PROJECT SUMMARY

Overview:

Catastrophic wildfires, dwindling water supplies, and rapid urban population growth are some of the most pressing challenges of the Intermountain West (IMW). However, the current services and resources available to urban and rural systems (URS) in the IMW leave communities ill-equipped to face these issues. The Transforming Rural-Urban Systems: Trajectories for Sustainability in the Intermountain West Research Network (TRUSTS-RN or Network) is a transdisciplinary research effort representing diverse communities, sectors, disciplines, and backgrounds aimed at improving regional sustainability. Using a convergent research and education plan, the Network focuses on how headwaters and headwater dependent systems, regional food-energy-water systems, and innovative institutions and approaches to governance can be integrated to help direct URS along trajectories that result in a sustainable future for humans and the environment. Network research projects and educational activities are designed to co-produce knowledge with regional partners across these three systems and utilize a novel framework for Guided Transformation (GT) that incorporates diverse perspectives, includes Indigenous and place-based knowledge, and values community and environmental well-being. Over the course of five years, the Network will: (1) improve our understanding of inter-linked URS system feedbacks, processes and actors; (2) create a diverse and engaged network of IMW partners to advance understanding of community needs and explore sustainable solutions; (3) train a new cohort of scientists and leaders with expertise in convergent, complex systems thinking; and (4) record and share the processes for developing sustainable URS through a GT framework.

Intellectual Merit:

This Network uses a convergent research approach to explore how a GT framework can be employed to build synergistic system connectivity across urban-rural gradients to promote sustainable cities, landscapes, and livelihoods across the IMW. The TRUSTS-RN's diverse academic disciplines and non-academic partnerships will embrace and integrate western and Indigenous cultural knowledge and use a system-of-systems research approach to advance the theory and applied knowledge of the dynamics, resilience, and transformational opportunities of URS. In so doing, the Network will increase traditional and western knowledge of regional sustainability with cultural open-mindedness and unprecedented scientific granularity, while identifying and addressing real-world ecosystem issues and community challenges. Through broad cross-disciplinary integration, the Network will create impact through fundamental and use-inspired science projects, advancing sustainability science through regional-scale implementation of projects in the IMW. The Network will advance GT theories for collaboratively and equitably transforming URS structures and processes towards sustainability.

Broader Impacts:

The Network will develop new and expand existing partnerships between universities, state/local governments, non-governmental organizations, and tribal, rural and urban communities. Research outcomes will advance understanding of GT and contribute to community and environmental well-being. Societally relevant outcomes include co-production of innovations in headwater systems, food-energy-water systems, and governance systems. The Network is highly committed to STEM diversity, equity, and developing a culture of inclusion. Convergent education activities will contribute to the training of undergraduate and graduate students, postdocs, and community members, including collaborations with tribal communities and tribal college students. The Network will serve to build capacity by training a workforce in sustainability principles, convergent research methods, and intercultural awareness using active, experiential, and inquiry-based learning approaches. Research will be shared publicly through the Transformation Blueprint, as well as our Extension Network, while curation of convergence-themed graduate courses, bootcamps, and micro-credentialing opportunities will train participants in GT theory and practice. Annual colloquia, a citizen science program, research internships, and science-meets-art initiatives will provide opportunities to broaden interests, build excitement, and engage new members as participants chart a path towards a sustainable URS future.

A. Vision, Themes, Goals, and Scope and Scale of the Research Network

"Overcoming the existential crises of climate change, a growing urban-rural divide, and growing economic inequalities demands action from all of us. We need new partnerships, inclusive approaches, and agents of change who will fight together for a sustainable future for our urban and rural communities and landscapes." - Congresswoman Deb Haaland in her opening address at our Sustainable Urban Systems workshop (NSF #1929769) on *Exploring Connections Between Urban and Rural Communities and Environments* (2019).

A.1 The Network

This call to action from Congresswoman Haaland was followed by a diverse array of speakers, discussion panels, and breakout sessions—all highlighting the extent of the challenges our region faces and also the extent of the innovative approaches being used to transition towards a sustainable Intermountain West (IMW). Those innovations include regenerative food systems based on traditional practices, web-based platforms for building resilience of food-energy-water systems, and grassroots organizations leading collaborative stewardship of headwater watersheds. The significance of linkages across space and time was illustrated by Dr. Ted Jojola, director of the University of New Mexico (UNM) Indigenous Design and Planning Institute. Dr. Jojola shared perspectives on Indigenous planning including the Seven Generations Model [1], which provides a useful framing for connecting human decisions with natural processes across time and space and for considering how human decisions change the trajectories of future generations. The need for convergent research that connects partners across sectors, disciplines, and worldviews was a consistent message throughout our workshop.

Our Transforming Rural-Urban Systems: Trajectories for Sustainability in the Intermountain West Research Network (henceforth: TRUSTS-RN or the Network) is a transdisciplinary research effort representing diverse communities, sectors, disciplines, and backgrounds. *Our aim is to advance basic theory and applied knowledge of the dynamics, resilience, and trajectories of sustainable urban-rural systems (SURS) through convergent research that catalyzes transformations in the way we use, manage, and protect environmental resources to improve well-being and to create a sustainable future in the IMW.* Our convergence research and education plans focus on headwaters and headwater dependent systems; food-energy-water systems (FEWS); and innovative institutions and approaches to governance (Fig. 1). We will characterize connections, dynamics, and resilience across gradients of urban to rural settings and explore innovative technologies and governance approaches to enable sustainable transformations. The Network will also contribute to building capacity to catalyze transformation of SURS. Our educational plan includes active, experiential, and inquiry-based learning approaches towards convergent practices and transformative capacity.

Our research partners are distributed across the IMW and include: UNM, Colorado State University (CSU), Washington State University (WSU), The University of Arizona (UArizona), Northern Arizona University (NAU), Utah State University (USU), New Mexico Institute of Mining and Technology (NMT), New Mexico State University (NMSU), and Sandia National Laboratory (SNL). UNM, UArizona, NMT, and NMSU are federally recognized Hispanic Serving Institutions (HSI). Our Network will build upon ongoing and emerging convergent research with a broad cross-section of partners, described in "B.1 Partnerships and Stakeholder Engagement for Impact".

Geographically, the TRUSTS-RN will focus on the IMW of the United States (Fig. 2). This region has exceptionally diverse cultures, histories, politics, and landscapes. The IMW also shares many common characteristics, including a reliance on mountain-derived waters,

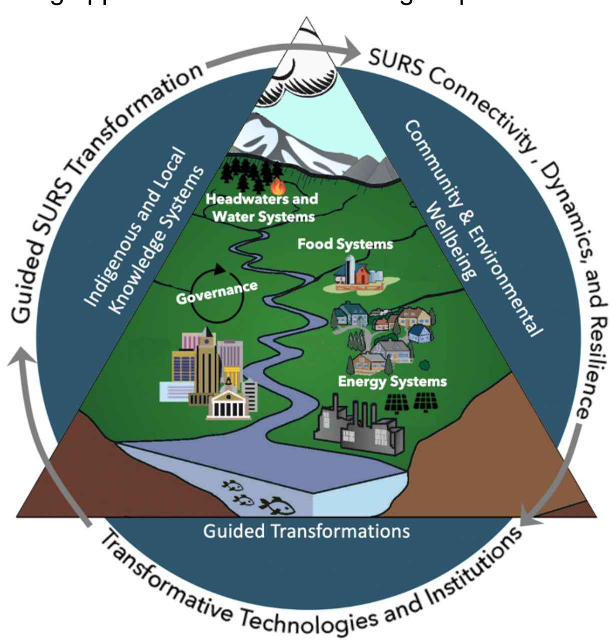

Figure 1. Conceptualization of the core-themes of the TRUSTS-RN.

challenges arising from climate change (e.g., drought and wildfires), rapidly expanding urban populations, depopulating rural communities, and a growing rural-urban divide. Similarly, the IWM shares sources of optimism for a sustainable future, including visionary leadership and local action from grassroots organizations, ample potential for renewable energy production, and dynamic and attractive communities and landscapes with the potential to transition towards SURS. Our approaches will be cross-scale including local communities, regional systems, and the entire IMW. Target regional systems include: (1) Albuquerque and the Upper Rio Grande and San Juan watersheds; (2) Denver and the Colorado Front Range Corridor; and (3) Spokane/Tri-Cities and the Inland Pacific Northwest (see section A.5).

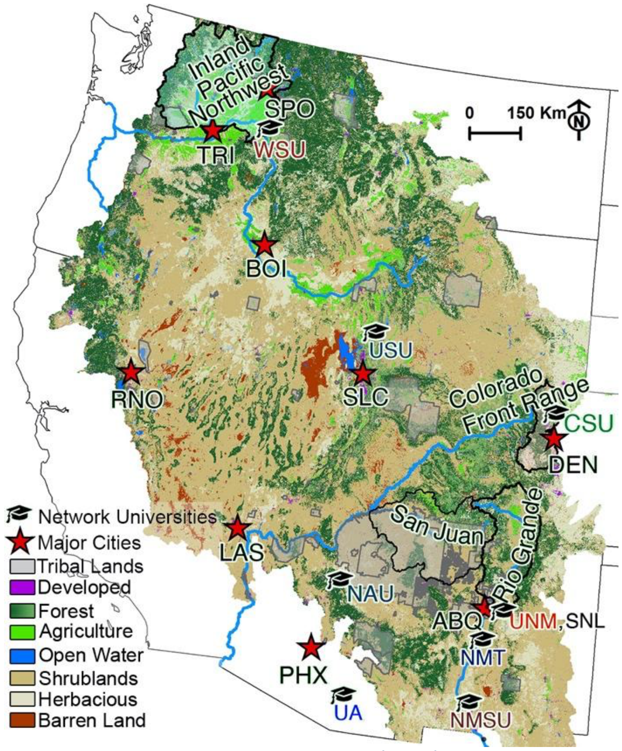

Figure 2. The Intermountain West (IMW) including tribal nations, major cities, and the universities involved in the Network. Cities are by airport codes except for Spokane (SPO) and the Tri-Cities (TRI).

A.2. Core Themes and Cross-Cutting Threads

Convergent research aims to address complex societal problems through the use of integrated knowledge, methods, and expertise from different disciplines. The TRUSTS-RN will form novel frameworks to catalyze scientific discovery and innovation and is designed to enable guided transformations towards SURS. Such transformations require a *deep, multifaceted understanding* of the current states of systems, connections, and dynamics across a gradient of urban and rural settings, and an assessment of the *vulnerabilities and opportunities* that can or could contribute to the transformation capacity of SURS. From there, *cooperatively developed innovations* across a spectrum of spatial, temporal, and social gradients create the long-term capacity to re-envision, re-design, and re-connect regional systems to better foster trajectories toward sustainable transformation. Our Network is organized around the conceptual model shown in Fig. 1, which focuses on the following three **core themes (CTs)**:

CT1. Resilience of headwaters and headwater dependent socio-ecological systems (Headwaters): Water supply is a direct physical linkage between urban and rural systems (URS). In the IMW, urban water supplies are primarily derived from mountainous headwater systems or aquifers that are predominantly recharged through headwater precipitation [2]. Human and ecological processes of population growth, urbanization, wildfires and droughts, compounded by climate change, interact to place severe strains on these water sources. Communities in the IMW are increasingly forced to develop alternative strategies to protect their access to water. We aim to catalyze, conduct, and synthesize convergent research that will help regions chart paths towards more resilient headwaters and headwater dependent systems. Our convergent research will focus on water security, the role that ecosystems play in reducing risks from climate change and other human induced disturbances, and the shared stewardship of watersheds. CT1 will address topics related to social-ecological systems resilience and sustainable regional transformations by building upon existing NSF funding (NSF-CNH #1826709, NSF-EAR #2101068, NSF-CBET #1916780).

CT2. Regional food-energy-water systems (rFEWS): Regional FEW systems are deeply intertwined in global food production, supply chains, and water and energy management. Small and mid-sized regional food producers make significant contributions to food security, and rFEW systems require new pathways to achieve social, economic, and environmental sustainability. Regional FEW systems interconnect with other rFEW systems as well as contributing to global FEW circuits. Within the Network, food and energy systems have large external components, while water systems are primarily encompassed in the geographical rFEW footprint as headwaters. Supply chains and markets connect rFEW systems to both global and other regional FEW systems [3] [4]. We will investigate rFEWS and their transformative capacity across scales from local communities to the IMW region, including market connectivity and potential, risk assessments, regenerative agriculture innovations, innovative greenhouse technologies, food sovereignty for Tribal Nations, expanded use of non-potable water, and energy system transitions. CT2 will build upon existing NSF funding (FEWSION Award #1639529, ColumbiaFEW Award #1639458, NSF REU-INFEWS Award #1950877: Indige-FEWSS Award #1735173, and InTERFEWS #1828902).

CT3. Innovative Institutions and Governance: Governance systems comprise the formal and informal institutions, processes and relationships that facilitate social coordination. Hierarchical, market-based, community-based, and hybrid governance modes are different forms of achieving this coordination [5]. Over the past several decades, various governance approaches aimed at achieving sustainability have emerged, featuring a wide range of structures and approaches with a general shift away from hierarchical governance approaches toward more inclusive and participatory approaches, including structures that revalue ecosystems and their contributions, and depend on collective action from myriad stakeholders who design the rules and implementation [6] [7]. We will focus on local and regional governance systems, where and why new collective responses and governance systems are emerging, and the factors that facilitate the likelihood of success of new responses including the role of science in informing ongoing adaptation. Governance systems that can equitably adapt to change are central to any effort to enhance the resilience and sustainability of regional systems. CT3 will build upon existing NSF funding (NSF-CBET #1929824).

