A generalizable framework for enhanced natural climate solutions

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OPINION PAPER

A generalizable framework for enhanced natural climate solutions

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Abstract
Background The natural removal of carbon dioxide (CO_2) from the atmosphere through land conservation, restoration, and management is receiving increasing attention as a scalable approach for climate change mitigation. However, different land-use sectors compete for resources and incentives within and across geopolitical regions, resulting in divergent goals and inefficient prioritization of CO_2 removal efforts. Thus, a unifying framework is needed to accelerate basic research and coordinated interventions to accelerate climate change mitigation.
Scope We propose a generalizable framework for *Enhanced Natural Climate Solutions (NCS+)*, which we define as activities that can be coordinated to increase carbon drawdown and permanence on land while improving livelihoods and the provision of natural resources in vulnerable communities and ecosystems. The framework builds on interdisciplinary scientific convergence, including critical socioecological interactions, to inform both top-down policy incentives and bottom-up adoption by industries and managers. To achieve this goal, we suggest a multi-tiered approach for the prioritization of projects at local to regional scales that would simultaneously accelerate scientific discovery and broad implementation of CO_2 removal projects.
Conclusions Our vision leverages input from hundreds of researchers and land managers, including social and environmental scientists as well as representatives from tribal governments, state, and federal agencies in the Pacific Northwest of the USA, as a model system. Five guiding principles orient the framework which would be applicable in any region. As evidence of feasibility, we provide a synthesis of

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interdisciplinary studies that illustrate how coordinated action, with explicit consideration of system-specific technical and socioecological limitations, can lead to scalable projects with multiple co-benefits. Using theory as a linchpin for innovation, we propose that NCS + could better align climate change mitigation, adaptation, and justice goals at multiple scales.

Keywords Climate change mitigation · Climate change adaptation · Data science · Environmental justice

Introduction

The failure of nations to meet their carbon emission reduction targets makes it urgent to invest in new ways to draw down atmospheric CO_2 across multiple land-use sectors (UN Climate Change Conference UK 2021 2021). A wide range of potentially scalable ecosystem conservation, restoration, and management measures have been proposed to remove CO_2 from the atmosphere (Duarte-Guardia et al. 2018; Nave et al. 2018; Turner 2018) but, despite significant untapped potential, we still lack a shared vision that could optimize the implementation of such efforts. For example, it is estimated that land ecosystem conservation and sustainable land management practices could provide > 30% of the atmospheric CO_2 sequestration needed to keep global warming to < 2 °C through 2030 (Erb et al. 2018; IPBES 2019; Seddon et al. 2020). In high emitting countries, such as the USA, sustainable land management could potentially offset ~ 21% of national emissions (1.2 Pg CO_2-equivalent per year) (Fargione et al. 2018). This potential could be increased by the replenishment of depleted soil carbon pools in working landscapes (i.e. agriculture, forestry, and urban systems) (Bossio et al. 2020) or through conservation of carbon-rich habitats and avoided conversion of irrecoverable land sinks (Ruwaimana et al. 2020; Günther et al. 2020; Qiu et al. 2021). To enhance the technical and socioecological climate mitigation potential of restoration and conservation efforts we need a generalizable framework to orient research and implementation across key regions and land-use sectors.

A recent assessment led by the German Environmental Agency concluded that the potential for natural carbon capture to mitigate global emissions is likely overestimated in the scientific literature (Reise et al. 2022). One reason for this is rooted in fundamental tradeoffs that exist between resource use, carbon drawdown, and permanence across sectors that compete for land and financial incentives within key regions. On the other hand, the same study suggests that natural carbon capture can bring multiple social and ecological benefits to vulnerable regions and thus should be actively promoted. Indeed, land managers and policymakers alike are already making decisions aimed at boosting carbon sequestration, incentivized by governments and market forces all over the world. But climate mitigation actions conceived independently for different sectors may work inefficiently as a set, or even act in opposition to one another. For example, an area three times as large as the USA would have to be dedicated exclusively to reforestation projects to keep global warming within a safe margin by 2050 (Skidmore et al. 2019). This is not a realistic target in terms of land use, especially given major discrepancies between projected and observed permanence of carbon pools, and their likely responses to changes in climate across different land use systems (Georgiou et al. 2021).

Looking ahead, the critical question to be addressed is how and where might we focus our efforts to create meaningful and lasting climate change mitigation efforts while simultaneously providing tangible benefits for people and ecosystems? We posit that basic and applied research in this field could be advanced by applying a generalizable framework for *Enhanced Natural Climate Solutions (NCS+)*. We define NCS + as activities that can be coordinated to increase carbon drawdown and permanence on land while improving livelihoods and the provision of natural resources and essential ecosystem functions, especially in vulnerable communities and regions. We agree with previous assessments that suggested that natural processes alone are unlikely to achieve what is needed in time (Anderson et al. 2019; Brown et al. 2019; Schlesinger and Amundson 2018). Therefore, our vison for NCS + focuses on innovative interventions to accelerate carbon drawdown and/or improve its permanence on land, while improving biological conservation and socioeconomic sustainability. At the same time, we take into account fundamental biophysical constraints on the sequestration of organic (Baldocchi and Penuelas 2019) and inorganic carbon (Beerling et al. 2020) pools. To this end, we build on well-established theories and emerging discoveries in the social and environmental sciences to coordinate efforts across managed and unmanaged systems.

In the following sections, we explain how we arrived at our vision for NCS+and propose a pathway to inform research and implementation. First, we make a case for interdisciplinary convergence, emphasizing the need to incorporate social and ecological factors into scalable data-driven strategies. Second, we describe how hundreds of leaders from different fields contributed to our shared vision, which recenters the scope of previously proposed solutions. Third, we suggest a generalizable framework for overcoming key barriers to innovation and adoption. Finally, we provide examples from model systems in temperate and tropical regions which illustrate how NCS+could lead to transformative discovery while grounding adaptation plans toward a more resilient and just society.

A shared vision for NCS+

In October 2019, the National Science Foundation (NSF) Convergence Accelerator program funded a two-year project 'Landscape Carbon Sequestration for Atmospheric Recovery'. As the principal investigators, we sought ideas from 93 leaders in the field of carbon sequestration research or implementation. Of those, 67 people actively worked on the development of a research coordination plan during a three-day workshop to distill and critique the core principles of NCS+. This group included academic experts, software engineers, and representatives from industry and federal, tribal, regional, and state agencies.

The overarching workshop goal was to evaluate the potential of meaningful and lasting climate change mitigation efforts in the US Pacific Northwest (PNW) as a model for a generalizable NCS+framework. The PNW is a valuable model system because it encompasses extensive forests, prairies, and riverine wetland system in public and private ownership, as well as rapidly expanding rural–urban interfaces across strong natural climate gradients. The coexistence of ancient cultures, natural ecosystems, and rapid urban growth in the region provides a unique setting for evaluating the costs and benefits of landscape-to-regional scale implementation of CO_2 drawdown efforts across key sectors.

