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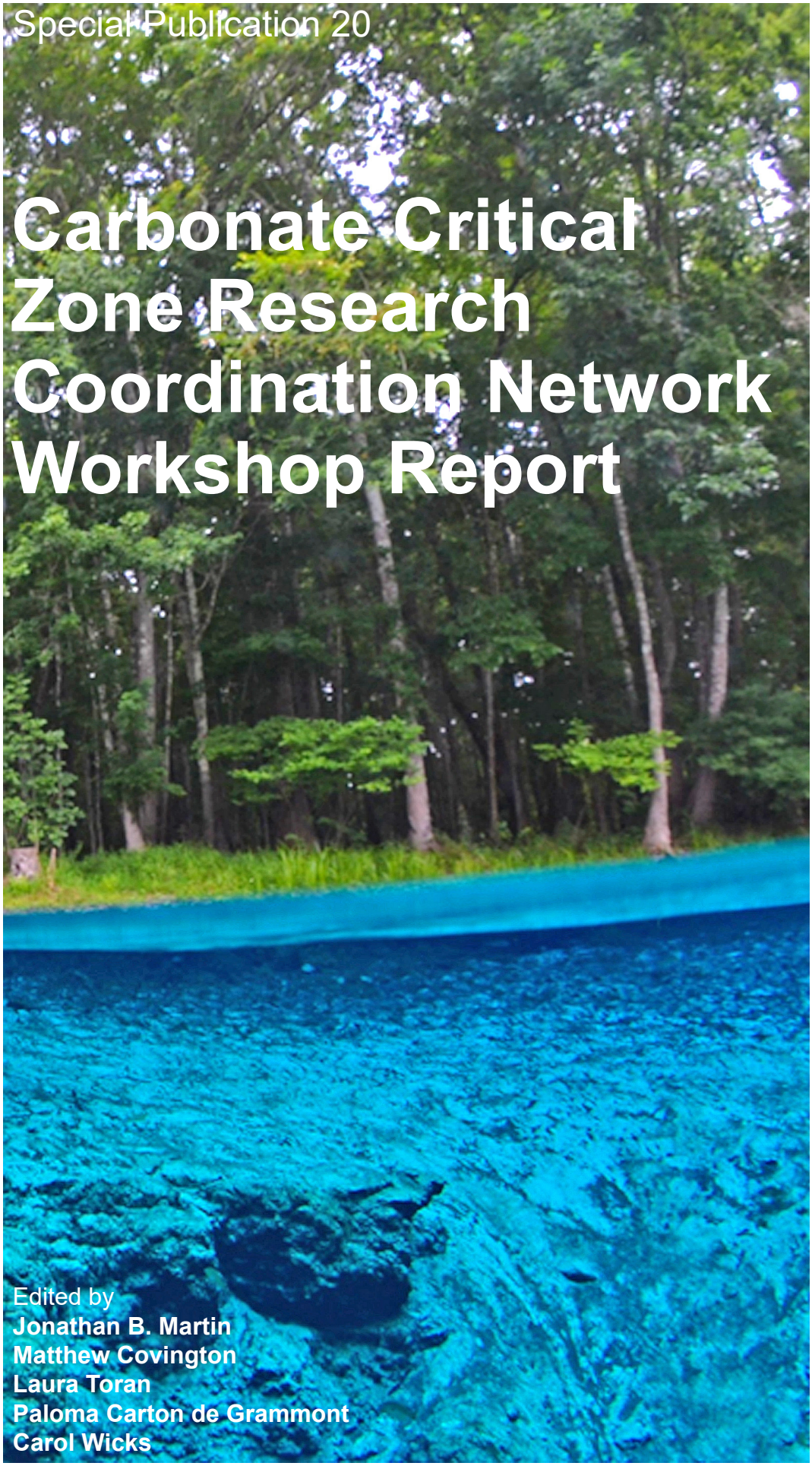
Carbonate Critical Zone Research Coordination Network Workshop Report



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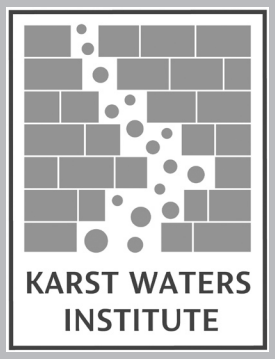

Carbonate Critical Zone Research Coordination Network Workshop Report

2021

Proceedings and recommendations from the virtual workshop held August and September 2020

Edited by
Jonathan B. Martin
Matthew Covington
Laura Toran
Paloma Carton de Grammont
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EXECUTIVE SUMMARY

Research into Earth's critical zone has been coordinated through Critical Zone Observatories (CZO) and recently in the United States through Critical Zone Networks (CZN). All United States CZOs and CZNs focus on landscapes underlain by bedrock composed predominantly of silicate minerals, which limits similar coordinated studies of the approximately 15% of Earth's landscape composed of nearly pure carbonate minerals. Consequently, this Carbonate Critical Zone Research Coordination Network (RCN) was developed to coordinate, support, and enhance the community of people with interests in the critical zone where bedrock consists largely of carbonate minerals, as well as landscapes with bedrock of mixed silicate and carbonate minerals. The RCN began with an inaugural workshop, described here, that aimed to expand the community, connect people within the community, and initiate discussions to identify key research directions. The workshop was held as a series of virtual sessions between August 3 and September 29, 2020 and was attended by 70 participants with a range of backgrounds, experiences, and career stages. The workshop began and ended with three-hour virtual plenary sessions. Six subsets of participants met between the plenary sessions in working group sessions that were organized by themes related to critical zone characteristics. Working groups included 7 to 11 participants who were chosen to maximize demographic and career stage diversity. Working groups were charged with (1) developing a prioritized list of research questions, describing their importance, and identifying missing data that would be needed to address the questions, and (2) brainstorming ideas, actions, and resources for fostering diversity, equity, and inclusion (DEI) in the RCN and geoscience community. Each working group developed and synthesized three or four research questions. All questions from the working groups were synthesized in the plenary session into 22 primary questions that clustered into five key research directions. Participants at the final plenary session refined the research directions to support future activities of the RCN. The research directions provide a framework for continued working groups activities aimed at addressing specific research questions and strategies, data needs, and identify relevant extant data available to answer questions. Working group outcomes will be the focus of the next major workshop tentatively scheduled for spring 2022 in Florida.

INTRODUCTION

Earth's critical zone extends from the base of weathered bedrock to the top of the vegetation canopy. The critical zone has been studied for centuries because of its importance to human activities and over the past few decades, coordinated critical zone studies coalesced in the U.S. around a set of ten Critical Zone Observatories (CZOs), which have now been replaced by nine newly created Critical Zone Networks (CZNs). The original CZOs facilitated collaboration among researchers through shared infrastructure and data within individual or clustered watersheds. The U.S. CZOs were developed in parallel with many other CZOs scattered around the world, mostly in Europe and China. The switch from CZOs to CZNs changed the research focus from place-based studies in individual or neighboring watersheds to thematic clusters where specific problems are studied across multiple watersheds regardless of location.

Much CZO and CZN research is linked to bedrock weathering and weathering impacts on other critical zone features, including soil development, water retention and composition, surface morphology and drainage, surface and subsurface biomes, and land use. However, of the ten U.S. CZOs, only one, the Shale Hills CZO, contains bedrock that includes some carbonate minerals. No U.S. CZO or CZN has nearly pure carbonate bedrock with characteristics that are common to karst landscapes, such as large voids caused by mineral dissolution.

Considering that around 15% of Earth's critical zone occurs in regions with karstic carbonate bedrock, which is estimated to support between 10 and 25% of humanity's water supply, it is vital to understand how variations in carbonate mineral content may impact critical zone characteristics and processes. One key impact stems from differences in how the two mineral groups weather. Silicate minerals weather incongruently, leaving behind modified mineral compositions that alter biological, physical, and chemical characteristics of the critical zone. In contrast, carbonate minerals weather congruently, leaving behind little insoluble residue and creating zones of high permeability that control water flow paths and delivery (Fig. 1). The lack of CZOs or CZNs in carbonate terrains motivated development of this Carbonate Critical Zone Research Coordination Network (RCN), which aims to (1) identify important research directions for focused and coordinated studies of Earth's carbonate critical zone and (2) connect people in the community around common interests. The RCN was initiated through a virtual workshop that took place between August 3 and September 29, 2020. This report describes the planning, activities, and outcomes of that workshop and potential future activities of the RCN.

RCN GOALS AND IMPLEMENTATION

The Carbonate Critical Zone RCN has two primary goals. The first is to build a network of researchers with common interests in the characteristics of the carbonate critical zone and the processes that produce and modify those characteristics. This goal will be accomplished by hosting a series of workshops to provide opportunities for researchers, teachers, students and others who otherwise may not meet or collaborate, to discuss their current interests, research activities, identify potential future research and teaching needs, and build research, teaching, and training teams. The inaugural workshop, which is described here, was open to anybody expressing an interest in the topic; participants were both invited and self-identified. The initial invitees were identified by the RCN steering committee to include people known to have interests in carbonate systems and/or the critical zone. Participants were expanded from this initial group through advertising in multiple venues, including society listservs and websites, and from suggestions made by the invited participants. The expansion of the network had a clear goal of increasing demographic diversity of the network through expansion of participation by members of underrepresented groups in the geosciences.