Our three CTs are interconnected by the following three **cross-cutting threads (CX)**:

CX1. Guided transformation and transformative capacity: The design and analysis of system transformations ties together concepts of resilience, sustainability, and governance. Transformations occur when a system's identity shifts from one regime to another with different structures, processes, or outcomes [8]. Transformations can occur from both intentional and unintentional disruptions (e.g., new infrastructure, natural disasters) and changes in social-ecological context (e.g., economic incentives, demographic shifts, climate change) [9]. Intentional transformation requires high transformative capacity within governance and economic structures, stakeholder interactions, and responding to the social-ecological-technological context [10] [11]. Transformative capacity framework analysis has been successfully applied to urban and connected rural-urban river basin management to identify and quantify constraints and intervention points [12] [13]. This cross-cutting thread will focus on the transformative capacity of urban-rural connected systems, barriers to implementing resilient and sustainable trajectories, and combined bottom-up and top-down frameworks for guided transformation. CX1 will include quantitative and qualitative analyses of past transformations, the impact of emerging multiform water governance models on transformative capacity, and convergent research on trajectories of resource reallocation between rural and urban communities, and during rural and urban transformations.

CX2. Indigenous and Local Knowledge Systems: When researching headwaters, rFEW systems, and governance systems in the IMW, it is essential to acknowledge that prevailing research and educational methods are rooted in colonial knowledge and approaches [14]. For millennia, Indigenous Peoples across this region have sustained their unique worldviews and knowledge systems even while outside powers attempted to destroy their knowledge and cultural systems. An extensive repository of knowledge comes from a deep and long connection to a particular landscape and embraces sustainability and resilience in a way that cannot be reduced to conventional western research and teaching methodologies [15] [16]. Western research and teaching often exclude place-based knowledge in the development of research questions, data collection and analyses, and implementation of research findings. Transformative URS research will require careful attention to researcher positionality, ethical data collection and use, and careful, decolonial collaborations with community partners that investigate problems that are important to residents and communities. This type of transdisciplinary research is also considered critical in breaking historic practices and approaches to governance that impedes adaptation [17]. CX2 will connect and enhance convergent research projects that are grounded in co-generation of knowledge with diverse perspectives including Indigenous and local knowledge, values, and methods of discovery.

CX3. Community and Environmental Well-being: Systemic changes impact community and environmental well-being and can result in trade-offs among different social and ecological outcomes [18]. Engaged, co-produced processes can lead to innovations to meet multiple aims, but in other cases, trade-offs occur such as armoring a riverbank that protects riverside property while degrading fish habitat [19], or amenity and visitor-based local economic development changing local power dynamics and introducing conflicting cultural values [20]. The benefits and burdens can be evaluated using traditional metrics (income, race and ethnicity, age, environmental health indices) to demonstrate which human and ecological communities or groups within communities benefit from the changes, how new burdens are distributed, or how ecosystem health changes. Nuanced measures such as assessments of satisfaction and well-being, holistic views of environmental integrity, intrinsic ecosystem values that may not directly benefit people are also needed to elevate values and priorities as well as conduct broad assessments of long-term outcomes [21]. Deeper integration of economic, social and ecological dimensions of urban-rural well-being underlies the potential for collaboration to overcome the inequities from trade-offs [22]. CX3 will explore, conceptualize, and develop metrics for evaluating synergies, innovative approaches, collaborative paths, as well as trade-offs among potential well-being outcomes.

A.3 TRUSTS-RN Research Goals

To support our vision for transformations towards SURS in the IMW and to integrate the CTs and CXs of our Network, we will pursue the following four goals:

1. Develop a research network that builds institutional capacities and governance strategies needed to set the IMW region and sub-regions on trajectories for transformation towards SURS.
2. Engage in convergent research to analyze and explain the structures, functions, and interactions of interconnected SURS based on resilience theory and other theoretical and applied frameworks.
3. Explore socioeconomic, governance/management, and technological strategies that create trajectories and pathways towards interconnected SURS.
4. Co-envision and co-generate a Transformations Blueprint for the IMW that advances convergent practices and builds transformative capacity.

A.4 Conceptual Model and Key Concepts

We define urban-rural systems (URS) as interconnected natural, social, and built systems along a gradient of urban-to-rural environments. We define sustainable urban-rural systems (SURS) as URS that are collaboratively and equitably transforming their structures and processes towards sustainability. Our Network approaches the concept of SURS transformation using a novel framework that incorporates conceptual elements of: (1) socio-ecological systems (SES) resilience theory; (2) sustainability transitions research (STR); and (3) linked social, ecological, and technological systems (SETS) theory. In this section, we first summarize key principles of these foundational frameworks. Next, we introduce our guided transformation (GT) conceptual model. Finally, we describe the connections between our conceptual model and interconnected URS and SURS.

Background on Principles of Resilience and Transformation: Resilience theory has been advanced through the fields of ecology, engineering, and psychology. We adopt SES resilience theory as originally conceived by Holling [23] and advanced by Walker & Salt [24] and others. Specifically, we focus on *resilience as the capacity of a system to absorb internal and/or external change while exhibiting a similar set of structures and processes* (i.e., maintaining the same system identity or state). If a system's resilience is compromised by shifting demographics, climate change, natural disasters, and other factors, it potentially becomes more vulnerable to transformational change—shifting the SES from one state to another state characterized by a different set of structures and processes [25]. It is important to note that **resilience does not represent a positive or negative attribute of a system**; but rather the system's resistance to changing states as the result of a disturbance. Our Network is focused on the concept of system identity to capture the human and natural dynamics that shape the interconnections within URS. Resilience in this context describes a suite of social, ecological, and technological system properties. The TRUSTS-RN will focus on system dynamics and processes that form a system's identity and the importance of community members' "mental models" in determining the state of that identity, as well as internal and external drivers that influence its capacity to maintain that identity. After the system state is characterized, frameworks can be developed to identify desirable and undesirable characteristics of the system state, perturbing factors and disturbances, and capacity to control those factors [25] [26].

Sustainability transitions research (STR) is a rapidly evolving interdisciplinary field focused on the challenge of promoting and governing transitions towards sustainability [27]. STR research focuses primarily on socio-technical systems including food, water, and energy supplies. Such systems consist of networks of actors (individuals, firms, organizations, etc.) and institutions (societal and technical norms, regulations, standards of good practice) that interact to provide services for society [28] [29]. STR emphasizes the importance of these interactions to understand system dynamics and system transformation with a forward-looking emphasis [30].

A number of conceptual frameworks have emerged in the STR field, the most prominent of which is the Multi-Level Perspective (MLP) [31]. The MLP framework argues that transitions come about through dynamic processes within and between three analytical levels or scales: (1) *niches* at the local-scale – protected spaces allowing for radical innovations; (2) *socio-technical regimes* at the meso-scale – the institutional structuring of existing systems or the status quo; and (3) the *socio-technical landscape* at the macro-scale – government policies, global markets, and supply chains [32]. Within the MLP framework, transitions in socio-technical regimes arise through innovations at the niche scale, but the existing regimes (status quo) will commonly act to resist transition. The opportunity for a break-through is increased when the socio-technical landscape puts pressure on the regime for changes such as new regulations, tax incentives, or shifting consumer preferences [28].

Yet, techno-centric approaches focused predominantly on infrastructure to manage resources and withstand disturbances fall short in complex systems. The social-ecological-technological systems (SETs) approach emphasizes the importance of thinking beyond technology and infrastructure to the complex social and ecological processes that interact with infrastructure [28]. The SETs approach highlights the constraints inherent in the complex interactions and interconnections between social, ecological, and technological subsystems that "lock-in" vulnerabilities, constrain adaptation, and lead to fragile systems [33]. Lock-in is a constraint on existing infrastructure decisions resulting from past decisions and actions [34], such as construction of levees and associated floodplain development. Applying a SETs approach to landscapes reveals how interactions within complex systems, particularly human responses, influence whole system reaction to disturbances and extreme events [35] [36]. While the SETs literature emphasizes misalignments and constraints to infrastructural resilience, the interactional approach is likewise critical to transdisciplinary efforts, shared learning, collaborative decision-making, and building in multifunctionality within SETs [37]. Guided transformations help to overcome lock-in and can shift SETs to new desired and more sustainable states.

The Guided Transformation (GT) Conceptual Model: Building upon the transformability principles introduced by Folke et al. [8] and others, we propose an integrated model for Guided Transformation (GT) that builds upon SES resilience principles and adds the forward-looking perspectives of STR including the principles of multi-level connections (top-down and bottom-up controls). Further, we incorporate the SETs approach – especially the concepts of interconnections between subsystems and lock-in vulnerabilities that often constrain adaptation [33].

Our conceptualization is illustrated in Fig. 3, where Fig. 3a represents the well-established *basins of attraction (BoA)* model for SESs [36]. Each dip in the curve represents a *system state* in which the SES resides. Fig. 3a contains three potential system states: (1) the current or status quo state; (2) an undesirable state following a disturbance (e.g., catastrophic wildfire); and (3) a desirable system state (e.g., SURS). The depth of each basin of attraction represents the system's resilience to changing to an alternative state and the peak of each curve represents the threshold(s) to change. The black arrows represent different types of disturbances (positive or negative) that can potentially drive the system to a new state. In the conceptualization presented in Fig. 3a, a negative disturbance pushes the system towards the undesirable state and a positive disturbance pushes the system towards the desired SURS. However, neither disturbance overcomes the system's resilience and it remains in State 1.

Figure 3b incorporates principles of bottom-up mechanisms acting to increase or decrease system resilience and hence increase or decrease the likelihood of transformation. The change in resilience is represented by increasing or decreasing the depth of the BoA. Adaptation increases resilience through internal adjustments when current conditions are desirable. On the other hand, lock-in can also increase system resilience, but often in an undesirable direction because it discourages transformation away from the status quo. Conversely, stressors can reduce system resilience and increase the likelihood of system transformation (e.g., extended drought increases the risk of catastrophic wildfires). When the current system state is undesirable (e.g., inequitable food security), innovations can decrease resilience and catalyze change. In the conceptualization of Fig. 3b, resilience was decreased, and the negative disturbance pushed the system beyond the threshold and transitioned the system to the undesirable State 2. In this example, the positive disturbance was inadequate for transformation to State 3.

Figure 3c represents the process of GT through the combination of bottom-up and top-down interventions, as characterized in the STR MLP framework. Top-down controls such as new policies, tax incentives, and pandemics act to '*tip the scale.'* GT involves the strategic combination of bottom-up (e.g., innovation) and top-down (e.g., tax incentives) strategies to develop trajectories towards a desired system state. In the illustration, bottom-up innovations reduce system resilience of the undesirable state and top-down mechanisms tipped the scale towards the desired system state, resulting in the desired trajectory to State 3. Similarly, the undesirable State 2 was guided towards the original system State 1 (e.g., pre-wildfire).

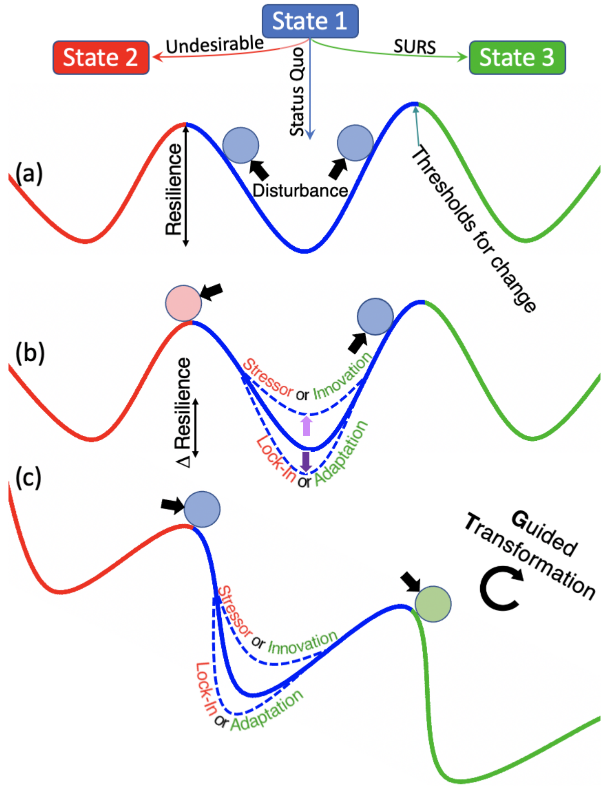

Figure 3. Conceptual representation of the GT framework based on SES, STR, and SETS concepts.

Connectivity, Dynamics, and Transformation of SURS: Urbanization is one of this century's most transformative trends [37] [38] [39]. Urban activities have strong impacts on the natural environment and their scale of influence far exceeds the urban boundary. In the IMW, approximately 50% of the population lives in towns and cities with populations over 10,000 people, and 25% in cities over 100,000. However, these developed areas account for only 1.5% of the land cover. Between 2010 and 2015, the estimated population in cities over 10,000 grew by nearly 12% and population growth was nearly 20% for cities with populations over 100,000. These figures and trends underscore the importance and urgency of managing urban-rural linkages and dynamics in order to foster transformations towards SURS.