As a starting point, we considered two major domains (or axes) of interdisciplinary convergence for the integration of scientific disciplines in the broader context of policy and governance (Fig. 1). The first convergence domain refers to an expanded interdisciplinarity in which multiple bodies of specialized knowledge come together in research and education to create opportunities for transformative discovery and data synthesis directed toward decision making. The second domain represents a framework to translate basic science to applied knowledge through innovative partnerships that can catalyze on-the-ground action, fostering public and private sector buy-in that could trigger broader societal benefits. In this way, convergence could catalyze research investments that support timely on-the-ground action through collaboration among partners with policy and implementation expertise, while interdisciplinary teams would go beyond identifying problems to propose solutions with input and engagement from affected stakeholders, thus creating a form of closed-loop research that anticipates the full suite of needs and barriers for implementation.

Based on this model, we established from the outset that a "convergence-ready" research plan would

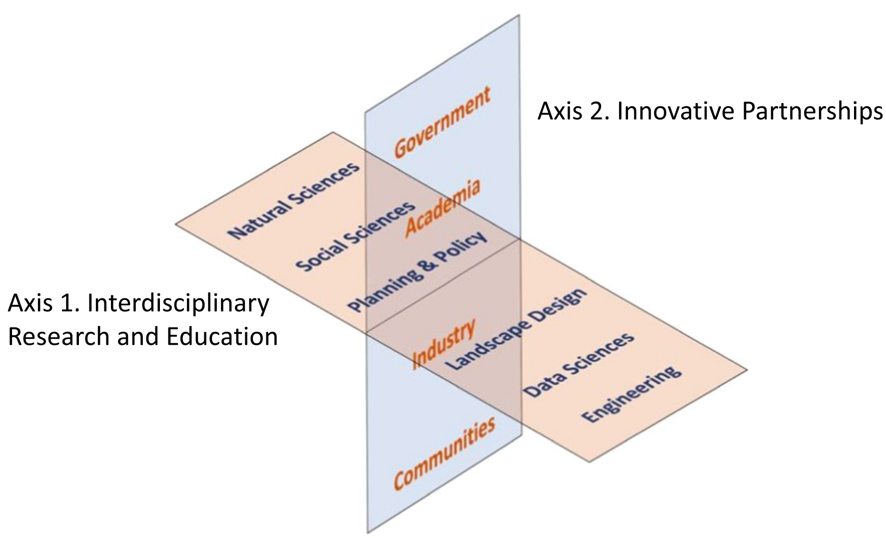

Fig. 1 Domains of convergence for integrated science practices and policies adapted from the National Research Council's conceptual framework for interdisciplinary convergence (National Research Council 2014)

directly respond to societal needs by testing emerging technologies and datasets as well as traditional knowledge of diverse socioecological systems to enable rapid implementation (i.e. within a 5- to 15-year time horizon). Such a plan would also foster workforce development through community engagement to improve land management and conservation while ensuring the just distribution of natural resources, especially in climate-vulnerable communities. We then reviewed the existing literature on "natural climate solutions" to arrive at the working hypothesis that climate mitigation projects can be accelerated by basic research that integrates multiple disciplines and land-use sectors to scale-up implementation. Finally, we considered top-down investments and bottom-up adoption as a reciprocal pathway to overcome socioeconomic and political barriers.

Our goal was to include different knowledge bases and experiences, including critics of previously proposed natural climate solutions. Participants included scientists, investors, planners, land managers, technology specialists and law scholars (Fig. 2). Despite large variability in training and experience, there was broad consensus, with no recorded objections (before, during, or after the workshop) for five principles. However, we found significant disagreement with respect to the barriers hindering progress and the ways in which those barriers might be overcome. In the following sections we provide a synthesis of agreements as well as divergent outcomes, which include contributions from all participants named in the acknowledgements section who helped build a shared vision for NCS+.

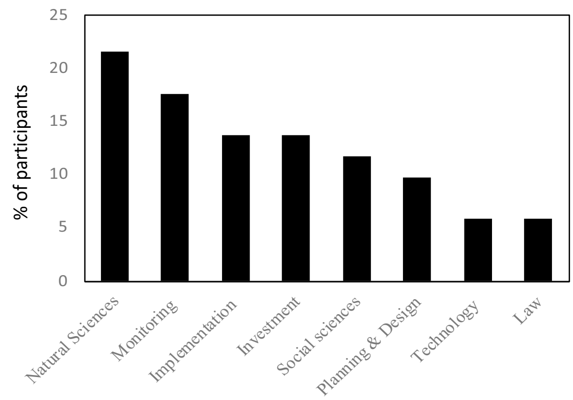

Fig. 2 Participants by self-identified area of expertise

Guiding principles

The capacity of ecosystems to remove carbon from the atmosphere and store it on land is limited by laws of physics and ecological processes. In general, the rates and amounts of natural carbon sequestration are slow and low compared to the rates and amounts released by human activity. Natural carbon capture is also limited by the amount of solar radiation, soil water, and nutrients per land area, and thus, the strength and longevity of carbon sinks vary across landscapes and can decline under land use and climate change. Consequently, enhancing climate change mitigation would require:

Historical context. Understanding social and ecological trajectories to align conservation, management, and restoration efforts.

Sustainable futures. Anticipatory planning to increase the likelihood that carbon sinks will persist under environmental change.

Co-benefits. Creating and maintaining carbon sinks while restoring and maximizing other essential ecosystem services.

Community partnerships. Partnering with government agencies, industries, and communities to accelerate climate mitigation and adaption to climate-related hazards such as droughts, floods, and wildfires.

Justice. Ensuring equitable distribution of natural resources and economic benefits, and creating opportunities for sustainable development under mounting environmental and socioeconomic pressures.

Barriers and solutions for implementation

Oriented by the guiding principles described above, we identified a total of 104 researchable strategies that could be applied across multiple land-use sectors and were potentially scalable for NCS + research and development. Those ideas were synthesized to establish five major thematic areas (Table 1, rows) that were used to systematically explore barriers to implementation and research priorities for potential solutions. Each participant was tasked with identifying barriers and opportunities for accelerating implementation at landscape to regional scales within their thematic area group through an introductory team exercise followed by a set of four breakout sessions, each organized around one of the four identified "pillars" of convergence:

1. Current state of knowledge

What is the potential for lasting landscape carbon sequestration in each land-use sector?

2. Data-enabled prescriptions

How might we combine existing data to prescribe best practices for CO_2 drawdown across sectors?

3. Implementation and monitoring

What new or "rediscovered" technologies might we deploy to accelerate CO_2 drawdown and/or permanence in working landscapes and conservation or restoration of natural ecosystems?

4. Socioeconomic priorities for sustainable development

How might we use basic interdisciplinary research to enhance CO_2 drawdown and/or permanence while addressing socioeconomic needs and ensuring the just distribution of resources?

