Landscape Carbon Sequestration for Atmospheric Recovery

White Paper

A Perspective on Convergence to Accelerate Carbon Sequestration

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I. Statement of Need

The failure of nations to meet their emissions reductions targets (*1*) makes it urgent to invest in new ways to draw down atmospheric carbon by accelerating convergence across key disciplines. Looming climate tipping points require engagement of public and private sectors to scale-up climate response by creating opportunities for rapid advances that improve people's livelihoods through the provision of ecosystem services and socioeconomic development. Climate change mitigation efforts rest on two imperatives: decarbonization of our energy production systems and removal of carbon dioxide (CO_2) from the atmosphere. As described below, natural climate solutions (NCS) provide a promising pathway to regaining climate stability through atmospheric CO_2 drawdown while sustaining and often enhancing critical production systems and ecosystem services.

Climate change mitigation efforts need to stabilize atmospheric greenhouse gas concentrations at levels that prevent dangerous anthropogenic interference. For example, the Intergovernmental Panel on Climate Change (IPCC) defines several categories of climate impacts on ecosystems and society, ranging from risks to vulnerable ecosystems to broad-scale changes in temperature and precipitation patterns. To avoid dangerous anthropogenic interference, climate policy discussions have been focused on limiting increases of global mean temperature to an average of 1.5 to 2°C relative to preindustrial times. State-of-the-art models project weather extremes and biophysical impacts of greater magnitudes for 2°C global warming than 1.5°C, but major uncertainties in the range of impacts limit regional risk assessments (*2*). In either scenario, probabilistic risk assessments based on coupled climate-carbon cycle models suggest that dangerous interference in the climate system can only be avoided if climate response goes beyond net carbon neutrality to sustained net negative emissions via atmospheric CO_2 drawdown (*3*).

Natural climate solutions have been proposed as a pathway for achieving effective CO_2 drawdown. Recent estimates suggest that NCS could provide more than one-third of the cost-effective climate mitigation needed to stabilize warming below 2°C between now and 2030 (*4*). Current NCS practices consist of conservation, restoration and management of natural areas to increase land-based carbon storage, which present a readily implementable way to drawdown CO_2 while providing an array of socioeconomic and ecological co-benefits (*5–8*). However, there is a critical and widening gap between the development of scientific knowledge and on-the-ground implementation at the necessary pace and scale. On a practical level, the techniques to implement CO_2 drawdown initiatives are poorly defined because best practices are sector-specific and highly dependent on individual ecosystem characteristics. For example, current practices include afforestation, reforestation and forest management; no-till and other agricultural practices; wetlands and other "blue carbon" restoration projects; and sustainable cropping or grazing of rangelands. Yet, most NCS research efforts involve overly simplified landscapes and hypothetical actors, whereas real-world decisions involve space constraints, ownership complexities, and finite resources. It is possible to prevent dangerous anthropogenic interference while, at the same time, improving peoples' livelihoods through coordinated carbon sequestration, biodiversity conservation, and social equity action (*4*). However, the gap between basic science and mitigation strategies still needs to be bridged for rapid on-the-ground implementation across heterogeneous landscapes.

The task of implementing NCS is urgent and requires accelerated convergence across multiple sectors. Convergence that can transform the promise of NCS into real-world implementation is defined as fundamental research that are likely to trigger advances through partnerships across multiple disciplines, sectors, and stakeholders (e.g., industry, non-profits, government entities, and the general public) to propel CO_2 drawdown. Moreover, the mechanisms for carbon drawdown and accountability must be transparent and adaptable that a broad range of professionals can implement them while ensuring energy, food, and water security. In turn, the scientific community requires data-enabled capabilities to support monitoring and training programs that can inform adaptive management and refine empirical and modeling techniques for the predictive scaling of drawdown efforts.

II. Convergence Accelerator Workshop

On October 25-27, 2019, the University of Oregon hosted the Landscape Carbon Sequestration for Atmospheric Recovery (LSCAR) workshop, funded by the National Science Foundation (NSF) Convergence Accelerator Program. The overarching goal of the workshop was to assess the readiness of CO_2 drawdown for accelerated convergence. Specifically, the workshop sought to evaluate the potential of climate change mitigation through NCS and CO_2 drawdown in the Pacific Northwest (PNW) as a model system for landscape-to-regional scale implementation across the nation. The PNW encompasses extensive forests, prairies, and riverine wetland system in public and private ownership as well as rapidly expanding rural-urban interfaces, all available for NCS consideration. The coexistence of ancient natural ecosystems and rapid urban growth in PNW landscapes provides a unique setting for evaluating the costs and benefits of CO_2 drawdown in comparison to other ecosystem services and the economic stimulation of developing and deploying new technologies. To this end, the LCSAR workshop convened academic experts, software engineers, and representatives from industry and federal, tribal, regional, and state agencies to assess how basic science could be leveraged to implement CO_2 drawdown initiatives.

Participants were asked to identify research pathways for accelerating convergence across land-use sectors to optimize CO_2 drawdown and long-term carbon storage on land. *The working hypothesis explored was that CO_2 drawdown through NCS can be improved by research that leverages principles and practices from multiple disciplines and land-use sectors to coordinate and scale-up implementation*. A "convergence-ready" research CO_2 drawdown initiative would be capable of directly responding to societal needs by streamlining the development of knowledge that enables rapid implementation (i.e. within a 5- to 15-year time horizon). It would also trigger rapid advances through partnerships that craft data-enabled technologies capable of improving land management. Finally, it would be capable of spatially prioritizing investments for innovation and mechanisms to overcome socioeconomic and political or jurisdictional barriers. What follows is a synthesis of contributions from LCSAR participants, which provides compelling support for a new NSF track focused on CO_2 drawdown for simultaneously advancing environmental security, ecological resilience, and social equity.

III. Workshop Methodology

A total of 93 leaders in the field of carbon sequestration research or implementation were invited for the workshop, 67 people responded and provided feedback pre- or post-workshop, 34 were able to attend the workshop in person, and were joined by 18 University of Oregon researchers and 2 NSF representatives, for a total of 54 people actively participating in the workshop. All participants were asked to contribute ideas for "convergence-ready" themes prior to the workshop. A total of 104 researchable strategies that could be applied across entire landscapes (i.e. across multiple land-use sectors at large spatial extents) for rapid LCSAR implementation were proposed. Those ideas were synthesized to establish five different thematic groups (each containing 6-10 participants from different sectors or disciplines) that were used to systematically explore convergence-readiness over the three days of the workshop.

<u>Thematic Groups</u>

1. Productive Landscapes
2. Urban & Urban-Rural Interface Planning & Design
3. Fire Management & Adaptation
4. Landscape Prioritization & Optimization
5. Policies, Regulations, Incentives & Investments

Each participant was asked to choose one main thematic group for the entire duration of the workshop. All thematic groups had representatives from land-use, policy, and technology sectors. Each group was tasked with identifying barriers and opportunities for accelerating CO_2 drawdown at landscape to regional scales. Specifically, each group explored their theme through an introductory team exercise followed by a set of four breakout sessions organized around four "pillars" of convergence.

<u>Pillars of Convergence (Breakout Sessions) and Motivating Questions</u>

1. Current state of knowledge
   What is the potential for lasting landscape carbon sequestration?
2. Data-enabled prescriptions
   How might we combine existing data to prescribe best practices for CO_2 drawdown?
3. Implementation and monitoring
   What new technologies are needed to accelerate CO_2 drawdown across sectors?
4. Socio-economic barriers and opportunities
   How can we use convergent research on CO_2 drawdown to address socioeconomic needs?

At least one of the LCSAR workshop's co-principal investigators (co-PIs) facilitated discussions within each group and working session, assisted by graduate students taking detailed notes. Each breakout session employed a common worksheet that was used by all groups to guide their discussions and to provide a common framework across the different working groups. At the end of each breakout session, LCSAR co-PIs synthesized barriers and opportunities across and within themes.

As an introductory exercise, each working group member was asked to consider their theme's potential for convergence acceleration by rating each of the four pillars in terms of the relative impediments they presented for achieving on-the-ground CO_2 drawdown implementation. Ratings were reported to the group by each member, discussed by the group as a whole, and finally re-rated by the group to achieve consensus if possible, and to record the range of differences if consensus did not emerge. This initial conversation helped each group prioritize and structure their time for the next four sessions. Similarly, for each of the four main breakout sessions, each team was provided a common worksheet with three questions, and space for up to five responses for each question:

A. What are the key opportunities and strengths - things ready to implement or close to ready?
B. What are the top needs, gaps, limitations or barriers to implementation?
C. What key questions need to be resolved or better understood to accelerate LCSAR convergence?