Rural and urban spaces are connected through the flow of people, goods, and services. Although distinct in forms of living and different across numerous political and social measures, they are mutually constituted. Interconnections within URS come in many forms, including rFEW systems [40] [41] [42] connect people and resources; economic and cultural connectivity, including workforce exchange, economic interdependencies, and exposure to natural hazards [43]; and adherence to multiple governance structures, such as federal laws for water and natural resources management, tribal sovereignty, and state or regional governance [44] [45]. These interconnections occur over a wide range of scales with great variability between sectors (e.g., energy, water, and health) and systems [46]. At the same time, urban centers require resources such as water, forest, arable land, and minerals, and social resources including people for the urban workforce. Rural areas face challenges that include loss of cultural identity, decreased populations, reduced social services and jobs, and problems due to poverty and substance abuse [47]. In at least some cases, these changes have reduced the resilience of rural systems to both natural and human-based disturbances [26] [48]. Because of the interconnections, the loss of resilience in rural systems influences associated urban systems. For example, decreased forest health, increased wildfire frequency and severity, and increased energy production in rural settings all have a strong potential to impact the security of urban water supplies [49] [50]. Bryant et al. [51] argue that rural areas can also replenish clean water and fresh air, and supply food, energy, and materials for hungry cities. Many solutions for a sustainability transition are already known, adopted, and tested by some early actors, or are in advanced stages of development. Entrepreneurial energy fosters urban-rural connectivity, decreases spatial disparities [52] and can lead to collaborative tools that are not restricted to market-based exchanges. Within our GT framework, characterizing the connectivity and dynamics of SURS will require improved knowledge of system elements (e.g., infrastructure, FEWS supply chains, policies), actors (e.g., Tribal Nations, municipalities, industry, non-profit organizations), and the factors controlling system stability and system change.

A.5 Scope and Scale

Challenges in the Intermountain West: The call to action by Congresswoman Deb Haaland invokes research, education and engagement on challenges and issues of high complexity requiring involvement of many experts and partners and integration of these issues across multiple scales. In response, our Network is designed as a cross-scale collection of research, education, and partnerships ranging from individual communities to the entire IMW. The full network extends across six states, dozens of Tribal nations, multiple major watersheds, and eight major urban areas (Fig. 2). The overlapping and interconnected regional systems that comprise the IMW are facing a similar set of threats and opportunities with respect to pathways to SURS. Challenges across this semiarid region are characterized by a dependence on snowmelt runoff for water supplies [52], widespread reliance on irrigated agriculture [53], over allocation of water supplies [54], rapidly changing energy systems [55] [56] and forested watersheds that are threatened by urbanization, wildfires, pests, and drought [57] [58] [59].

The impact and severity of these challenges depend in large part on the nested local and regional socio-economic and cultural dynamics that dictate how communities can transition to SURS in light of a complex set of connected issues related to these challenges. Managers trying to confront or mitigate impending resource issues in the IMW must contend with hydrologic, food, and energy system boundaries that often do not align with geographic, jurisdictional, or tribal boundaries. Historically, Indigenous Peoples have migrated based on resource availability, but today are confined to reservation boundaries with limited food, energy, and water availability and off-reservation subsistence. This is compounded by legacy effects of colonization which have reduced the adaptive capacity of Indigenous communities. Many IMW characteristics share similar issues and approaches of its semiarid regions, including resource constraints and allocations, policies, and environmental stewardship. Indigenous communities view these challenges differently and require a cultural and decolonized approach.

The proposed, comprehensive TRUSTS-RN is designed to tackle the complex resources issues in the IMW by taking a system-of-systems approach to understanding and empowering URS towards sustainability and resilience. We bring together a broad network of researchers, stakeholders, tribal, and community groups to help shape the regional understanding of overlapping biophysical, sectoral, social, and cultural challenges while simultaneously leveraging this network to explore where local pitfalls and successes in one area may help other areas overcome or transform under similar challenges. *Acting as a central hub, the TRUSTS-RN will generate new, co-produced knowledge (Task 1), integrate and co-produce ideas, investigations, and insights on strategies for sustainable transformation (Task 2), and serve as an information broker (Task 3) across the IMW system-of-systems*.

Through the TRUSTS-RN, we will study supra-aggregations of connected SURS within the IMW. We will emphasize URS in the regions we define as the Upper Rio Grande/San Juan River, Colorado Front Range Corridor, and Inland Pacific Northwest (see Focus Study Regions below), and we will also work with collaborators and partners in the Network to identify other relevant URS of interest. Through convergent research approaches within the research network, we will integrate the following elements to advance the sustainable regional system science through: (i) *data and mixed methods* to collect, synthesize, characterize, and model interdependencies in SURS; (ii) *outcomes* that highlight the co-benefits and well-being of human and natural systems and build transformative capacity; (iii) novel *theories of change* for Guided Transformation based on SES, SETS, and STR frameworks; (iv) *generalizable theories* on scalability of innovations to SURS evaluated through mixed-methods approaches and multi-scale systems dynamics models; (v) innovative *systems dynamics modeling* of multi-layered systems that will capture the depth and complexity of layered and nested URS; (vi) *stakeholder participation* with emphasis on convergent co-innovation and community-participatory research; and (vii) *equity*, recognizing the historical exclusion of Indigenous rights and values in environmental management and the importance of Indigenous and Local Knowledge and community-driven research as a vital component for transitioning towards SURS.

Successful History of Collaboration: Our research scope is achievable within the cost and timeframe of this proposal due to the history of productive collaboration already established by institutions and partners in our Network. Our Network will coordinate eight universities with over two dozen partners including Tribal entities, state and federal resource agencies, municipalities and utilities, and non-governmental organizations. The Network will leverage resources from a variety of existing and former research projects including four NSF-FEWS grants, multiple NSR-NRT grants, and two NSF Centers of Research Excellence in Science and Technology grants, amongst others (see Prior NSF Support).

Focus Study Regions: Though many regions in the IMW share similar challenges and characteristics, we will use the existing collaborations of our Network to focus our efforts on three regions that contain major urban areas with large connected rural areas as well as unique headwaters: *Albuquerque–Upper*

Rio Grande/San Juan River Region (URG/SJ), *Denver–Colorado Front Range Corridor (CFR)*, and *Spokane/Tri-Cities–Inland Pacific Northwest (IPNW)*.

Albuquerque–Upper Rio Grande/San Juan River Watersheds: The Albuquerque Metropolitan Area (population nearly 1 million), the largest urban center in New Mexico, depends on water stored as snowpack in the Rio Grande and San Juan River basins. These two basins arise in the Sangre de Cristo and San Juan subranges at the southern extent of the Rocky Mountains. Our Network will focus on the Upper Rio Grande (URG), defined as the area above Elephant Butte Reservoir in central New Mexico. The San Juan River (SJ) flows over 600 km before entering the Colorado River at Lake Powell. These two rivers are linked by a transbasin water transfer that diverts 123 million m^3/year from the SJ to the URG, and which is a critical water supply for the Albuquerque Metropolitan. The URG is home to 18 Pueblos (Tribal Nations) and portions of Navajo Nation and the Jicarilla Apache Reservation. The SJ borders the Ute Mountain Ute Tribe, Southern Ute Tribe and Jicarilla Apache and flows across 443 km of the northern border of the Navajo Nation along with the tribal border town of Farmington, NM serving as an urban regional supply center for the tribes. Irrigated agriculture is an important economic and cultural practice with a history dating back for millennia by Native Americans, expanded upon by Spanish Settlers via acequias (technology imported from ancient Arabia and Spain), and expanded again into irrigation districts by Anglo settlers. The URG/SJ watersheds have experienced hydrologic change as a result of climate change in recent decades including a 25% loss in spring snowpack since the 1950s [60].

Denver–Colorado Front Range Corridor: The Denver–Colorado Front Range (CFR) Corridor is over 300 km long and contains nearly 5 million people, including major population centers of Denver, Fort Collins, and Colorado Springs. The CFR defines the eastern edge of the IMW and is characterized by an abrupt shift in elevation as the Rocky Mountains rise from the Great Plains, extending from near the Colorado-Wyoming border in the north to the city of Pueblo, CO, in the south. In addition, this region is the headwaters for the South Platte River (~63,000 km^2) and its numerous tributaries, including the Cache la Poudre River, Big Thompson River, and Boulder Creek [61]. Like the URG watershed, the South Platte River is supplemented by transbasin water deliveries from the western side of the continental divide. The region depends on 17 transbasin delivery projects to feed the growing population and agricultural needs in the CFR. Watersheds of the CFR are undergoing rapid biophysical change due to extreme stressors exacerbated by climate change, including massive forest die-off from pine beetle infestations [62], reduced snowpack runoff [63], and recently the largest wildfires in Colorado's recorded history burned through the Cache la Poudre watershed [64].

Spokane/Tri-Cities—Inland Pacific Northwest: Containing major urban areas, including Spokane (population over 200,000) and the Tri-Cities (population over 300,000), the Inland Pacific Northwest (IPNW) lies within the vast Columbia River Basin (CRB). With an area of 671,000 km^2, the CRB spans seven US states, one Canadian province, and 13 federally recognized Native Nations. Climate change is reducing snow storage, advancing timing of peak spring runoff, and altering peak and low flows [65] which is contributing to wildfire seasons that are longer and more damaging over a wider spatial domain [66]. Meanwhile demographic changes are placing new demands on water and energy resources across a diversity of landscapes, economies, and cultures [67] [68]. The dams on the Columbia River and its major tributaries form the backbone of the IPNW's economy, providing 60-70% of the IPNWs electricity, controlling floodwaters, irrigating vast tracts of farmland, and forming an extensive navigation system [69]. However, these benefits have come at a high environmental cost, including reduced annual salmon runs vital to Yakama Nation, The Confederated Tribes of Warm Springs, Nez Perce Tribe, and The Confederated Tribes of the Umatilla Indian Reservation [70].

Coordination of Research Across Focus Study Regions: Research tasks, described in Section B, will focus on one or more study regions depending on our partnerships and the unique characteristics of each region. However, our goal is to develop generalizable findings that extend beyond an individual study region, and this goal will be on the forefront of our research task coordination.

A.6 Convergent Research

Convergent research has two primary characteristics that it is: (1) driven by a specific and compelling problem and (2) involves deep integration across disciplines. Convergence research is central to the work of our Network, as we create new and novel frameworks to address complex challenges in the IMW that are driven by a societal need. These complex challenges stem from a changing climate and its associated land use changes (e.g., water security; natural hazards from flooding, wildfire and drought;

policy and technology driven change in energy systems; and social justice issues stemming from FEWS disparities). We will engage in convergent research through our Network in the following ways.

Strategies for transdisciplinary integration across disciplines and partners: Our Network will engage in a transdisciplinary research that is horizontally and vertically integrated [71] [72]. Our logic model for convergent research and education (Fig. 4) is centered on the concept of building a *university-community incubator* that fosters a convergent culture by incorporating diverse perspectives as input, collaboratively integrating research and educational activities, and co-producing outputs with value for all partners. We will continue our engagement with non-profit, tribal, industry, and municipal partners in the research design, data collection, knowledge production, and dissemination. One key element in our convergent research design is equitable partnerships with Indigenous communities where research questions and educational activities are community-driven, Indigenous knowledge is valued and foundational to the project, and the research steps are centered within the Indigenous epistemologies and values. We seek guidance and direction from the Indigenous Resilience Network consisting of Indigenous partners across the IMW. From a convergent research standpoint, the opportunity to work with varying ontological as well as epistemological perspectives increases our capacity to reach the overarching goal of convergent research - to develop truly new ways of seeing and approaching the world to address the challenges we face. To date, most convergent research has focused on the technology fields including nanotechnology, biotechnology, information technology, bioengineering, and cognitive sciences. The National Research Council [73] notes the need to better integrate a broader range of academic fields, including the social sciences and humanities included in this proposal.

Creating a convergent research culture across the Network: To foster convergent research and address the multi-institutional nature and large scope and scale of the Network, the shared commitment to convergent research by our academic and non-academic partners will create the capacity for success [74]. Specific examples of how we will foster a convergent research culture include: trainings and webinars on convergent research; Network incentives for work that advances convergent research scholarship; ongoing reading groups; trainings on conducting research with tribal communities, tribal consultation, and cultural humility (e.g., CITI Native American module).

Creating an integrated research design that will foster convergence: By its very nature, a convergent research design requires deferral of major decisions until after community partners can be fully engaged.