We identified a total of 161 unique barriers and solutions for implementation using a systematic content analysis (Anderies et al. 2019) of tabulated responses provided by all participants, which we then organized in four major categories (Fig. 3). We facilitated discussions within each group and working session. Each breakout session employed a common worksheet used by all working groups to guide their discussions and provide a common framework for results. At the end of each breakout session, team leaders synthesized barriers and opportunities across and within pillars. Each working group member was asked to rate each of the pillars in terms of the relative impediments they presented. Ratings were reported to the group by each member, discussed by the group, and re-rated to achieve consensus if possible, or to record the range of differences if consensus did not emerge. Finally, we summarized agreed-upon priorities and range of disagreements, and asked participants to propose priority research areas to address the identified barriers by thematic area in relation to each of the four pillars (Table 1).

The need for optimization of existing knowledge infrastructures and practical mechanisms for translating information to practice were the most frequently identified barriers for implementation (Fig. 3). However, priorities for potential solutions to each barrier differed by thematic area. For example, 61% of research priority areas that were listed under "*landscape prioritization*" were related to 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 under "*policies*" were related to mechanisms for translating current knowledge into practice. During group

Table 1 Priority areas to address barriers for implementation in relation to five thematic areas needed for NCS +

Thematic Area	Current Knowledge	Prescriptions & Practices	Technologies & Data Products	Socioeconomic Sustainability	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%

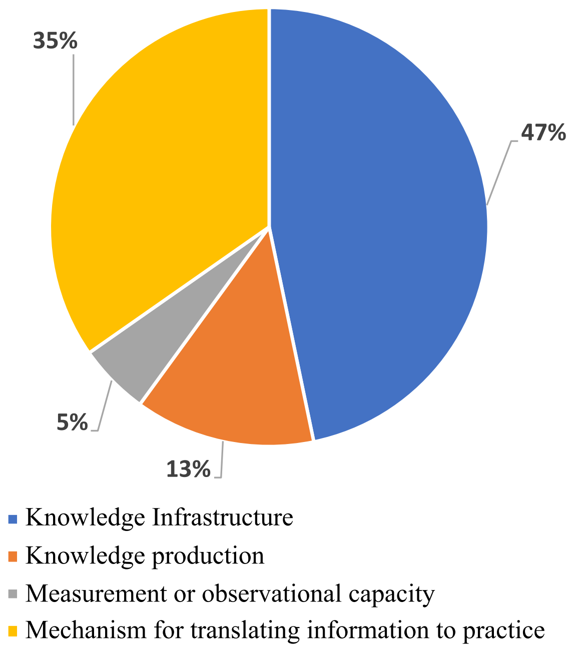

Fig. 3 Barriers for implementation

discussion, the latter mechanisms were linked to proposed improvements in knowledge infrastructure for prioritization schemes with user-defined data products, as well as workforce development for programs that reward decentralized actions that empower sectors to innovate.

Socioeconomic barriers presented major uncertainties in implementation, especially under "*urban–rural planning* " and "*productive landscapes*". Examples of knowledge gaps include tradeoffs and synergies between biological diversity, community and ecosystem resilience to disturbance, and baseline soil carbon sequestration rates. Additionally, quantification of risk and uncertainty in carbon sequestration were key barriers for "*fire management*", where 43% of promising research areas were associated with traditional knowledge of practices that decrease fuels (Table 1).

Other important research priorities (discussed under recommendations below) that could help resolve implementation barriers included: (i) basic knowledge of the life cycles of plant and soil microbial communities to inform end-user adoption of "regenerative farming", whose long-term benefit for soil carbon sequestration (especially in deep soil layers) is not fully understood; (ii) data syntheses on soil–plant interactions to support climate mitigation decision-making and prescriptions that can also address the need for climate adaptation to hazards such as drought and wildfire; (iii) quantitative information about the risks and benefits of different incentive models to improve social and environmental justice; and (iv) funding for interdisciplinary teams of scientists and practitioners with experience in socioeconomic and ecological systems to work in and with vulnerable communities.

A generalizable framework

We propose a generalizable framework that can be used to support NCS + convergence from basic research to implementation at regional scales (Fig. 4). The framework is organized around three tiers of interdisciplinary convergence. Taken together, the framework's key activities and deliverables are designed to produce deployable projects that encompass multiple land-use sectors, subject to system-specific incentives and constraints.

Tier 1. Opportunity Mapping through Data Synthesis

Approach: Build a multi-source data science framework for the collection and dissemination of quantitative information for enhanced carbon drawdown, permanence, and co-benefits across socio-environmental systems. This requires investigating how conservation, management, and restoration efforts can be prioritized to protect existing carbon pools and rebuild depleted ones at landscape to regional scales.

Goal: Spatiotemporal analysis of harmonized datasets can reduce uncertainties and guide optimized plans for enhanced carbon drawdown and permanence across multiple sectors.

Rationale Scientific research of natural climate solutions is heterogeneous and not easily integrated into actionable recommendations. Similarly, where implemented, climate mitigation projects have been physically scattered and uncoordinated, lacking the scale necessary to test protocols for maximizing carbon drawdown at large spatial extents. To address this issue and crystalize recommendations, we focus on the fact that natural carbon capture is limited by the amount of solar radiation, soil water, and nutrients per unit of land. Therefore, policies that encourage the coordinated deployment of conservation and interventions (e.g. sustainable management and restoration) of ecosystems are essential to reshape landscape carbon balance with potential regional implications. Conservation is important because vulnerable ecosystems contain at least 260 Gt of *"irrecoverable carbon"* that could be released upon land use (Goldstein et al. 2020). Innovative interventions are also important because 25% of natural carbon capture gains depend on rebuilding depleted carbon pools (Bossio et al. 2020). To advance both conservation and intervention we need to map opportunities under future climate and land use, which remains a barrier for the creation of meaningful and lasting sinks. For example, the strength and longevity of carbon sinks vary across landscapes and can decline under land use and climate change. For this reason, top-down incentives to plant forests for carbon gain can be ineffective if the potential for net drawdown and long-term persistence of captured carbon are not mapped a priori. Similarly, bottom-up agreements for collective action would benefit from quantitative information to compare actions for carbon gains relative to business as usual. This research tier would provide data-driven maps for landscape prioritization and regional coordination, which are currently lacking.