As in the introductory exercise, each group member first filled out a worksheet individually. Their answers were then discussed by the group as a whole, and a final summary worksheet developed to capture their agreed-upon priorities and range of responses. As a final workshop session, participants were invited, as individuals or in teams, to propose convergence-ready projects as a means to synthesize workshop outcomes, and to further test the proposition that LCSAR could be offered as an NSF Convergence Accelerator track. *See Appendix 1 for the workshop agenda, explanation of workshop organization, and common worksheets provided to each participant and working group.*

IV. Workshop Outcomes

The workshop provided a rare opportunity to share perspectives from different knowledge bases and experiences. Participants spanned multiple sectors and areas of expertise, and included scientists, investors, planners, land managers, technology specialists and law scholars (***Figure 1***). As a result, participants were able to conceive of NCS as a launching point for a robust Atmospheric Recovery Plan that might also include engineered carbon stabilization, materials

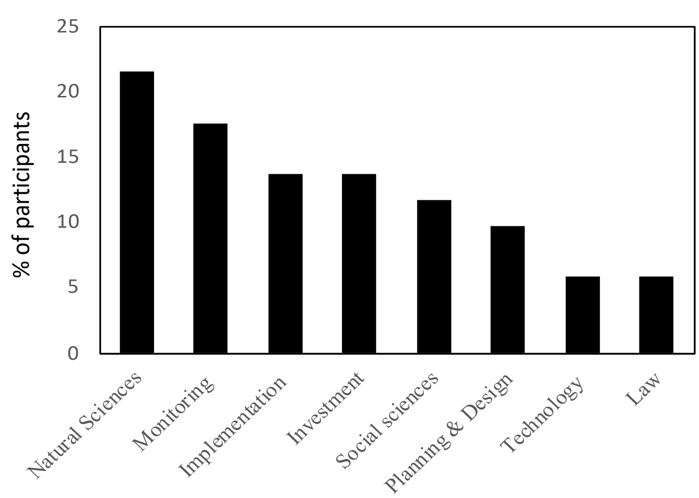

Figure 1. *Participants by self-identified area of expertise.*

substitutions, and energy efficiency technologies. There was broad consensus that CO_2 drawdown initiatives are ready for convergence based on five guiding principles, with no recorded objections before, during or after the workshop.

Guiding Principles

The ability of managed and natural ecosystems to remove CO_2 from the atmosphere is limited by the laws of physics and ecological processes that govern photosynthesis and organic matter decomposition. In general, the rates and amounts of carbon sequestration through NCS are slow and low compared to the rates and amounts of CO_2 released by fossil fuels combustion (*9*). Consequently, five principles were proposed as a common basis for framing the needs for meaningful CO_2 drawdown in the context of a broad need for atmospheric recovery:

1. To increase carbon stocks across large landscapes requires quantifying baselines and predicting carbon storage potential based on geography, land-use sector, vegetation cover, and soil resources.
2. Efforts to improve CO_2 drawdown will come with the cost of added resources (e.g. water and nutrients). Minimizing those costs is crucial to increasing long-term carbon sequestration.
3. Large areas are needed for ecosystems that mitigate anthropogenic CO_2 emissions. Public-private partnerships are crucial for identifying and allocating lands for long-term carbon storage.
4. The potential for using landscapes to sequester carbon depends on their capacity to serve as persistent carbon sinks, which varies across regions depending on socioeconomic and environmental drivers.
5. The rates of net CO_2 drawdown are low compared to those of emissions from wildfires and land use practices. Thus, reducing landscape emissions is as important as accelerating carbon sequestration.

Envisioning Convergence-Ready Projects

As noted above, participants were invited to envision convergence-ready projects at the intersection of interdisciplinary research and public-private partnerships that would be supported by the four pillars of convergence. The focus of this exercise was on landscape to regional processes that could serve as blueprints for guiding NCS through specific protocols, analysis of tradeoffs between strategies, and prioritization of sectorial investments across the nation. While adoption for an effective atmospheric recovery plan is ultimately needed at the national scale and beyond, the implementation of socio-ecologically and socioeconomically sensible NCS practices is necessarily region-specific. The PNW, as noted previously, served as a model system to assess carbon drawdown potential within the framework of an Atmospheric Recovery Plan. The central challenge posed during this exercise was “finding the promise of transformative potential in the collaboration itself to support the major leaps forward that are required” (*10*). To this end, projects were envisioned in the context of domains (or axes) of convergence for integrated science practices and policies adapted from the National Research Council’s framework for “transdisciplinary integration of life sciences, physical sciences, engineering, and beyond” (***Figure 2***).

Outputs of Work Sessions and Thematic Groups

All participants used their work sessions in thematic groups to identify barriers and potential solutions (i.e. areas of fruitful research) for atmospheric recovery in the PNW as a model system for the nation. Collaboration across sectors and disciplines (including across funding agencies, investors, and communities on the ground) was acknowledged as necessary to develop cost-effective CO_2 drawdown initiatives that combine NCS and other co-benefits to local communities by spurring job innovation and promoting socioeconomic and ecological stability. Current NCS practices implemented in the USA offer an average potential for drawdown of 1.2 Pg CO_2 equivalent per year, or the equivalent of 21% of national net annual emissions, based on individual sectors (i.e. agriculture, forestry, wetland restoration) (*11*). Taking PNW forests as an example, there is potential for carbon sequestration in productive landscapes where drought and fire vulnerability is low. In such landscapes forests could sequester up to 5,450 Tg CO_2 equivalent by 2099 (i.e. up to 20% of the mitigation potential identified for temperate and boreal forests, or up to ~6 years of current regional fossil fuel emissions) (*12*). However, land-use decisions at landscape to regional scales require allocation of finite resources across different land-use types and sectors with different biophysical and socioeconomic constraints and tradeoffs. For example, the limited supply of water and soil nutrients make it impossible to maximize CO_2 drawdown in all ecosystems at all times. Thus, there is a need for land prioritization through concerted action that harnesses methods and knowledge across sectors.

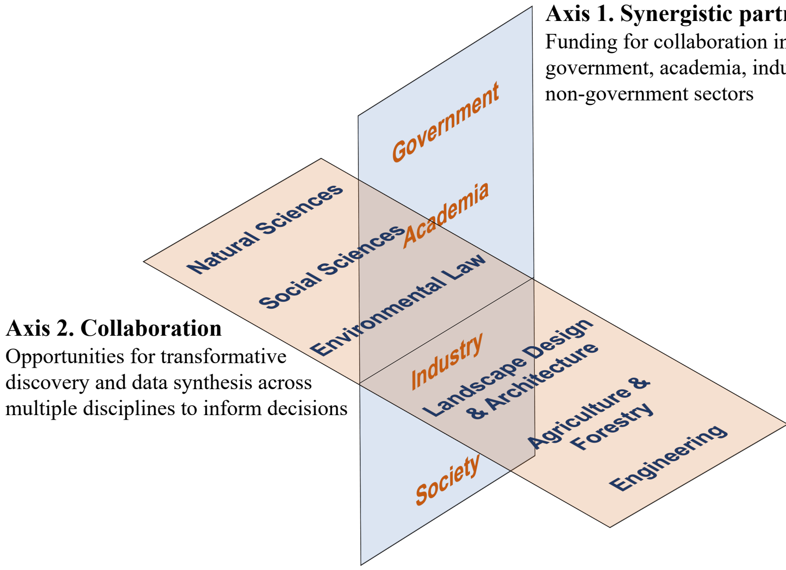

Figure 2. *Orthogonal domains (or axes) of convergence for integrated science practices and policies for atmospheric recovery. Adapted from the National Research Council's conceptual framework for convergence* (*13*).

Some participants noted that the balance between carbon and water cycles in PNW forests has been stable for thousands of years (*14*). Others noted that in some PNW landscapes climate-induced drought stress has now brought iconic ecosystems to "the verge of switching from being carbon sinks to carbon sources" (*15*). As in many other drought- and fire-affected regions, the likelihood of catastrophic disturbance is high in the PNW, but preparedness is low, as management and conservation priorities diverge. For example, human-induced climate stress is estimated to have added 4.2 million ha of forest fire area during 1984–2015; i.e. "nearly doubling the forest fire area expected in its absence" (*16*). Growing tensions between rural and urban communities pose a challenge for carbon and water governance centered around fire disturbance adaptation and socioeconomic stability (*17*). To address this issue, a data-driven plan is needed for building trust around CO_2 drawdown initiatives in rural and urban communities. Specifically, interdisciplinary initiatives are needed to improve mapping of existing and monitoring future carbon stocks across landscapes while, at the same time, fostering new discoveries that can make NCS and related initiatives socioeconomically viable.

A total of 161 unique barriers and solutions for carbon drawdown were identified by LCSAR participants and a systematic content analysis (*18*) was used to determine major barriers for implementation and potential solutions to address those barriers. Tabulated responses provided by all participants were classified into four interrelated barriers:

- Knowledge infrastructure (research networks, technologies for information exchange and dissemination)
- Knowledge production (new data)
- Measurement and monitoring capacities (instrumentation, methodologies, evaluation frameworks).
- Mechanisms for translating information to practice (data synthesis and prescriptions)

The need for optimization of existing knowledge structures and practical mechanisms for translating information to practice was most frequently identified as a barrier for implementing NCS at landscape to regional levels (***Figure 3***). An analysis of responses by each of the four pillars of convergence and thematic groups reveals how priorities differed by both pillar and theme. For example, 61% of research priority areas that were listed by the *landscape prioritization group* were classified as technology and products needed for improved measurement and monitoring capacities in the form of instrumentation and/or systems for data integration and assimilation (***Table 1***). In contrast, 50% of priority areas listed by the *policy theme group* were classified as mechanisms for translating current knowledge into practice. During group discussion, those mechanisms were linked to proposed improvements in knowledge infrastructure for NCS prioritization schemes with user-defined spatial and temporal scales of interest, as well as innovative job creation models for stewardship and incentive programs that link rewards to stakeholders via decentralized, low risk strategies to empower individuals to innovate.