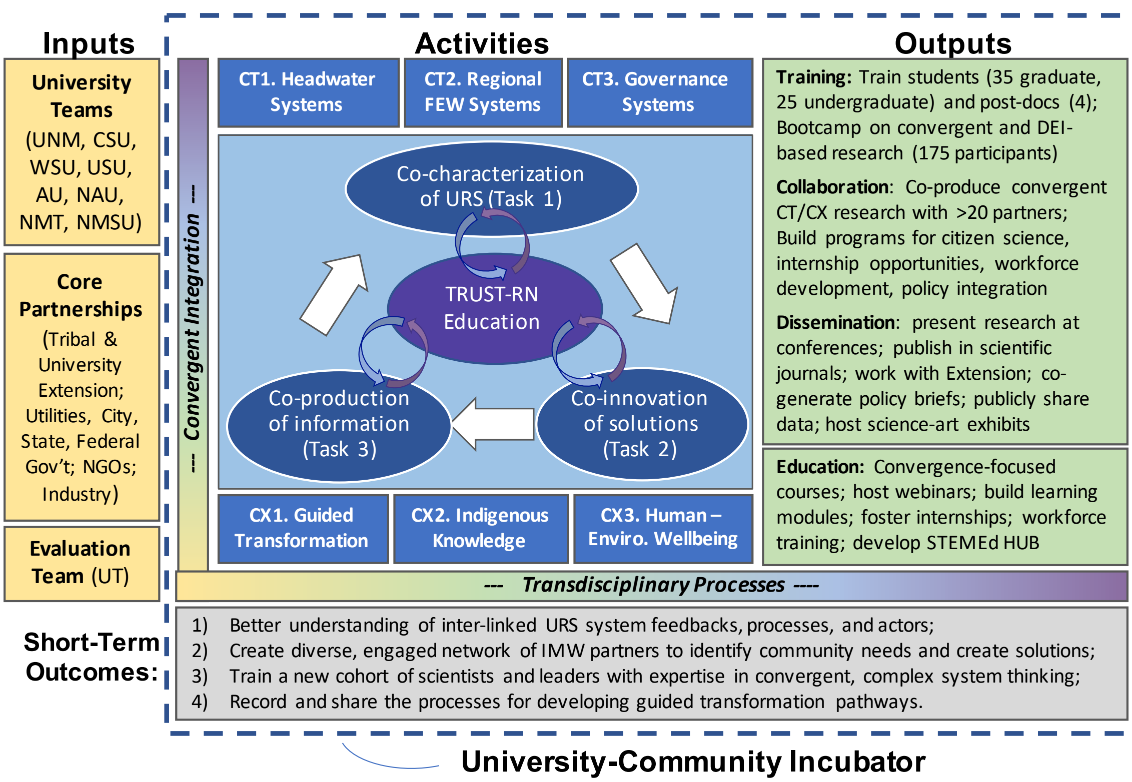

Figure 4. Logic model for transdisciplinary integration including input, activities, output, and outcomes.

This is an ongoing process that does not typically match externally imposed deadlines. As such, the research and educational activities described in this proposal have varying degrees of specificity. In some cases, years of convergent research have allowed us to quickly identify convergent research and educational needs, as described below. In other cases, the process of developing meaningful convergent research questions and educational programs will require deeper community engagement and take time.

A.7 Diversity and Culture of Inclusion

The Network vision for diversity, equity, and inclusion (DEI): We will set anti-racism as a core value and nurture a culture of inclusion through diverse, equitable, inclusive, and just collaborations and partnerships. We recognize that white privilege is deeply embedded in our educational systems and that policies targeting collaboration with members of disenfranchised groups in STEM often fail to be sustainable. Black, Indigenous, and People of Color, LGBTQIA+ individuals, women, and individuals with disabilities also frequently face additional burdens in daily exchanges including microaggressions, tokenisms, and othering. Nurturing a culture of inclusion can only be successful if and when all members of the Network recognize manifestations of privilege in working relationships and acquire skills to actively oppose such ideas, cultures, and policies. This is because inclusion is a matter of process while diversity is a matter of representation. In all fields, race, ethnicity, sexual orientation, or gender, diversity of participating members cannot be achieved without truly nurturing a culture of inclusion. Equitable partnerships ensure all members enjoy the same quality of experience through our program, and justice ensures that we eliminate barriers that keep disenfranchised individuals out of the STEM field.

Our DEI plan: To ensure that our collaborations and partnerships will be meaningful and sustainable, we will begin with completing antiracism and equity training to: (a) begin building trust, (b) establish a common/superordinate identity as a team, (c) identify root causes of disparities in resources and factors explored in our research, and (d) learn to apply an equity lens in our project. We will address institutional and systemic racism throughout our research and network activities by acknowledging social and environmental injustices in the past and the present, recognizing the inequity within the paths towards sustainable futures, uplifting the needs and voices of minoritized, disenfranchised, and historically excluded communities, and establishing mechanisms to annually benchmark, report, review, and improve our antiracism and equity work to create a mutually beneficial inclusive culture in which all members feel valued and welcomed. We will incorporate aspects of NSF Inclusion by establishing a decentralized alliance to connect academic institutions, industries, and communities with shared goals to (i) develop STEM identity and skills through experiential learning that foster intercultural fluency and empathy, (ii) empower learners through professional and leadership trainings that result in skills and credentials valued by relevant industry members, and (iii) create authentic mentorship and leadership opportunities through connecting participants in the decentralized alliance and beyond.

B. Research Program

B.1 Partnerships and Stakeholder Engagement for Impact

Building upon this existing capacity, we will build an engagement framework that connects practitioners, policy makers, and researchers and educational programs to train the next generation on conducting convergent SURS research and engagement. In building our research network, we are leveraging the strong connections and intellectual frameworks already developed through years of collaboration. For example, UNM and CSU have collaborated on workshops to investigate rural-urban resilience with partners in the southwestern USA. WSU and UNM have collaborated to form an international research network known as the Transect of the Americas involving ten universities in eight countries. UArizona has worked with the Navajo Nation and Diné College since 2011 on community driven water research (e.g., The Gold King Mine Spill of 2015); tribal extension and outreach; tribal college and community training; and capacity building. These partnerships developed into a NSF NRT Training program to train graduate students to have intercultural awareness and FEWS transdisciplinary training to work in Indigenous communities to co-design FEWS solutions.

In the TRUSTS-RN, stakeholder engagement is embedded through: (1) co-production of knowledge described in section A.6 and detailed in the remainder of the Research Approach; (2) participation of key stakeholders on the advisory board (see Project Management Plan), in the incorporation of citizen science in research (e.g., project 2.B.3); and (3) in the education plan (see Activity 2). In the co-production framing, we refer to 'stakeholders' as equal partners in the research process. Project Personnel (listed in section F.1.a) have engaged with each of our partners listed in section F.1.b extensively through previous and ongoing NSF and non-NSF funded projects, which, in turn, have had substantive stakeholder engagement efforts related to the CTs in this proposal. These stakeholder engagement efforts along with additional recent communications in preparation of this SRS-RN (including two SUS workshops hosted by Network members, NSF #1929769 and # 1929824) have resulted in the framing of TRUST-RN research goals, task specific questions, and the detailed projects described below.

Our research and education efforts towards SURS start regionally through our partnerships, build from many ongoing community efforts (e.g., water funds), and will leverage the Cooperative Extension Service (CES). Our partnership network ensures the capacity for IMW wide potential of implementation of co-produced knowledge. For example, our work on regenerative food systems in Task 2.B is based on local food producers in Washington who are implementing sustainable practices on larger farms and scientists assisting in the evaluation of their progress in terms of soil health, economics, and yields. In New Mexico and Arizona, ongoing collaborations between researchers and Navajo food producers and the Quivira Coalition are improving food security. Together and iteratively, this co-production of knowledge results in continual evolution and implementation of these new innovations. We will rely on similar partnerships by the 32 researchers involved who have identified over 45 existing collaborations.

Our Network partner list includes trusted connectors to actors and innovators in the landscape, groups with deep traditional, technical and ecological knowledge, and communication experts. Connectors are provided by: five land-grant universities in the Network and their associated CES with a presence in every county of participating States and a national reach; Tribal Nations; County Soil and Water Conservation Districts; state and local government entities (e.g., the Albuquerque Bernalillo Water Utility Authority, City of Albuquerque Emergency Management, the Washington Department of Agriculture), and by partnership organizations (e.g., New Mexico Tribal Resilience Action Network, Peaks to People, Sustainable Obtainable Solutions, Western Center for Metropolitan Extension and Research). These partners provide place-based connections and expertise with long histories of supporting translational research and implementation amongst communities and researchers.

We are committed to nurturing tribal and community partnerships where trust is critical for equitable participation and collaboration in our proposed convergent research. We will ensure that we develop sustainable trajectories with academic-community relationships that will build on trust, respect, and an understanding that shared history often places tribes and communities on divergent paths. This will create the foundation for moving towards a sustainable future and for the co-production of knowledge across contrasting histories and perspectives. For example, improved knowledge and outcomes for water management projects may result from the integration of Indigenous and western sciences [75].

B.2 Research Approach

The three CTs (headwaters, rFEWS, and governance) can be represented as three interconnected domains (Fig 5). Headwaters are defined through biophysical boundaries; the rFEWS system can be described as a network via supply chains; and the governance system is represented by the social, institutional, and legal conditions that assign jurisdiction. Our approach is separated into three overarching tasks that will be carried out for each subsystem and then for the interconnected system of systems. First, we will co-characterize the connectivity across the URS gradients. Next, we will co-generate transformative opportunities and trajectories in the IMW through specific case studies in our target systems. Finally, we will co-produce and communicate transformational capacity for the IMW including dynamic web-based tools, an annual Resilience Colloquium, policy briefs, and scientific papers. Within the first two tasks, we will identify the regions of study

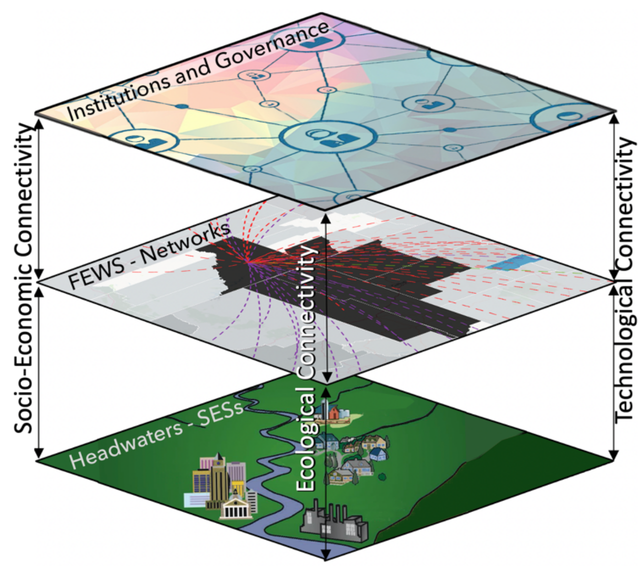

Figure 5. Connectivity between the domain types of our CTs.

where research with partners will be initiated using URG/SJ, CFR, IPNW, or entire IMW. Research will expand to the other study regions based on progression of convergent research in those areas.

Task 1: Co-characterize connectivity and dynamics across the gradient of urban-rural systems in the IMW for headwaters, rFEW systems, and social and governance systems

We will improve basic understanding of connectivity within URS across the IMW by evaluating past, current, and future dynamics of climate, land use, resource management, and community structure and well-being. Relying on academic and community-engaged data collection and modeling efforts, Task 1.A will identify the connections between headwater resources and headwater dependent SESs in the IMW by leveraging and expanding on existing work (NSF #1826709). Task 1.B will explore connectivities in the rFEW building upon research in the FEWSION and ColumbiaFEW projects. Task 1.C. will examine the connectivity among governance systems and well-being, expanding upon the Utah Wellbeing Project (managed by Senior Personnel Courtney Flint). Task 1.D. will focus on synthesizing information across CTs to provide a clearer picture of the key players and processes in URSs, how URSs are functioning, and where there are "friction points" that prevent guided transformations. In Task 1, we will address the following key questions: A. *What watershed conditions contribute to the resilience of headwaters in the IMW? Where will disturbances make diverse watersheds most vulnerable? Where are the most severe threats to ecosystem services? Where could investments improve watershed structure and function and ecosystem health? B. How will rFEW systems change in response to climate and land use change? What will be the impact of natural and human-induced disturbances on rFEW systems? How are urban and rural areas interconnected in storage and distribution of rFEW resources? C. How does well-being vary across URSs and in light of different disturbance experiences? What is the degree of experienced connectivity between rural and urban populations? What types of institutional relationships govern URSs?*

Task 1.A: Characterize headwaters and headwater dependent systems in the IMW

Many IMW watersheds and communities face a similar set of water-related challenges due to the offset of winter precipitation with summer water needs. This sub-task will use a combination of data collection and synthesis, modeling, and survey work to characterize upstream-downstream connections to better understand where there may be opportunities to build resilience or pursue transformation. The Network will focus on key processes that drive connectivity along URSs via: (1) changes to headwater hydrologic budgets; (2) impacts from watershed disturbances; and (3) alterations in ecosystem services and health.

