community engagement customized to specific CDR types. For meaningful and effective engagement, the group discussed the need for open CDR science communication approaches and tools, such as accessible dashboards and maps that follow FAIR Principles for data management. The CDR compendium from the Interagency CDR Coordination Group (I-CDR-C) was discussed. The need for increased and improved coordination among academia, industry, and government, was identified. Thoughts offered included a USDA Extension System-like service or platform as an example to follow for multilateral engagements and sharing of knowledge and best practices among stakeholders in the CDR MRV sector

Appendices

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February 2023 Workshop Agenda

U.S. Carbon Cycle Science Program/NACP Community Workshop on Carbon Dioxide Removal (CDR): towards a unified Monitoring, Measuring, Reporting and Verification (MMRV) framework

Workshop Organizing Committee: Sarah Cooley (Chair) (Ocean Conservancy and NACP SLG member), Zac Cannizzo (NOAA), Pam Chu (NIST), Shiv Das (NOAA), James Egbu (DOE), Libby Larson (NACP/NASA), Yiqi Luo (Cornell University and NACP SLG co-chair), Jeffrey Morisette (USDA FS and NACP SLG member), Gyami Shrestha (Lynker Corporation and formerly U.S. Carbon Cycle Science Program), Peter Warwick (USGS).

Location: Virtual
Dates: February 21-23, 12-3pm Eastern Standard Time

TUESDAY FEBRUARY 21

12:00-12:10 *in plenary*
Welcome: Sarah Cooley

12:10-12:15 *in plenary*
Logistics & Code of Conduct: Libby Larson

- Welcome from NACP, review participant code of conduct.

12:15-12:35 *Begin in plenary, move to breakouts, return to plenary*
Meet some other attendees & breakout room practice: Sarah Cooley, moderator

12:35-13:30 *in plenary*
Panel discussion: Current state of CDR. Moderator: Pam Chu

- Panel discussion about types of CDR, definitions of MMRV, and state of activities in different Earth system sectors.
- Panelists: Kevin Kroeger, USGS; Kim Novick, U. Indiana; David Ho, U. Hawaii; Tony Feric, DOE FECM
- Moderator: Pamela Chu, NIST

13:30-13:45 Break (15 min)

13:45-14:30 *Begin in plenary, move to breakouts, return to plenary*

Breakout 1: CDR needs and how to resolve them.
Gyami Shrestha

- Identify the big uncertainties related to CDR in specific sectors, how they relate to other issues, and how likely they are to influence research progress. What could help resolve these uncertainties? Are there particular types of community products that would help carry the message to people who need to hear it?
- Breakout groups:
    - Mineralization/subsurface (Peter Warwick (Ning Zeng backup/co-facilitator) & rapporteur Hamid Samouei)
    - Atmospheric & DAC (Pam Chu & rapporteurs James Egbu & Aditya Anil Bhandari)
    - Ocean & coastal regions (Zachary Canizzo & rapporteurs Patrick Duke, Kalina Grabb)
    - Cropland, grassland, soils (Yiqi Luo & rapporteur Maoya Bassiouni)
    - Forests (Susan Crow (Day 1), Jeff Morisette (Frenchy) (Days 2-3) & rapporteur Aspen Reese)
    - Governance, policy, society & economics (Gyami Shrestha & rapporteurs Sena McCrory and Yishen Li)

14:30-15:00 *in plenary (30 min)*
Discussion of CDR needs. Moderator Gyami Shrestha

- Report-outs from breakout groups and discussion.

15:00
Adjourn for the day Gyami Shrestha

WEDNESDAY FEBRUARY 22

12:00-12:05 *in plenary*
Welcome & plan for the day: Sarah Cooley

12:05-12:35 *in plenary*
Focus on MMRV: the GGGI as an example. Moderator: Pam Chu

- Phil Duffy, Climate Science Advisor, White House Office of Science and Technology Policy.
- James Whetstone, Special Assistant to the Director for Greenhouse Gas Measurements Program, NIST.