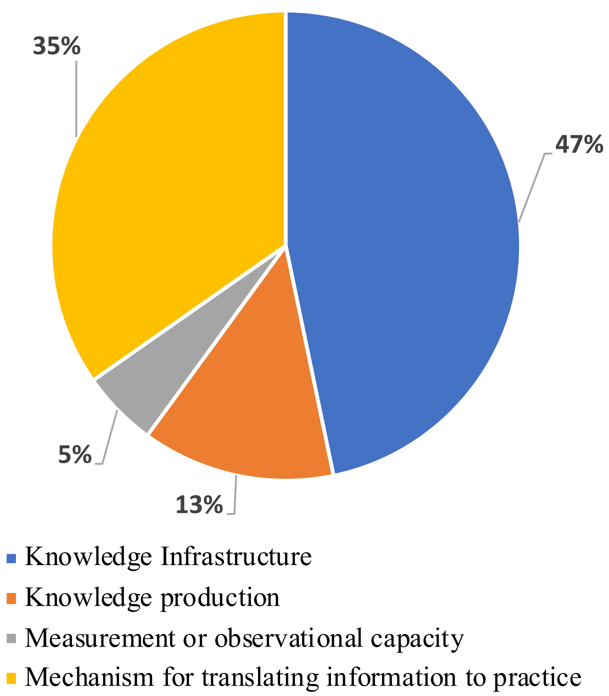

Figure 3. *Barriers for NCS implementation across all thematic groups and sectors.*

Socio-ecological barriers presented major uncertainties in NCS implementation, especially for *urban-rural planning* and *productive landscapes*. Examples of knowledge gaps include trade-offs and synergies between biological diversity, community and ecosystem resilience to disturbance, and baseline carbon sequestration rates beyond the surface. Additionally, quantification of risk and uncertainty in carbon sequestration and *fire management*, whose 43% of promising research areas for NCS were found to be associated with prescriptions and practices to decrease fuels accumulation (***Table 1***).

Other important research priorities that could help resolve existing implementation barriers included: a funding pathway for assembling interdisciplinary teams of scientists with experience in socioeconomic and ecological resilience; and a data-driven analytical framework for testing new strategies for scaling carbon drawdown in vulnerable (i.e. aridifying and fire-prone) landscapes.

Across all sectors, basic knowledge about the life cycle of plant and microbial communities hinder predictive scaling of NCS as well as end-user adoption of regenerative technologies, such as organic farming, whose long-term benefit for soil carbon sequestration (especially in deep soil layers) is not fully understood. Indeed, the development of data-syntheses for decision-making and prescriptions based on soil-plant interactions emerged as a top research area for climate adaptation efforts. New research initiatives would need to leverage a vast amount of as-of-yet disparate disciplinary or sector-specific principles for the preparation of research projects supported by data from previous and ongoing DOE, DOD, NASA, NSF, and USDA initiatives. The long-term goal of such an effort would be to develop a framework for quantifying risks and benefits of different governance models to simultaneously improve carbon sequestration and environmental and social security from landscapes to regions.

Table 1. *Priority areas for future research that hold most potential for addressing major barriers (**Figure 3**) through interdisciplinary research within each thematic group.*

Thematic Groups	Pillars of Convergence: Current Knowledge	Prescriptions & Practices	Technologies & Products	Socioeconomic Barriers	Total
Productive Landscapes	**31%**	23%	15%	**31%**	100%
Fire Management & Adaptation	14%	**43%**	21%	21%	100%
Landscape Prioritization & Optimization	6%	11%	**61%**	22%	100%
Policies, Regulations, Incentives & Investments	**50%**	17%	17%	17%	100%
Urban & Urban-Rural Interface Planning Design	16%	28%	24%	**32%**	100%

As noted in *Section III* Workshop Methodology, at the end of the workshop, participants were asked to envision convergence-ready projects as examples of the types that might be proposed under a LCSAR Convergence Accelerator track. The outcomes of this exercise were used to design a multi-tiered funding structure for convergent projects as described next, with project examples described in *Section VI*.

V. Recommendation: A Multi-Tiered Approach for Atmospheric Recovery

Current scientific research is heterogeneous and not easily integrated into actionable recommendations or techniques. Similarly, where implemented, projects have been scattered and lack the scale necessary to remove significant amounts of legacy carbon from the atmosphere. To address this limitation, two complimentary domains of convergence are proposed for the purpose of integration (***Figure 2***) aimed at addressing major barriers for implementation (***Figure 3***). The first convergence domain refers to an expanded form of interdisciplinarity in which multiple sectors or bodies of specialized knowledge comprise interdisciplinary research activities that create a path for addressing environmental challenges in natural and human-engineered systems. The second domain represents a framework to translate basic science to applied knowledge readiness utilizing NSF funding to academia, enabling individual actors and industry buy-in to trigger broad societal benefits through:

- Data syntheses and quantitative guidelines and protocols for maximizing carbon drawdown at local to landscape scales
- Opportunity mapping to provide spatially- and temporally-explicit analyses of high potential for carbon sequestration and pertinent land management data (e.g. ownership and jurisdictional boundaries) at landscapes to regional scales
- Implementing technologies, products, protocols and incentives that are necessary to implement and monitor carbon drawdown and other greenhouse gases for each relevant land use sector and for the planning and design of expanding metropolitan areas
- Delivery systems for adaptive management, and training to improve and disseminate techniques and skills needed for climate change mitigation and adaptation
- Development of predictive scaling function to evaluate the net regional successes of local climate mitigation projects and to refine protocols and prescriptions
- Atmospheric recovery plans to institutionalize and optimize carbon drawdown as well as to support the transfer of knowledge and training within regions and nationwide

There was broad consensus around this set of recommendations, which were then used to envision a new NSF research track for Atmospheric Recovery using a multi-tiered scheme that leverages existing initiatives across public and private sectors, detailed below and summarized in ***Figure 4***.

Tier 1. Data Synthesis and Mapping

Projects in this tier would focus on data synthesis for carbon mapping ($300-500k US). This type of project would be conducted by small teams of researchers to identify and fill data gaps for the purpose of translating knowledge to implementation. Effective research teams would involve local residents, indigenous knowledge keepers, government agencies, scientists and/or industry partners focused on NCS or other complimentary approaches. To identify and inform decision-makers, research teams would need to consider the distribution of costs and benefits involved in carbon drawdown activities. New tools and technologies might also be included to enable fulfillment of data needs identified in other NSF-funded initiatives. Ideal projects in this tier would be designed to deliver useful data synthesis across scales that matter for practitioners and legislators. This goal might be accomplished by leveraging existing NSF data sources, as well as other landscape-based as-of-yet disparate data gathering initiatives (***Box 1***).

Box 1. Data sources for convergence ready NCS research and technologies:

- **Soil Survey Geographic Database (SSURGO)**. Contains information about soils collected over the course of a century for most areas in the United States and the territories served by the United States Department of Agriculture – Natural Resources Conservation Service;
- **National Ecological Observatory Network (NEON)**. Provides open access ecological data, including plant traits and soil physicochemical data and educational resources to better understand ecosystems;
- **Continuous (Automated) Soil Respiration Database (COSORE).** An open-science database of continuous soil respiration datasets, intended as a community resource for syntheses housed at the Pacific Northwest National Laboratory (PNNL);
- **Parameter-elevation Regressions on Independent Slopes Model (PRISM)**. Interpolates point data from all Remote Automatic Weather Stations (RAWS) in the nation housed at Oregon State University (OSU);
- **Fluxes of trace gases between ecosystems and atmosphere (FLUXNET).** Eddy covariance measurements of carbon and water exchange measured across a confederation of networks in North, Central and South America, Europe, Asia, Africa, and Australia;
- **Landscape Evolution and Disturbance Maps, Digital Elevation Models (DEMs), Light Detection and Ranging (LiDAR)**. Multi-layer maps of forest cover and disturbance and landscape evolution available through NSF Long Term Ecological Research network (LTER), United States Geological Survey (USGS); and other public sources;
- **USGS stream flow gauging station networks**. Including reference old-growth, managed, and disturbed ecosystems to be leveraged as a means to assess water costs of increasing carbon drawdown through NCS;
- **Reflectance-based remote sensing datasets.** Including spaceborne (MODIS, LANDSAT, Sentinel-2) and airborne (NAIP, NEON AOP, AVIRIS) sensors and their derivatives (LANDTRENDR and others).

Tier 2. Prescription and Monitoring

Projects in this tier would focus on translating scientific knowledge into specific landscape prioritization protocols and implementation for monitoring and carbon accounting ($1-2 M US). Multi-institution collaborations would generate and transfer data to and from end users in coordination with citizen science and/or cooperative extension initiatives. Such efforts would require validation of data quality and compensation mechanisms to make carbon drawdown techniques more affordable. It would also involve a framework for determining whether an approach is suitable for outreach and science communication. Specifically, emphasis would be placed on cost-effective technologies to predict and monitor carbon stocks from local point data to landscapes including transparency and accountability tools calibrated for specific land uses and regions. Broader impacts of this type of project would include direct and indirect benefits for local, underserved communities by spurring training and/or job innovation. New data and data products for landscape prioritization of carbon sequestration would be required in this tier, as well as technologies to enable the fulfillment of previous NSF-funded initiatives that leverage existing data (Tier 1) and that are on the verge of becoming operational at regional scales across the nation (Tier 3).