Opportunity mapping for researchers and decision makers can be developed through the spatiotemporal integration of socio-environmental variables and biophysical constraints. Harmonized datasets can enable statistical models for the identification of target areas to be protected and areas with low carbon stocks that could be prioritized for other uses or restoration. Machine-learning algorithms could be trained on social, ecological, and

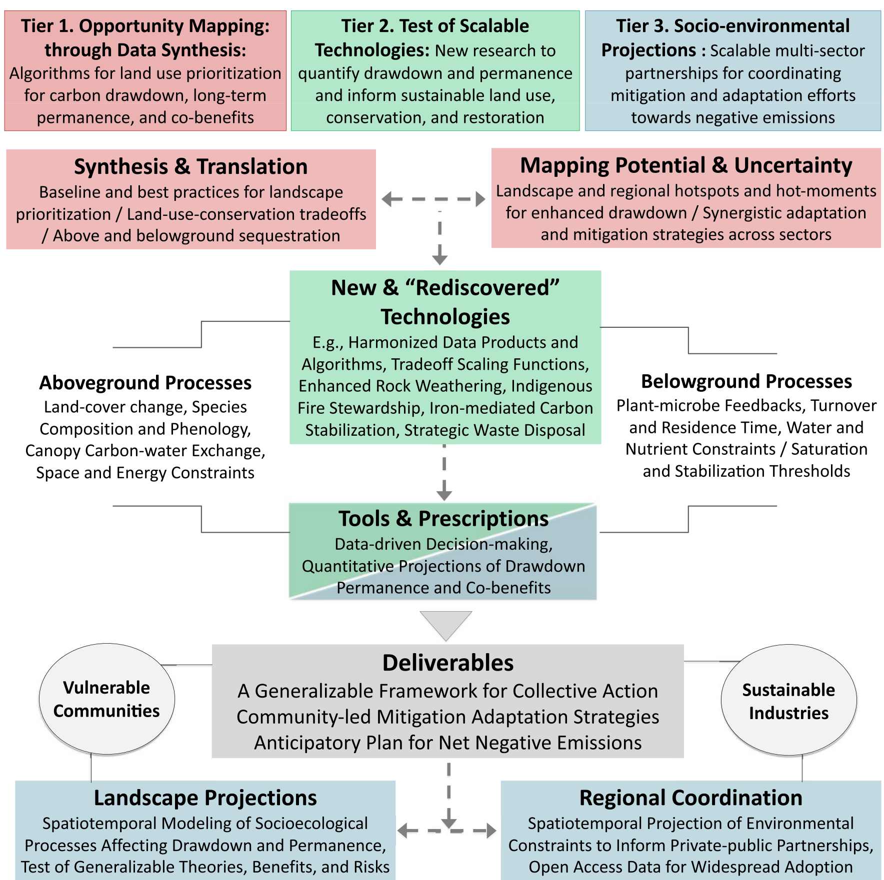

Fig. 4 A multi-tiered framework for NCS + convergence with examples of research activities and deliverables

environmental data to calibrate high-resolution opportunity maps to communicate potential and uncertainties to policymakers and managers. A multitude of data networks can be leveraged to attract public and private investment (Table 2) in concert with open-source human-Earth systems models (Bond-Lamberty et al. 2019) to identify *hotspots* (i.e., where to leverage management or conservation efforts) and *hot moments* (i.e., when to implement management or conservation) to maximize carbon gains and co-benefits.

Evidence of feasibility Coordinated action across land-use sectors can improve conservation of carbon sinks and the design of new systems for carbon gain with co-benefits (e.g. biodiversity, water quality, and resilience to disturbances (Graves et al. 2020). To this end, this tier would determine baselines and estimate future carbon gains across multiple land-use sectors (e.g., forestry, farming, wetland restoration, rangeland management) to stimulate public engagement and incentives with consideration of system- and landscape-specific constraints. For example, existing barriers associated with prioritization across ownership mosaics (e.g. public and private lands) could be reduced by coordinating individual owners' priorities and public investment, leading to decreased uncertainties in mitigation potential and adaptation benefits for community decisions (Davis et al. 2020). Guidelines and protocols tailored to different land-use sectors and land users for the short and long terms could inform anticipatory planning, for example, prioritizing certain species mixtures (Maxwell et al. 2018) with consideration of landscape properties and disturbance history to increase carbon sequestration and resilience to environmental change going forward. To this end, drivers of socio-environmental dynamics might include land-use, administrative and parcel boundaries, zoning regulations, and demographic information using a wealth of available data (e.g. Table 2) to train existing algorithms that can merge more than 20 input datasets to create maps of carbon fluxes (Harris et al. 2021) on comprehensive ground measurements for the purpose of initializing new experiments (Tier 2) projections (Tier 3).

Table 2 Examples of available data sources to be harmonized for Tier 1 opportunity mapping

Acronym	Name	Since	Data Type
3DEP	USDA BLM 3D Program	2016	Light Detection and Ranging
AIM	Assessment, Inventory, and Monitoring	2008	Rangeland community and biomass
AmeriFlux	Eddy Covariance (EC) Flux Network	1996	Ecosystem CO_2, H_2O and energy fluxes
AVIRIS	Airborne Visible Infrared Spectrometer	1986	Spectral radiance remote sensing
COSORE	Continuous soil respiration	2003	Soil CO_2 flux
DIRT	Detrital Input and Removal Treatment	1997	Soil C land-use experiments
EROS	Earth Resources Observatory Science Center	1972	Land-use change (Landsat, Sentinel-2, etc.)
FIA	Forest Inventory and Analysis Program	1994	Vegetation properties, AG carbon
IPBN	Indigenous Peoples Burning Network	2015	Indigenous fire stewardship
GeoMAC	Geospatial Multi-Agency Coordination	2001	Fire perimeter history
LANDFIRE	Landscape Fire & Resource Planning	1994	Vegetation, fuel, disturbance, and fire regimes
LP DAAC	Land Processes Distributed Active Archive	1999	Land cover & Ecosys (GEDI ECOSTRESS, etc.)
LTER/ LTAR	Long-Term Ecological/Agricultural Network	1910	Long-term multi-system plant and soil data
NEON	National Ecological Observatory Network	2017	Long-term multi-system ecological data
PNW-BCWG	PNW Blue Carbon Working Group	1991	Carbon stocks & ecosystem drivers
PNW-PSP	PNW Permanent Sample Plot Program	1910	Species distribution, soil, climate
PRISM	Parameter-elev Regr Indept Slopes Model	1895	Current and historical meteorological data
RAP	Rangeland Analysis Platform	1986	On-demand rangeland management data
SageSTEP	Sagebrush Steppe Treat Evaluation	2005	Experimental rangeland data
SoDaH	The Soils Data Harmonization Database	2020	Long-term observations of soil carbon stocks
SSURGO	Soil Survey Geographic Database	1899	Soil taxonomy & basic properties
TWE	U.S. West Coast Tidal Wetland Extent	1850	Historical wetland extent
USGS	US Geological Survey's Hydrology	1815	Current and historical streamflow data

Tier 2. Test of Scalable Technologies

Approach: Quantify the potential of new technologies and landscape prioritization, and investigate how intervention for social, ecological, and cultural benefits can enhance net carbon drawdown and permanence.

Goal: New and "rediscovered" technologies can enhance carbon drawdown and/or permanence on land while improving the socioeconomic sustainability of major land-use sectors at landscape scales.

Rationale New and "rediscovered" technologies offer opportunities to improve the sustainability of production systems (e.g. agriculture and forestry) where synergies between climate mitigation and adaptation to climate-induced hazards (e.g. drought and wildfire) have yet to be realized. The disconnect between climate mitigation policies and land managers is currently a major blind spot in terms of estimating what can be realistically achieved. Managers are driven by multiple incentives, which vary across regions and land-use types, but mostly they need to achieve economic sustainability. For this reason, a co-production of knowledge approach with managers would be critical to experimentally test the feasibility of technologies for carbon gains, climate adaptation, and socioeconomic benefits.