The second RCN goal is to identify, describe, and record important new research directions that could enhance the understanding of how critical zone characteristics and processes would be affected by variable fractions of carbonate mineral contents of the critical zone. The two RCN goals are linked because developing research directions provides a context for shared activities and discussions that offer networking opportunities among workshop participants and with the broader critical zone research community. For the inaugural workshop, the basis for identifying new research directions was built from seven distinct but interrelated themes that were identified by the RCN steering committee and described below. These themes provided a framework to develop and organize workshop activities with an expectation that the original themes would be modified and expanded through contributions of new ideas and perspectives derived from each participant's interests. New research directions identified during the workshop and presented in this report are a key outcome of the workshop.

The inaugural workshop originally was designed to take place over three days in early August 2020 in Philadelphia, Pennsylvania, with a field trip to central Pennsylvania. Planning was nearly complete when the COVID-19 pandemic forced a switch from an in-person to virtual workshop. The switch required a revision of all workshop activities so that workshop goals could be reached with a virtual platform. The major

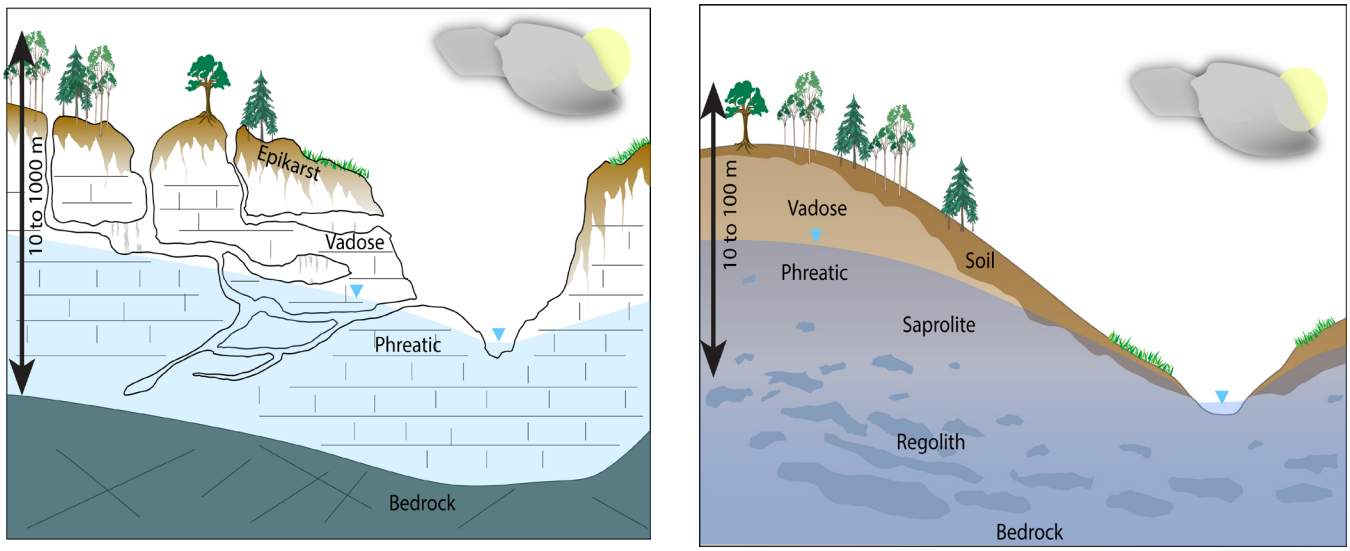

Figure 1. Comparison schematic diagrams of A. a carbonate mineral rich critical zone and B. a silicate mineral rich critical zone. Note the difference in vertical scale of the two panels.

change was an expansion of the workshop length to a nearly two month long series of virtual sessions that began and ended with plenary sessions. The intervening sessions convened small subsets of the participants into working groups. The working groups were assembled both by common interests in critical zone processes, as reflected in participants' statements on the workshop application, and to ensure diversity of career stage and demographics. The plenary session that initiated the workshop occurred August 3 and was attended by 64 participants (Appendix A). The workshop ended September 29 with a second plenary session attended by 44 participants. Between these two plenary sessions, six working groups met. Four working groups included 10 participants and the other two working groups had seven and 11 participants, for a total of 58 participants. In total, 70 individuals participated in the various sessions of the workshop. Development of networking opportunities and identification of research interests, needs, and directions were enhanced by several strategies. These strategies, along with the discussion outcomes, are described below.

NETWORK COORDINATION

People make connections and form collaborations through communal activities that allow them to identify shared goals and interests. Creating successful collaborations thus involves not only bringing people together, but also, and perhaps most importantly, coordinating and facilitating meaningful interactions. Interactions are enhanced by collegial settings that allow people to express differing views, needs, and expectations regardless of demographics, career stage, or experience. Creating collegial settings was complicated in the workshop by the need for activities to occur in a virtual format. To alleviate the complications, workshop planning and most of its activities were developed and led with the support of professional workshop facilitators Sharon Ryan (Luneer LLC) and Paloma Carton de Grammont (UF Water Institute). During the workshop, they used proven participatory methods drawn from the Technology of Participation™ (ToP) body of knowledge of the Institute of Cultural Affairs to facilitate and encourage contributions from all participants, thereby enhancing interactions and network development.

Participant Demographics and Existing Networks

Reaching the RCN goal of developing and expanding a network of people with similar interests required the workshop participants to represent a broad range of backgrounds, experiences, and career stage. Achieving this broad range was enhanced by the lower cost of a virtual rather than in-person workshop, which allowed the workshop to be open to all applicants (perhaps the primary advantage among the many disadvantages of a virtual workshop). The range of experience and career stage is reflected in the institutional affiliations and positions of the participants. Nearly 85% of the participants are affiliated with academic institutions with ranks approximately evenly distributed between Full Professors (14), Associate Professors (9), Assistant Professors (16), and graduate students (16) (Appendix A). Additional academic participants included an undergraduate student, Adjunct Professor, Emeritus Professor, Research Associate, and Head of Unit. Many of the remaining participants have affiliations with governmental agencies, including the U.S. Geological Survey, Indiana and Kentucky geological surveys, and the National Science Foundation. The breadth of career stage supported an additional important networking goal of developing mentorship relationships among the participants. This

mentorship goal is a critical aspect of transforming scientific culture towards diversity, equity, and inclusion (DEI) principles. Thus, the networking goal of this RCN includes a specific objective of connecting participants at various career stages to improve planned mentoring capacity, both between career stages and among peers, with particular emphasis in supporting students from underrepresented groups.

The RCN has established an evaluation protocol to aid the development and expansion of networks among people interested in carbonate terrains and critical zones. The protocol will include a series of surveys to be distributed throughout the RCN to assess the effectiveness in developing the networking and DEI goals. The initial survey (Study Approval IRB202001855, Evaluation and monitoring of the Carbonate Critical Zone Research Network: Building social capital and increasing diversity) was distributed before the workshop and completed by 59 of the workshop participants (84.2%). Survey responses provided information about institutional and disciplinary affiliations, demographics, career stage, current collaborations among participants, and relative strengths of those collaborations. Respondents represent a similar distribution between male and female participants (55% male and 45% female). A majority of the respondents (62%) identified as White or European American with the remainder of participants identifying with various other ethnic and racial groups (Fig. 2). Nearly 30% of the respondents were first generation college students. This baseline information will guide development of strategies to improve participation among underrepresented groups. Comparisons with future surveys will help evaluate changes in participation, demographics of participants, and development and strength of networks.

The survey asked each participant to describe their collaboration with all other participants as non-existent, limited, occasional, or ongoing. The ranking of paired collaborations was enumerated according to an algorithm. If both listed limited, occasional, or ongoing, the rank was assigned a value of 1, 3, or 5, respectively. Responses between two people as limited and occasional were assigned values of 2 and occasional and ongoing were assigned values of 4. If one person of a pair listed a collaboration, but the other of the pair did not, then the value was reduced by 1 point, except if one of the respondents listed the collaboration as limited and the other as non-existent, in which case a value of 0.5 was assigned. Enumeration of the initial survey showed that many participants had established connections of varying strengths prior to the workshop (Fig. 3).