Tier 3. Implementation at Regional Scales

Projects in this tier would fund Atmospheric Recovery Institutes (ARIs), hubs or interdisciplinary research centers akin to existing NSF Center Grants ($5-10M US), to attract or maintain leading scholars who are capable of supporting our transition to a stable future climate while enhancing socio-ecological resilience and preparedness. Projects in this tier should encompass research on NCS and other forms of CO_2 drawdown, and mitigation of other land-based greenhouse gas emissions, to address the problems arising from scattered and perhaps redundant research efforts that lack an organizing nucleus. The scope of this project type would be region-specific to match the biophysical and socioeconomic barriers for atmospheric recovery plan implementation. Specifically, projects in this tier should leverage landscape ownership patterns and data-enabled prioritization to coordinate regional-to-national scale efforts. These projects should be designed to generate atmospheric recovery at spatial and temporal scales that meet the magnitude and urgency of the climate challenge. Region-specific Atmospheric Recovery Institutes or Centers would form a network of data generation, training, and implementation experts in carbon drawdown, setting forth project-design parameters that engage both individual actors and industry partners. The goal of such a large coordination would be to support effective implementation practices and policies that are sensitive to local and regional contexts driven by funding models that support training of a rural and urban workforce that comprises the next generation of data-literate professionals.

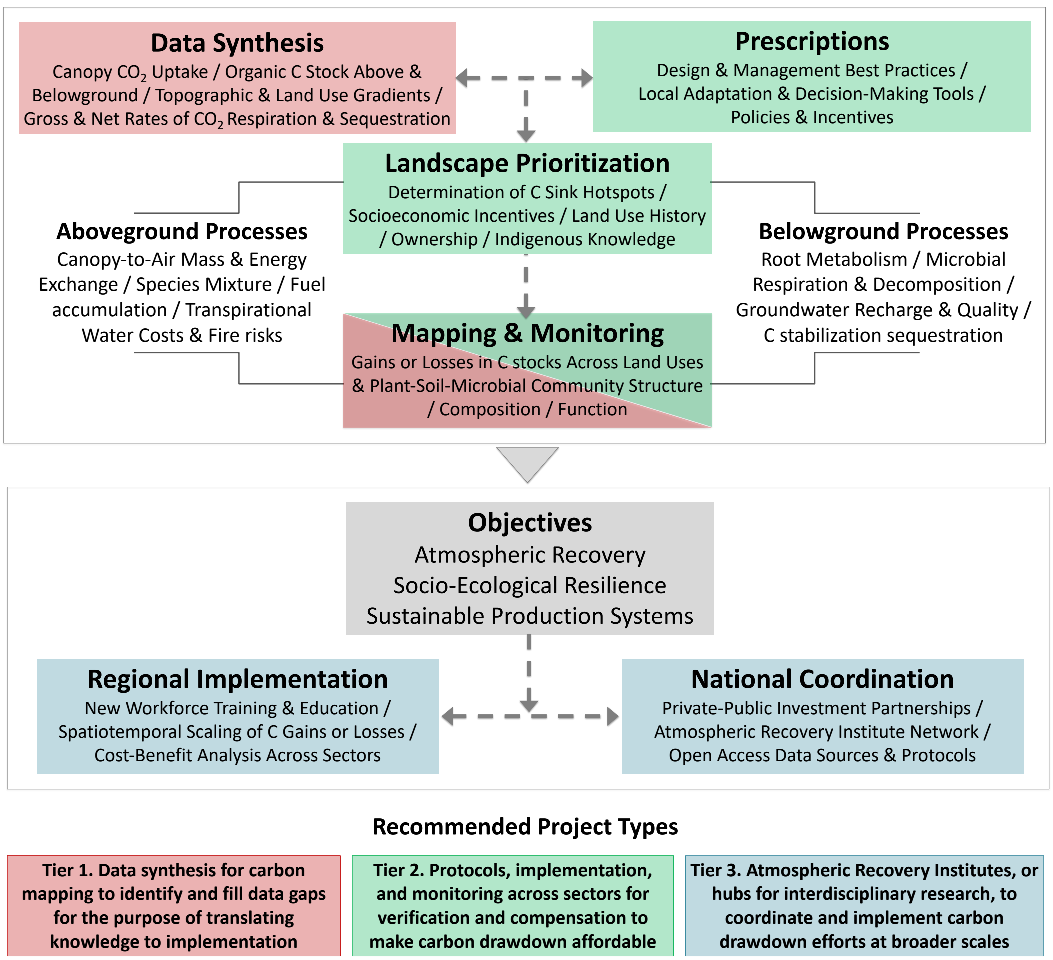

Figure 4. *Linked processes and project types to support interdisciplinary convergence for atmospheric recovery. Objectives and recommended research project types derived from the four pillars of and axes of convergence with emphasis on barriers and solutions described above.*

VI. Examples of Convergence-Ready Projects

Workshop participants offered potential scenarios through which convergent carbon drawdown activities would provide new mechanisms for translating information to practice. Over half of the barriers for NCS implementation were centered on knowledge infrastructures that produce, curate, and disseminate information (***Figure 3***). Proposed solutions for those barriers included: (i) using existing networks and channels to strengthen messaging about NCS; (ii) developing stakeholder cooperatives for cross-boundary

NCS programs; (iii) supporting interdisciplinary research, education, and collaboration; and (iv) creating advisory groups that cross academic, industrial, and end-user sectors (***Table 1***). Lastly, participants suggested that measurement and monitoring capacities could be improved by designing technologies and systems that harness "citizen science" programs to provide informational feedback for monitoring and assessing NCS success. This, in turn, could help build community engagement as part of crafting viable projects that bridge regionally prioritized carbon-drawdown hotspots to address local constraints and opportunities for implementation. Specifically, the LCSAR workshop's recommendation is that CO_2 drawdown as a convergence-ready topic would require interdisciplinary integration in one of three main tiers of research (***Figure 4***).

What would a proposal for atmospheric recovery look like?

To help NSF design and evaluate convergent initiatives for atmospheric recovery, workshop participants were invited to leave their thematic groups, as the final workshop session, to envision convergent-ready projects either as sole principal investigators (PIs) or as team of co-PIs. Each participant received a hypothetical grant of $1 Million US to develop a transformative convergent-ready project. Approximately one-third of the participants chose to develop a project vision as a sole PI with collaborations outside academia (primarily with industry partners, software engineers, and other practitioners on the ground). Approximately two-thirds chose to develop multi-PI collaborative projects. Of those multi-PI projects, about 70% contained five collaborators or less, with projects costing no more than $5 million US. The remaining 30% envisioned center grants comprised of 5 to 10 co-PIs and costing $5-10 million US.
In the examples outlined below, there are different degrees of readiness on behalf of the communities of scientists and researchers interested in each topic. Accordingly, NSF could encourage and support interdisciplinary communities that have the potential to create convergent collaborations at different scales from: Tier 1 groups working on existing data to develop proof-of-concepts for implementation; Tier 2 groups that are ready to implement and monitor large, carbon-drawdown initiatives at the scale of landscapes to subregions; and Tier 3 groups that have demonstrated leadership and potential for leading transformative convergence projects at the regional level to inform national and international efforts.

<u>*Tier 1. Data Synthesis and Mapping*</u>

Integrating Plant and Soil Data to Increase Carbon and Water Security*. This project would combine interdisciplinary knowledge to develop a hierarchical approach, leveraging extensive field-based and remotely sensed data, to create prioritization maps for carbon and water security. These maps would directly assist in prescribing species mixtures to increase carbon sequestration, water-use efficiency, resilience to fire, and maintenance of stream flow in drought-prone landscapes.*

Landowners and policymakers seek to boost forest carbon sequestration and conserve water resources. However, this is challenging both because of physical laws and ecological processes govern a tradeoff between photosynthetic removal of atmospheric CO_2 and the amount of water lost through transpiration. Integrating principles and knowledge from multiple disciplines is necessary in order to generate maps that could be utilized for prioritization of NCS implementation based on a high-resolution, spatially explicit understanding of carbon stocks and vulnerabilities across landscapes and regions of interest. Studies that utilize both in situ measurements and bottom-up biophysical models show that both carbon drawdown and water loss through transpiration increase with tree cover (*9*, *15*). Efforts to enhance forest productivity and cover to maximize carbon sequestration can therefore negatively impact water yields (*19*). Extensive research has been done to determine the limits of this carbon-water tradeoff in agricultural crops and many dominant forest species (*20–24*); however, plant-soil interactions make it difficult to predict those limits in natural and managed landscapes at scales relevant for policy and management. For example, precipitation variability is a major driver of species co-existence in the PNW (*25*), but soil nutrients and bedrock type also exert a major influence on the composition and function of PNW landscapes (*26*). In other words, the water cost of CO_2 fixation (which is nutrient limited) should vary across different geological settings and gradients of soil development. For example, the water-use efficiency and survival of PNW forests in response to extreme drought have been linked to variation in moisture and nutrients stored in deep regolith, which varies with topography (*24*, *27*). In order to build a system for understanding these tradeoffs and developing prioritization across landscapes, it is essential to integrate a variety of heterogenous data sources to predict biomass stocks, land cover (species communities, crop types, etc), geology, topography and climate. Many of these datasets exist (***Box 1***) and could be immediately leveraged. Developing spatial estimates of above and belowground carbon stocks is challenging but is increasingly possible via the integration of field sampling with airborne and space-borne remote sensing (*28*). An important next step in developing prioritization is to synthesize our understanding of the tradeoffs dictated by physical laws the actual landscapes where we hope to implement NCS efforts. In order to achieve both carbon and water stability we need to assess where the carbon-water tradeoffs are likely to result in decreasing water resources or where forests will be vulnerable to die backs and wildfire. While it can be difficult to gain spatially explicit understandings of soil and regolith properties that could influence these tradeoffs, it is possible to utilize satellite based remote sensing records to estimate vulnerability and resilience of forest ecosystems in particular (*29*). In addition, ongoing efforts are seeking to utilize vegetation properties and topographic information to constrain estimates of soil carbon at high spatial resolutions. Expanding these types of methods and combining them with more detailed hydrological datasets would enable predictions of ecosystem resilience and vulnerability across a variety of land uses which will be important for determining the security of carbon stocks and water resources.