New empirical tests would achieve three goals: 1) *fill critical gaps* in data and knowledge to identify priorities for land-use, restoration, and conservation; 2) *test scalability* using data-driven, community-based activities for lasting impact; and 3) *reduce vulnerability to climate change* such as planning for fire risk mitigation, enhanced agricultural production and carbon storage, and to promote equitable distribution of natural resources. Ethnographic research (participant observation, semi-structured interviews) would deliver a holistic perspective on scalable NCS + projects.

Evidence of feasibility A bottom-up approach, which considers ecological and socioeconomic co-benefits of mitigation and adaptation efforts, would be transformative in at least three major systems:

Anticipatory Planning of Urban Systems: Urbanization is at the center of conflicts over land-use policies that can inhibit the potential for enhanced drawdown and permanence at and beyond the urban boundary. Urban land area in the contiguous US increased 15% from 2000 to 2010 and cities are likely to occupy 8.6% of the land area by 2060 (Nowak and Greenfield 2018). The boundary and transboundary impacts of urban expansion into rural areas can be measured in the flows of carbon, water, and energy shaping what may be defined as landscape "metabolism" (Marull et al. 2018). A new paradigm of collective action is needed to devise synergistic urban and rural strategies toward shared goals.

Examples of landscape processes to be leveraged for NCS + include the construction of infrastructure to interrupt sediment transport and accumulate carbon to mitigate storm damage in coastal cities (Lovelock et al. 2015; Mills et al. 2016). In floodplains, management of water and sediment flows can be used to biogeochemically enhance carbon sinks through ferric sulfate addition, which can reverse subsidence in water-treatment wetlands surrounding urban centers via iron-induced flocculation of dissolve organic carbon (Liang et al. 2019). In upland systems, the addition of iron-rich biosolids generated from urban waste can trigger natural succession in severely degraded barren land (e.g., abandoned gravel mines) and lead to rapid carbon accumulation (Silva et al. 2013). Large-scale multi-decadal experiments – originally aimed at restoring plant productivity and aesthetic value of such barren landscapes within the urban fabric of a capital city – unexpectedly surpassed the predicted soil carbon saturation thresholds of undisturbed ecosystems due to enhanced microbial stabilization of plant-derived carbon inputs into soil aggregates (Silva et al. 2015). Translating this approach to natural ecosystems surrounding urban areas would require new research to minimize potential detrimental environmental effects and the potential ecological and environmental risks of using waste materials to improve carbon sequestration. (e.g., sulfides can be highly toxic to plants and could have major effects on nutrient cycling). Another challenge for the success of this type of project is the transport of waste materials to target landscapes which inevitably generate fossil fuel emissions. Therefore, scalable NCS + projects should include opportunity maps for planning safe and energetically efficient boundary and transboundary flows of carbon, water, and nutrients for the restoration and creation of sustainable carbon sinks.

Urban climate adaptation efforts (e.g., sea-level rise and storm damage protection) could benefits from NCS + projects that also leverage other types of Negative Emission Technologies (NETs) – which are defined as *"any human action that removes CO_2 from the atmosphere, including afforestation and reforestation, bioenergy with carbon capture and storage, direct air capture and carbon storage, enhanced weathering, soil carbon sequestration"* (Hilaire et al. 2019). For example, ocean iron fertilization is regarded as a potentially scalable NET (Harrison 2017) and it is the only ocean NET on which there exists considerable social science research (Cox et al. 2021), warning of risks for people and ecosystems. In contrast, the potential for urban planning to reshape landscape "metabolism" through NCS + (e.g., creating and maintaining waste flows and iron-induced carbon stabilization) has yet to tested at sufficiently large scales. The potential benefits for climate change mitigation are significant as approximately 100 million tons of low cost, iron-rich sludge are produced globally as a by-product of urban water treatment (Chen et al. 2015). However, the integration of carbon capture and waste management in coupled urban–rural systems presents multiple risks that should be assessed to establish their feasibility as a safer alternative to other technologies.

Anticipatory planning and design to maximize both livability and carbon sequestration could be achieved using a combination of automated image classification algorithms validated with field data for a network of reference sites (Tier 1), targeted community-driven experiments (Tier 2), and socio-environmental projections informed by broad stakeholder engagement (Tier 3). A particular concern to be addressed is that rapidly expanding low-density urban and rural development may convert productive lands capable of sequestering carbon into emission-producing urban zones. The social and economic dimension of NCS + should not only consider factors that facilitate the implementation of carbon capture projects, but also its potential in decreasing CO_2 emission through cultural change and collective action. For example, promoting energy-saving techniques and products, using clean energy, and improving energy using efficiency will greatly reduce fossil fuel emission, facilitating the implementation of net zero targets. Simultaneously, there are key concerns about how dense urbanization impacts peoples' quality of life, particularly for vulnerable communities who are differentially restricted to urban areas with the least ecological amenities and the greatest environmental hazards (Schell et al. 2020). Critical gaps in carbon accounting and models include the effects of development trajectories across large and small urban areas and their wildland interfaces. Changes in urban surfaces, carbon stocks, and soil stabilization under sealed surfaces, which can slow carbon cycling and protect organic pools from decomposition (Tobias et al. 2018), should be quantified for the effects of pavement, buildings, and vegetation cover (tree/forest, grass/herbaceous, bare ground, etc.) on both carbon and the quality of people's daily lives. Therefore, in addition to the examples discussed above, the potential benefits of *"rediscovered"* technologies, such as prescribed fire and enhanced weathering, would be an important component of anticipatory planning of urban and rural landscapes.

Prescribed Fire in Fire-prone Systems: As a direct result of climate change, many people and ecosystems have become more vulnerable to increasingly frequent and intense droughts and wildfires. This is true in several historically mesic regions (Jones and Hammond 2020), where carbon markets encourage high-density tree plantations to increase carbon sequestration, which can exacerbate the risk of drought-induced and wildfire. In the PNW, large areas of federal land are protected from logging (e.g., wilderness or Northwest Forest Plan reserves); on the other hand, forests with high fuel loads due to fire suppression and industrial timber production increase the risk of catastrophic fires (Zald and Dunn 2018) endangering resident's homes and lives. Recent examples include the 2020 Oregon Labor Day wildfires (~5,000 km^2 burned, 3,000 structures destroyed, 11 fatalities, and $7-$13 billion in losses to homes and belongings), the 2018 Camp Fire in California (>600 km^2 burned, 18,000 structures destroyed, 85 fatalities, and $16.5 billion in losses) and the 2021 Dixie Fire in northern California (>3,980 km^2 burned, >1,020 buildings destroyed, and $610 million in losses over three months before containment). Such catastrophic events set back development goals for urban and rural communities well beyond the affected areas, exemplifying why coordinated climate change mitigation and adaptation research is critical for regional sustainability.