Pre-existing networks of participants tend to cluster with the steering committee members (Fig. 3A) as workshop participants were initially recruited with people known to the steering committee members and subsequently expanded through advertising. Working group leaders also have numerous connections to the steering committee, and these connections extend to others in the workshop and across career stage. However, many participants have few or weak connections and others have no connections to other participants, which

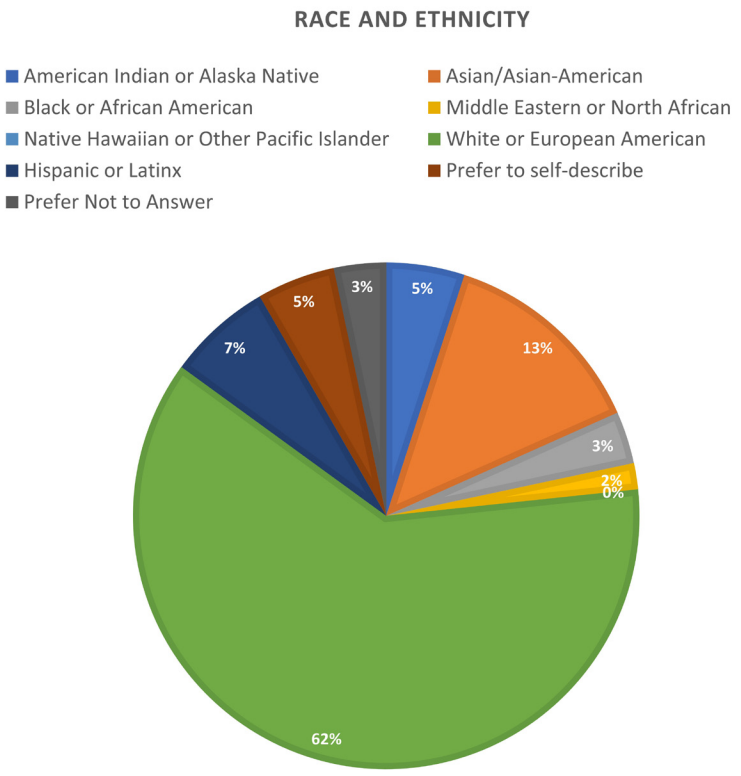

Figure 2. Network demographic composition based on the baseline survey.

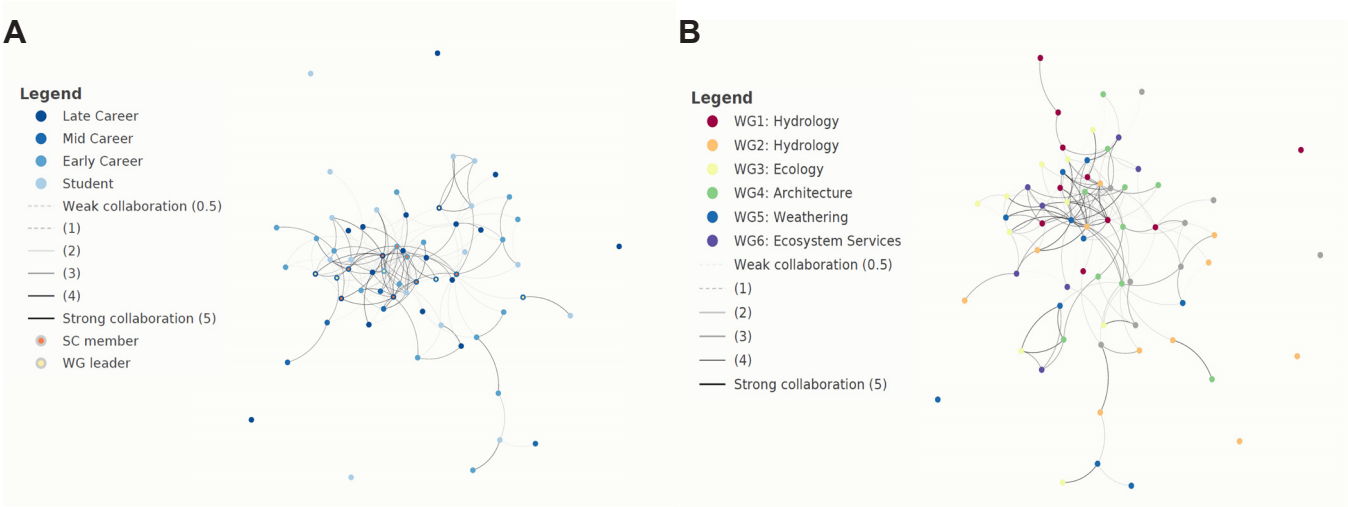

Figure 3. Sociograms depicting composition and strengths of collaborations between workshop participant by A. career stage and B. working group. Elements (circles) represent workshop participants, and lines represent the strength of collaboration. See text for a description of how collaboration strength was determined.

reflects the potential of the RCN to create new connections as well as to enhance and strengthen pre-existing connections. As shown in Figure 3B, the steering committee members and working group leaders were divided among the different working groups, as were most of the participants without connections. This distribution reflects the aim of populating the working groups to provide the best opportunity for creation of new connections among the participants. New connections should be created through common activities as the RCN progresses, including additional stand-alone workshops, workshops at disciplinary meetings, and activities that foster training in various research skills.

Training

The wide range of career stage represented by workshop participants reflects varied expertise in many techniques commonly used to study the critical zone. Consequently, future activities of the RCN will involve exchange of skills derived from the experiences of the participants of this and future workshops. Training programs may be led by senior participants, but could also be led by junior participants who may have recently developed skills, for example with greater expertise in digital platforms.

Identification of which topics workshop participants deemed as important for training exercises was derived from responses from the survey (Fig. 4). Results of the survey show interests in distinct research methodologies, from which training activities could be developed. Although training needs were fairly evenly distributed among the various categories listed on the survey, the top three identified needs were (1) use of digital instrumentation and methods for analyses, including tools for modeling, (2) programming to manage data, and (3) utilizing data loggers to monitor physicochemical parameters. A highly ranked fourth topic was training in the use of tracers. This information will be used to guide development of training activities within the RCN and at future workshops. These training needs also impact the identification of research directions as new methodologies become more widely known and could be used to plan research strategies.

Diversity, Equity, and Inclusivity (DEI)

Expanding boundaries, strengths, and abilities of the community of people with interests in carbonate systems and critical zones can be enhanced with added contributions from people of various demographics and backgrounds. The inaugural workshop was purposefully designed to facilitate this expansion and as an initial step toward inclusion, all workshop guest speakers were members of groups underrepresented in the geosciences. The workshop was initiated with a virtual icebreaker to construct an environment of inclusion and introduce the topic of the lack of diversity within geosciences. The working groups provided dedicated time and structured activities for small groups to reflect on the causes and consequences of the lack of diversity in the geosciences, ponder on the barriers faced by colleagues from underrepresented demographics, learn from participants' experiences with successful DEI efforts, and brainstorm ideas on how the RCN can enhance its DEI efforts. During this exercise, participants were asked to share their ideas, experiences, and suggestions with the use of the Google Jamboard tool, which allowed anonymity for the contributors. The information shared by the working group participants was synthesized by members of the RCN steering committee during presentations in the second plenary session (Fig. 5). This information will form the foundation of a RCN DEI Action plan.

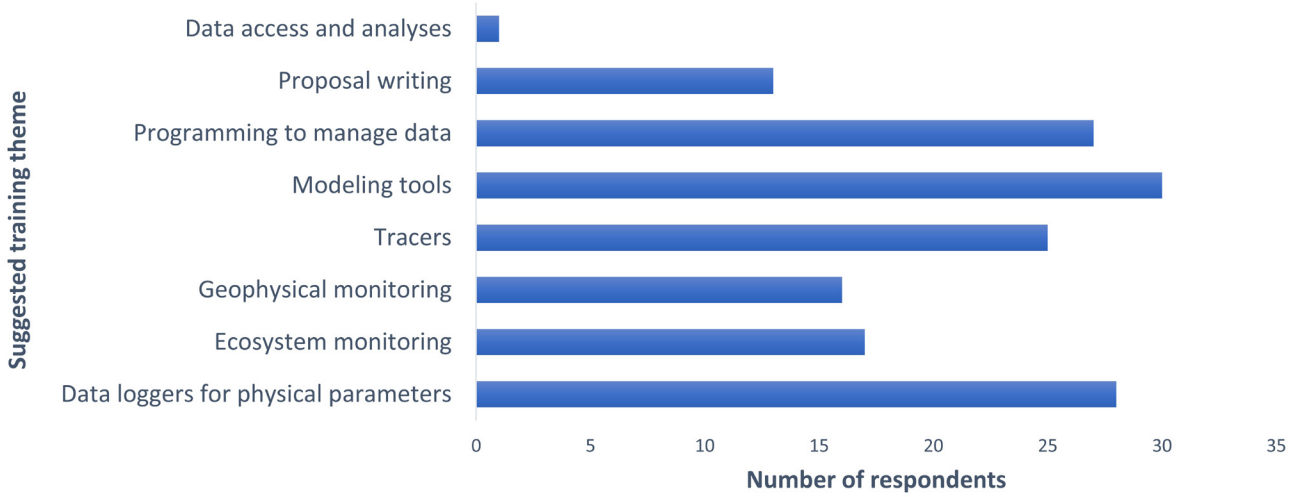

Figure 4. Number of respondents to the survey indicating a desire for training in the topic indicated.