12:35-13:05 *in plenary*
Focus on MMRV: Terrestrial state of MMRV. Moderator: Pam Chu

- Yiqi Luo, Liberty Hyde Bailey Professor, Cornell University. “Measuring, Reporting, and Verifying for Land Carbon Dioxide Removal.”
- Jeffrey Morisette, Human Dimensions Program Manager at the US Forest Service’s Rocky Mountain Research Station. “CDR MMRV from a Federal Land management perspective.”

13:05-13:35 *in plenary*
Focus on MMRV: Governance, Regulation, and Markets. Moderator: Pam Chu
Julie Suarez, Associate Dean for Land-Grant Affairs, Cornell University. “Re-thinking State Leadership for Climate Action: What do states need help with? A NY Experience.”

13:35-13:50 *in plenary* **Break (15 min)**

13:50-14:30 *Begin in plenary, move to breakouts, return to plenary*
Breakout 2: MMRV challenges & solutions. Moderator: Gyami Shrestha

- Identify the top solvable obstacles to MRV associated with each earth system sector, and solutions (practical or aspirational) to them. What’s needed to develop these solutions?
- Breakout Groups:
    - Mineralization/subsurface (Peter Warwick (Ning Zeng backup/cofacilitator) & rapporteur Hamid Samouei)
    - Atmospheric & DAC (Pam Chu & rapporteurs James Egbu & Aditya Anil Bhandari)
    - Ocean & coastal regions (Zac Canizzo & rapporteurs Patrick Duke, Kalina Grabb)
    - Cropland, grassland, soils (Yiqi Luo & rapporteur Maoya Bassiouni)
    - Forests (Susan Crow (Day 1), Jeff Morisette (Frenchy) (Days 2-3) & rapporteur Aspen Reese)
    - Governance, policy, society & economics (Gyami Shrestha & rapporteurs Sena McCrory

14:30-15:00 *in plenary*
Plenary discussion. Moderator Gyami Shrestha.
Discussion of top solvable obstacles to MRV and needs

- Report-outs from breakouts and discussion.

15:00
Adjourn for the day

THURSDAY FEBRUARY 23

12:00-12:30 *in plenary*
Welcome & recap: Moderators Sarah Cooley and Gyami Shrestha

12:30-14:20 *Begin in plenary, move to breakouts, remain in breakouts during break, return to plenary*
Breakout 3: Develop a plan

- Consider the status, needs, and opportunities associated with MRV in different earth system sectors. Identify a path forward to resolve major uncertainties around MRV, and suggest outputs/products that can help communicate the findings of this workshop.

Breakout Groups

- Mineralization/subsurface (Peter Warwick (Ning Zeng backup/cofacilitator) & rapporteur Hamid Samouei)
    - Atmospheric & DAC (Pam Chu & rapporteurs James Egbu & Aditya Anil Bhandari)
    - Ocean & coastal regions (Zachary Canizzo & rapporteurs Patrick Duke, Kalina Grabb)
    - Cropland, grassland, soils (Yiqi Luo & rapporteur Maoya Bassiouni)
    - Forests (Susan Crow (Day 1), Jeff Morisette (Frenchy) (Days 2-3) & rapporteur Aspen Reese)
    - Governance, policy, society & economics (Gyami Shrestha & rapporteurs Sena McCrory and Yishen Li)

14:20-14:50 *in plenary*
Plenary discussion: Moderator Gyami Shrestha
Discussion of path forward & communicating that plan

- Report-outs from breakouts and discussion.