Indigenous fire stewardship is one the most effective approaches to mitigating fire risks to people in aridifying landscapes (Lake et al. 2017). However, the use of this "rediscovered" technology is constrained by the public perception of risks and insurance liability near rural homes (e.g., escape of prescribed fires and their smoke). Quantifying the benefits of prescribed fire at local and regional scales (e.g., wildfire risk mitigation, habitat restoration, food production, and carbon market incentives) could leverage more widespread adoption if we find that areas burned with low-intensity fire hold more carbon than unburned areas or those burned in wildfires. In some cases, prescribed fire might increase soil organic carbon stocks by decreasing microbial priming (e.g., due to high carbon-to-nutrient ratios in debry input to the top soil; Pierson et al. 2021), with the potential benefit of mitigating wildfire risk through fuel removal. To test the scalability of this approach, new experiments are needed to determine the carbon consequences of prescribed fire on traditional native grazing food systems using low-intensity high-frequency burns of culturally important habitats and species. As climate change adds 4.2 million hectares of burned landscapes "*nearly doubling the forest fire area*" since the 1980s (Abatzoglou and Williams 2016), including rapidly urbanizing landscapes, indigenous fire stewardship serves as a roadmap for the sustainability of rural and urban systems (Ramos-Castillo et al. 2017).

About half the world's urban population lives in areas with fewer than 500,000 inhabitants – the largest category after rural (United Nations 2016). In the United States, 33 cities have >500,000 people and 807 cities have 50,000–500,000 people (ESRI 2019), where suppression of the natural fire regime increases the risk for carbon permanence. Although the extent and potential for carbon removal on urban lands is low compared to other sectors, science-driven policy can prioritize resilience at the rural–urban interface as a way to expand carbon sinks with co-benefits of aesthetic value, cultural and structural protection, and equitable development (Groffman et al. 2017; Lombardi et al. 2017; Smith et al. 2018).

Enhanced Weathering in Mesic Systems: Grinding silicate rocks into small particles to accelerate weathering of primary minerals and sequester carbon in inorganic pools (i.e. carbonates) is considered among the most promising land-based NETs (Beerling et al. 2020; Kelemen et al. 2019). The idea that rock weathering can accelerate carbon drawdown and long-term storage as CO_2 is consumed and bicarbonate is generated is not new. However, the scalability of this approach is still uncertain. Surveys administered in Australia ($N = 1000$), the UK ($N = 1000$), and the USA ($N = 1026$) where enhanced weathering experiments are ongoing find a high level of support across all three countries, pending assessments of potential ecological and environmental risks (Spence et al. 2021). This potentially scalable technology is an option for advancing climate change adaptation and mitigation goals. It could be economically competitive as a soil amendment that replaces other inputs such as liming, which generates large emissions (Lehmann and Possinger 2020), with the crucial parameters defining its potential being the local availability and quality of the source materials (Strefler et al. 2018). Additionally, some biological systems can be designed to accelerate weathering, as in irrigated agriculture via root-microbe interactions (Verbruggen et al. 2021), or in mesic regions where newly formed carbonates would be transported to persistent pools in deep soil layers or large bodies of water.

As in the organic waste experiments described above, one central challenge for the success of enhanced weathering projects is the local availability and transport of materials to target areas, which generate fossil fuel emissions. To assess scalability for mitigation and adaptation, a regional focus should be placed on sustainable sources of silicate rocks, which in the PNW are available as inexpensive mining waste biproduct (i.e. basalt dust). Additionally, new experiments should consider analyses of carbon–water-nutrient tradeoffs coupled with microbial activity and genomic approaches (e.g. Bomfim et al. 2020, 2019; Mueller et al. 2016; Durrer et al. 2021)for the selection of plant and microbial communities to optimize carbon sequestration under different conditions. New experiments are also needed to assess the effects of waste materials such as silicate amendments on soil pH and base cation levels, primary production, and carbon retention into root biomass or stabilized mineral-associated soil carbon. Plant and soil scientists could advance this field by focusing on silicate-induced changes in coordinated stress responses and gene expression of species whose rhizospheres are linked in common mycorrhizal networks. In such networks, resource exchange occurs via advective mass flow, diffusion, and mycelial growth, such that the soil resource return on plant carbon investment varies with soil type, landscape position, and stage of soil development, all of which control how ecosystems respond to variation in climate and CO_2 (Silva and Lambers 2020). The multi-scale data integration and numerical models proposed by Silva & Lambers, and others who proposed a hierarchical system to integrate those variables (e.g. Maxwell et al. 2018; Maxwell and Silva 2020), could inform the artificial selection and design of plant and soil microbial communities for NCS + projects. For example, fast- and slow-changing processes at the soil–plant-atmosphere interface, as described by those authors (e.g. gene expression and soil development, respectively), could be prescribed to accelerate specific ecosystem functions (e.g. enhanced carboxylate-releasing or aggregate-forming rhizospheres) that are central to NCS + and other NETs.

Tier 3. Socio-environmental Projections at Landscape to Regional Scales

Approach: Test how plans for improving livelihoods in urban and rural systems can maintain carbon sequestration and disturbance mitigation by applying Tier 1 and Tier 2 data and technologies under future projections that integrate different process-based models within a multiagent simulation system.

Goal: Data-enabled socio-environmental projections can help reconcile mitigation and adaptation strategies for enhanced carbon drawdown and/or permanence with benefits for vulnerable communities at regional scales.

Rationale Collective-action theory postulates that authorities must determine actions, monitor behavior, and impose sanctions or incentives from the top down. However, top-down directives can be ineffective if not supported by decentralized action (Ostrom 2010; Schultz and Moseley 2019). For example, if uniformly implemented across sectors, climate mitigation policies can negatively impact people more than climate change itself (Hasegawa et al. 2018), particularly in vulnerable communities (Ramos-Castillo et al. 2017). In contrast, bottom-up agreements can serve as a mechanism for self-organizing action for improved climate change mitigation and adaptation relative to business as usual (Damon et al. 2019). Having sustainable development and net negative emissions as a shared goal, regional research coordination toward reconciling climate change mitigation, adaptation, and environmental justice could be supported through data-enabled projections for anticipatory planning.

Projections of coupled socio-ecological environmental dynamics can be used to assess the impact of NCS + across multiple land-use/land-management types, regulatory environments, ecosystems, under plausible future climate scenarios. The interplay of policy, management, and biophysical processes and constraints is multi-scalar, requiring flexible and adaptable modeling systems in which the spatial grain and extent can be adjusted to match the questions posed, as well as available data inputs and model capabilities. High-resolution datasets of urban and rural systems (Tier 1) and new technologies to enhance draw down and/or permanence (Tier 2) can be combined to generate spatial carbon consequences and co-benefits in coupled urban-natural systems. When applied within a socio-environmental simulation modeling system, these evaluative technologies can be used to assess how voluntary, incentivized, or regulatory actions of residents, private landowners, and developers can alter carbon sequestration under different landscape planning strategies, in particular by testing different spatialized prioritizations of conservation, restoration, or development. This would require new data technologies such as data-drivem algorithms for landscape prioritization of land use. For example, urban growth inhibits the critical use of prescribed fire and managed wildland fire in the wildland-urban interface due to concerns over smoke exposure and the risk of escaped fire. Yet from 2000–2013, the wildland-urban interface accounted for 69% of US structures destroyed by wildfire (Kramer et al. 2018). In terms of numbers of houses and land area, the wildland-urban interface is the fastest growing US land-use type (Radeloff et al. 2018). Data-driven projections could be used to anticipate how boundary and transboundary couplings, including the exchange of carbon, water, nutrients, and energy mentioned above (Fig. 5), shape decisions in urban and rural settings and how those affect societal capacity for local climate adaptation and regional atmospheric carbon sequestration.