Focus on DEI issues in the second plenary workshop was enhanced through invited presentations by two guest speakers, both of whom have wide ranging experience in fostering DEI in the geosciences. Dr. Brenee King (Kansas State University) provided information about a program she runs, the NSF-supported "Sparks for Change", which addresses the problem of the lack of meaningful numbers of underrepresented faculty in tenured positions or institutional leadership positions. She described efforts in the Sparks for Change program to develop ways to overcome the institutional inertia that leads to the lack of underrepresented groups in faculty leadership roles. Dr. Laura Crossey (University of New Mexico) pre-

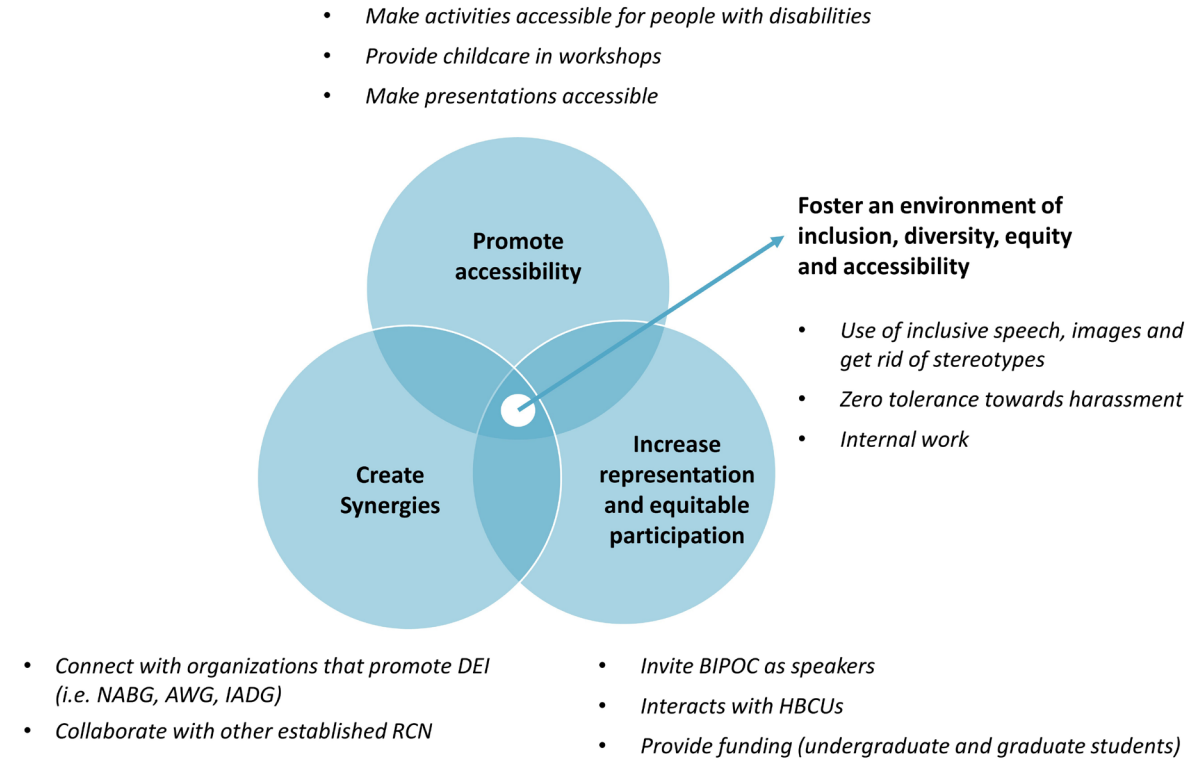

Figure 5. Synthesis of ideas, experiences, and suggestions from workshop participants as it relates to ways this RNC should focus its DEI efforts. Text in italics are examples of the entrances provided by workshop participants which were classified in three major areas. At the intersection of those areas is the main goal of the Action Plan: foster an environment of inclusion, diversity, equity, and accessibility.

sented information about the "Louis Stokes Alliances for Minority Participation (LSAMP)", which is a National Science Foundation program aimed at integrating research, education and outreach to leverage efforts in diversity and inclusion in undergraduate research. The program has been active since 1992 with hundreds of affiliated institutions across the nation and many successes at recruiting and retaining underrepresented minorities in the STEM fields. Information about both programs can be found on the Virtual Workshop Plenary Presentation page at the RCN website.

The workshop DEI activities led to development of an ad hoc committee (DEI Interest Group) that is in the process of drafting a DEI Action Plan to establish and advance an environment of diversity, equity, and inclusivity within the RCN as a potential step toward increased diversity within the broad geoscience community. The Action Plan is currently being designed with the aim to be SMART (Specific, Measurable, Agreement, Realistic, Time-specific, Supportive back-up) and to guide and be implemented in future RCN activities. These guided activities range from recruitment of additional participants, formatting of both virtual and in-person activities to be inclusive, and allocation of resources. The design of a SMART Action Plan will influence the behavior and culture of the RCN and may serve as a successful example for other RCN efforts and more broadly across the geoscience community.

RESEARCH COORDINATION

In addition to increasing the number of workshop participants, the switch to a virtual format benefited the workshop by allowing it to expand into a sequence of sessions that lasted a couple months. The sequential sessions provided benefits by allowing modification of activities based on previous outcomes that improved discussions and idea development as the workshop progressed. Unfortunately, the two month-long workshop also created time conflicts for some participants, particularly for teachers and students, as later sessions occurred after the start of the fall semester. Time conflicts restricted involvement in all workshop sessions but a continuity of ideas was maintained by the numerous participants who could participate in multiple sessions. The following description of ideas developed during the workshop is organized chronologically by session to illustrate how topics in early sessions were modified in subsequent sessions to aid in the identification of important research directions.

Initial Plenary Session

The workshop began with a presentation of how the RCN may provide opportunities for networking and development of research directions among the community of people interested in the intersection of the critical zone and landscapes underlain by bedrock that contains carbonate minerals. The presentation emphasized that the opportunities could be used to guide future research agendas and that guidance should originate by consensus of the community through collaborative identification of pressing science questions related to carbonate critical zones and hypotheses that spring from those questions. Equally important aspects that were stressed included the need for (1) justifications for how results of hypothesis testing will advance understanding of carbonate critical zones, (2) considerations of what may be the best methods for testing the hypotheses, and (3) compilations of metadata that lists information currently available to test the hypotheses. Each of these issues was included in the workshop discussions to varying degrees. Although focused on carbonate mineral-rich regions of the critical zone, the opening presentation also emphasized that research directions should be placed in the spectrum of silicate- and carbonate-rich bedrock of the critical zone and how this spectrum affects general critical zone characteristics and processes (Fig. 1). These ideas were reinforced by an invited presentation by Dr. Daniella Rempe about weathering, water storage, and carbon of bedrock vadose zones, with an emphasis on findings from the Eel River CZO, where the critical zone is composed of non-carbonate sedimentary and metamorphic rocks.

The initial plenary session provided an opportunity to organize participants around common research interests that could foster network development. However, the large number of participants and virtual format limited the ability to have open discussions in a plenary session that would be equitable among participants with varied experiences and seniority. Therefore, participants were distributed into six working groups to ensure all participants had the opportunity to present their views and to enhance discussions (Appendix A). The distribution was based on the participants' ranking of their interests in seven themes related to critical zone characteristics, as indicated on their workshop applications. The themes were developed by the workshop steering committee and are listed below in alphabetical order to emphasize their equal importance to the critical zone and that none is independent of the others.

Architecture

Physical, chemical, and lithological characteristics of the critical zone depend in large part on weathering of its bedrock. The effects of weathering on critical zone characteristics vary with the relative amounts of congruent dissolution of carbonate minerals and incongruent dissolution of silicate minerals. The mineralogical composition of the critical zone is thus of primary important in controlling critical zone characteristics.

Climate and Land Use

Critical zone processes respond to natural long- and short-term climate change and local human activities that alter land

use at rates comparable to human life spans. Responses may occur at local scales, for example, through infrastructure development (e.g., paving, dam construction) to regional and global scales, for example, as caused by changing climate and anthropogenic production of weathering acids.

Ecology

Biological processes at microscopic to regional scales produce and buffer acids and alter concentrations of electron donors and acceptors throughout the critical zone. The distribution of biological processes with depth and laterally within the critical zone thus control pH and redox gradients. These gradients will affect critical zone processes in differing ways that depend on the mineralogical composition of the critical zone bedrock.

Ecosystem Goods and Services

The critical zones of karst landscapes provide important ecosystem goods and services, including water supplies for domestic, agricultural, industrial, recreational, and ecosystem needs, food security, potential for carbon sequestration, and habitats for endangered species including many troglobitic and troglophilic organisms. Many of these services are threatened by modifications related to human activities, including climate change, sea level rise, human water use, and point and non-point source pollution from urban, industrial, and agricultural sources.

Hydrology

Mineralogical composition and its control on the magnitude of congruent relative to incongruent dissolution controls the permeability structure of the critical zone and thus distributions and magnitudes of flow. Variations in flow will provide feedbacks to dissolution and weathering mechanisms and thus magnitudes and chemical composition of fluids in the critical zone. The mineralogical composition, as linked to flow and chemical composition, also impacts rates and magnitudes of exchange of water and gases between the critical zone and Earth's surface and atmosphere.

Time

The critical zone is impacted by processes that occur across a large array of time scales, ranging from events (floods, fires, droughts) to human (biological community assemblage and succession, response to events) to geologic (biologic evolution, geomorphic change). Critical zone responses depend on reaction rates of minerals that compose bedrock composition, with faster reactions rates for carbonate than silicate minerals. These differences thus dictate how critical zone characteristics will be modified by processes across various time scales.

Weathering

Perhaps the master variable of the critical zone, weathering will vary with the mineralogical composition of the critical zone bedrock and will depend on all other physical, chemical, and biological processes within the critical zone. Weathering will impact distribution, concentrations, and fluxes of solutes and gases within the critical zone, which will provide feedbacks to other processes, for example, ecology with changing nutrient concentrations and distributions and climate with variable greenhouse gas fluxes and exchange with the atmosphere.