14:50-15:00
Final thoughts and next steps. Sarah Cooley, Gyami Shrestha (10 min)

15:00
Adjourn workshop

List of Participants

First	Last	Institution
Maricar	Aguilos	North Carolina State University
Anisah	Assim	Third Way
Akinbiola Sehinde	Ayoola	First Technical University
Tom	Baribault	DroneSeed
Samantha	Basile	U.S. Global Change Research Program
Maoya	Bassiouni	UC Berkeley
Kohen	Bauer	University of Victoria, Ocean Networks Canada
Louiza	Bell	Teck Metals Ltd.
Aditya Anil	Bhandari	YouWeb
Shannon	Brown	University of Guelph
Toby	Bryce	OpenAir Collective
Elizabeth	Buescher	WinField United
Brian	Buma	Environmental Defense Fund, University of Colorado
George	Burba	LI-COR
Zachary	Cannizzo	NOAA Office of National Marine Sanctuaries
Elizabeth	Canuel	National Science Foundation

First	Last	Institution
Xiangkun Elvis	Cao	MIT
Dunbar	Carpenter	Massachusetts Executive Office of Energy & Environmental Affairs
Julien	Caubel	Senate
Meg	Chadsey	Washington Sea Grant & NOAA PMEL
Juliette	Chausson	U.S. EPA
Victor	Choquet	Sinkco Labs
Pam	Chu	NIST
Sophie	Chu	Captura
Ronald	Cohen	UC Berkeley
Sarah	Cooley	Ocean Conservancy
Greg	Cooney	U.S. Department of Energy
Isabella	Corpora	Carbon Business Council
Susan	Crow	University of Hawaii Manoa
Shibajyoti	Das	NOAA CPO
Manish	Devana	University of Miami
Judith	Drexler	U.S. Geological Survey
Manvendra	Dubey	Los Alamos National Laboratory

First	Last	Institution
Patrick	Duke	University of Victoria
Michael	Durante	Pavement Technology, Inc.
Chase	Dwelle	Fix6
James	Egbu	U.S. Department of Energy
Sarah	El Kaissi	Carmeuse
David	Ertl	Iowa Corn
Grant	Faber	Carbon-Based Consulting LLC
Yanlei	Feng	Carnegie Institute for Science
Tony	Feric	U.S. Department of Energy FECM
Aaron	Fuller	U.S. Department of Energy
Katerina	Georgiou	Lawrence Livermore National Lab
Kalina	Grabb	NOAA Ocean Acidification Program
Evan	Granite	U.S. Department of Energy
Ryan	Green	University of California, Santa Cruz
Christian	Haselwimmer	Chevron Technical Center
Robert	Hayes	CarbonDrop, Inc
Robbie	Hember	BC Ministry of Forests

First	Last	Institution
Kyle	Hemes	Amazon Worldwide Sustainability / Stanford Woods Institute
Meytal	Higgins	ExxonMobil
April	Hillier	BMO Radicle
Jennifer	Holm	
Mowgli	Holmes	Submarine PBC
Ryan	Hostak	Vesta
Jinxuan	Hu	Select Energy Services
Anna	Hughes	Oregon State University
Fred M.	Jacobs	DOI - Bureau of Safety & Environmental Enforcement
Stephanie	Jacobs	US EPA
Libby	Jewett	NOAA
Wei	Jia	General Electric Company
Sharon	Kanfoush	Utica University
Yanghui	Kang	University of California, Berkeley
Alicia	Karspeck	SilverLining/[C]worthy
Kunal	Khandewal	Ocean Networks Canada
Gabby	Kitch	NOAA Ocean Acidification Program