Empowering Change Through Scientific Discovery at the Rural-Urban Interface. *This project would develop a system to support agents of change for NCS implementation in rural landscapes and small cities. The predominant focus of urban design and ecological research has been on large cities (e.g. all urban LTERs are in large metropolitan areas). However, there are many more small cities than large cities in the US and around the world. About half the world's urban population lives in cities with fewer than 500 thousand inhabitants. Empowering change by engaging communities at the rural-urban interface through citizen science initiatives would revolutionize mapping and training opportunities for carbon drawdown in this fast-expanding and understudied system.*

This project responds to a need to strengthen the general public's sense of ownership and agency in contributing to climate solutions through novel technologies that disseminate best practices in rural communities and small cities. The initial focus would be on identifying the most promising venues for carbon draw down in fast-growing rural-urban interfaces. The next step would be to characterize factors that could stimulate lasting behavioral change through specific policies, practices, procedures, and regulations designed to address carbon-emitting land use behaviors and/or social and cultural barriers to NCS implementation. Cities are integrated social-ecological systems, comprising a variety of ecosystems that are different from the rural landscapes they replaced. People's past and future influence on metropolitan landscapes is determined by bottom-up sociocultural activities and top-down governance processes, whose interactive effects on carbon cycling are notoriously difficult to predict. This project would include a citizen-science effort coordinated with high-schools and universities for storage and management of data generated through existing technologies, such as carbon concentration quantifications using ubiquitous cell phone cameras (*30*). Activities would respond to recent studies that show a positive effect for social-media-related environmental actions that connect conservation messaging to web-based citizen science (*31*). This project would develop a new model for climate change education in which learning activities address both behavior-change efficacy and social norms (*32*).

Tier 2. Prescription and Monitoring

Landscape Prioritization for Optimal Carbon Sequestration. *To prioritize the best locations for investing in NSC applications requires considering not only the carbon storage potential of different locations and land uses, but also the socioeconomic barriers to implementation, and the opportunity costs of investing on one location or land use type over another. This project would develop protocols and* *technologies for assessing such choices in the context of large landscapes comprised of a mosaic of ecosystem and land use types, and monitoring results over time.*

There is significant potential for carbon sequestration in croplands through sustainable agriculture, waste and residue management, increased perennial plantings, and organic soil amendments among other well-established techniques. Additionally, grazing can in some cases help build soil carbon while, at the same time, mitigating fire risks and fire-related carbon losses from biomass combustion and subsequent soil erosion. In the PNW, for example, by mimicking the natural herding process, traditional knowledge of grazing patterns holds potential for restoring carbon to barren pasturelands. Shifting management priorities to harness the resilience-building power of biological processes in coastal wetlands (mangroves, tidal marshes, and seagrass) hold enormous potential for further carbon drawdown (*33*), but could significantly increase the emission of other greenhouse gases, such as methane, at local to regional scales and beyond (*34*). Reforestation is considered the most promising NCS technique nationwide, but most if not all of the decisions made to select areas for carbon sequestration stem from land ownership rather than data-enable mapping of carbon sequestration potential and stability under future climates. For example, most of the variability in carbon drawdown in PNW landscapes is associated in with biophysical factors that control photosynthetic rates, but there is a statistically significant covariance between photosynthesis and respiration. Consequently, the same biophysical conditions that increase ecosystem photosynthesis to tend to be associated with CO_2 efflux through plant and microbial respiration, which is estimated to be on average 40% as large as the year to year change in photosynthesis (*15*). The joint impact on plant and microbial metabolic rates and thus carbon sequestration remains difficult to predict and scale from individual organisms to ecosystems. Developing predictive scaling functions capable of representing carbon-water-nutrient relations above and belowground remains a research priority (*35*). Maps developed in Tier 1 efforts could be used to guide and prioritize landscapes where these predictions are especially critical for decision-making and field-based research could be designed accordingly.

Designing Landscapes to Increase Carbon Drawdown. *Data-driven planning, design and monitoring of urban, rural, and urban-rural mosaics associated with metropolitan areas could add a new dimension to climate solutions. This effort would coalesce around spatially- and temporally-explicit maps showing high-potential for carbon sequestration, along with an overlay of pertinent information as to ownerships, jurisdictional boundaries, and ecosystem types. Such geographically explicit information would be easily conveyed through innovative platforms and apps to private and public sector actors and investors positioned to advance NCS opportunities.*

This project would engage each sector in doing its own work to help reverse atmospheric carbon buildup, while, critically, assessing the potential role of a landscape strategy based on its land area, spatial distribution, biophysical capacities, and projected cost-benefit contributions of traditional and non-traditional land use. Urban areas would be an important component of working landscape design. In the US, urban areas comprised 3% of the total land area in 2000 and are projected to rise to 9% by 2050. Although this is a small proportion of the total land surface area, and the potential for carbon sequestration on urban lands is low compared to other sectors, the sprawl and unconstrained urban expansion on the spatial domain of the other sectors is substantial, and the demand for products that can drive carbon-depleting practices is large at the urban-rural interface.

To gain a common understanding of risks and opportunities for carbon drawdown and reduced emissions we need adequate and representative data for expanding urban areas in relation their immediate surroundings. This includes data on carbon emissions and other greenhouse gases and socioeconomic dynamics that affect ecological processes by, for example, regulating the demand for and extraction of natural resources as well as the flow of pollutants to rural areas. The current state of urban carbon science focuses on the contribution of urban metabolism studies, remote sensing, big data approaches, urban economics, urban climate and weather studies. There are at least three paths for scaling up urban data science for regional and global climate solutions (*36*): (i) harmonizing data collection in cities; (ii) machine learning methods to scale solutions while maintaining data privacy; (iii) applying computational techniques to analyze existing information on climate solutions; Each of these paths require collaborative efforts towards a joint data platform and integrated urban-rural sustainability science. To build scientific collaboration while engaging the general public a high-resolution data-sampling methodology might be devised. For example, by combining spatially-explicit information systems and neural networks to model energy demand based on standard indicators (*37*). Such models would provide an integrated analysis of landscape "metabolism" that optimizes rural-urban interface design, including new materials and strategies, microbial data, waste flows, and to explore the links between social-ecological resilience regional gradients of contribution to the land-sharing versus land-sparing debate (*38*).

Tier 3. Implementation at Regional Scales

Atmospheric Recovery Institute. *The implementation of regionally appropriate NCS at national and international scales for the purpose of atmospheric drawdown, rather than emissions reduction efforts, is urgent and underprioritized. An Atmospheric Recovery Institute (ARI) would position itself as a leader in the urgent effort to implement NCS via interdisciplinary research and education. The ARI would develop, publish, assess, and update an Atmospheric Recovery Plan—setting forth a regional strategy of atmospheric* CO_2 *drawdown with criteria to generate new funding streams in collaboration with industry partners and government to guide priority funding of projects.*

Over the long term, the ARI must have the institutional capacity and longevity to: (i) serve as a third-party monitor verifying carbon removal plans to achieve drawdown objectives; (ii) monitor and connect regional efforts with national and global accounting systems to verify predicted drawdown targets; and (iii) develop region-specific Atmospheric Recovery Plans according to adaptive management principles, taking into account opportunities from emerging methods, training, and technology. Although leading research now occurs throughout the world in these three areas, the research is scattered and lacks an organizing nucleus. Moreover, the research has not for the most part progressed into project design scaled toward massive carbon drawdown. The ARI would act as the hub to compile and consolidate leading science into one carbon drawdown plan setting forth project design parameters. To guide the project design, the Institute will overlay climate projections, geological features, and landscape properties for identifying carbon drawdown "hotspots", via Tier 1 and 2 type efforts. The ARI can also create standards for monitoring reductions associated with particular project categories. Finally, it can inform ongoing cumulative accounting of regional to national carbon drawdown as the projects begin to yield results. Following the initial phase of developing the Atmospheric Recovery Plan, the ARI could position itself to engage in training workers to monitor and implement the plan. Finally, the ARI could position itself for a third phase assessing the progress under the plan against benchmark goals in partnership with industry and governments to report progress to the global community of leaders, scientists, and citizens.

VII. Potential Deliverables

The potential of NCS to contribute to atmospheric recovery has yet to be unlocked. Tapping this potential requires interdisciplinary research that harnesses innovations in data and technology, informational platforms, and socioeconomic incentives for policy implementation. Accelerated convergence across a range of sectors and perspectives—including scientists, technology experts, rural economists, urban planners, landscape architects, conservation lawyers and communication specialists—is needed to actualize pathways that integrate carbon drawdown with additional societal co-benefits. A multi-tiered convergence accelerator program that addresses barriers for carbon drawdown implementation across sectors and scales could lead to the following deliverables:

Convergence Framework for Decision Making. A convergence framework would provide a transferable approach to the development of the necessary knowledge and assessments for decision makers to institutionalize mechanisms that achieve carbon drawdown. Funded interdisciplinary research and implementation teams would conduct a comprehensive assessment of existing and proposed regulatory and incentive structures that can be integrated with newly standardized and accessible baseline information to monitor and measure NCS efficacy. This data then serves as the foundation for the development of a regional system for assessing and prioritizing drawdown in a way that is agnostic to and allows for integration with a variety of potential policy futures for carbon drawdown. Coordination of regional protocols through NCS could be executed across of variety of landscapes with varying ownerships, baseline capacities, workforce types, socioeconomic conditions, and political jurisdictions. The framework will further activate targeted funding sources for atmospheric recovery projects, and support "agents of change" who will guide and drive the adoption of NCS as a local to regional solution for a nationally coordinated atmospheric recovery plan.