Workshop participants recognized the interconnectedness of the themes, which led to an uneven distribution of interest among the themes; many participants expressed interests in the Hydrology and Climate Change and Land Use themes. To ensure that all themes would be discussed in the workshop and to form working groups of participants with similar interests, the working groups were populated around clusters of themes rather than focusing on a single theme (Appendix A). Two working groups focused on the same cluster of themes while the remaining four working groups had unique but overlapping clusters of themes. By creating clusters of themes, all participants were allowed to join working groups that included at least one of their top ranked themes. The primary interests of the working group's participants is reflected in the order of themes within the working group titles shown in Appendix A, which also reflects the emphasis within the working group discussions. Clustering of themes also allowed an even distribution of backgrounds, levels of experience, and topical interests among participants of each working group as well as inclusion of a cross section of representation among demographic groups based on self-identified membership in an underrepresented group (Fig. 2).

Introduction of working group participants was done in breakout sessions during the initial plenary session. The goal of these icebreaker sessions was to allow people to get to know each other through prescribed activities. Each participant was asked to identify themselves in terms of their affiliations, background, scientific interests relative to carbonate minerals in the critical zone, and to describe a non-job activity they enjoy. The premise behind the icebreaker was that understanding similarities and differences in the group could create a more welcoming academic community. These initial conversations also allowed for increased efficiency of discussions during the subsequent working group sessions in August and early September.

After the working group breakout sessions ended, the remainder of the initial plenary session was dedicated to developing plans for subsequent working group sessions, descriptions of activities needed to prepare for working group discussions,

and the expected outcomes of the working group. The workshop closed with a virtual field trip that was created by Drs. Jim Berglund and Laura Toran. The field trip, which is posted to YouTube and available at the RCN website, highlights the karst springs of Nittany Valley, Pennsylvania, which was to be the site for the planned in-person field trip that was canceled because of travel restrictions. The five minute virtual field trip features imagery captured by drones and is narrated by Dr. Will White, Emeritus Professor at Penn State University, who describes some of his and his students' early classic work on karst hydrology in the region. The field trip provides great historical context about methods used to study hydrology and chemistry of carbonate critical zones and how new methodologies, particularly sensor development, can help expand the critical early work. It is also an important example of how virtual field trips could be used to expand the accessibility of field experiences.

Working Group Sessions

Times for the working groups to meet were scheduled during the eight weeks between the initial and final plenary sessions. Session meeting times were identified to maximize the number of participants in each working group. Discussions were headed by a volunteer leader, as identified in Appendix A, with support from a facilitator and steering committee member. Each working group followed a common agenda to ensure a similar format and organization of the meeting outcomes. The facilitation was critical to the success of the working groups because virtual meetings can suppress the exchange of information compared with in-person meetings. Working group leaders and facilitators strove to ensure that all participants had equal opportunities to provide their views of important future research directions. The facilitated discussions thus allowed working groups to sort through, gather, and organize the many ideas presented by all participants of the working group sessions.

Working group participants were asked to spend a short amount of time prior to the working group sessions to review the themes of their working group. Prompted by the themes, participants were to identify in a short written statement or bulleted list a description of two to three science questions they thought addressed important aspects of carbonate critical zone science that are currently unknown. The questions were to be justified with statements about their significance, what may have hindered finding answers to those questions, and justifications for why it would be important to address them with future research activities. To enhance equitable input at the working group sessions and to ensure that the greatest breadth of ideas was presented, small breakout groups were created, which were composed of three to four participants and contained diverse demographic and career stage distributions similar to the working groups. Discussions in the working groups identified a total of 73 individual research questions that cover a broad range of topics, and while some questions overlap, many of them are unique (Appendix B). Although each question addresses important issues, the large number of questions required synthesis to identify key research directions that could be addressed.

A series of steps were used to synthesize the questions identified in the breakout session and cluster them into common themes. After the breakout sessions ended, the working groups reconvened for discussion about the list of all identified questions. A spokesperson from each breakout group presented to the working group participants all questions identified in each breakout session, described the potential significance of addressing those questions, and justified how the questions were most likely to provide new important information. During these presentations, key questions from each breakout group were compiled using a Google Docs spreadsheet that was accessed in real-time by all participants of the working group. The spreadsheet was used by working group participants to narrow the list of questions by having all participants ranking the questions that originated from the breakout groups by their significance. This process led to a consensus of three to four questions that the participants considered to have captured the most important research needs related to the themes of each working group. These top questions were either verbatim from the individual questions, combinations of the individual questions, or modifications of questions derived from the breakout group. The need to reach a consensus opinion using this voting method, rather than reaching a consensus through discussions, stemmed from complications of having open dialogue among many people in a virtual format.

The three to four top-ranked questions from each working group were deemed to represent the most likely research directions to advance understanding of the themes for each working group. These questions were the primary outcome of the working group sessions and provided a start toward synthesizing findings of the overall RCN workshop. The development of these questions was enhanced following the working group sessions through email exchanges and virtual meetings among the working group leader and participants. From these discussions each working group created a PowerPoint presentation describing the identified questions and research directions. These presentations are archived at the RCN website. None of the key questions developed by the working group participants were identical, but some questions represented overlapping topics, both within individual working groups as well as among working groups. The overlap allowed the working group questions to be synthesized into common topics that represent five primary research directions (Table 1). This synthesis was completed between the end of the last working group session and before the start of the final plenary session and as described below, fostered additional discussion among all RCN participants during the final plenary session of the workshop.

Table 1. Key research questions and directions.

Questions	Background and Justification	Data Needs*	Ancillary Themes	WG**
Boundaries and Scales				
What defines the base of the critical zone in karst systems?	The lower boundary of the critical zone is often planar and subparallel to the surface, but may be non-planar in carbonate terrains because of heterogeneous permeability of karst. Increased carbonate mineral content of the critical zone alters the propagation depth of surface properties (temperature, chemistry, biology).	C, G, L, T		1
How do biological impacts on bedrock composition vary across spatial scales (microscopic to landscape) and organisms (microbes to trees)?	Energy allocations, morphological traits, and microbial diversity and activities may vary for species across lithological gradients within the critical zone. Causes of variations are poorly known.	G, R		3
How does partitioning of deep and shallow flow alter critical zone architecture and water availability?	The separation and interactions of surface and subsurface flow alters surface weathering and erosion, pollutant behavior, stress on water supplies, and dissolution and speleogenesis in the deep critical zone. Interdisciplinary studies (geomorphology, geochemistry, hydrology, geophysics, mathematical modeling, etc.) are needed to improve understanding of effects of flow separation.	B, C, G, L, M, R, S, T		4
What processes and lithological characteristics control development of karst and subsurface critical zone architecture?	Critical zone architecture at all depths results from processes include fracturing, water-rock interactions, diagenesis, orogenic events and characteristics including grain size, primary porosity, insoluble residue content, age of rock, carbonate versus silicate mineral content, topographic relief, and availability of acids. These processes stem from external forcing such as climate, tectonics, sedimentary cover, and ecology.	B, M	Biological, chemical, and physical processes	4
How does the vadose zone homogenize water, energy, and nutrient sources delivered to the critical zone?	Signals of time variations in compositions of water isotopes, temperature, and nutrients become muted with depth in the critical zone, despite highly variable flow paths through the epikarst. These variations may depend on thresholds in recharge or mixing in local critical zone reservoirs. Interpretation of the signal that are muted in the vadose zone require tracking variations along flow paths.	C, G, M, T	Biological, chemical, and physical processes	4
How do small scale heterogeneities affect large-scale solute transport as climate and land use changes alter hydrological processes?	The scales of critical zone processes and characteristics dictate which observations may be transferable between distinct carbonate critical zones. The transferability of observations is an important step to integrate research across the breadth of characteristics of carbonate critical zones and allow the generalization and integration of research findings from groups of individual systems.	C, G, T		2
Biological, Chemical, and Physical Processes				
How does critical zone lithology alter sensitivity of primary productivity to climate change?	Carbonate lithology amplifies the impacts of climate change on terrestrial production by reducing regolith water holding capacity and altering soil nutrient availability.	R	Critical Zone in Society	3
How do physical and chemical weathering interact, particularly as fractures form with depth in the critical zone?	Feedbacks exist between chemical and physical weathering as fracturing increases surface area to enhance chemical weathering and as rock rheology varies with chemical weathering to change physical weathering mechanisms. The interdependence of chemical and physical weathering alters surface topography and subsurface characteristics, such as porosity and permeability.	B, L, M	Boundaries and Scales	5
What processes control formation and locations of critical zone redox and pH gradients and how do gradients respond to variations in flow?	Redox and pH can be linked by biochemical processes that form carbonic, sulfuric, and nitric acids. Both redox and pH control weathering reactions of bioreactive components such as metals and nutrients. These component concentrations depend on distributions of electron donors and acceptors, which in feedbacks are modified by flow and biogeochemical reactions. Redox and pH conditions may depend on both amount and reactivity of organic matter.	C, G, M, T	C dynamics	5
How do magnitudes of N_2O and CH_4 emissions vary across critical zone ecosystems (e.g., aquatic vs. soil) and lithologies (carbonate and silicate)?	The greenhouse gases, N_2O and CH_4, have greater greenhouse warming than CO_2 and yet little is known of their dynamics in and emissions from surface water and groundwater in carbonate critical zones. Redox variations in carbonate critical zones could provide both sinks and sources to Earth's atmosphere of these greenhouse gases.	C, G, T	Critical Zone in Society	6