<u>Project 1.A.1: Determine water storage type, trends, and trajectories of headwater systems (WSU, UNM).</u>

In the IMW, water at high elevations is stored in seasonal snowpack, groundwater, lakes and reservoirs, and wetlands – providing a buffering effect that supports a consistent supply during drier periods. In partnership with the U.S. Bureau of Reclamation (USBOR), the Navajo Department of Water Resources (NDWR), and the Ojo Encino Chapter of Navajo Nation, we will quantify the hydro-climatic processes of the hydrologic budgets (i.e., snowpack dynamics, rainfall-runoff processes, groundwater recharge) across watersheds within the URG and CRB basins. We will use existing data sources and regional hydrologic models [79] [80] [81] [82] to describe hydrologic systems storage, transport, and release of water and solutes and how future conditions change headwater storage resilience. *Region: IPNW & URG/SJ.*

<u>Project 1.A.2: Characterize the impacts of disturbances on headwaters and headwater-dependent communities (CSU, UNM, WSU).</u> Climate change and anthropogenic activity both create disturbances to watershed function and can negatively impact the communities that rely on them. Through partnerships with the City of Albuquerque (ABQ), the New Mexico Tribal Resilience Alliance (NMTRANS), and the Federal Emergency Management Agency (FEMA), we will characterize potential and realized impacts of disturbances (e.g., wildfire, drought, and human activities) across multiple urban-rural gradients. Using field work and modeling [83] [84] [85], we will explore disturbance risks and how they are distributed among watersheds and water users by: (1) predicting how future wildfire and drought regimes impact headwater runoff quantity and quality; (2) exploring the effect of water and forest management on watershed-scale resilience over large areas; (3) assessing the impact of water demands on watershed resilience; and (4) examining how perceptions about resilience differ across the URS. *Region: URG/SJ.*

<u>Project 1.A.3: Characterize transitions in ecological connectivity, ecosystem services, and community resilience (CSU, NMT, USU, WSU)</u>. River-floodplain systems connect headwaters and headwater dependent SES and provide ecological connectivity. These systems are increasingly being fragmented due to land and hydrologic alterations when high flows in rivers are captured in upstream reservoirs, levees are constructed to protect agriculture or urban development, and rivers are simplified through

channelization [86]. Loss of connectivity, in turn, affects floodplain function, ecosystem services, and community resilience [87]. In partnership with Intermountain West Joint Ventures, the Audubon Society's Western Rivers Action Network, Spokane River Forum, Big Thompson Watershed Coalition, and the Coalition for the Poudre River Watershed, we will identify: 1) where human stressors are most concentrated in river-floodplain systems, 2) the degree to which these stressors cause loss of watershed integrity and river-floodplain connectivity, and 3) spatial alignment of community preferences for enhancing ecosystem services. We will elucidate where vulnerable connections require community and management attention along our SUR gradients in multiple watersheds across the IMW. *Region: CFR.*

Task 1.B: Characterize rFEW systems in the IMW

Management within FEW sectors has become increasingly compartmentalized while simultaneously experiencing more pressure to tightly integrate across FEW systems to increase resource management synergy [88] [89]. However, the resilience of each sector is dependent on a capacity to accommodate and capitalize on FEW interdependencies in response to external perturbations [90]. These opposing tensions have resulted in unintended trade-offs and conflict [91] [92]. This sub-task creates a deeper understanding of the FEW interdependencies needed to quantify how changes in storage and efficiency in one part of the system impact the economic, political, and environmental resilience of rFEW system.

<u>Project 1.B.1. Characterize current status and trajectories in IMW rFEW Systems (WSU, CSU, UA).</u> Current friction points in the FEW nexus may be exacerbated (or alleviated) under future climate and land use change. Innovations to the FEW system must therefore be evaluated within a regional and global context. Through collaborations with the Southwest and South-Central Climate Adaptation Centers, we will leverage efforts from three NSF-INFEWS projects to explore climate change impacts using CMIP6 data for multiple Shared Socioeconomic Pathways (SSPs; SSP2-4.5 and SSP5-8.5) and fine-resolution CMIP5 global climate projections (downscaled via Abatzoglou & Brown [93]. Land use land cover (LULC) changes and energy system transitions will be explored through simulations from the Global Change Assessment Model (GCAM) downscaled to the regional scale to include local constraints related to water rights for irrigation [94], water supply impacts on electric grid operations [55], and the availability of alternative source waters (e.g., wastewater) on changing water demand regimes [95]. In addition, a WEAP modeling effort funded jointly by USDA (#2018-69011-28369) and NSF (#1828902) will be used to explore how water allocation institutions adapt to changing water availability under alternative population growth, climate change, and development scenarios while incorporating place-based knowledge as developed by the Indige-FEWSS project. *Region: IPNW.*

<u>Project 1.B.2. Evaluate disruption feedbacks caused by threats and bottlenecks through IMW rFEW systems (WSU, NAU).</u> Threats in current rFEW systems can percolate from the hyperlocal to continental and global scales due to systems interconnectedness. For example, hyperlocal threats of seismic activity along the Wasatch Front near Salt Lake City, UT from petroleum and natural gas production and distribution across the IMW will have continental impacts. Food consumption in urban areas can induce environmental stress in distant rural areas exemplified by the nation's beef demand centered in urban areas across the U.S. causing measurable streamflow depletion and fish imperilment across the IMW [4]. Through convergent research with Avista Utilities and GamePlan Tribal Ventures, we will use FEWSION data and tools to analyze major threats (social, economic, environmental, natural hazard) and bottlenecks (environmental, social, economic, infrastructural) that can cause rapid or long-term deformation of IMW rFEW systems, where urban-rural cooperation can reduce the magnitude of multi-scale impacts created by disruptions to IMW rFEW systems. WSU's ColumbiaFEW SusTainability And Resilience (STAR) calculator will be used to assess tradeoffs in the face of a changing climate and different management and innovation scenarios to account for interconnections of rFEW systems [95]. *Region: URG/SJ, CFR, IPNW.*

<u>Project 1.B.3. Interrogate the structure and function of IMW rFEW systems (NAU, AU, WSU)</u>. Interactions within IMW rFEW systems are dominated by urban areas acting as accumulators of the FEW produced in water-intensive surrounding agricultural areas, and as redistribution hubs for consumption at continental and global scales. These are hub-and-spoke rFEW systems. For example, Boise, ID is one of the largest virtual water trade hubs in the U.S. as it accumulates food from agricultural areas in ID, OR, and WA and redistributes food to cities across the nation [96]. Working with ISET International, we will use the FEWSION database [97] along with new methods to analyze network structures underlying IMW rFEW systems and their multiplex interlinkages, and how the structure of rFEW systems increase or lessen the resilience and sustainability of the IMW. This work will be integrated with efforts from the Indige-FEWSS project, which works collaboratively with tribal partners to identify place-based, data-driven, resilience

indicators that can help tribal communities better respond to FEW system shocks. *Region: entire IWM.*

Task 1.C: Characterize well-being conditions and governance systems

Systematic characterization of the well-being conditions and governance systems is needed to highlight vulnerabilities and capacities in IMW URSs and their resilience and transformation capacity in the face of environmental or socio-economic disturbances. Robust indices and measurements of perceived or subjective well-being have replaced outdated unidimensional economic indicators to assess well-being [98]. New procedures are needed to systematically measure conditions along SURSs in the United States. Characterizing SURSs also requires assessing governance capacities and how well urban and rural actors work together to form flexible frameworks for addressing mutual issues [99] [100] [101]. By assessing multi-dimensional, formal and informal URS governance mechanisms, we can better understand transformative opportunities to enhance sustainability. This mixed-methods, qualitative and quantitative research will be co-conducted by scientific and beyond-science network members.

<u>Project 1.C.1: Assessing well-being across URS gradients (USU, UNM)</u>. Working with the Utah Wellbeing Study, the Mid-Regions Council of Governments, the Puget Sound Regional Council, and others, we will develop foundational data and maps of well-being for URS across the IMW using publicly available indicators. Data collection efforts will focus on time-series data that can show impacts of environmental and socio-economic disturbances. Secondary data and mixed-mode survey research will representatively characterize the experienced well-being and perspectives on urban-rural connectivity and regional governance among residents, local leaders, and business leaders across the IMW. Online, mail, and targeted drop-off/pick-up surveys [102] will target populations with different points of contact, adding meaningful educational and community engagement dimensions to help facilitate local data collection. IRB approval will be sought through universities and tribes with established IRB permission. To complement this approach, we will explore applications of other measures of well-being and sustainability, including measures of comprehensive or inclusive wealth. We will also empirically explore rFEW market linkages between rural and urban areas to identify conditions in which urban population and productivity growth lead to improved rural economic outcomes. *Region: entire IMW.*

<u>Project 1.C.2: Innovative governance arrangements and barriers (UNM, WSU).</u> With guidance from the Western Rural Development Center and Sixth World Solutions, we will assess existing or proposed efforts to connect rural and urban areas particularly related to headwater systems and rFEW systems using policy document analysis and key informant interviews. We will focus on characterizing key governance processes and decision-making networks to document processes, legal frameworks, and policies related to the implementation of, or barriers to, innovative rural-urban governance approaches (e.g., alternative water transfer mechanisms, adaptive reservoir management). In particular, this project will pay attention to governance issues tied to SURS disturbances (see Task 1.B.2) by focusing on institutional relationships governing rural-urban landscapes, community responses to system shocks, and innovative governance arrangements serving as models. *Region: URG/SJ, CFR, IPNW.*

<u>Project 1.C.3: Characterizing rural and urban ways of life to inform adaptive governance (USU, UNM, CSU).</u> Focus groups, semi-structured interviews, and ethnographies will be used to document local perspectives, including tribal perspectives, on changing rural and urban ways of life, well-being, environmental attitudes and values, and livelihoods, especially as they relate to environmental health. Through our partnerships with the Washington Conservation Commission, Middle Rio Grande Conservancy District (MRGCD), Western Extension Directors Association, and Spokane Public Works, we will conduct a qualitative inquiry to explore degrees of connectivity along rural-urban gradients and relationships with ecosystem health and a changing climate. Thematic analysis will highlight (mis) alignments that enable or constrain connectivity in URSs. Our analysis will help us understand how beliefs about and experiences of well-being and potential futures differ across URS [103] and community types [50], and the potential for new governance arrangements to address rural-urban connectivity and sustainability that are grounded in place-based contexts and cultures. *Region: URG/SJ, CFR, IPNW.*

Task 1.D: Define and model connections across systems

One goal of the Network is to build a systematic understanding of headwater dependent SESs, rFEWS systems, and governance systems at various scales by developing system dynamics (SD) models. SD models provide an adaptable, scalable platform for simulating the complex dynamics of URS (e.g., water allocation [104] [95], ecological health [105], energy policy [106], environmental health [107], community development [108], and dynamics of water storage in rFEW [109]. We lay the foundation for this goal in this Task by identifying spatial and temporal interdependencies and improving understanding of the main components, internal feedbacks, governing system processes, and interconnectedness of all systems.

Project 1.D.1. Participatory modeling of regional systems (UNM, CSU, NAU, UArizona, WSU, SNL). Data characterizing watersheds, rFEWS networks, governance structures and local well-being will allow for targeted inquiry on the connections across the IMW as well as within regional study areas. Working with SNL, we will employ a participatory modeling approach [110] by developing conceptual models and identifying the key actors, processes, and feedbacks for SD model development (e.g., using VenSim). We will focus on identifying interdependent structures of governance (e.g., legal, economic, policy decision making), energy (e.g., oil/gas energy production, electric grid), regenerative agricultural (e.g., crop yield and water use), environmental (e.g., water quality and quantity), and community (e.g., preferences) components. In addition, watershed integrity indices with human well-being data from Tasks 1.A-C will illuminate a new typology of contexts in which the social, ecological, and economic characteristics of a landscape are on different trajectories in terms of vulnerability and sustainability [111]. Knowledge from this Task will be used to frame current system states and set the stage for exploring potential future system states to test the concepts of guided transformation (Task 2D). *Region: entire IMW.*

Project 1.D.2. Characterize interactions within complex systems (All academic partners). Many real-world complex systems involve multiple types of interactions that can be represented as layers of a network [112]. In collaboration with SNL and other community partners, we will explore the system dynamics of the IMW as a multiplex network to improve evaluation of scalar dynamics. Specifically, watershed SES data, rFEW supply chains, and human well-being data will be transformed into layers of a network such that nodes of a given layer are connected across the convergent themes of the project. The node and edge characteristics will vary to reflect the associated properties of the layers to capture both physical and socioeconomic interactions. For example, nodes within the human well-being layer could represent decision-making heuristics which could be used in agent-based modeling to better explore dynamics of the system. This will help us understand how variations in network layer configurations shape the connectivity and dynamic interactions between complex systems in regional models. *Region: entire IMW.*

Task 1 Outcomes and Impacts: Major co-characterization efforts accomplished in Task 1 will require that faculty, graduate students, and Network tribal and non-tribal partners work together to generate a shared understanding of IMW URS and research needs. Those directly engaged in this co-generation process will be encouraged to participate in the Network's Convergence Bootcamp to build a shared starting point for doing convergence research among participants (see C.2 Activity 1). In addition, projects proposed in this Task will be able to take advantage of the Network's citizen science initiatives to help collect key information and data where feasible on each CT to build a richer and more nuanced understanding of the IMW (see C.2 Activity 2). Meanwhile, engaging with communities through participatory modeling and survey efforts will help shed light on where communities have specific needs for workforce training (see C.2 Activity 4), and will provide the foundation for how to structure the IMW Transformation Atlas to ensure it is a useful tool for community members interested in understanding water security, ecosystem health, and community wellbeing (see Task 3.C).

Task 2: Co-generate transformative opportunities and trajectories in the IMW that span watersheds, rFEW systems, and social and governance systems.

Following the characterization of connectivity in Task 1, we will co-generate and evaluate opportunities for system transformation with community partners across regions. These opportunities include watersheds and landscapes (Task 2.A), rFEW systems (Task 2.B), and governance in SURS (Task 2.C). In Task 2.D, we will use SD modeling to evaluate alternative scenarios and potential futures for URS transformation. Through this effort, we will address the following key questions: *A. How do water management strategies differ across the IMW and where can partnerships using Indigenous-led management strategies help achieve and sustain balance between human uses/impacts and natural watershed systems? B. What role can regenerative FEW management play in improving the sustainability of URS in the IMW? C. What are the key SES attributes where these new, innovative governance efforts are emerging and succeeding in SURS, and how can science support these new approaches to governance? What important cumulative effects and synergies occur along the pathway from source to supply when communities work together?*

Task 2.A: Co-generate transformative opportunities for watersheds and landscapes

Innovative approaches are emerging across the IMW with the aim of restoring hydro-ecological structure and function in watershed systems. In this sub-task, we will advance understanding of transformative opportunities through synergies and shared stewardship within headwater watersheds and landscapes across the IMW. Our convergent research approach will connect tribal, federal, and state resource managers, non-profits, and academic researchers and build collective capacity to increase the pace, scale, and effectiveness of transformations across the IMW.