Interactive Applications for Data-Driven Community Engagement. The uncertainty associated with carbon stock change and estimates goes down as more verifiable data is continuously reported. Robust data integration can be constructed as more crop, livestock and forest managers report and update their operating data. Most of the models that are currently used to estimate CO_2 draw down and retention rely, heavily, on under-funded academic research and land users' voluntarily supplied operations data. Even with respect to data that US farmers supply in compliance with insurance mandates and USDA reporting rules, much of the data that is currently informing the models we use to estimate terrestrial mineral and organic carbon stocks is not well-verified. If and when new carbon markets are introduced, the private sector will demand verification of the land use and practice claims of commercial users of the natural environment. This private sector introduction of verification requirements can lead to accelerated research convergence to allow a new self-reporting integration framework as long as data verification can be executed cost-effectively. All sectors would benefit from citizen engagement and for a more nuanced approaches to the carbon sequestration effort. For example, tree planting and reforestation may be recommended in some latitudes but not others, whereas compost application and wetland restoration may be undesirable for net greenhouse gas emission reduction in some circumstances (*39*–*42*). Scientifically designed parameters are rapidly emerging but must be conveyed to the landscape professionals who can put them to use and could catalyze transformative change by adhering to scientific prescriptions for improved flexibility, interoperability, and agility of "big data" analysis. For example, data captured from social media-related citizen science approaches (*31*, *32*) could provide feedback in real time to cloud GIS services and analytics and remote sensing data resources and analytics (Geo-Cloud). For example, Data Development and Analytics, Modeling as a Service and Simulation as a Service linked to the Geo-Cloud (MaaS), Modeling and Simulation, Ground and Air-based Remote Sensing systems using a System of Systems (SOS) approach used in other scientific fields (*43*, *44*).

Sensors, Other Equipment, and Networks of Networks. Efficacy of NCS implementation is measured based on key data, such soil carbon stocks, and changes in plant and microbial community composition and activity in response to drought and disturbances. There is a need to develop devices to measure such data that can be easily used by third party monitors and landowners. A wealth of NSF- and USDA-funded networks (e.g. NEON and NRCS) can be used to provide data for proof-of-concept prototypes and carbon accounting platforms. Each sector requires different sets of tools to implement NCS approaches. For example, a farmer will require no-till tools for planting using biosolids or biochar and natural alternatives to pesticides and herbicides, as well as possible microbial or fungal soil amendments to increase soil organic carbon pools and residence time. To ensure broad application and distribution of key data networks of networks can leverage recent developments in data science and artificial intelligence to parameterize spatially-explicit models for predicting the net benefit (and co-benefits) of coordinated carbon drawdown initiatives (*37*). Recent developments in data science hold potential for transforming NCS application by, for example, using continuous-depth residual networks and continuous-time latent variable models for the parameterization of complex models to allow better end-user implementation (*36*). Current models have constant memory cost and such an effort would simultaneously advance hardware and software engineering to address an need for numerical precision or speed of prediction for flexible decision making (*45*).

Training Programs for Underserved Communities. Science education has been shown to facilitate connections between actionable research findings and on-the-ground practices through stakeholder collaboration and commitment to ecological conservation (*32*). In the realm of climate solutions, the path to achieving tangible impacts requires high-quality data production and/or synthesis of quantitative measures to report or predict carbon drawdown. According to the United States Bureau of Labor Statistics (https://www.bls.gov/ooh/fastest-growing.htm) NCS-related jobs, such as forest fire inspectors and prevention specialists, mathematicians and statisticians, alongside wind and solar power technicians, comprise 5 of the top 20 occupations with the highest percent increase in employment between 2018 and 2019. In every industry there has been an explosion in the data available for decision making. Unfortunately, most students leave high school with quantitative skills far below what the job market demands and virtually every college finds that a large proportion of science students lack technical skills to tap the opportunities of a data-rich world (*46*). On the other hand, even our best quantitative students do not typically get enough training in social sciences. This is a crucial limitation for NCS implementation, which must account for ecological as well as socio-economic-political considerations that hinge on incentives for land use restoration or conservation (*18*, *47–49*). A significant part of the national endeavor involves training landscape managers in NCS techniques and training students and third-party monitors to evaluate the success of projects and reliably quantify changes in carbon stocks above and below ground. To better harness the research-implementation spaces for education, the climate benefits of environmental education can be maximized through interdisciplinary curricula. Specifically, training in this area would foster opportunities for research-inspired implementation spaces that combine ecosystem sciences, geosciences, and social sciences with a focus on localized issues of globally relevant dimensions. Furthermore, it would enhance the connectivity of local educational programs with a broad community of scientists, land stewards and legislators through existing measurement and reporting structures.

Other Co-benefits. The scientific community has produced a vast array of research and scholarship demonstrating the potential for NCS to draw down and sequester carbon, while simultaneously achieving important co-benefits (*50*) such as economic revitalization, habitat protection, water protection, enhanced food production, and community resilience to catastrophic disturbances (e.g. carbon-rich fire-prone landscapes). The demonstrated potential to “mine” CO_2 from the atmosphere point to NCS as a powerful strategy that is broadly applicable across public and private lands if landscape prioritization and data-informed prescriptions can be developed. For example, conservation and land management actions that increase carbon storage or avoid net emissions in forests, wetlands, grasslands, agriculture and developed lands must be clearly outlined for the purposes of evaluating restoration needs as well as the associated, tradeoffs, costs, and co-benefits.

VIII. Likely Partners

Research priorities for carbon drawdown align with funding trends with emphasis on interdisciplinary research and data synthesis, which require explicit integration of social and environmental systems. Data and models generated by this initiative will likely attract funding from several arenas, including federal agencies (DOE, DOD, NASA, NSF, USDA) and the private sector (e.g., energy timber companies, utilities, carbon market, water managers), as well as state and local municipalities and regional authorities. Potential partnerships between the scientific, private, and public sectors, which would engage with scientists to catalyze carbon drawdown throughout the PNW and across the nation would include those listed in ***Box 2***. Using NSF programs as examples of feasibility, the research priorities described would leverage and improve existing infrastructure to expand the scope of several tracks including:

Computational and Data-Enabled Science and Engineering (CDS&E): The goal of the CDS&E program is to identify and capitalize on opportunities for major scientific and engineering breakthroughs through new computational and data analysis approaches.

Cyber-Physical Systems (CPS): Cyber-physical systems (CPS) are engineered systems that are built from, and depend upon, the seamless integration of computation and physical components. Advances in CPS will enable capability, adaptability, scalability, resiliency, safety, security, and usability that will expand the horizons of these critical systems. Moreover, the integration of artificial intelligence with CPS creates new research opportunities with major societal implications.

Prediction of and Resilience against Extreme Events (PREEVENTS): PREEVENTS is part of the NSF-wide Risk and Resilience initiative, which has the overarching goal of improving predictability and risk assessment, and increasing resilience, in order to reduce the impact of extreme events on our life, society, and economy.

Signals in the Soil (SitS): SitS is a NSF multi-directorate program that aims to encourage convergent research that transforms existing capabilities in understanding dynamic near-surface processes through advances in sensor systems and dynamic models.

Dynamics of Integrated Socio-Environmental Systems (CNH2): Program supports interdisciplinary research that examines human and natural system processes and the complex interactions among human and natural systems at diverse scales.

Integrated Earth Systems (IES): The program provides an opportunity for collaborative, multidisciplinary research into the operation, dynamics, and complexity of Earth systems that encompass the core of the Earth through the surface.

Artificial Intelligence (AI) Institutes: There was a lot of discussion of data needs and AI tools which I think could potentially be fruitfully developed in a planning grant.

Accelerating Research through International Network-to-Network Collaborations (AccelNet): funding to connect US networks with international networks to create networks of networks.

Box 2. Key partnerships to be leveraged in convergent NCS projects:

- Indigenous communities, trade groups, cooperatives and associations.
- Technology companies investing in carbon modeling for cap-and-trade and sustainable practices.
- Pacific Northwest National Laboratory (PNNL) received $20 million for soil research, $10 million of which will be used to launch a soil-plant-atmosphere integrated research program.
- United States Department of Agricultural (USDA) Natural Resource Conservation Service (NRCS) has a $25 million budget for Conservation Innovation Grants for fields such as energy conservation, soil health, greenhouse gas markets, and conservation finance.
- The Rockefeller Foundation has invested over half a billion dollars over the past decade to fight climate change and promote resilience.
- Entrepreneurs such as Patagonia's CEO who has committed financial to support the Land Institute to research and develop products partnered with Carbon Underground to restore over 4 million acres of degraded agricultural lands.
- Google Earth Engine and ESRI have partnered to make available a "multi-petabyte catalog of satellite imagery and geospatial datasets with planetary-scale analysis capabilities".
- Real-time monitoring services such as those offered by Amazon Web Services (AWS) and IBM
- USDA Forest Service – Forest Inventory Assessment (FIA)
- United States Geological Survey– National Landcover Database, Carbon Sequestration Program
- USDA NRCS – Soil Carbon Database
- The Canadian Forest Service (CFS), the National Forest Carbon Monitoring, Accounting and Reporting System (NFCMARS).
- Innovative synthesis projects such as NATURA's Network of Networks: Nature-based Solutions for Urban Resilience in the Anthropocene, funded by the NSF 2 million US$ for five years.
- NSF Long-Term Ecological Research (LTER) network, including natural and urban systems across the nation.