Table 1. continued

Questions	Background and Justification	Data Needs*	Ancillary Themes	WG**
How does anthropogenic climate (e.g., extremes of floods and droughts) and land use changes (e.g., modified vegetation) affect weathering of the carbonate critical zone?	Climate change is projected to alter water cycles by increasing extreme events such as flooding and droughts, with impacts on weathering rates, evapotranspiration, and land use through changing vegetation. Changing vegetation will alter weathering as roots contribute to physical weathering with increased permeability and chemical weathering by hosting microbial communities and generating acids.	C, G, L, M, R, T	Critical Zone in Society	5
Rates and Time				
What are the effects of infrequent but extreme events that may shift equilibrium states of the critical zone?	Large magnitude infrequent events (e.g., floods, extreme weather, forest fires, land use changes, paving) represent short periods of "work" that may shift systems to new equilibrium states. Much research is biased toward long intervals between events. Effects from these events may include conduit collapse, sinkhole formation, sedimentation, point and non-point source contamination.	C, G, M, T		1
What are rates and time scales of flow, carbon cycling, and weathering, as climate and land use changes alter these processes?	The carbonate critical zone is sensitive to short term changes, such as driven by human activities, and thus is a bellwether for change. A critical factor to develop adaptation and mitigation strategies is to understand human impacts on the carbonate critical zone and the timescales over which they are important.	C, G, L, T	Critical Zone in Society	2
What new methods will improve use of solute and tracer breakthrough curves to understand carbonate critical zone processes such as conduit versus matrix flow?	Karst aquifers are often treated as "black boxes" in models where transformations occur between input and output signals. Variations in tracer behaviors provide opportunities to study key characteristics of residence time, advection, dispersion, and architecture in the subsurface. Tracers may be used to relate contaminant and solute transport to aquifer flow conditions. Opportunities exist to reexamine existing tracer datasets.	C, G, L, T	Boundaries and Scales	4
How are materials (dissolved, suspended, bedload) transported within and out of the critical zone?	Weathering reduces particle size and affects magnitude of bedload or suspended loads and alters porosity and permeability as small pore throats are clogged or porosity develops as sediment is flushed from the system. Weathering also controls dissolved and colloidal water compositions, which could alter surface ecosystems as they discharge from the critical zone.	L, M	Biological, chemical, and physical processes	5
Carbon Dynamics				
What impact does carbonate content of the critical zone have on the global carbon cycle and how will this impact shift with future climate change?	Some conceptual models of critical zone processes may be transferable across the spectrum of mineralogical compositions of critical zones. The transferability of models requires context to develop understanding of how differing bedrock compositions affect critical zone processes. Carbonate critical zones may be an important bellwether of effects from changing climate.	M	Biological, chemical, and physical processes	2
How does ecosystem metabolism, including carbon cycling and chemolithotrophic processes, control karst weathering rates?	Organisms force chemical transformations that impact bedrock dissolution via production of CO_2 and other acids. The spatial patterns of organic matter storage, remineralization, and effects on Fe and S oxidation are poorly constrained but important to determine modes and magnitudes of biological influence on weathering. Similar to silicate landscapes, microbial Fe and S oxidation may be important for weathering of carbonate critical zones, despite their limited Fe and S contents.	C, G, T, F	Biological, chemical, and physical processes	3
Does spring water CO_2 concentrations represent average soil CO_2 concentrations of karst landscapes and do mismatches vary with climate and landscape maturity?	Equilibrium is often assumed to occur between soil CO_2 and groundwater, but recharge and respiration are not evenly distributed in space or time. Groundwater CO_2 concentrations will depend on the heterogeneous distribution of recharge and respiration. Developing an understanding of the relationship between CO_2 and recharge and respiration will guide predictive frameworks for instrumentation, sampling, and effects of landscape scale weathering patterns.	C, G, T, P		3
What controls the distribution of CO_2 within the carbonate critical zone?	Controls are poorly known of spatial and temporal variations of CO_2 within the carbonate critical zone but are related to competing processes of production, transport by water and air, and consumption. Many potential feedback mechanism exist, but are poorly understood, between biological, physical, and chemical processes and the evolution of permeability.	C, G, L, O, T	Biological, chemical, and physical processes	1

Table 1. continued

Questions	Background and Justification	Data Needs*	Ancillary Themes	WG**
Critical Zones in Society				
How can we advance our science and its communication by engaging local stakeholders (e.g., indigenous people) and decision makers in carbonate critical zone research?	Coproduction of new science with local communities is critical to improving research outcomes; researchers can learn from stakeholders' experiences and traditional ecological knowledge. Facilitating new research and the social impact of that research requires breaking barriers that separate scientists, decision makers, and people (e.g., stakeholders) affected by research outcomes.	M, S		2
Do differences in critical zone characteristics contribute to inequitable provisions of environmental goods such that aspects of social geography reflect the differences in critical zone structure and processes?	Critical zone mineralogy and structure affect its function and value, for example in providing reliable water supply or fertile soils. Disempowered communities may be pushed toward landscapes where limited environmental goods may be derived from the critical zone, such as badland reservations. Re-assessment of canonical environmental justice issues through a critical zone lens and new case studies should rely on social scientists to help shape critical zone questions and approaches.	M, S		6

* B = boreholes and geophysics; C = chronology; F= gas fluxes; G = geochemistry; L = logger monitoring; M = modeling; O = organic matter, sediment, pollen; P = microbial populations; R = remote sensing; S = surveys; T = tracers.
** WG = Working group that developed the question.

Although identification of these key science questions was the main task for each working group, working group activities also included dedicated time to start conversations about diversity, equity, and inclusivity in the geosciences and this RCN. Participants were asked to reflect on the lack of diversity in the geosciences, the barriers faced by colleagues from underrepresented demographics, share successful DEI efforts of which they are aware, and brainstorm ideas on how this RCN can enhance its DEI efforts. The information shared by participants was summarized by steering committee members at the final plenary session to foster discussion of future activities in support of DEI activities. That discussion, along with information from the working groups, is currently being used by a DEI interest group of self-selected RCN participants to develop a DEI Action Plan. One goal of this Action Plan will be to enhance the diversity of the RCN, as well as to provide examples of ways to foster diversity, equity, and inclusivity for other groups within the geosciences and across the geoscience community.

Closing Plenary Session

The closing plenary session had multiple goals that centered on identifying ways to move the RCN forward for both networking and research coordination. The session had nearly a third of its time dedicated to discussions and presentations related to increasing DEI within the RCN (e.g., Fig. 5). Issues surrounding DEI were emphasized during the two invited presentations (described above in the Networking section) by Drs. Brenee King and Laura Crossey that led to development of the DEI interest group. The remainder of the final plenary session was dedicated to providing overviews by the working group leaders to workshop participants of the 22 research questions and five research directions. The presentations also described ancillary information about the research question and directions, including why answers to the questions were lacking, their potential to further the state of knowledge of carbonate impacts on the critical zone, and what activities and/or new data may be required to find answers to the questions. The five common research directions that emerged from the key questions are distinct from the original themes described above that were identified prior to the initiation of the workshop. Four topics relate to critical zone characteristics and processes while a fifth topic focuses on the relationship between the critical zone and human activities. Brief descriptions of each of those topics are synthesized below:

- The Boundary and Scales topic focuses on characteristics within the critical zone, how distribution of the characteristics relate to critical zone processes, and the intersection of characteristics and processes. Some key knowledge gaps within this topic include how deep the base of the critical zone may be where it is composed largely of carbonate minerals. The base of the critical zone should be deeper in carbonate than silicate terrains because congruent dissolution forms zones of elevated permeability, such as air and water filled caves that extend hundreds of meters below the land surface (e.g., Fig. 1). Congruent dissolution also enhances exchange of water and gases across the land surface and raises questions related to homogenization of fluid characteristics in the vadose zone with impacts on phreatic zone processes.
- The Biological, Chemical, and Physical Processes topic focuses on a variety of key processes that cross individual disciplinary boundaries. One key knowledge gap exists in the understanding of relationships and feedbacks between physical and chemical weathering. This knowledge gap also relates to the Boundaries and Scales topic because of the role weathering plays in increasing critical

zone permeability with depth in carbonate terrains as opposed to the critical zone in silicate terrains where permeability often decreases with depth. Knowledge gaps that link to biology and chemistry include how ecosystem functions may control redox and pH gradients within the critical zone. These gradients link to physical processes because of their effects on permeability distribution and flow through the critical zone. Gradients in redox conditions control cycling and emissions of greenhouse gases from the critical zone. Linkages between biological, chemical and physical processes reflect the importance of basic natural science questions to the Critical Zone in Society topic.