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Edib	Korkut	N/A
Karn	Krishna	Rutgers University
Kevin	Kroeger	U.S. Geological Survey, Woods Hole
Rachel	Lamb	Maryland Department of the Environment / University of Maryland
Alyse	Larkin	NOAA GOMO
Anna Lis	Laursen	IBM Research
Yishen	Li	U.S. Global Change Research Program
James	Liao	New Initiative
Amy	Luers	Microsoft
Spencer	Mains	CarbonDrop
Jiafu	Mao	Oak Ridge National Laboratory
Annarita	Mariotti	NOAA, Climate Program Office
Sarah	Mastroni	Ocean Visions
Allegra	Mayer	Lawrence Livermore National Lab
Sena	McCrory	U.S. EPA
Neha	Mehendale	GEOMAR Helmholtz Centre for Ocean Research Kiel
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Stefan	Metzger	National Ecological Observatory Network, Battelle
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Tessaria	Mihangel	Tessaria
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Brian	Muirhead	NASA/Caltech/JPL
Lara	Murray	USDA Forest Service
Reza	Nazemi	Colorado State University
Nikhil	Neelakantan	Ocean Visions
Sangeet	Nepal	Indiana University Bloomington
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Nithya	Rajan	Texas A&M
Greg	Rau	Planetary Technologies
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Mallory	Ringham	Stony Brook University/ Ebb Carbon, Inc
Carmen	Rodriguez	U.S. Department of Energy Water Power Technology Office
Cristhian	Rodriguez Parejo	BSEE OORP
Ben	Rubin	Carbon Business Council
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Babak	Safa	University of Hawaii
Hamid	Samouei	Texas A&M University
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Nilou	Sarvian	Northwestern University
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Robert	Shortt	Department of Environmental Science, Policy, and Management

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Laura	Stieghorst	Básico
Hariprasad J.	Subramani	Chevron
Wu	Sun	Carnegie Institution for Science
Veronica	Tamsitt	University of South Florida
Eric	Tan	National Renewable Energy Laboratory
Kathy	Tedesco	NOAA GOMO and UCAR CPAESS
Alison	Tune	Running Tide
Maria	Tzortziou	City University of New York
Adam	Usadi	ExxonMobil
Rodrigo	Vargas	University of Delaware
Amanda	Vieillard	U.S. Department of Energy Water Power Technologies Office
Tia	Vontver	Washington Department of Natural Resources
Mark	Waldrop	U.S. Geological Survey
Huiqi	Wang	UC Berkeley
Z. Aleck	Wang	Woods Hole Oceanographic Institution
Eric	Ward	U.S. Geological Survey

First	Last	Institution
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Eli	Wheat	University of Washington
Steven	White	AECI
Lisamarie	Windham-Myers	U.S. Geological Survey
Alex	Wong	SilverLining
Ning	Zeng	University of Maryland
Yimin	Zhang	National Renewable Energy Laboratory
Yongjiang	Zhang	University of Maine
Qing	Zhu	Lawrence Berkeley National Lab
Lori	Ziolkowski	University of South Carolina, currently at the National Science Foundation.

Post-script: CDR MMRV Technical Work Group Activities

Following the workshop, the organizers and a subset of the participants have been working on developing products and activities informed by the discussions at the workshop. This group of individuals was collectively designated as the '**CDR MMRV Technical Work Group**', representing the authors of this report, all interested participants from the workshop and those interested in follow-up activities. Anyone interested in joining this community group and in contributing to relevant product development and public engagement ideas informing future science and policies should contact Gyami Shrestha. This group is guided by open and inclusive participation principles and will also be working on refining and utilizing the outcomes from the workshop breakout discussions to inform future activities and needs in the CDR stakeholders communities. In addition to planned publications, this group has been active in developing and organizing outreach activities, some of which are listed below.

Conference sessions

American Geophysical Union (AGU) Annual Meeting, Dec 11-15, 2023

Town Hall:

> TH13C - Agency Research Pathways for Measuring Carbon Dioxide Removal

Collaborative Sessions by the CDR MMRV Technical Work Group and Interagency CDR Coordination Group:

> Science-Based Gigaton-Scale Carbon Dioxide Removal (CDR): Strategies for Monitoring, Measurements, Reporting, and Verification (MMRV)
>
> > Oral Session
> >
> > Poster Session
> >
> > eLightning Session

American Meteorological Society Annual Meeting, Feb 2024

Toward a Unified Monitoring, Measurements, Reporting, and Verification (MMRV) Framework for GHG Mitigation and Carbon Removal