Project 2.A.1: Integrating Indigenous ways of knowing into landscape scale forest and watershed protection and restoration efforts (UNM, UArizona, NMT). There is a need to integrate Indigenous water and wildfire management practices with contemporary Western management practices [112]. Indigenous peoples have been stewards of forests and water since time immemorial, which is reflected in their daily and cultural practices. However, the extended effects of colonization and colonial resource management approaches have prevented effective co-stewardship of forested lands and rangelands. This convergent research will be designed and completed in partnership with NDWR, NMTRANS, and other Indigenous partners and it will focus on the development of key partnerships between Indigenous and non-Indigenous stakeholders to co-develop strategies for joint stewardship. Structured focus groups and participatory modeling will be used to identify where Western and Indigenous management strategies complement each other or could enhance current management practices. Through these partnerships, we will focus on how current forest thinning, controlled burns, and erosion control management strategies that can be utilized or improved to facilitate a SURS trajectory. The results will also be used to inform workforce development training described in section C.2. *Region: URG/SJ.*

Project 2.A.2: Water governance opportunities in urban-rural transitions (CSU, WSU, UNM). Historical and planned infrastructure projects, such as dams, water delivery pipelines, and trans-basin water transfers often compete with instream water rights and ecological flow needs in water-limited basins such as the Cache la Poudre, Rio Grande and Yakima River basins. In collaboration with Albuquerque Bernalillo County Water Utility Authority (ABCWUA) and the New Mexico Acequia Association, Mid-Region Council of Governments, Navajo Nation Water Resources Department, and other potential partners, we will identify the most pressing water governance concerns. Work will include both retrospective and prospective modeling activities, and rely on multiple methodological approaches, including statistical and SD modeling, qualitative field interviews, and spatial analyses to contribute to biophysical and socio-economic integration. The combined effort will examine what types of trade-offs exist, and which management strategies (e.g., urban-ag transfers, green infrastructure, water demand, alternative water sourcing) may be best for reducing vulnerability. *Region: URG/SJ.*

Project 2.A.3: Community impacts of green stormwater infrastructure (GSI) and low impact development (LID). GSI and LID center on nature-based solutions that have many environmental and social benefits (e.g., urban agriculture, bioswales, rain gardens) and are popular for meeting multiple regulatory and capital demands and for creating opportunities to build healthy and resilient human communities and ecosystems. While GSI and LID efforts are being encouraged throughout the IMW, there is little growing scientific evidence of the long-term local or cumulative impacts of nature-based solutions at the landscape scale [113]; [114]; [115]; [116]. To ensure GSI and LID installations are producing efficient and just solutions to water-related challenges, more needs to be understood about the influence of GSI and LID on upstream and downstream water dynamics and where such solutions should be placed within the URS to provide the most benefit. Working with the Western Center for Metropolitan Extension and Research, the Washington Stormwater Center, and Sustainable, Obtainable Solutions, the Network will engage communities in project development to ensure the researchers understand the communities' goals and expectations around GSI, health, and well-being. *Region: IPNW.*

Project 2.A.4. Watershed organizations as catalysts for socio-hydrologic resilience (USU). Watershed organizations foster collaborative approaches to water management by integrating diverse stakeholders, reducing conflicts, and seeking technically-sound and locally-acceptable solutions [117] [118]. This project will be conducted in partnership with the Santa Fe Watershed Association, Coalition for the Poudre River, and Spokane County Conservation District, we will determine what role watershed organizations play in transforming the sustainability trajectories of watersheds and URSs. A systematic assessment of over 450 watershed organizations will provide a comparative backdrop to examine specific collaborative efforts underway in the study regions. In-depth field observations and interviews with watershed organization representatives will shed light on the role these groups play in protecting watershed health and enabling human-river relationships that enhance stakeholder well-being. Best practices for successful organizational actions will be synthesized and shared across the region to facilitate new and ongoing efforts to enhance landscape resilience in SES as well as workforce development. *Region: entire IMW.*

Task 2.B: Co-creating transformative rFEW systems

Our proposed framework captures rFEW interactions around physical (e.g., FEW supply infrastructure, smart technology), natural (e.g., hydrology), biological (e.g., regenerative crop production, soil health), and social/behavioral (e.g., resource decision making, social equity, well-being) processes. We will employ network, process-based, and SD evaluation platforms already developed in the FEWSION, ColumbiaFEW, and Indige-FEWSS projects for exploring the sustainability of IMW FEWs. Four projects here describe examples of transformative rFEW systems in the IMW through community engagement: (1) regenerative food systems; (2) food, energy, and water security and sovereignty; (3) scenario testing with evaluation platforms; and (4) FEWSION for Community Resilience (F4R) cohorts.

<u>Project 2.B.1: Using co-production of knowledge to build regenerative food systems (WSU, UNM, NMSU)</u>. Sustainability of agricultural food production systems comprises four goals (NRC 2010): "(1) Satisfy human food and fiber needs, and contribute to biofuel needs; (2) Enhance environmental quality and the resource base; (3) Sustain the economic viability of agriculture; and (4) Enhance the quality of life for farmers, farm workers, and society as a whole." These systems encompass the farms, communities and ecosystems around them, referred to as the agroecosystem. To be sustainable, agroecosystems need to be productive, use resources efficiently, and balance the four goals considering stresses and fluctuating conditions [73]. This project will present a farm and regional scale approach that engages producers, tribes, community partners, and agencies as major actors in the co-production of knowledge to advance the adoption of sustainable cropping systems in the IMW. In collaboration with the Spokane Conservation District in Washington and the New Mexico Healthy Soils Working Group, we will evaluate innovations producers are exploring on their farms to achieve more sustainable agroecosystems with no-tillage, precision farming, crop diversification, judicious agrichemical and amendment uses, and cover crops [119]. Through community-based co-production, we will develop local, actionable research on quantifiable metrics that tie interventions with sustainability outcomes for stakeholders and their local communities, regenerative agricultural practices combining Indigenous and traditional knowledge, and how communities can transition to sustainable farm-to-table or circular food production models. *Region: IPNW & URG/SJ.*

<u>Project 2.B.2: Indigenous food, energy, and water sovereignty (UArizona, NMSU)</u>. The goal for this project is to increase Indigenous community resilience to perturbations and to support desired transformation of a perturbed rFEW system state to a recovered state by establishing smart, connected, off-grid solar-powered water and greenhouse (SWG) units that are co-designed, built and operated by Navajo citizens and assessing the need and current use of regenerative agricultural practices in Indigenous communities. Since 2017, UArizona has partnered with the oldest tribal college in the United States, Diné College, to develop a SWG unit (Indige-FEWSS) to address FEW challenges on the Navajo Nation [75] [120] [121]. Using innovative and integrated approaches the SWG units treat non-potable water nanofiltration powered by solar panels – providing water security for approximately 30 families. The SWG uses controlled environment agriculture (CEA) technology to support year-round production of highly nutritious, high crop-yield foods [122]. Photovoltaic technologies for light collection, light management and energy production can enhance CEA deployment, particularly in remote locations challenged with access to power. This project will leverage prior and ongoing efforts with Diné College, the Navajo Ethno-Agriculture Education Farm, and DigDeep to work collaboratively with the Navajo Nation to co-design and implement first-generation, research based SWG units. It is emphasized that designs will be scalable, sustainable, and premised on Navajo priorities. SWG technology in remote areas can reduce FEW insecurities amplified during pandemics, thus enhancing Navajo resilience. *Region: URG/SJ.*

<u>Project 2.B.3. Mapping the last mile of rFEW systems using citizen scientist cohorts in IMW cohorts (NAU, UNM, WSU, CSU).</u> Citizen science methods have been widely used to increase resilience within SES by building both technical and social capacity at a local level [123] [124] [125]. One method of citizen science used to engage citizens in the scientific and policy process is Public Participation in Scientific Research (PPSR). PPSR designs address the social, political, and economic goals of community stakeholders and scientists [126]. The FEWSION for Community Resilience (F4R) process applies a PPSR framework to map supply chain data for a community's FEW system, to identify the social network that manages the system, and to generate a data-informed conversation among stakeholders [127]. F4R was piloted and

co-developed with participants over a two-year NSF-funded study, using a design-based research process to make evidence-based adjustments as needed. The F4R model was successful at improving volunteers' awareness about nexus and supply chain issues, at creating a network of connections and communication with stakeholders, and in facilitating data-informed discussion about improvements to the system [128]. F4R includes a suite of interrelated interventions that address training for volunteer citizens to collect and validate local FEW system data, use data analysis and visualization tools to identify local FEW system vulnerabilities and resilience, and generate community-based conversations that would influence regional SURS [127]. We will develop one cohort per year in each partner state; in year 1 will work with the Quivira Coalition to apply the F4R approach in New Mexico while identifying partners in other regions for years 2, 3, and 4. We will compare bottom-up, citizen-identified to top-down data-driven rFEW system threats and bottlenecks and determine the FEW system information gain derived from co-producing knowledge between citizen science cohorts and university researchers. *Region: entire IMW.*

Task 2.C: Transformative governance in SURS

Governance systems that can adapt to shocks and stressors are critical components of any SURS. Identifying pathways forward for innovative, flexible, inclusive resource management will require an investigation into how emerging governance efforts are building adaptive capacity for transformation in URS currently. There are two main projects related to this question that focus on new innovations that are moving beyond traditional governance approaches.

<u>Project 2.C.1: Emerging approaches to forest, fire and climate change management (CSU, UNM, UArizona, WSU).</u> Throughout the IMW, our collaborators are experimenting with novel approaches to headwaters management with an overarching goal of building resilience to stressors including drought, wildfires, climate change, and declining economic opportunities. These innovative partnerships are securing funding from government, non-government and private organizations, and investing it upstream, in PES style approaches. For example, The Rio Grande Water Fund (RGWF) aims to restore 240,000 ha of forests in the headwaters of the Rio Grande by 2034 through a diverse partnership of over 80 charter signatories, including UNM. This is complemented by the Audubon Society and World Wildlife Foundation initiative titled, *Charting a Resilient Future for the Rio Grande* and the IMW Venture efforts to protect migration corridors and flyways. In Colorado, numerous collaborative groups work across jurisdictional boundaries to restore headwater ecosystems including the Upper South Platte Partnership and the Peaks to People Water Fund (PPWF). Arizona has a multi-year partnership across four National Forests to expand forest restoration efforts through the Four Forest Restoration Initiative (FFRI). In Washington, the Yakima Basin Integrated Plan, developed in collaboration with diverse interests, is working with numerous partners to implement projects that respond to drought and a changing climate, assuring water is clean and ample for communities and the environment. Working with the organizations mentioned above, we will apply convergent, mixed methods designs to compare and contrast the efficacy of these approaches, and the contextual factors that lead to their success. We will specifically investigate their (1) emergence; (2) persistence; and (3) effectiveness across the IMW. *Region: CFR.*

<u>Project 2.C.2: Integration of payment for ecosystem services (PES) approaches within Indigenous, place-based contexts (UNM, CSU, NMT)</u>. The extent in which PES-like governance models are reductive and predisposed to undervaluing the cultural, religious, and aesthetic benefits of nature is well documented [44]. Less discussed but equally important is the way PES models focus on human needs, which is a dominant, western perspective not shared across cultures [44]. This project will work with partners in the Network, including the RGWF, PPWF, and Audubon Society, to move beyond critique of PES to understand how PES approaches can encompass diverse perspectives and cultures [129], including what defines "success" of these projects to partners. It recognizes that Water Funds and other PES models have their place in ecosystem services governance, but these approaches also need to reflect the context in which they work. *Region: URG/SJ.*

Task 2.D: Connections across sub-systems

A sustainable system requires technologic and environmental viability to achieve sustainability, economic viability, and social acceptance. The same applies to inter-connected, dynamic systems. Exploring sustainable futures requires an understanding of not only the individual systems, but also the intra- and inter-system outcomes. The innovations explored by our Network (e.g., Tasks 2A-C) incorporate heterogeneity between and across disparate, interconnected systems. In this Task, will build on the SD frameworks developed in Task 1.D to explore alternative, future scenarios and compare outcomes along different trajectories and scales. From this, we will identify critical interconnections that influence transformative outcomes and trade-offs between modeling scale choice (e.g., aggregated scales simplify modeling, but may miss nuanced interactions). In the short-run, SD model assessment will form the basis for policy analysis for resilient futures, and in the long-run, this will provide the scientific community with the 2nd generation of research questions that examine system feedback, path dependencies, and friction points. This will inform the influence of different climate or governance scenarios and guide the pursuit of long-term sustainability of inter-connected systems.