Evidence of feasibility This tier is in keeping with recently proposed transformative pathways for climate mitigation, using integrated assessment models (IAMs) to envision plausible low-carbon futures. At their core IAMs incorporate a plurality of perspectives on plausibility and desirability through iterative participatory planning, interdisciplinary collaboration

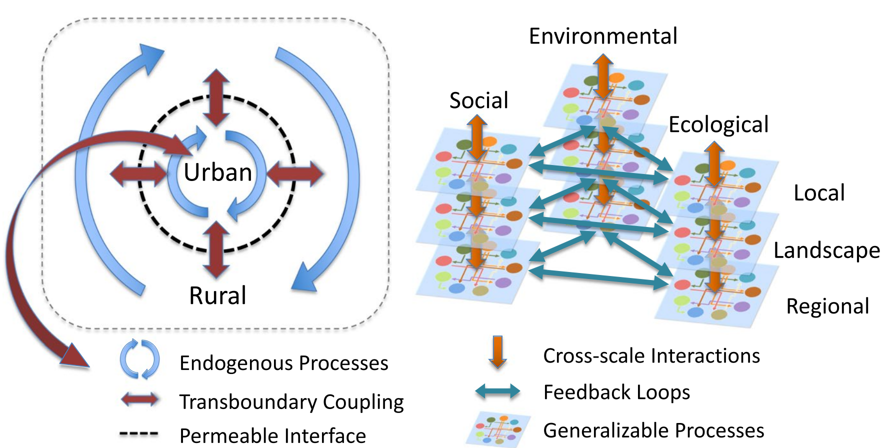

Fig. 5 Conceptual model of endogenous and transboundary couplings at the urban–rural interface (left) including land-use for food, wood, and energy production within and across socioecological systems, and multi-scale feedbacks driving shifts in boundary location (right). Modified from (Johnson and Ko 2022)

to expand the range of imagined futures, so that different actors can understand and engage at local, regional, and global scales (Braunreiter et al. 2021). For NCS +, the integrated projection of socio-environmental futures under climate change is focused on advancing mitigation, adaptation, and environmental justice goals, such as the provision of natural resources for vulnerable communities (Duarte-Guardia et al. 2019). Central to this effort are biodiversity protection and conservation of carbon- and water-rich habitats (Sheil et al. 2016) and avoided conversion of irrecoverable carbon pools in biodiversity hotspots (Ruwaimana et al. 2020). Such an effort could also increase ecological resilience and socioeconomic prosperity by, for example, contributing to the avoidance of future pandemics (Daszak et al. 2020; Di Marco et al. 2020; Graham and Sullivan 2018).

In the USA, 22 states currently have climate action plans, but of these, only six consider carbon mitigation, negative emissions, and social equity issues (Brown et al. 2021). Despite this limited number of examples, it is clear that socioeconomic and ecological goals can be synergized through opportunity mapping from airborne and satellite data (Correa-Díaz et al. 2019; Brodrick et al. 2019; Chadwick and Asner 2018), and through new or "rediscovered" technologies focused on enhancing soil carbon accumulation (Bomfim et al. 2020; Durrer et al. 2021; Silva et al. 2021; Winsome et al. 2017). To integrate scientific information into actionable recommendations, socio-environmental projections could be designed to receive continuous decentralized local input. This can be achieved using region-specific hubs for contributors and land-users to refine policies for regional response in sectors ranging from agriculture to forestry and public health (Goldman & Hyams 2019). By informing regional policies that benefit all land use sectors, such projections would address concern that the risks and costs of CO_2 removal may be disproportionately borne by communities that are most vulnerable to environmental change. Over the long term, modeling systems to project NCS + costs and benefits could be used as an organizing tool for climate response efforts, tailored to the unique character of different regions. They could also serve as a third-party monitoring system to verify and connect local efforts with accounting systems and targets.

To scale up predictions from local jurisdictions to regions, hierarchical power-law scaling functions can be used for combining slow-changing and dynamic processes that control carbon cycling (Maxwell and Silva 2020) in tandem with soil water and nutrient thresholds that govern species composition and ecosystem productivity (Hahm et al. 2014). The net effect of these interactions on carbon drawdown is currently unknown, as are the socio-ecological processes controlling permanence, but they can be quantified and projected using a combination of existing biophysical-agent-based models to incorporates decision-making and socioecological feedback into *alternative future scenarios* (Hulse et al. 2016). Of particular interest are the couplings between urban "demand" for carbon offsets and other mitigation strategies, the flow of resources to support these strategies, and the capacity or willingness of rural and urban landowners, and land managers to incorporate NCS + in their plans. Key drivers of socio-environmental dynamics include land-use, administrative and parcel boundaries, zoning regulations, and demographic information. Social data can be used to parameterize how the perceptions and decision propensities of people and institutions affect their land-use and land-management actions under different policy scenarios (Ferguson et al. 2017; Fischer and Jasny 2017; Nielsen-Pincus et al. 2015). Data technologies could aid land users and policymakers alike by filling knowledge gaps that limit carbon pricing appraisals and other incentives for legal funding mechanisms, such as cap and trade subsidies, or court-awarded natural resources damages (Wood and Galpern 2015). Innovations and incentives should include scientific tools that consider social structures and traditional knowledge to support and drive implementation. To coalesce public engagement, *"citizen science"* training (Wheaton et al. 2016) can be used to foster behavior change (Busch et al. 2019), leveraging readily deployable technologies (such as cell phone cameras), for estimating local soil carbon concentration (Liles et al. 2013). Such an approach would provide a feedback loop for regular updates of field protocols and investment portfolios. Multi-institution public–private collaborations would generate and transfer information from end users in coordination with stakeholders, providing co-benefits of spurring science literacy and granular data gathering in underserved communities.

Examples of spatial and temporal outputs of socio-ecological-environmental projections in the PNW include the effects of climate and land-use impacts on water availability (Jaeger et al. 2019, 2017), wildfire risk mitigation (Ager et al. 2017; Spies et al. 2014), and urban planning (Penteado 2021, 2013) under multiple climate-fire-development scenarios (Hulse et al. 2016) constrained by limiting resources (Wu et al. 2015; Wu and Johnson 2019). In all these examples, landscape simulations were used to explore how alternative policy strategies, land-use-climate feedbacks, and dynamic socio-environmental interactions affected land use change and key landscape productions and scarcities. The same systems can be used to assess carbon drawdown and permanence at local to regional scales. At the simplest level, carbon outcomes could be calculated from mapped land-use and land-cover outcomes. At a more sophisticated level, carbon drawdown and release could itself be incorporated as a modeled feedback to impact future decision making.