- The Rates and Time topic focuses on time scales of change within the critical zone and the rates of processes that control those time scales. This topic is also broadly important because time scales of processes may affect the transferability of findings from one critical zone setting to another. Critical zone settings that are composed predominantly of carbonate minerals and that have enhanced permeability will be characterized by faster flow rates and transport of solutes and gases than those composed predominately of silicate minerals. Flow within the carbonate critical zone will be affected by infrequent and short-lived extreme events, which will alter equilibrium states within the critical zone. Because these events are projected to become more common with climate change, their effects on processes will likely become increasingly important in the future. The fast rate of processes (flow, dissolution etc.) in the carbonate critical zone makes the setting ideal to elucidate effects from these processes. This topic thus links to the Biological, Chemical and Physical Processes topic as well as the Critical Zone in Society topic.
- The Carbon Dynamics topic focuses on cycling of both inorganic and organic carbon in the critical zone and other related elemental cycles. The role of carbon in the critical zone of carbonate terrains is particularly important considering these terrains hold Earth's largest carbon reservoir. This topic is closely linked with the Biological, Chemical, and Physical Processes topic, but was separated because of the important role that carbon plays throughout the critical zone, whether composed predominantly of carbonate or silicate minerals. Organic carbon cycling is tightly linked to ecosystem metabolism both through fixation of inorganic carbon to organic matter as well as remineralization of organic matter to CO_2 and other nutrients including nitrogen and phosphorous. The carbon-related reactions form heterogeneous distributions of carbon and other nutrient species throughout the critical zone and these distributions affect other processes that include mineral dissolution reactions resulting from changing pH and redox conditions.
- The Critical Zone and Society topic emphasizes the important role of the critical zone in societal functions and the link between human activities and scientific study of critical zone processes. Many aspects of the critical zone of carbonate terrains link to human activities ranging from water resources to geohazards. This topic cuts across all of the other four topics, which points to the fact that the standard methodology of scientific studies (hypothesis testing through observation and experimentation) may be enhanced through the coproduction of knowledge based on experiences of and information from local stakeholders. Similarly, the stakeholder benefits from ecosystem provisioning of critical zones must include equitable distributions to disempowered communities. In all instances, social scientists should play roles in the studies of natural processes.

All five of these topics were presented to the participants at the closing plenary session along with the list of key questions. In real time, participants identified which topic they had the greatest interest in pursuing. This expressed interest was then used to divide the session participants into "similar interest groups" that were separated into breakout rooms for a short time during the session. These breakout groups enhanced the networking goal of the RCN by facilitating discussion among groups of participants that differed from the original working groups. The similar interest groups thus allowed new connections among participants and the ability to develop a dialog about the generated science questions and research directions. Although breakout sessions of the similar interest groups represented the end of the workshop, they helped initiate discussion about the outcomes of the workshop and potential new directions for the RCN. Because of limitations of time, little additional science discussion occurred during similar interest group breakout sessions, but nonetheless, they set the stage for continued development of working groups. New working groups will represent the continuation of the RCN and future workshops focused on the topics related to the key research questions.

NEXT STEPS

The principal outcome of the inaugural RCN workshop was to develop a broad overview of knowledge gaps concerning the role of carbonate minerals in critical zone processes. The overview is organized around a series of related science questions. The questions were synthesized into five distinct research directions that could aid planning of strategies to approach the research and to build collaborative networks of researchers. Research strategies could include generation of new data with innovative field sampling meth-

odologies, novel model developments, and improved sensor and tracer technologies. Implementation of these strategies require community involvement in their design and use, such as currently being done in the CZN. Many of the knowledge gaps may also be addressed through judicious use of legacy data and new data that are being collected routinely through on-going monitoring programs, such as the new CZNs as well as governmental agencies such as the USGS.

Most important to addressing knowledge gaps is the coordination of the human capital to ensure collaborative, focused, and integrated approaches to addressing the key issues. Because the overview of various knowledge gaps was accomplished during the inaugural workshop, future workshops will have a more narrowly focused design that will expand on one or more of the research directions identified among the key questions (Table 1). Planning for the next workshop is underway with tentative plans for it to occur in spring 2022 in Gainesville, Florida. The exact nature, timing, and location of the workshop will depend on many factors including when competing meetings occur and the status of the COVID-19 pandemic. The workshop will be structured to advance activities and outcomes of new working groups that are being developed based on ideas from the inaugural workshop.

The new working groups will focus their attention prior to the next workshop on one or more of the five research directions identified during the inaugural workshop. They will be populated, in part, by the inaugural workshop participants. Although the groups have not yet been formed or working group leaders identified, the working group leaders from the first workshop have been invited to co-lead the new working groups, along with members of the steering committee. The plan is for the new working groups to have occasional virtual meetings and/or converse through email exchanges or other web-based dialogs prior to the second workshop. Working group activities are wide open, but could include identifying and compiling available legacy data to address some of the theme's questions, determining what data may be missing, developing plans to obtain those data, and analyzing and modeling the data to address specific research questions. If sufficient data are available, the working groups could begin developing peer-reviewed papers based on models and analyses. Starting in January 2021, some RCN participants will present talks to support data discovery, analysis, and archiving. Those presentations will be archived to support the new working group activities.

Along with participants from the inaugural workshop who will be invited to join the working groups, new participants will be recruited from the broader science communities of researchers interested in critical zone processes and processes in landscapes underlain by carbonate minerals. Recruitment for the RCN will focus on specific DEI goals including expanding participation by underrepresented groups within the RCN with a goal of reducing the White/European-American demographic from ~62 to ~50% of the participants (Fig. 2). This goal will be achieved by targeting Historically Black University and Colleges that offer bachelor's degrees in geology and/or environmental sciences, tribal colleges and universities, Hispanic-serving Institutions, and other minority-serving institutions. Assuming the second workshop can be held in person, the number of physical participants will be more restricted than the first workshop because of increased cost related to travel, meeting room rentals, and housing expenses; however, the potential to include virtual participation by others will be explored. Nonetheless, the integration of the large community of researchers with interests in the critical zone where composed predominantly of carbonate minerals will be important to further understanding general critical zone processes. A strong network of collaborators is needed to address key questions and knowledge gaps as well as increase the diversity in the geosciences.

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APPENDIX A

Participants in Carbonate RCN Virtual Workshop

Working Group 1. Hydrology, weathering, climate and land use change

Participant	Title	Affiliation	Plenary	
Yongli Gao	Associate Professor	University of Texas at San Antonio	1	2
Patricia Beddows	Associate Professor	Northwestern University	1	2
James Berglund	Assistant Professor	Montana Tech/Montana Bureau of Mines and Geology	1	2
Matthew Covington	Assistant Professor	University of Arkansas	1	2
Laura Crossey	Professor	University of New Mexico	1	2
Alan Fryar	Professor	University of Kentucky	1	2
Sanju Khatri	Graduate Student	Florida Atlantic University		
Edward Mallon		Triple Point Design, LLC	1	2
Andrew Oberhelman	Graduate Student	University of Florida	1	2
Ira Sasowsky	Professor	University of Akron	1	2

Working Group 2. Hydrology, weathering, climate and land use change

Participant	Title	Affiliation	Plenary	
Liz Hasenmueller	Associate Professor	Saint Louis University	1	2
Peter Abanda	Professor	Houston Community College	1	
Daniel Bittner	Research Associate	Technical University of Munich	1	
Rachel Bosch	Graduate Student	University of Cincinnati	1	2
Behzad Ghanbarian	Assistant Professor			
Wendy Graham	Professor	University of Florida	1	2
Rachel Havranek	Graduate Student	University of Colorado Boulder	1	
Jessica Oster	Assistant Professor	Vanderbilt University	1	
Daniella Rempe	Assistant Professor	University of Texas at Austin	1	
Randy Stotler	Assistant Professor	University of Waterloo	1	2
Laura Toran	Professor	Temple University	1	2

Working Group 3. Ecology, ecosystem services, climate and land use change, weathering

Participant	Title	Affiliation	Plenary	
Matthew Cohen	Professor	University of Florida	1	2
Hazel Barton	Professor	University of Akron	1	
Nicole Cordoba	Graduate Student	Florida International University	1	2
Jessica Corman	Assistant Professor	University of Nebraska-Lincoln	1	2
Xiaoli Dong	Assistant Professor	University of California Davis	1	2
Timothy Gallagher	Postdoctoral Associate	University of Texas at Austin	1	2
Daniel Jones	Assistant Professor	New Mexico Tech	1	2
Jennifer Macalady	Associate Professor	Pennsylvania State University	1	2
Mackenzie Vecchio	Graduate Student	Florida Atlantic University	1	2
Carol Wicks	Professor	Louisiana State University	1	

Working Group 4. Architecture, hydrology, weathering

Participant	Title	Affiliation	Plenary	
Andrew Luhmann	Assistant Professor	Wheaton College	1	2
Teresa Baraza	Graduate Student	Saint Louis University	1	2
Daniel Doctor	Research Geologist	US Geological Survey	1	2
Lee Florea	Assistant Director for Research	Indiana Geological and Water Survey	1	2
Jacob Gochenour	Graduate Student	New Mexico Tech	1	2
Charles Shobe	Assistant Professor	West Virginia University	1	2
Blake Stone	Graduate Student	Florida International University	1	2
Michael Sukop	Professor	Florida International University	1	
Pamela Sullivan	Associate Professor	Oregon State University	1	
Jobel Villafane-Pagan	Undergrad Student	University of Puerto Rico - Mayaguez Campus		