Project 2.D.1. Using systems dynamics to explore sustainability outcomes of IMW rFEW systems (NAU, UNM, SNL). Recent NSF funding initiatives have greatly increased our knowledge about FEW systems. However, as a nascent discipline, a significant knowledge gap still exists related to FEW feedbacks within local and regional systems that result from network-wide interactions. Given the wealth of existing state data on the interconnectedness of IMW rFEW systems, it is imperative to explore the range of potential sustainable outcomes that may result from targeted interventions. Using a SD models, we will examine how regional outcomes differ between national-level and detailed rFEW studies, what key intervention points within these systems could potentially improve overall sustainability, and how these systems may gain resilience to production disruptions and supplier shocks. *Region: entire IMW.*

Project 2.D.2: Influence across scales and sub-systems (UNM, CSU, SNL). Multiple priorities and drivers influence URS dynamics leading to asynchronous changes across subcomponents of a complex system [131]. Such system behavior has been found to profoundly impact the degree to which collaboration and cooperative resilience efforts succeed [132]. This project will explicitly investigate how changes and decisions made within URS multiplex networks contribute to the evolution of system resilience. This system-of-systems modeling effort will provide an IMW-scale perspective of the extent to which various sustainability trajectories may succeed under different scenarios, and where parts of the IMW system benefit or lose under each potential future. *Region: entire IMW.*

Project 2.D.3: Impacts of governance choices and disturbances (UNM, CSU, SNL). Using the SD modeling platform, Monte Carlo simulations will be run for individual future policy scenarios (as developed through the collaborative modeling efforts with Network partners (e.g., Task 1D) related to headwater system and rFEWs change to assess impacts on system components (e.g., community well-being, river system viability), and map potential impacts. We will compare the outcomes of future governance scenarios and potential disturbances (e.g., how a community water supply system responds to water quality changes after a catastrophic wildfire) and classify components by a level of sustainability (e.g., always sustainable; rarely sustainable). This categorization will allow an improved understanding of critical components and feasible sustainable futures. *Region: URG/SJ, CFR, IPNW.*

Task 2 Outcomes and Impacts: The modeling efforts of Task 2 leverage knowledge gained in Task 1 and critically rely on Network Partner participation to co-produce scenarios and identify key innovations for evaluating GT strategies. The projects proposed in this Task will continue to provide Network researchers, Extension, and partners opportunities to meaningfully engage (e.g., Tasks 3.A, 3.B, 3.E, 3.F) while also enhancing our understanding of workforce needs (see C.2 Activity 4) and community resilience (Task 3.D). Outputs from Task 2 projects will offer insights into the IMW system-of-systems with a depth and clarity previously not possible, and therefore will be the focus of our Transformation Atlas (Task 3.C). We will use the Atlas to engage with existing and new partners, and to identify where we can add to, improve, and update our many of our Educational Activities (e.g., C.2 Activities 1-3, 5-6).

Task 3: Co-produce and communicate transformational capacity for the IMW

Dynamic Network engagement is crucial for the success of Tasks 1 and 2, and for the development of long-lasting, sustainable, and resilient community transformations. To foster meaningful engagement and to expand the reach of our Network the TRUST-RN will engage in multiple, synergistic outreach activities. In addition to traditional outreach activities, we will engage in web-enabled outreach through interactive visualization systems. These will include one-way (informational) and two-way (communication) activities. In all cases, the activities will be updated as we move forward with the Network to address the dynamic nature of information, the Network and our communities.

Task 3.A. Develop the IWM TRUST Transformation Network and Blueprint (UNM, CSU, WSU)**.** Successful implementation and Network perpetuation requires information dissemination and communication across diverse, evolving partners. To ensure success, a Transformation Blueprint will be constructed that allows for the development of a robust communication strategy to reach a broad, diverse, evolving, and expanding audience. This is key to our convergence research and to the success of building transformative capacity for the IMW. The Transformation Blueprint will provide mechanisms to bring together researchers from our Cross-Cutting Threads, partners and the broader audience for access to innovative practices, policy and planning guidance (e.g., Task 3.B, 3.E), data (see Task 3.C), and existing resources from within and beyond our Network. The Transformation Blueprint will follow the framework being implemented by the UN Habitat: Urban-Rural Linkages program. The main platform for the Transformation Blueprint will be through our Network's website. The website will also contain ongoing and upcoming TRUSTS-RN activities and publicly accessible and -digestible summaries of research outcomes, publications, and partner Network activities. We will create an active social media presence to drive traffic to our Network and Blueprint, provide bite-size summaries of RN activities and publications, and amplify the voices of those we work within IMW communities. Through the website, we will also cultivate an email list-serve and mailing list with national and international reach to provide broad access to our activities and findings. We will broadcast quarterly newsletters and press releases over the TRUST-RN media channels. We will develop a podcast series on the science and people of IMW URS. Many in the communities we seek to engage and draw into the network may not have broadband access or may choose not to engage in social media. We will seek to make much of the above information available through hardcopy delivery, where applicable (e.g., Task 3.B), and through news media outlets.

Task 3.B. Leverage the Cooperative Extension Services (CES) network (UNM, CSU, WSU) Beyond the TRUST-RN, we will leverage the CES network to reach county and tribal Extension offices throughout the IMW. Extension will play a key role in helping Projects connect to partners and facilitate data collection (e.g., Projects 1.A.3, 1.B.2, 1.C.1, 1.C.3, 1.D.2) as well as to connect to relevant Extension professional societies (e.g., Association of Natural Resource Extension Professionals, National Association of County Agricultural Agents, National Association of Community Development Extension Professionals, Federally-Recognized Tribes Extension Program), and regional organizations (e.g., Western Rural Development Center, Western Center for Metropolitan Extension and Research) through their newsletters, annual conferences, and other organized activities. Given CES's historically strong connections with local, tribal, county, and municipal governments, we will also develop Community Engagement Plans with their assistance (see Project Management Plan) as well as 1-page policy relevant summaries of science outcomes for Extension offices across IMW states. Participation of community members is vital to many of the TRUST-RN activities, including creating a CR culture.

Task 3.C. Develop the IMW Transformation Atlas (UNM, CSU, WSU)***.*** Working with a wide range of our partners including the Colorado Water Center and Urbanova, we will develop a dynamic web-platform for sharing transformative case studies and data known as the IMW Transformation Atlas. The Atlas will integrate and research, training materials, and inspiring examples of innovation from across the IMW. The web-based analytical tool will allow users to: (1) understand the extent and severity of some of the key stressors and shocks that are affecting URS in the IMW; (2) gain insights into the ways that different system states and trajectories of headwater systems, rFEWS, and well-being are distributed throughout the IMW; (3) review and comment on transformational pathways towards SURS; and (4) access a central repository of relevant and varied datasets that are often not easily accessible or transparent for our partners and stakeholders. We will use the Atlas to host our research results for easy access across our Network as well as for disseminating our results to partners. The Atlas will be particularly useful for summarizing research outputs in easy-to-understand maps that can shift focus from regional to national and, where the availability and resolution of the data permit, to local scales. We anticipate the IMW Transformation Atlas will provide new insights to help catalyze system transformations and support for the growing community of practice around resilience.

The IMW Transformation Atlas will be developed at the One Water Solutions Institute (OWSI) at Colorado State University. We will develop the Atlas to include both structured (database management systems, GIS layers, etc.) and unstructured datasets (images, texts, multimedia, etc.). Big data analytics approaches will be adopted in the Catena platform, which is an open platform supporting the development of geospatially enabled web applications for sustainable management of land, water, energy, and governance resources. It harnesses open-source technologies to provide geospatial data analysis, presentation, processing, and visualization to build custom analytical tools that incorporate Cloud Services Integration Platform (CSIP) model and data services. We will leverage the existing Environmental Resource Assessment Management System (eRAMS) geospatial web framework and the CSIP services developed at CSU.

Task 3.D. Disaster Recovery and Resilience Building with Community Partners and FEMA (UNM, FEMA, SNL, CSU, WSU). Resilience to overcome with disturbances, or natural disasters requires technological, human, and natural resource capacity and place-based technical assistance. We will develop a collaborative effort between communities, the National Disaster Recovery Support cadre (NDRS) of FEMA, and our researchers. The NDRS, is part of the Office of Response and Recovery within the Interagency Coordination Division of FEMA with the role of facilitating long-term disaster recovery coordination and collaboration between federal, state, tribal and local governments, the private sector, NGOs, and voluntary organizations. We will work with communities to advance their recovery goals and build/enhance their resilience capacity to the most likely disturbances (e.g., wildfire, flood, drought). Skills-building workshops, preparedness and long-term recovery planning, data analysis (from across our CT's), and peer engagement (utilizing 3.A, and 3.B). These activities will be derived from our convergence research activities including Indigenous and place-based solutions.

Task 3.E. Organize the Annual Resilience Colloquium (UNM, CSU, WSU) Building upon the success of four Resilience Colloquiums hosted at UNM, the TRUST-RN will hold an Annual Resilience Colloquium, held in-person and virtually in an IMW community with ongoing TRUST-RN research activities. These events will include three activities: the colloquium, workshops, and educational opportunities. As with past colloquiums, this public event, will bring together local and external expertise and experiences. The two-day program will provide a platform for an exchange of ideas and accomplishments that contribute to our thematic areas while also providing a platform to disseminate research findings and build connections. We will recruit for the Colloquium throughout the Network and the F4R Cohorts that are active in the communities including local, regional, and national decision makers. In addition, we will hold a series of workshops with wide-ranging, relevant topics, that tie to our research activities. For example, developing successful policies for ecosystem protection, requires a definition of success acceptable across constituent groups, a focus if Task 2.C (Project 2.C.2). The Colloquium provides the platform for additional training and outreach activities including our Convergence Research Bootcamp and Science Meets Art Night (see Section C.2). Podcasts from the Colloquium will be developed for Task 3.A.

Task 3 Outcomes and Impacts: Towards our overall aim of building transformative capacity towards SURS in the IMW, Task 3 activities will provide the products and platforms to reach a broad audience across the IMW. This strengthens the research, grows the Network, and broaden its impact on scientific literacy, public engagement, and increased partnerships between academia, tribal/state/local governments, and non-governmental organizations. Our Transformation Blueprint will include both cutting-edge research results and practical strategies for building transformational capacity through policies, planning, and innovative technologies and institutions. Ongoing communication provides a natural updating of information and communication and build community. Long-term success of the Network requires this successful blueprint.

C. Education and Education Evaluation

C.1 Educational Components of the TRUSTS-RN

We envision empowering IWM communities through convergent education that embraces multiple ways of knowing [133] and our diversity, equity, and inclusion (DEI) plan (see section A.7) by integrating voices and participations of underrepresented minority groups [134].

Educational activities will be tightly integrated with research activities, will be co-developed with our partners advancing convergent practice and transformative capacity based on the principles of 'Transformations Identify'. We have designed active, experiential, and inquiry-based educational activities for K-12 and college students and for adult learners via workforce development and citizen science. Consistent with our vision for convergent approaches, many of these activities have been or will be designed in cooperation with our community partners. Our Network's approach to convergent education is unique because our partnerships and commitment to Indigenous and place-based knowledge serves as a basis for understanding SES resilience. Network-wide educational goals are:

Goal 1: Catalyze transformation in our universities by engaging in convergent education to strengthen the Education-Research interface (E-R). We aim to develop a Transformations Identity through experiential learning.

<u>Goal 2:</u> Elevate DEI in education to produce a diverse workforce while empowering learners through professional and leadership training to strengthen the Education-Practice interface (E-P). We aim to broaden participation of underrepresented minority groups in STEM from K-12 through adult learners.

<u>Goal 3:</u> Build a workforce skilled in convergence science approaches to strengthen the Research-Practice interface (R-P). We aim to provide research-based, experiential learning and professional development through upskilling and reskilling opportunities as valued by our industry partners.

<u>Goal 4:</u> Build a community of Convergent Practice and Transformative Capacity (CP&TC) through the integration of research, education, and practice. We aim to advance convergent and transformative practices through art and through outreach and training to K12 students and teachers.

C.2 Educational Activities

Activity1: Convergent Research Bootcamp (Goal 1, E-R): Experiential-learning is an evidence-based instructional strategy [135]. We will design and deliver a Convergent Research Boot Camp annually the day before the annual Resilience Colloquium. The boot camp will advance participants' understanding of convergence principles and practices. As the annual Resilience Colloquium rotates among the partner states (NM, WA, CO, AZ, UT), host institutions will showcase a key topic aligned with their strengths catalyzing transformation in our universities. In the first year, UNM will host the boot camp with focus on developing convergent research with UNM's Indigenous Design and Planning Institute. We will recruit participants based on our DEI plan (see section A.7), with participation of ~15 students, 10 community partners, and 10 university researchers per camp. At the conclusion of the boot camp, participants will be able to describe convergence principles and their significance, apply convergence principles to a scenario-based key topic emphasized by the host institution, and evaluate effectiveness of convergence principles as solutions to the applied scenario. Participants' competencies will be evaluated by a series of formative assessments during experiential learning activities and a summative writing assignment at the conclusion of the camp.

Activity 2: Citizen Science Initiatives (Goal 1, E-R): Citizen science is an effective way to engage our community members into research, especially when tied to existing environmental issues [136]. Citizen science catalyzes transformation by (i) connecting community members to research activities and (ii) developing citizens' transformation identity. Citizen science initiatives will be designed to contribute to Network Task 1 & 2 efforts. We aim to (i) elevate community members' understanding and appreciation of convergent research while (ii) providing professional skill development opportunities to underrepresented minority undergraduate students. We will deploy approximately eight citizen science initiatives (one at each Network university) throughout this grant. For example, in Project 2.B.3, we will collectively design, build, and deploy an instrumentation network with the Navajo Nation Department of Water Resources. The network will use the UNM LEWIS platform as its core technology. Additional sensors, communication protocols, and data management processes will be added to meet community needs. Undergraduate students will practice their professional skills by participating in the collective network design as liaison between researchers and community members and designing outreach materials to accompany the deployment of the network.