To develop a suite of contrasting policy scenarios that bracket plausible ranges of future variability, simulations of policy scenarios can be run under different climate scenarios derived from downscaled climate projections. The latter can be implemented using statistically downscaled climate scenarios using the Multivariate Adaptive Constructed Analogs method (Abatzoglou and Brown 2012) to a 4-km grid resolution. This archive contains output from 20 global climate models of the Coupled Model Inter-Comparison Project Phase 5 (CMIP5) including projections for historical (observed) forcings from 1950 to 2005, and for future Representative Concentration Pathways until 2100. Importantly, uncertainty in the timing, types, and locations of decisions (actions) and disturbances (events) can be simulated with stochastic mechanisms so that the variability within and among model runs of each scenario supports robust assessments of potential risks and benefits in space and over time. Industry and community stakeholders must be consulted in each case to capture local processes related to land-use and carbon dynamics for each sector across ownership parcels, county boundaries, and broader categories of land cover and soil types. For example, coupled models that captured climate, population growth, and policy choices as drivers of socioecological dynamics provided spatial representations of plausible variation in land-use patterns and carbon flows at multiple scales (from 2020 to 2100) based on water and land availability (Fig. 6). This type of analysis is heavily informed by stakeholders and social scientist who work with them to capture the effects of both bottom-up decisions

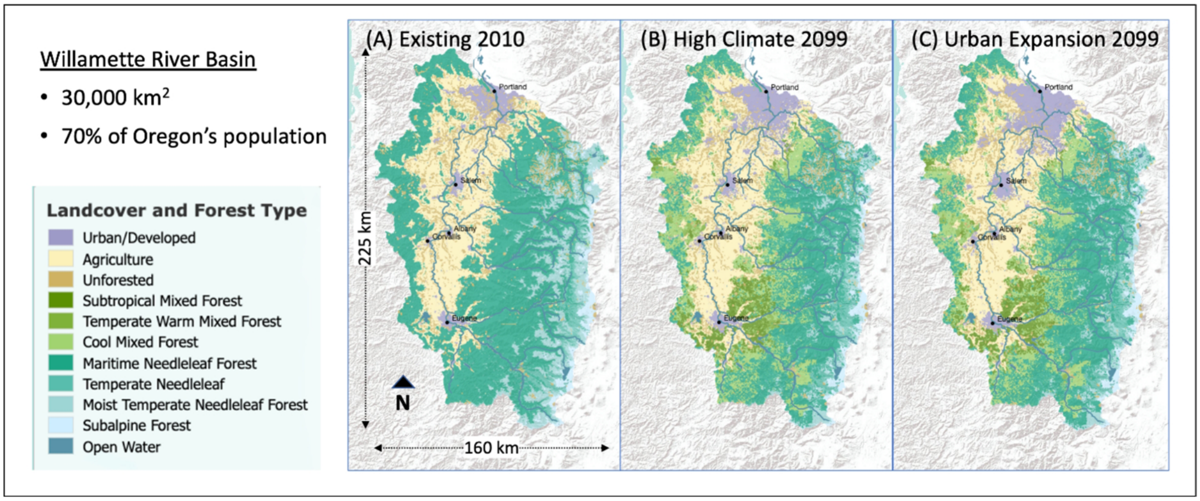

Fig. 6 Simulations of alternative futures scenarios for Willamette Valley, OR, USA urban expansion, rural land and water use. (**A**) 2010. (**B**) 2099 limited urban expansion due to high climate change impact. (**C**) 2099 unconstrained urban expansion (OSU 2022)

and top-down incentives across all relevant land-use sectors (Willamette Water 2100; Jaeger et al. 2017, 2019).

Final considerations

A pathway toward meaningful atmospheric carbon drawdown requires large ambitions tempered to the realities of biophysical and sociocultural constraints. Our framework for NCS + is an attempt to organize the components of that challenge into manageable steps that bridge between top-down and bottom-up processes and site-scale to regional scale planning and implementation. To this end, prescriptions and protocols arising from this framework should be accessible to a broad range of actors who are in positions to implement practices that improve socioecological resilience, accelerating innovation that transcends sectorial and jurisdictional boundaries.

Emphasis must be placed on cost-effective technologies to predict and monitor carbon stocks toward an integrated understanding of landscape metabolism (Marull et al. 2018). At the same time, ground truthing must be prioritized to accelerate information transfer and adoption of technologies at the necessary pace and scale, and to ensure adequate representation of the needs and values of all affected communities. Effective science education and communication is necessary to prevent maladaptive outcomes (e.g., those that can emerge from *"climate insurance"* in agriculture; Müller et al. 2017). This would address the ambivalence in carbon appraisal liabilities, which capitalize on growing climate change risks (Johnson 2014), and heighten uncertainties in mitigation potential (Betts et al. 2018). Crucially, co-production of knowledge with communities, and economic costs, are important barriers to the implementation of NCS +. Therefore, the design of research projects and implementation of prescriptions should include a mechanism of compensation to encourage the involvement of the local communities in regional plans. To this end, legal mechanisms could be explored based on precedents that are particular to each region, using existing funding mechanisms, as in compensation for the environmental impacts of pollution and oil spills.

The public trust principle imposes a sovereign duty on government to regulate greenhouse gas emissions which jeopardizes the stability of social and ecological systems, yet governments do little to enforce system change, which authorizes citizens to turn to the courts (Wood and Galpern 2016). Collective behavior can bring actionable insight to policymakers toward systemic change (Bak-Coleman et al. 2021) and major fossil fuel emitters now face potential liability for their actions. However, a quantitative and systematic plan for tangible atmospheric recovery is still needed. The legal impetus for such a plan is taking shape and, here, we argue that NCS + provides a unifying nucleus to orient environmental sciences and policy alike, perhaps providing a path for orienting collective behavior. A convergent regional focus to climate mitigation through NCS + would catalyze action across sectors while recognizing that the technical and social implementation potentials of climate change mitigation and adaptation vary among communities and ecosystems.

To devise tangible and scalable solutions, NCS + strategies should be tailored to landscapes in which production, conservation, and restoration can co-exist. Regional coordination of local implementation has the potential to contribute toward greater climate stability while improving people's livelihoods through landscape prioritization for both conservation and intervention. Spatial variability and time lags between land use and climate change can make it difficult to discern the actual benefits and costs of implementation across different sectors (Brown et al. 2019). Currently, the definition of best practices is sector-specific and dependent on an individual system's characteristics. However, the five NCS + principles provide a unifying nucleus for research and implementation across disciplines and land-use sectors. Opportunities vary widely among regions depending on types of land-based measures available, their potential co-benefits and risks, and their feasibility (Roe et al. 2021). Top-down investments (e.g., from policy and carbon markets) and country-specific policies that accommodate this complexity could help realize the large global potential from improved climate mitigation with major ecological and socioeconomic co-benefits. Breakthroughs are to be expected from science-driven policies that foster collaboration and attract investment to reduce uncertainties and inform decisions for generations to come.

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