IX. Caveats

Interdisciplinary proposals required for multi-sector convergence and CO_2 drawdown are likely to be difficult to evaluate in conventional funding programs. There are several challenges that will face funding of convergent research projects in NCS. Frist, researchers should demonstrate benefits to end users while, at the same time, address the fact that neither current models nor existing data are sufficient for reliably predicting all environmental costs, benefits, and co-benefits of removing CO_2 from the atmosphere (*51*). Second, there are fundamental tradeoffs that complicate implementation of NCS, such as a progressive depletion of limiting soil resources (i.e. water and nutrients) that typically occurs as a result of increasing carbon sequestration (*52*). Third, many participants identified land ownership as a critical component of any atmospheric recovery plan. Indeed, socioeconomic factors were ranked as the most important limitation for effective CO_2 drawdown implementation in the long run.

The skepticism of some participants around the idea of NCS at the scales needed for atmospheric recovery was a topic of discussion and disagreement. Several participants noted significant differences between the technical potential of CO_2 drawdown through NCS and its practical feasibility. Arguments against NCS as a feasible solution added value to the discussion by highlighting precisely the areas of greatest need for technological and scientific innovation (***Figures 3 and 4***). Skeptical participants have proposed that strategies for incorporating NCS with energy and industrial mitigation in the climate portfolio should not be an “either/or” (*53*). Others went one step further in delineating a threshold for feasibility, beyond which engineered NCS (e.g. silicate weathering stimulation and biochar production at large scales) emerge as promising, yet costly, techniques (*54*). Despite biophysical, ecological, and socioeconomic limitations for implementation all participants agreed that NCS would offer co-benefits in the form of ecosystem services, such as water filtration, flood and soil erosion protection, biodiversity and habitat conservation for enhanced resilience to disturbances.

Scientists should be focused on providing opportunities for transformative discovery while advancing technical knowledge to help implementers prescribe best practices that can maintain reasonable rates of carbon accrual (*55*) and, crucially, to reduce uncertainties and verify carbon gains for atmospheric recovery at local to regional scales (*56*). Moreover, NCS projects should combine strong social science and natural science components for fundamental advances to be made, and for systematic, transferable solutions to emerge. The most significant advances will likely be made by projects that transcend traditional disciplines to address challenges for implementation that improve environmental security as well as human well-being.

X. Summary

The workshop outcomes are well aligned with the established notion that existing practices for CO_2 drawdown provide a robust foundation for rapid progress toward tractable climate solutions (*4*). The workshop’s main conclusion is that the challenges posed by climate change provide multiple opportunities for convergent scientific research that combines technology and policy development. Potential directions for effective climate solutions through CO_2 drawdown require innovations that also improve socioeconomic metrics. In other words, implementation challenges for NCS at scales that match the urgency and magnitude of the problem can be used to catalyze scientific research and training aimed at the development of supportive technologies that would attract investments from all land-use sectors.

Most participants agreed that climate solution prescriptions and protocols must be displayed in user-friendly devices that farmers, foresters, ranchers, and industry can use on the ground. Equipment prototypes must enable new methods of monitoring carbon sequestration above and below ground. Software applications distributed through existing geospatial data repositories are needed to enable landowners, managers, private funders, and industry to optimize investments and landscape prioritization. Ideal prescriptions and protocols would be translated and deployed in a form accessible to a broad range of managers and landowners who are in a position to implement practices for improved energy, food, and water security. In turn, the scientific community requires increased technological capacity for data collection in key areas, enabling mapping and predictive scaling to inform adaptive governance.

There is already a long history of convergent research within many of the sectors involved in climate and CO_2 drawdown research. For this reason, there is already a significant degree of readiness and acceptance of the atmospheric recovery goal through interdisciplinary multi-sectorial collaboration. However, socioeconomic barriers to broad-scale carbon drawdown ranked higher than physical and ecological limitations inherent in natural solutions for CO_2 drawdown. Foremost among issues to be addressed is the need for funding sources capable of combining basic science with data synthesis and training opportunities to address socioeconomic barriers for implementation at landscape to regional scales.

The diverse types of scientists and stakeholders needed to effectively translate existing knowledge into opportunities requires initiatives that identify and prioritize actionable solutions by leaders from the scientific community, the public sector, as well as industry and non-profits. National and international coordination of landscape-based research has the potential to simultaneously improve climate stability, environmental security, and people's livelihoods across on the basis of new technologies and investment in training that would lead to implementation at the scales needed to meet the needs of an atmospheric recovery plan.

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Appendix 1 LCSAR Workshop Materials

Table of Contents

Landscape Carbon for Atmospheric Recovery (LCSAR) Workshop Schedule

October 25-27, 2019, UO White Stag Building, Portland Oregon

Date & Time		Min.	Topic
Friday	**25-Oct**		
12:00	13:00	60	Registration & light lunch (or coffee + refreshments)
13:00	13:30	30	Framing, schedule and goals of the meeting. LCSAR team brief introduction
13:30	14:00	30	Motivating questions and key background points on NCS / Convergence definition
14:00	14:45	45	**Establishing a landscape framework for NCS in the PNW:** Finalize working group themes developed from pre-meeting survey
14:45	15:15	30	**(cont'd) Establishing a common vision**- All-group discussion & wrap-up w/straw vote to select & populate thematic working groups for WGS 1-4
15:15	15:45	30	Break (LCSAR organizing team finalizes groups)
15:45	16:15	30	**Perform introductory exercise in thematic working groups**
16:15	17:45	90	**WGS1*: Current state of knowledge -*** What is the potential for impactful, lasting sequestration, including risks and uncertainties?
17:45	19:00		Happy hour/informal discussion
Saturday	**26-Oct**		
8:00	8:30	30	Morning Refreshments
8:30	9:00	30	Plenary check-in on day 1 progress and plans for today
9:00	10:30	90	**WGS2: Data-enabled prescriptions and practices to improve NCS efficiency and implementation** (incl. critical knowledge gaps)
10:30	10:45	15	Break
10:45	12:15	90	**WGS3: Implementation and monitoring technologies, products and protocols - What kind of new technologies are needed for NCS implementation & optimization?** What dream tool or app would revolutionize NCS?
12:15	13:15	60	Lunch
13:15	14:30	75	<u>Workshop-wide check-in on progress and approach across themes</u>
14:30	16:00	90	**WGS4: Socio-economic barriers and strategies to overcome limitations** (e.g., investment, incentives, infrastructure, policy, outreach and training)
16:00	17:30	90	**Organize theme synthesis presentations (**w/flip charts or digital presentations)
17:30	21:00		Drinks and catered dinner at White Stag building

***** *All **"WGS"** working group sessions are breakout groups by participant-elected convergence-ready themes*

Date & Time		Min.	Topic
Sunday	**27-Oct**		
8:30	9:00	30	Morning refreshments
9:00	10:30	90	**Synthesis presentations by theme** (5 min. presentations + 5-10 min. discussion/group)
10:30	11:30	60	**Synthesis across themes: All-Member Discussion**
11:30	12:30	60	Strategy for white paper and next steps
12:30	13:30	60	Lunch (including a brown bag discussion between early-career and senior researchers)
13:30			End of Workshop

LCSAR Workshop Organization around Working Groups, each one tackling a specific Theme

The Vision:

In coming decades, natural climate solutions (NCS) are implemented on a transformative scale. This Big Idea has catalyzed economic revitalization by spurring NCS innovations across diverse land uses. Scientifically devised, data-enabled platforms spur investment and partnerships with willing landowners and industry associations. Carbon-sequestering farming, forestry, ranching, urban-rural development, and blue carbon initiatives have become standard economic activities. Measurable carbon sequestration has begun to draw down atmospheric carbon. Climate mitigation is conjoined with economic security, soil health, water quality, wildlife habitat, food production, and community livability.

Delimitation of Workshop Scope

This workshop focuses on how ***natural climate solutions (NCS)*** could be applied at regional scales, optimized across all ***landscape sectors*** (e.g. forestry, agriculture, ranching, urban, wetlands) for effectiveness and efficiency, so as to provide significant long-term drawdown of excess atmospheric CO2 through increased sequestration and reduced emissions. The recommended delimitation of this scope for the purposes of an NSF Convergence Accelerator track will be an important meeting outcome.

What Do We Mean by "Convergence Ready"?

A "convergence-ready" theme is defined by NSF as an area of interdisciplinary research that can trigger rapid advances through application and multi-sector partnerships that include scientists, industry, non-profits, government entities, etc. The goal of the workshop is to examine the degree to which LCSAR, as delimited and defined by this workshop, is ready for convergence.

Working Group Sessions and Themes

We will establish 5-7 working groups, organized around key LCSAR themes from the poll sent to all participants. Each working group will examine the readiness of their theme for convergence. Participants will join one working group and remain in that group for the entire workshop as described below.