Working Group 5. Climate and land use change, weathering, ecosystem services

Participant	Title	Affiliation	Plenary	
René Price	Professor	Florida International University	1	2
Sam Anderson	Graduate Student	Tulane University	1	2
Ángel García	Assistant Professor	James Madison University	1	2
Jason Gulley	Associate Professor	University of South Florida		
Ellen Herman	Associate Professor	Bucknell University	1	2
He Huang	Graduate Student	University of Florida	1	
Kathleen Johnson	Associate Professor	University of California, Irvine		2
Jonathan Martin	Professor	University of Florida	1	2
Natasha Sekhon	Graduate Student	University of Texas at Austin	1	2
Fan Zhang	Graduate Student	University of Kansas		

Working Group 6. Ecosystem services, climate and land use change

Participant	Title	Affiliation	Plenary	
Ángel Acosta-Colon	Academic Unit Head	University of Puerto Rico at Arecibo	1	
Julian Alwakeel	Graduate Student	Florida International University	1	2
Cory BlackEagle	Adjunct Faculty	Eastern Kentucky University	1	2
Kelly Deuerling	Assistant Professor	University of Wisconsin-Green Bay	1	2
Madison Flint	Graduate Student	University of Florida	1	2
James Heffernan	Associate Professor	Duke University	1	2
Wesley Henson	Research Hydrologist	US Geological Survey	1	2

No working group participation

Participant	Title	Affiliation	Plenary	
Xavier Comas	Professor	Florida Atlantic University	1	
Jennifer Druhan	Assistant Professor	University of Illinois Urbana Champaign	1	
Zhiyong Fu		Chinese Academy of Sciences	1	
Hassan Jebreen	Graduate Student	Ruhr University Bochum	1	2
Gregory Mount	Assistant Professor	Indiana University of Pennsylvania	1	
Ingrid Padilla	Program Director	National Science Foundation	1	2
Barclay Shoemaker	Hydrologist	US Geological Survey	1	
Dorothy Vesper	Professor	West Virginia University	1	
William White	Emeritus Professor	Pennsylvania State University	1	
Richard Yuretich	Program Director	National Science Foundation	1	
Chi Zhang	Assistant Professor	University of Kansas	1	
Junfeng Zhu	Geologist V	Kentucky Geological Survey	1	

APPENDIX B

Listing of all science questions presented in each working group

Working Group 1. Hydrology, weathering, climate and land use change

What defines the critical zone in karst systems (active and past)?
What defines the base of the carbonate critical zone?
How does depth of the critical zone vary across the range of silicate-carbonate mineral mixture?
What are the best methodologies and locations to deploy sensors across karst landscapes?
How do external controls (including climate and land use and land change) interact with lithology to regulate karst development and hydrologic response to forcings over different time scales (event, seasonal, annual, glacial/interglacial)?
What are the effects of infrequent but extreme events that may shift equilibrium states?
Do carbonate critical zone structures, hydrology, and weathering reach equilibrium and if so what range of time scales are required to reach equilibrium (human, climate variations, tectonics)?
What controls the distribution of CO_2 within the carbonate critical zone?
What are the relationships between hydrology and geomorphology, in particular sinkhole genesis and morphology?
How do climate and topography control cave morphology?
How will rising sea level affect freshwater-saltwater mixing zones in coastal karst systems and degrade freshwater resources by mobilizing pollutants?

Working Group 2. Hydrology, weathering, climate and land use change

How do small scale heterogeneities affect solute transport at larger scales?
What role do different spatial scales play when considering changing hydrological processes under climate and land use change?
How does increasing carbonate content affect gas flow through vadose critical zone and impact vadose zone processes?
How do changing snowmelt patterns (alpine, pre-alpine) impact groundwater recharge and quick flow/runoff processes?
What processes allow carbonate bedrock to supply water to vegetation?
Under what circumstances does the substrate control and/or limit productivity?
What are the relative roles of carbonate and silicate critical zones in the global carbon cycle and how will these roles shift with future climate change?
How can we better understand the role of inorganic carbon storage across the gradient from silicate to carbonate dominated critical zones?
How do we work in collaboration with native communities – in true partnership and community-building ways?
How do we communicate the value, uncertainty and limitation of karst critical zone research to broad audiences, for education, water resource managers, and other decision makers?
How do carbonate critical zones vary between different existing climates and in landscapes with varying water quality, quantity, and human demographics?
How does constructed impermeable land cover alter weathering signals (denudation rates, soil changes)?
Does secondary mineral formation record signals of climate change and/or land use change?
How do we integrate tracers across the gradient of silicate to carbonate dominated critical zones to address questions related to hydrologic timescales in these end-member environments?
What information from silicate critical zone informs carbonate critical zone processes and vice versa?

Working Group 3. Ecology, ecosystem services, climate and land use change, weathering

What is the impact of mineralogy and architecture at root depths within the critical zone?
Do biota amplify karst weathering rates and if so by how much and does the amplification vary with maturity and development of karst drainage?
What is the impact of carbonate buffering of pH in critical zones on microbial community structures and processes?
What links exist between microbial and geochemical processes?
What are the relative fractions of weathering driven by sulfuric acid from chemolithoautotrophy versus carbonic acid derived from respiration?
How does the depth distribution of organic matter storage and respiration change along the silicate-carbonate gradient?
How does organic matter storage vary across the wide variety of carbonate critical zones (e.g., telogenetic to eogenetic)
To what extent does the presence of carbonate parent material modulate the soil CO_2 signal?
How does ecosystem carbon cycling control karst weathering rates?
Is groundwater in equilibrium with soil CO_2 concentrations?
How well matched are soil CO_2 and stream CO_2 concentrations in karst landscapes?
What is the fate of nitrogen in groundwater and why does it accumulate in caves?
Why do predicted weathering rates differ from observed weathering rates based on spring water solute concentrations?
What are the relative importance to emerging contaminants from transport (hydrological) compared with reactions (rock-water or rock-water-microbe interactions)?
What are the effects, retention, transportation, and processing of emerging contaminants (pharmaceuticals, medicines, general pollutants)?

Working Group 4. Architecture, hydrology, weathering

What processes control epikarst development?
How can interdisciplinary studies (geomorphology, geochemistry, hydrology, geophysics, mathematical modeling, among others) be fostered to enhance the understanding of the relationships between the deep and shallow critical zone?
How do geologic characteristics (water-rock interactions, diagenesis, lithology, the carbonate-silicate gradient, orogenic events, topographic relief, acids) form critical zone architecture?
How can hydrologic and chemical processes, and injected tracer breakthrough curves, be used to evaluate subsurface architecture such as conduit versus matrix flow?
How does partitioning of flow between surface water and groundwater impact critical zone surface and deep architecture and water availability?
How does the vadose zone homogenize water, energy, and nutrient sources to the subsurface critical zone?
What tools and techniques can be used to evaluate chemical and physical denudation rates?
How do we engage local populations to create a broader, more inclusive study of karst?
How does the social landscape influence the approach to understanding the architecture of karst?
How do human activities (short-term impacts from urban development and agriculture to long-term global-scale phenomena) impact weathering processes?

Working Group 5. Climate and land use change, weathering, ecosystem services

How do physical and chemical weathering interact, particularly as fractures form with depth in the critical zone?
How does deep critical zone architecture controls surface geomorphology and landscape distribution?
How does the moisture state at both micro and macro scale impact weathering processes in the critical zone?
How does anthropogenic climate change (i.e., projected extremes of floods and droughts) and anthropogenic land use change (i.e., vegetation) affect weathering characteristics in the critical zone?
What biogeochemical transformations occur along flow paths from soil recharge to spring discharge and how do they change with climate and land use?
How are materials (dissolved, suspended, bedload) transported within and out of the critical zone?
How does saturated water flow conditions impact the carbonate weathering process?
What physical and biological process control gas exchange in vadose zone and what are those effects on drip water chemical composition?
How are gradients in pH and redox potential related to flow within the CZ?
How do depositional environments and facies affect flow and locations of weathering in eogenetic limestone?
What controls formation of gradients in redox potential and pH, especially considering production of carbonic, sulfuric, and nitric acids?

Working Group 6. Ecosystem services, climate and land use change

How does climate change vulnerability differ between siliciclastic and carbonate landscapes?
What are the magnitude of greenhouse gas (N_2O, CH_4) emissions from various karst ecosystems (e.g., aquatic vs. soil) and the range of lithologies (carbonate and silicate)?
How will greenhouse gas emissions change with time (through events and/or seasons)?
How can critical zone greenhouse gas emissions be mitigated in the future?
Considering increases in environmental reactive nitrogen, what are N dynamics in karst ecosystems and how might they change as climate changes?
How do differences between carbonate and silicate rocks contribute to inequitable provision of environmental goods?
Do aspects of social geography reflect underlying critical zone structure and processes?
What differences in hazards, resources, and vulnerabilities between carbonate and silicate critical zones are recognized and accounted for in policy and infrastructure?
How do interactions and relationships between society and the critical zone change over time in response to natural and human-induced factors?
How is land use change affected (or enhanced) in carbonate- relative to silicate-dominated critical zones?
What interactions and relationships between society and the critical zone differ between siliciclastic and carbonate critical zones?