Activity 3: Convergent Science Curricula (Goal 2, E-P): Convergent Science Curricula will elevate DEI by re-designing course elements that provide social equity and environmental justice frameworks, offering diverse viewpoints of literature and researchers, demonstrating multiple ways of knowing, co-instructing courses in community partnership with local industry experts, and engage in antiracist education. These activities will (i) strengthen efficacy of existing courses to provide professional skills, (ii) develop and disseminate best practices for education in areas of convergent research and systems thinking, and (iii) contribute to a diverse workforce by implementing our DEI plan for student recruitment. We will develop common modules for all instructors which emphasize the principles of sustainable regional systems, SES and SETS theory, systems thinking and systems dynamics, and social equity and environmental justice. We will also align course experiential learning activities with the Network's research program (e.g., greenhouse monitoring systems and SD models). Lessons learned through this effort will be shared through the RN regularly, posted on the project website, and presented at conferences. This activity will impact approximately 25 undergraduate and 25 graduate students from represented minority groups each year. At the conclusion of each course, students will be able to design, evaluate, and defend convergent science approaches. The summative assessment will be a design project. Five curricula with convergent science components already exist across our Network: (1) Stone (UNM) teaches "Building Community Resilience". Students have completed design projects on earthquake relief in Nepal, an off-grid community design in Navajo Nation, and alternative infrastructure strategies for the Rio Chama Acequia Association; (2) Morrison's CSU "River Restoration Design" engages in real-world design problems; (3) Chief (UArizona) teaches "Indigenous FEWS" in coordination with communities on Navajo Nation; (4) NAU's "FEWSION for Community Resilience" addresses challenges facing regional food systems; and (5) WSU has launched the "Extension, Engagement and Education (E^3)" to deploy experiential learning through students and community engagement with faculty across the university.

Activity 4: Workforce Training Initiatives (Goal 2, E-P): Professional upskilling on convergent science contributes to diversify workforce and empower learners by (i) improving the alignment between training and employability or promotion opportunities, (ii) offering learner-owned credentials valued by our industry partners to signal desirability of underrepresented minority learners, and (iii) contribute to representation and visibility of underrepresented minority in the workforce. With a rapidly changing workforce driven by technological advancements, adequately preparing learners for the future of work is crucial. A majority of the workforce in 2027 will require constant upskilling to solve complex problems and to meet the demands of non-routine cognitive tasks facilitated by technology [137]. Consistent with our convergent science mission, the Network's workforce training components will be co-developed with our partners. Specifically, in concert with the surveys described in research Task 1.C and a series of focus groups, we will spend the first year of this project identifying workforce needs. From there, we will co-develop strategies providing that training. One component of the training has been already identified and will be implemented in Year 1, and that is of Red Card training for Tribal employees in New Mexico to allow for cooperative forest fire management (Research Task 2.a). We will coordinate with existing training centers in our Network to provide the requisite 32 hours of training, coordinate the "Pack Test" at a nearby location, and to guide their Tribal employers through the certification process. Examples of potential future activities include coding for data management, Geographic Information Systems for resource management, and Remote Pilot (drone) Certification for infrastructure assessments. The associated curricula will be shared amongst all Network partners and we will scale up the training with a goal of training at least 100 workforce members per year.

Activity 5: Student Internships with Research Partners (Goal 3, R-P): Student internships build a workforce skilled in convergence science by (i) placing graduate students in residence with our partners including the Audubon Society, the U.S. Bureau of Reclamation, the NM Acequia Association and others indicated in the Partnerships and Stakeholder Engagement for Impact section and (ii) training graduate students on research-based skills valued by our industry partners. These internships will follow our DEI plan and give students first-hand knowledge and experience of the research needs of our partners. The duration of the internship will be adjusted based on circumstances, but on average will last approximately three months. The internship will serve as the basis of the students' theses for MS students and for at least one chapter/paper for PhD students. The students will present the outcomes of their internships at the Annual Resilience Colloquium and at a professional conference. The internships will be completed by approximately 10 students per year.

Activity 6: Science Meets Art (Goal 4, CP&TC): Coupling science and art creates unique opportunities to present multiple ways of knowing by integrating research, education and practice. Steelman et al. [133] used art through a transdisciplinary sustainability science project focused on co-creating knowledge with inland delta communities in northern Canada undergoing ecological and social change. We will advance convergent and transformative practices by building upon a successful pilot-project implemented by the UNM and CSU through their SUS workshop grant (NSF #1929769), and we will partner with campus and community galleries to coordinate a Science Meets Art Evening at each of the annual Resilience Colloquiums. We will recruit art students and/or local artists three months in advance and pair them with interested STEM graduate students working on convergent or transformative research. The artist-scientist partners will collaboratively produce their artwork that convey scientific messages for display at the Science Meets Art Evening. Each event will be open to the public and publicized by the host institution. The artists will be paid a stipend for their contribution. A survey and a focus group will be administered for participating students and artists at the beginning and the end of their project to evaluate their knowledge, attitudes, and experiences surrounding convergent science. At each event, an exit survey will be set up to assess impacts of the event on their appreciation for convergent science and their sense of community.

Activity 7: Solar-Powered and Greenhouse (SWG) Project (Goal 4, CP&TC): We anticipate that many of our projects will lead to new, additional Educational Activities. An example of this is Activity 7, which supports Project 2.B.2 and integrates research, education, and practice by (i) advancing SWG research and technologies to reduce FEW insecurities and enhance Navajo resilience, (ii) educating Diné College students on SWG operations, and (iii) training the Navajo community of Thoreau, NM in partnership with local community organizations such as Dig Deep, Sixth World Solutions. SWG research will build on existing programs in UArizona's Indige-FEWSS NRT. SWG education will be a special topic short course. At the end of the course, students will be able to describe SWG operations from technical (e.g., planting procedures, water monitoring, and light and temperature management) and financial (e.g., cost analyses, distribution strategies) perspectives. For the SWG practice, we will develop an appropriate hoophouse kit for the community and provide training for them to launch their own SWG. We will offer a 5-session training each year, of which three will be at the community and two will be at UArizona. The developed education and training materials will be disseminated throughout the Network in the form of UArizona Extension publications and learning modules. The results will inform agricultural and greenhouse training.

C.3 Education Communication and Dissemination Plans

Educational outcomes will be disseminated through: (1) Quarterly webinars and the annual Resilience Colloquiums; (2) The professional networks associated with our institutions such as the New Mexico STEM Collaborative; (3) Presentations at professional conferences including the educational sessions at the American Geophysical Union and the American Indian Science and Engineering Society (AISES) Annual Meeting; and (4) online through the STEMEd HUB and other curriculum platforms and also through our Network's website. UNM has extensive experience in developing online learning modules in collaboration with the Southwest Indian Polytechnic Institute which we distribute through the UNM Center for Advancement of Spatial Informatics Research and Education (ASPIRE). Most of these outlets have mechanisms for tracking the number of people reached directly, website views, and downloads.

C.4 Education Evaluation Plan

External evaluation of the education and outreach components of the Network will integrate strategies for formative (implementation) and summative (outcome) feedback about convergence education activities using qualitative and quantitative methods to assess both individual learning as well as Network outreach, communication, and dissemination. This ongoing, comprehensive evaluation will be aligned to project goals and will be utilization–focused [138], emphasizing the use of data by project leadership for continuous project improvement. Regular communication between the evaluation team and project leadership will ensure that data are interpreted appropriately and used formatively for project improvement, and summatively to measure progress toward attainment of goals.

Evaluation of the project will be managed by Pamela Bishop, Director of the National Institute for STEM Evaluation and Research (NISER) at UT. Dr. Bishop has particular experience in evaluation of interdisciplinary research [139][140], and educational initiatives [141][142][143] and is well-suited for the task of evaluating the project. Dr. Bishop and her staff adhere to the American Evaluation Association's guiding Principles for Evaluators [144] and the Joint committee on Standards for Educational Evaluation Program Evaluation Standards [145].

This evaluation provides the opportunity to use data to examine the interdependence of the Network with outcomes designated for targeted local and regional communities, and to understand how the Network integrates education, research, and practice in the project model. Qualitative data will be analyzed using thematic analysis [146] and quantitative data will be summarized descriptively, using parametric or nonparametric statistical analyses, as appropriate. We developed a highly detailed evaluation matrix for our Network. Table 2 is an abbreviated version due to space limitations.

Evaluation Reporting and Communication. Network partners will each assign a liaison to work with NISER to support facilitation of data collection from stakeholders across the wide range of locations and activities. NISER will meet virtually with these liaisons as needed for data collection coordination (e.g., access to participants, activity records from various sites). NISER will provide Network leadership with regular feedback from the evaluation for ongoing assessment of the education, outreach, and associated communication and dissemination activities of the Network via monthly virtual meetings, annual presentations to coincide with the SRS RN Awardee Conference, as-needed data analyses, and formal annual reports at the end of the grant year (See Project Management Plan for Evaluation Timeline). Reports will include evidence-based recommendations for project improvement in the form of clear action items that project leadership can apply directly to project improvement. The reports will be provided to project leadership in advance of meetings so that NISER personnel can discuss recommendations with the leadership team and develop clear next steps and time frames to implement needed changes. Discussions about the utility of evaluation findings will inform subsequent evaluation plan revisions to ensure that it meets project needs.

Table 2: Evaluation Overview (SG = Stakeholder groups; NAPs = Network Academic Partners; UG = Undergraduate Students; GS = Graduate Students; URMs=Underrepresented minorities.

Activity (SGs)	Evaluation Questions (F=Formative, S=Summative)	Data Source (Timing)	Measures of Success
Convergent Bootcamp (BC) (UG & GS)	To what extent are targeted trainees, including those from underrepresented groups, involved in Bootcamps? (F)	Trainee surveys (pre/post BC)	Retention of trainees, including URMs, in Bootcamp programs
	To what extent do/did trainees advance their understanding of convergence principles & practice? (S)	Program staff interviews (annual, post BC)	Trainees demonstrate understanding of convergence principles and practice
Citizen Science Initiatives-CSI (Community, URM UG)	To what extent does participation develop students' transformation identity? (S)	Community member survey (post-CSI)	Students indicate gains in targeted professional skill development
	How does participation affect participants' abilities to describe convergence principles in the context of the Network? (S)	Community member focus group (annual)	Participants report increased abilities to describe how the collected data will inform the Network's research questions
Convergent Science Curricula-CSC (UG & GS)	In what ways are the NAPs working to coordinate the curricula? (F)	Student focus group (annual)	NAPs report positive CRC partnerships
	To what extent does the CSC increase students' abilities to design, evaluate, and defend convergent science approaches? (S)	Network Leadership interviews/ discussions (annual)	Students and faculty report increase in students' abilities to design, evaluate, and defend convergent science approaches
Workforce Training -WT (Adult Workforce-AWs)	Are NAPs able to adequately identify workforce needs? (F)	AW surveys (pre/post participation)	NAPs identify key workforce needs
	What impacts do WTIs have on AWM learning, employment, and visibility in the workforce? (S)	Key NAP interviews (annual)	AWs report multiple ways that WTIs are relevant regarding learning & employment
Student Internships (GS, Research Partners)	To what extent do students exhibit first-hand knowledge and experience of the research needs of partner organizations? (F, S)	Student intern interviews (annual)	Students and Research Partner Liaisons report gains in research-based skills valued by partner organizations
	In what ways are students using their experiences as basis for their graduate research requirements? (S)	Key Research Partner liaison interviews (annual)	Students exhibit first-hand knowledge and experience of the research needs of partner organizations
Science Meets Art (GS, Community Members, Artists)	How does participating change artist and other participating students' knowledge and attitudes surrounding convergent science? (S)	Artist and student surveys (pre/post projects)	Artists and students exhibit positive changes in knowledge and attitudes surrounding convergent science
	In what ways do community members in attendance change in knowledge and appreciation of convergent science and its place in their communities? (S)	Community member exit survey (post event)	Community members in attendance indicate greater appreciation for convergent science and its place in their communities
SWG (Community Partners, Diné Students, Navajo Community)	What value do Navajo groups find in interacting with NAP researchers? (S)	Navajo community focus groups (annual)	Community Partners and Navajo groups report positive and continued engagement
	To what extent are Navajo groups adopting technology developed by SWG in their communities? (S)	Diné College student surveys (pre/post participation)	Navajo groups adopt technology developed by SWG in their communities
	To what extent do Diné College students in the SWG program develop the ability to describe SWG operations from technical and financial perspectives? (F,S)	Key Community Partner liaison interviews (annual)	Diné College students in the SWG program demonstrate ability to describe SWG operations from technical and financial perspectives
Network Leadership	What efforts are being undertaken to recruit targeted participants? (F)	Analysis of project records (monthly)	Targeted populations are recruited and retained
	How is project leadership maintaining relationships with partners in the network? (F)	Network Leadership interviews/ discussions (monthly)	Network partners report positive working relationships with project staff and leadership
	Are the education and outreach projects being implemented as designed to integrate education, research, and practice? (F)	Network partner liaison interviews (annual)	Project stays on track with proposed timeline
	In what ways can the Network improve its operations in education and outreach? (F)	All stakeholder evaluation data (as described above)	Network Leadership makes data-based decisions to improve program

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