The workshop format of ***working group sessions and themes*** attempts to capture two dimensions of convergence: 1) **WG Sessions** use a common framework to examine what is required for convergence acceleration of any theme from the basic science of carbon sequestration to on-the-ground implementation, and 2) **WG themes** capture the need to synthesize across landscape sectors and thematic areas to inform a regional strategic planning effort. Descriptions of each workshop session and proposed themes are provided below. On Friday, we will work together to select a final set of 5-7 themes and populate them with people. After that, we will begin the first working group breakout session.

Worksheets and Process for Each Working Group Session

To align working group outcomes toward common products that can be used in the white paper synthesis and any other publications arising from this workshop, we have created a set of worksheets for each Working Group Session (WGS1-WGS4).

The common rhythm of each session is for each member of your working group to fill out the worksheet individually. Then discuss and deliberate your answers so that by the end of the session you have filled out a team worksheet that represents your best consensus. Take notes that detail key ideas and outcomes of your discussion. Concise points that summarize your rationale will be useful for developing your team presentation and for the white paper.

Plenary Check-ins, Presentations and Synthesis

In addition to the time allocated to working group sessions, each day includes times for workshop-wide discussion, feedback, and progress check-ins. For the last Saturday session, each team has 1 ½ hours to prepare a short presentation that synthesizes their findings and outcomes. Presentations will be made to all participants Sunday morning, and later incorporated in the white paper. After presentations and discussion, there will be a final session for synthesis across themes and to strategize the white paper.

Working Groups Sessions and Proposed Themes

From the poll, we created a matrix of responses and categorized them by thematic areas. We then extracted the most promising areas for possible selection as a working group theme. Critical issues that did not fit the profile of an independent theme were embedded into the Working Group Session topics (e.g. timelines, risks and uncertainties, economic scaling to achieve success).

	Working Group Session				**Proposed Working Group Themes**				
Session	**Topic and Questions**	Productive / Working Lands	Ecosystem Restoration & Conservation	Urban & Urban-Rural Interface Planning & Design	Fire Management & Adaptation	Landscape Prioritization & Optimization	Policies, Regulations, Incentives & Investments	Emerging Sequestration Technologies	Something Else?
WGS1	Current State of Knowledge								
WGS2	Landscape Prescriptions and Practices								
WGS3	Technologies, Products & Protocols Needed								
WGS4	Socio-Economic-Behavioral Barriers								
Synthesis	WG Presentations & Thematic Synthesis								

Working Group Sessions

WGS1 Current State of Knowledge
What is known about the potential for impactful, lasting sequestration, including risks and uncertainties? (e.g., quantification, baselines, potential for sequestration, uncertainties, tradeoffs, data sources to represent different sectors, life-cycle assessments of NCS.)

WGS2 Landscape Prescriptions and Practices
What are the most promising data-enabled NCS prescriptions or practices for sequestering carbon and reducing emissions? What is needed to improve efficiency and implementation on the ground, including to secure co-benefits alongside other priorities? Include key knowledge and data gaps. *For example, increasing urban density is a broad prescriptive strategy that can prevent the conversion of nearby agricultural and forest lands to urban land uses with less carbon-sequestering potential. No-till agriculture is a specific land management practice designed to reduce soil carbon loss and/or to increase below-ground sequestration.*

WGS3 Technologies Products & Protocols Needed
What kind of new technologies, products and protocols (including software) are needed for NCS implementation, optimization, monitoring, accounting, verification and knowledge dissemination? What dream tool or app would revolutionize NCS?

WGS4 Socio-Economic-Behavioral Barriers & Strategies
What are the key socio-economic and behavioral barriers to on-the-ground implementation? What strategies might be used to overcome these limitations so as to scale implementation up to needed spatial extents (e.g., investments, financing, incentives, infrastructure, policy, outreach and training)? This may include not only adoption of NCS practices but also issues related to social resilience, equity and community well-being

Proposed Working Group Themes

1. Productive / Working Lands
2. Ecosystem Restoration & Conservation
3. Urban & Urban-Rural Interface Planning & Design
4. Fire Management & Adaptation
5. Landscape Prioritization & Optimization Policies,
6. Regulations, Incentives & investments
7. Emerging Sequestration Technologies
8. Something Else?

Workshop Ground Rules

Collaborative workshops work best when participants can adopt and apply a common set of ground rules that establish rules of fair play and respect. We have a short list below that we hope everyone will abide by; if you'd like to propose others to add, please do so.

1. Honor the agenda or change by agreement
2. Monitor your air/speaking time (so that all have the opportunity to share)
3. Avoid side conversations (including cell phone/texts, etc.)
4. Respect diverse and differing perspectives
5. Ask questions for clarification
6. Focus on the issues, not on individuals

<u>The idea parking lot.</u> There will be times when we need to keep moving rather than on-the-spot address an issue raised by one or more participants. To ensure that such items don't get lost or overlooked, we'll have a **"parking lot"** with large poster paper where workshop organizers or participants can record notes on external conversations/further needs for discovery/other concerns with a commitment that we'll try to revisit them during the workshop or in the follow-up toward the white paper. If you use the parking lot to record an idea, please put your name beside the item so we can clarify any details later.

<u>Is there a doctor in the house?</u> If you need expertise that isn't available in your working group for a particular question or issue, we'll have a station with large poster paper where you can post requests for assistance and we'll alert participants to posted requests at opportune moments.

Breakout Session Common Procedures

Staying on time and using limited time effectively in working group sessions means staying on task and paying attention to producing requested deliverables in the time allocated. We can adjust timelines as a workshop or in some individual groups to better serve your working group needs. Please consult with Bart or Lucas if you'd like to propose a revision.

We will have a notetaker available for each working group who can work with the appointed "herder" (likely a member of the organizing team) who shepherds each session. They will be responsible for guiding the discussion toward the requested worksheet product of each working group breakout session. Each working group should also appoint a timekeeper to keep the process/discussion rolling, and so help achieve the targeted goals of each session.

Finally, to help keep on task, when people are filling out their individual ratings or items on their own worksheet, please try to maintain a practice of no talking or interaction with other group members until its time to compare responses.

Working Group Introductory Exercise Worksheet

Setting the Stage - What are the key limitations for region-wide implementation?
The four working group session topics below represent a path toward on-the-ground implementation. The goal of this first exercise is to explore each group members' sense of your theme's potential for "convergence acceleration", and to rank the topics that may present the greatest impediments to implementation.

Step 1 (5 minutes). For your theme, rate the following issues one a scale of 1-4 where:

1 = Not limiting
2 = Somewhat limiting
3 = Very limiting
4 = Extremely limiting

Rank	Session & Issue		Questions to Consider
	WGS1	Current State of Knowledge	What is known about the potential for impactful, lasting sequestration, including risks and uncertainties?
	WGS2	Landscape Prescriptions and Practices	What are the most promising prescriptions and practices for sequestering carbon and reducing emissions?
	WGS3	Technologies, Products & Protocols Needed	What are the available or needed technologies to support implementation and to monitor success?
	WGS4	Socio-Economic-Behavioral Barriers & Strategies	What are the key socio-economic and behavioral barriers to implementation, and strategies to overcome them?

**If you find in doing this exercise that your theme does not confirm to this 4-session path to convergence, you may develop an alternative framework for your four working group sessions. This will necessitate taking time now to craft an alternative approach that fits a 4-session framework.*

Step 2 (25 minutes). Start with a *one-minute* introduction by each person to describe your experience and interests related to this working group theme. Then, on large format paper, with rows for the issues and columns for each person, tally your individual scores and average them in a far-right column. Use this as a starting point to discuss your individual rankings and rationales, and work to achieve a synthesis. At the end of the session, complete a final worksheet that re-enters your individual scores and/or provides your consensus rankings if all agree. Bullet points that summarize your rationale and any differences that inhibit consensus will be useful for further consideration and use in the white paper. Then proceed to the WGS1 Common Framework Worksheet to assess the current state of knowledge for the remainder of this session.

Introductory Exercise Worksheet: Working Group Synthesis

Working Group Theme: ____

For your theme, rank the following issues from 1 (most known/least limiting) to 4 (least known/most limiting). To the degree possible, provide consensus rankings and explain your rationale and/or any differences that prevent consensus below

Rank	Session & Issue		Questions to Consider
	WGS1	Current State of Knowledge	What is known about the potential for impactful, lasting sequestration, including risks and uncertainties?
	WGS2	Landscape Prescriptions and Practices	What are the most promising prescriptions and practices for sequestering carbon and reducing emissions?
	WGS3	Technologies, Products & Protocols Needed	What are the available or needed technologies to support implementation and to monitor success?
	WGS4	Socio-Economic-Behavioral Barriers & Strategies	What are the key socio-economic and behavioral barriers to implementation, and strategies to overcome them?

Explanation/Rationale:

WGS1-WGC4 Common Framework Worksheet

Working Group Session (circle one) **1** **2** **3** **4**

Working Group Theme: ____

Take 15 minutes for each team member to fill out this worksheet individually. Then discuss and deliberate your answers so that by the end of the session you have filled out a team worksheet that represents your best consensus. Take notes that detail key ideas and outcomes of your discussion.

Provide a short phrase that captures your idea for up to five items. Add explanatory text as needed.

A. What are the key opportunities and strengths - things ready to implement or close to ready?

1.

2.

3.

4.

5.

Explanation/Rationale:

B. What are the top needs, gaps, limitations or barriers to implementation?

1.

2.

3.

4.

5.

Explanation/Rationale:

C. What key questions need to be resolved or better understood to accelerate LCSAR convergence?

1.

2.

3.

4.

5.

Explanation/Rationale: