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Connecting soils to life in conservation planning, nutrient cycling, and planetary science

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ABSTRACT

Soil supports life by serving as a living, breathing fabric that connects the atmosphere to the Earth's crust. The study of soil science and pedology, or the study of soil in the natural environment, spans scales, disciplines, and societies worldwide. Soil science continues to grow and evolve as a field given advancements in analytical tools, capabilities, and a growing emphasis on integrating research across disciplines. A pressing need exists to more strongly incorporate the study of soil, and soil scientists, into research networks, initiatives, and collaborations. This review presents three research areas focused on questions of central interest to scientists, students, and government agencies alike: **1)** How do the properties of soil influence the selection of habitat and survival by organisms, especially threatened and endangered species struggling in the face of climate change and habitat loss during the Anthropocene? **2)** How do we disentangle the heterogeneity of abiotic and biotic processes that transform minerals and release life-supporting nutrients to soil, especially at the nano- to microscale where mineral-water-microbe interactions occur? and **3)** How can soil science advance the search for life and habitable environments on Mars and beyond- from distinguishing biosignatures to better utilizing terrestrial analogs on Earth for planetary exploration? This review also highlights the tools, resources, and expertise that soil scientists bring to interdisciplinary teams focused on questions centered belowground, whether the research areas involve conservation organizations, industry, the classroom, or government agencies working to resolve global challenges and sustain a future for all.

1. Introduction

Many of us remember the draw to soil as children. The need to be connected to the earth beneath our feet is inherently engrained. Adults and children alike are reconnecting to soil whether that be through gardening, recreation, soil painting, or looking towards the stars and pondering how humans could grow food and survive on the surface of another planet.

1.1. The challenge

Soil sustains life. Soil filters the water that we drink, provides a medium upon which our entire agricultural system is sustained, and serves as the prime foundation for the terrestrial biosphere (Banwart, 2011; Food and Agriculture Organization of the United Nations, 2015). Soil provides humans with feed, fiber, food, and fuel (Wilding and Lin, 2006). Many of the world's most effective antibiotics are produced by microbes in the soil (Van Epps, 2006; Crits-Christoph et al., 2018; Nothias et al., 2016; Hover et al., 2018). Soil mitigates the effects of climate change by storing and consuming carbon dioxide and other greenhouse gases in soil organic matter (Bormann et al., 1998; Berner, 2004; Nezat et al., 2004). Human beings and most forms of terrestrial life rely either directly or indirectly on soil to live. The physical, chemical, and biological break down of rocks and soil minerals supplies nutrients to our terrestrial world, feeds elemental nutrients into the Earth's hydrosphere, and dictates coastal marine productivity (Berner and Berner, 1987; Eiriksdottir et al., 2015; Frings and Buss, 2019; Porder, 2019; The Editors of Encyclopedia Britannica, 2021). Burrowing and ground-dwelling animals, from ground-nesting bees to desert tortoises, depend on soils to survive (Woodbury and Hardy, 1948; Andersen et al., 2000; Cane and Neff, 2011; Bernheim et al., 2019; Harmon-Threatt, 2020; Antoine and Forrest, 2021). Soil supports an intricate mycorrhizal "underground highway" of plant roots and fungi that exchange carbon, nutrients, and water depending on the environment (Simard et al., 1997; Allen, 2007; Klein et al., 2016).

"Like a library, soil houses stories written from the microscopic to the landscape scale of human and evolutionary history" where "the memories retained by soil contain countless records, including a history of

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human encounters with the land" as stated by Dr. Derek Lynch in "Soil is the key to our planet's history (and future)." Dr. Paul Schroeder builds on this concept in "Clays in the Critical Zone (CZ)" when describing the important role of clays and clay minerals as the Critical Zone's most abundant and reactive components that "serve to proxy information about the deep time history of Earth and give us insight as to how and how fast our own CZ will change as we move into the future" (Schroeder, 2018).

Soil is being threatened and lost at an alarming rate despite its ever-growing importance to society and the global challenges we face (Food and Agriculture Organization of the United Nations, 2015). "'About 3.2 billion people worldwide are suffering from degraded soils,' said Intergovernmental Science-Policy Platform on Biodiversity and Ecosystems Services (IPBES) chairman Prof Sir Bob Watson" in a BBC article titled, "Climate change being fueled by soil damage" (Harrabin, 2019). Soils are being exposed, blown away, paved over, eroded, scraped, compacted, graded, desertified, and contaminated (i.e., Food and Agriculture Organization of the United Nations, 2015). Tremendous numbers of soil biota live belowground, many of which have not been identified, yet face the risk of extinction (Veresoglou et al., 2015). We need to "Save our soils!" as highlighted in an article by Dr. Steve Banwart stating that "Researchers must collaborate to manage one of the planet's most precious and threatened resources — for food production and much more" (Banwart, 2011).

Scientists are joining together to work in multidisciplinary teams and networks, such as the Critical Zone (CZ) Network, where soils play a critical role in addressing collaborative research questions. Professional soil societies and organizations worldwide comprise thousands of members who are advancing the discipline of soil science through the transfer of knowledge, the promotion of soil health and sustainable management practices, and the dissemination of basic and applied research through conferences, peer-reviewed publications, soil field tours, workshops, and more. The Soil Science Society of America serves as a professional home for 6000+ members, provides a flagship journal to the global soils community, organizes educational programs, contributes to science policy initiatives, and hosts an international conference annually. The World Congress of Soil Science meets every four years and additional renowned conferences offer sessions that integrate the study of soil including meetings organized by the Geological Society of America, Goldschmidt, and the American Geophysical Union (AGU).

Policy makers also understand the global scale challenges that our societies face, many of which directly involve soil, as indicated by the European Union Soil Thematic Strategy that identified seven functions of soil calling for protection. The United States Department of Agriculture National Resource Conservation Service (NRCS) has demonstrated commitment to promoting soil health and recognized that, "As world population and food production demands rise, keeping our soil healthy and productive is of paramount importance" (Natural Resources Conservation Service, 2022). Government leaders and international agencies are recognizing the importance of soil "ecosystem" services and the need to communicate the financial value of soil from a monetary valuation framework (Baveye et al., 2016). Overall, it is critical to engage students, the public, stakeholders, and scientists in the broader applications of soil science whether that be from a research, education, governmental, or applied practices perspective.

Three areas of research are presented herein to demonstrate where a stronger integration with soil science will advance knowledge and present opportunities for enhanced collaborations. The research areas center on i) conservation planning, ii) nutrient cycling, and iii) the exploration of extraterrestrial surfaces (Fig. 1). The key opportunities for collaborative research presented here are based on an extensive review, synthesis, and discussion of published literature. This work highlights

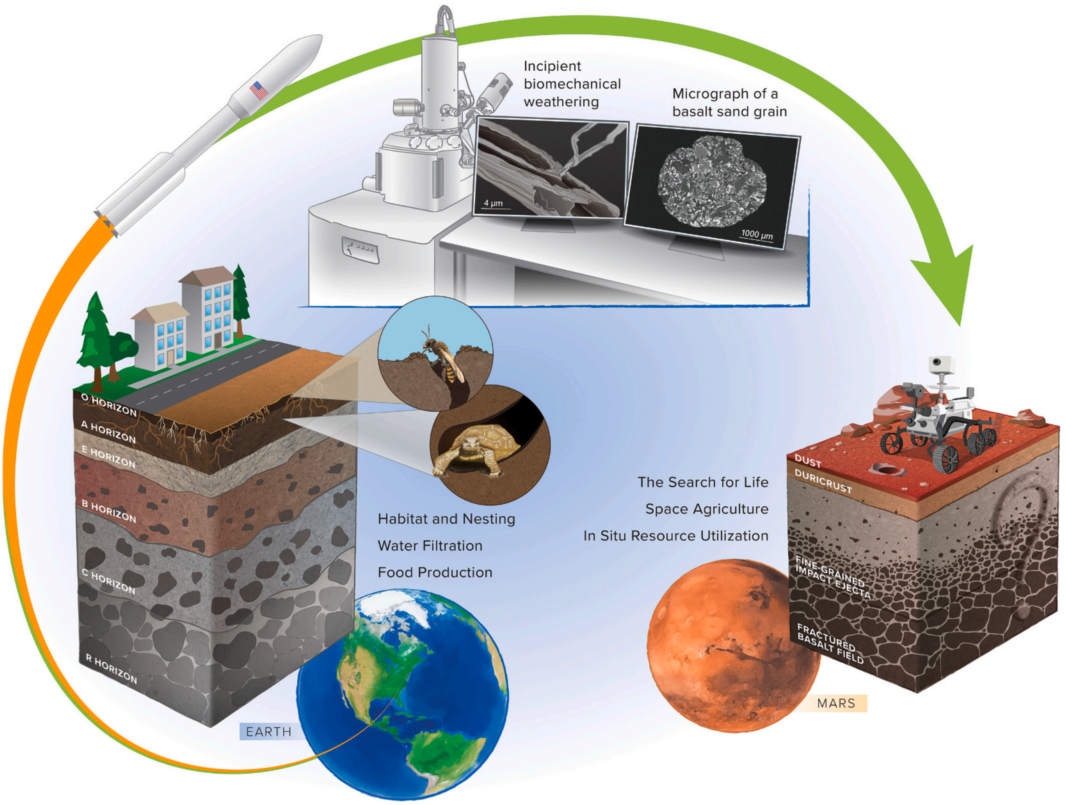

Fig. 1. An overview illustration presenting the main themes in the review including the important roles of soils on Earth, such as providing habitat to ground-dwelling organisms (e.g., desert tortoise, ground-nesting bee); the need to better understand microscale processes pertaining to nutrient cycling and mineral weathering (e.g., fungal-driven weathering of mineral grains); and opportunities to bridge soil science with the planetary and space sciences on Mars and other extraterrestrial surfaces. Illustration created by Rob Riedel and Matthew Verdolivo, UC Davis IET Academic Technology Services.

the need for the continued expansion of collaborative research networks to understand the complexity of interconnected processes in the Critical Zone that encompass the atmosphere, biosphere, hydrosphere, lithosphere, and the pedosphere- the soil mantle of the Earth.

2. Conservation planning and ecology

"Ecology is the study of the relationships between living organisms, including humans, and their physical environment." Ecological Society of America.

2.1. Overview

Ground-dwelling bees, termites, ants, earthworms, and even turtles are referred to collectively as ecosystem engineers who shape the structure of the soil environment and modify the resources available to other organisms (Figs. 1-3; Jouquet et al., 2006). Soil invertebrates and macrofauna transform soils across desert, rainforest, savanna, temperate forest and grassland systems (Zida et al., 2011; Sarcinelli et al., 2013; Lovich et al., 2018; Wills and Landis, 2018; Myer and Forschler, 2019) in addition to playing important roles in soil development, bioturbation, decomposition, elemental cycling, and dispersing or enhancing the germination of seeds (Lobry de Bruyn and Conacher, 1990; Six et al., 2004; Wang and Ruan, 2011; Culliney, 2013).

The ecological impacts of losing ecosystem engineers to climate change or land-use change are being recognized (e.g., Lovich et al., 2018). In the case of turtles, the ecosystem services provided by turtles have greatly diminished given that 61% of the 356 turtle species are now threatened or already extinct, which has left scientists asking, "[Turtles] survived the Cretaceous-Paleogene boundary cataclysm that wiped out the dinosaurs. Will they survive us in the Anthropocene?" (Lovich et al., 2018). We continuously question how organisms drive soil formation (Jenny, 1941) or how ecosystems will evolve in response to environmental change or the loss of keystone species. A more understated question remains, *How do the properties of soil influence the selection of habitat and survival by organisms, especially threatened and endangered species struggling in the face of climate change and habitat loss during the Anthropocene?*

Soil delivers underrecognized benefits and ecosystem services to our society by supplying habitat to ground-dwelling native pollinators (e.g., Cane, 1991; Potts and Willmer, 1997), mammals (e.g., O'Brien et al., 2005), amphibians (Dillard et al., 2008), and reptiles (Andersen et al., 2000; Heaton et al., 2006; Bernheim et al. (2019), to name a few. ***However, the study of the soil habitat itself is often excluded or poorly represented in microhabitat research, conservation efforts focused on addressing threats of habitat disturbance or climate change*** (Harmon-Threatt, 2020), ***or habitat preference modeling activities*** (Bernheim et al., 2019).

Here, two examples demonstrate important connections between soils and ground-dwelling organisms:

2.2. Ground-nesting bees

Wild bees collectively represent more than 20,000 species of insects globally that serve as major pollinators for over 90% of flowering plants in agricultural and natural systems (Klein et al., 2007; Ollerton et al., 2011; Potts et al., 2016; Antoine and Forrest, 2021). Pollination by bees accounts for $15 billion in crop value for the United States by pollinating 75% of the country's vegetables, fruits, and nuts (Hamilton, 2013). Bee populations face many threats ranging from climate change, pesticides, habitat loss, reduced access to resources, and exposure to parasites from managed bees despite the importance of bees to pollination services and economies worldwide (Potts et al., 2016; Harmon-Threatt, 2020). As a result, much interest has been generated to identify the floral and nesting requirements for bees, particularly in agricultural and urban systems (Cane, 2008; Fortel et al., 2016; Harmon-Threatt, 2020).

Surprisingly, quantitative data sets that identify the abiotic or soil nesting habitat requirements of ground-nesting bees remain limited or incomplete even though 64% to 83% of bee species are reported to construct nests in soil (Fig. 3; Cane and Neff, 2011; Harmon-Threatt, 2020; Antoine and Forrest, 2021). For example, soil texture (relative proportion of sand, silt, and clay-sized particles that comprise the mineral soil) was identified as a strong predictor for nest-site selection (Antoine and Forrest, 2021). However, the reporting of soil texture data or textural classes for nest substrates remains incomplete (Harmon-Threatt, 2020): "Soil was often described as sandy, with no specific soil texture mentioned." Ground-nesting bees have shown nest-site selection behavior based on soil-landscape properties including percent bare soil, aspect, slope, soil moisture/humidity, soil temperature, compaction, and soil texture where, for example, preferences for sand versus high silt+clay fractions varied by species, climate, and geographic location (Cane, 1991; Potts and Willmer, 1997; Srba and Heneberg, 2012; Sardinas and Kremen, 2014; Lybrand et al., 2020). Questions remain on how bees will respond to climate change including the influence of projected differences in rainfall, snow cover, and soil temperature on nest-site selection preferences. Soil and environmental properties still

Fig. 2. The Gopher tortoise (*Gopherus Polyphemus*) serves as an ecosystem engineer by constructing extensive, complex burrows up to 10-m in length that provide shelter and habitat for 350+ organisms who cannot dig their own burrows. Knowledge gaps remain in understanding how soil properties influence habitat preferences and activities of burrowing and ground-dwelling organisms and the behavior of species who utilize the burrows or shelter sites (e.g., burrowing owls, bobcats, rabbits, snakes, and lizards, among others; Lovich et al., 2018).

Fig. 3. Andrenid bees (*Andrena* sp.) have been documented a,b) digging a burrow; c) guarding a nest entrance, and d) emerging from a nest. Ground-nesting bees spend much of their life cycles in contact with soil across five primary stages of nesting including initiation, construction, development, overwintering, and emergence (Harmon-Threatt, 2020). Yet, the soil properties that dictate nesting habitat selection remain understudied, specifically work that connects nesting habitat preferences to individual bee species. Bees face threats from climate change and land-use change during each stage of nesting, which span multiple life stages from egg, larva, pupa to adult stages. All photographs in this figure were reproduced with permission from Whitney Cranshaw (Colorado State University/Bugwood.org).

need to be measured and reported more consistently in studies of ground-nesting bees to better understand how bees may respond to and adapt under changing environmental conditions, especially while nesting where natural mortality exceeds 80% for some species (Harmon-Threatt, 2020).

Much variation has been observed when assessing the influence of individual soil properties on bee habitat or nest-site selection (Harmon-Threatt, 2020; Antoine and Forrest, 2021). For example, some bees exhibit a strong preference for coarser soil textures (e.g., sand, sandy clay loam, sandy loam; Harmon-Threatt, 2020, Antoine and Forrest, 2021) while other bees nest in more silty or clayey materials (i.e., silt loam, clay, clay loam; Harmon-Threatt, 2020; Lybrand et al., 2020). Some research has shown that ground-nesting bees appear to prefer coarser textured soils since water drains more freely from nesting sites while others noted that sand grains are abrasive and could potentially be harmful to bees (i.e., mandibles, wings; Antoine and Forrest, 2021). Soil moisture is another important property for nesting site preferences given that bees require some level of moisture to promote larval development, especially in drier climates (i.e., May, 1972). Conversely, soil conditions that are too moist may lead to flooding or prolonged inundation, which in turn may cause disease, reduce emergence, or kill the ground-nesting bees altogether. Overall, the general relationships identified between ground-nesting bees and abiotic soil properties requires additional investigation given that the associations vary greatly by species, geographic region, and climate (Antoine and Forrest, 2021).

For now, more experimental soil studies of nesting habitats are needed to distinguish the influence of soil properties on nesting preferences for individual bee species as well as bee nesting activities in contrasting climates and geographic regions (i.e., Harmon-Threatt, 2020). Identifying the soil properties that influence bee nesting activities would be a step forward in producing the quantitative data required to construct predictive habitat models and to create habitat suitability maps as demonstrated for *Colletes inaequalis* (López-Uribe et al., 2015; Antoine and Forrest, 2021). Obtaining the quantitative soils data required to produce species and region-specific predictive models and habitat suitability maps for wild bees could be used for education and outreach purposes in order to expand access to suitable nesting sites to wild pollinators in agricultural or natural systems (i.e., Antoine and Forrest, 2021).

2.3. *Desert tortoises*

Desert Tortoises (*Gopherus agassizii*), a Federally threatened species under the Endangered Species Act, display specific soil habitat and geomorphic requirements that reflect the overall degree of "digability" of a landscape surface (Fig. 4; Andersen et al., 2000). The range of the desert tortoise spans from the Mojave Desert (southeastern California, southern Nevada, southwestern Utah, and northwestern Arizona, USA), the Sonoran Desert (southeastern California, western and southern Arizona, western Sonora, Mexico), and south into the semitropical Sinaloan thornscrub and Sinaloan deciduous forests found in eastern Sonora and northern Sinaloa, Mexico (Germano et al., 1994). Desert tortoises exhibit marked differences in habitat preferences based on geographic location, but the species does construct or utilize burrows across its entire range (Germano et al., 1994). Soil type was noted as a "critical factor in tortoise distribution" in the late 1940s (Woodbury and Hardy, 1948) and specific soil properties (e.g., structure, moisture, texture, aeration, chemical composition) that may impact reptile abundance and distribution have since been identified (Hendricks, 1985). Yet, as highlighted by Andersen et al. (2000), "Subsequent studies have failed to follow up on this observation" despite the importance of soil type for identifying potential preservation areas or translocation sites: **"Certainly, it is important to consider soil characteristics in studies of the habitat requirements of burrowing animals."**

Desert tortoises demonstrate contrasting patterns of habitat use across their range that appear to be based on topographic and geomorphologic properties (Zylstra and Steidl, 2009). Tortoises in the Sonoran Desert shelter in i) caliche caves associated with deeply incised washes, ii) soil burrows on more gently sloping terrain, and iii) in steep, rocky volcanic terrain when present (Riedle et al., 2008). Tortoises in the Sonoran Desert also live in hibernation burrows associated with vegetation, packrat nests (known as middens), or on steep, southerly slopes where soils were comprised of silt (sometimes with loose gravel),

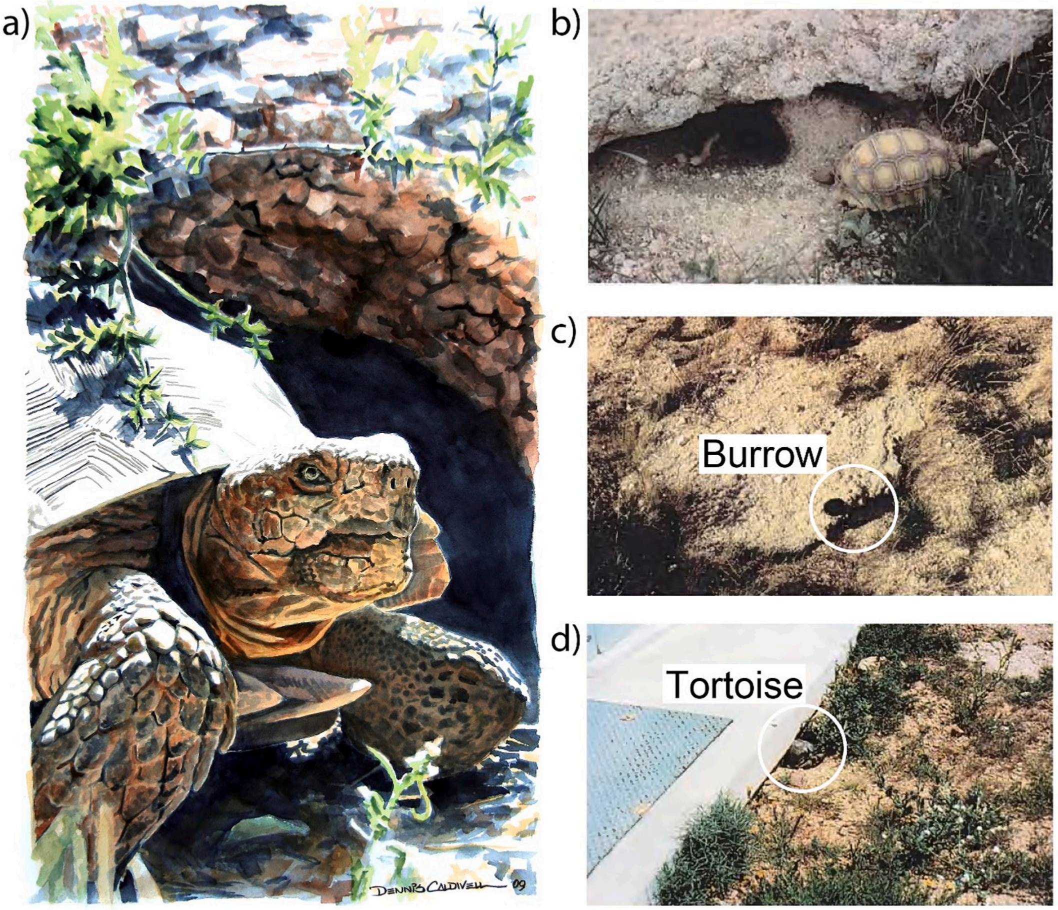

Fig. 4. a) Illustration of a desert tortoise in front of a burrow in the Mojave Desert (Illustration reproduced with permission from Dennis Caldwell; caldwell-design.com/). Examples of desert tortoise burrows that were associated with a disturbed industrial landscape including b,c) a juvenile desert tortoise near the entrance of a burrow made of waste concrete found near a wind turbine. d) A female desert tortoise constructed a burrow under a concrete pad of an electrical transformer and used the burrow for at least two years as evidenced by observations from the field. Fig. 4b-d and revised captions for each were used with permission from Lovich and Daniels (2000).

diatomite, or layers of lithified ash (Bailey et al., 1995; Lovich and Daniels, 2000). Desert tortoises in the Mojave Desert construct or occupy long, complex burrows in soil, within the walls of washes, or under caliche overhangs (Woodbury and Hardy, 1940; Woodbury and Hardy, 1948; Luckenbach, 1982; Berry and Turner, 1984; Germano et al., 1994). Mojave Desert tortoises construct burrows in sparsely vegetated, sandy-gravel soils that are both friable for digging and firm so that the resulting burrows do not collapse (US Fish and Wildlife Service, 2011). A modeling assessment of desert tortoise distribution in the central Mojave Desert, California predicted that tortoises would be found on south-facing, loamy soils instead of stony soils or north-facing landscapes with low plant cover (Andersen et al., 2000).

Additional research focused on an altered industrial area of the Colorado Desert of California where tortoises located burrows under the concrete foundations of wind energy turbines and in cut banks along gravel access roads (Fig. 4b; Lovich and Daniels, 2000). Here, the team postulated that the tortoises may be utilizing the concrete pads to simulate "artificial caliche" environments or for the thermal inertia offered by the concrete. Future conservation planning and recovery efforts for desert tortoises would benefit from research on the soil properties of the burrows given the constraints tortoises face if attempting to survive in locations without the soil types or properties for safe burrow construction that includes the ability to shelter from exposure to fire or predators (Lovich and Daniels, 2000). Understanding the nature and distribution of burrows as a function of soil type is important given that desert tortoise activity and distance traveled appear to significantly differ during drought versus more productive years (Duda et al., 1999; Duda et al., 2002).

Soil properties and type remain an outstanding factor to study for assessing habitats of desert tortoises as summarized by Bernheim et al. (2019): "…in land-dwelling ectotherms, an often-overlooked characteristic that may have a strong effect on habitat preference is soil type." Andersen et al. (2000) indicated that the composition of soils and geologic materials serve as important factors in habitat suitability modeling for desert tortoises and that "soil diggability should be assessed along with vegetation and topography" when reserves or translocation sites are under evaluation for burrowing or ground-dwelling organisms. Habitat modeling activities utilized soil and geologic data, among other factors, to identify areas of continuous habitat in efforts to define recovery units for desert tortoises in the Mojave Desert (US Fish and Wildlife Service, 2011). Here, desert tortoise density and distribution data sets from surveys spanning 80 years were combined with 16 environmental variables and spatial data spanning plant communities, soils, topography, geology, and slope (US Fish and Wildlife Service, 2011; Nussear et al., 2009). Landscape scale surveys of desert tortoises in the Mojave Desert, California also identified positive associations between the density of desert tortoises and the number of active burrows as well as total burrows across multiple spatial scales using three geospatial methods including linear regression and Ripley's geospatial functions (Duda et al., 2002). The study concluded that the energetic cost of constructing burrows would be nontrivial, especially since many of the active or occupied burrows occurred at greater depths. Thus, examining the soil properties associated with burrows or shelter sites of desert tortoises has been identified as a critical factor (Duda et al., 2002), "If indeed a non-trivial investment, tortoises should select soils for burrowing that maximize stability and longevity. ***Additional research is needed to determine the soil characteristics (e.g., texture, content, and moisture) most responsible for burrow site selection and longevity***."

Some research has started to address the soils knowledge deficits in habitat selection, such as work in Piute Valley, Nevada where the density of desert tortoises was analyzed as a function of soil map unit in order to examine the resulting associations among soil characteristics, geomorphic relationships, and the occurrence of tortoises (Wilson and Stager, 1992). The research identified over seven properties that appeared to influence the density and distribution of desert tortoises including available water capacity, soil consistence, depth to limiting layer (i.e., rock or hardpan contact), rock fragment content, soil salinity, soil temperature, and frequency of flooding. This research demonstrates the importance of and need for more work that integrates the study of soil into understanding desert tortoise habitat preferences and distribution within their range. As stated by Andersen et al. (2000) when emphasizing the need for interdisciplinary teams to identify habitat requirements of endangered species: "Without the geology and soils data, we would have not recognized the importance of soil composition and parent material in desert tortoise habitat selection."

2.4. *Additional examples connecting soil science to conservation planning efforts*

Ground-nesting bees and tortoises serve as two examples that demonstrated the need for more research connecting soil science and conservation planning efforts, especially to improve understanding of habitat preferences. However, there are a multitude of examples of organisms where soil has been identified as an important factor for predictive habitat modeling and conservation planning activities.

2.4.1. *Sonoran pronghorn (Antilocapra americana sonoriensis)*

Soil category was one of 5 explanatory variables identified in combination with slope, aspect, biome, and distance to wash for predicting potential habitat for Sonoran pronghorn in the development of landscape-level habitat models (O'Brien et al., 2005).

2.4.2. *Cheat Mountain salamander (Plethodon nettingi)*

The presence of the federally threatened Cheat Mountain salamander positively corresponded to high elevation landscapes formed on sandstone with northeasterly aspects (Dillard et al., 2008). A "landform/lithology" macrohabitat model best predicted distribution of the salamander with several abiotic factors attributed to moisture of surface and subsurface habitats formed on sandstone.

2.4.3. *Turtles, birds, and crocodiles*

Soil texture, soil moisture, and related properties influence the soil microclimate and the exchange of water between buried eggs and the soil environment for ground-nesting species (e.g., *Trionyx spineferus*, Packard et al., 1979; *Chelydra serpentina*, *Chrysemys picta*, Packard, 1999). The properties of the soil habitat significantly impact the soil types, depths, timing, nest monitoring, and degree of organic matter decomposition selected by turtles and birds for underground egg burial or mound constructions for nesting (*Trionyx triunguis, Mauremys capsica, Caretta caretta, Alectura lathami, Leipoa ocellata*; Frith, 1956; Seymour and Ackerman, 1980) as well as the mound or hole nesting patterns displayed by crocodiles when digging nests in soil or constructing mound nests of soil organics or vegetation (*Crocodylus niloticus*, *Crocodylus poros*; Seymour and Ackerman, 1980). The physical composition of the soil has also been assessed from the perspective of energy expenditure, particularly for gravid females or hatchlings with limited energy supplies (Wood and Bjorndal, 2000; Lamont and Carthy, 2007; Rusli and Booth, 2018). The nesting patterns and habitats of Loggerhead sea turtles have been investigated including how slope, salinity, temperature, and moisture, among other factors, may serve as cues or properties that influence nest site selection and timing by females (*Caretta caretta*; Lamont and Carthy, 2007; Wood and Bjorndal, 2000). Soil texture also influenced the energetics of nest escape and digging performance in freshwater Brisbane river turtles where hatchlings expended 33.8% less energy digging through fine sand versus those in coarse sand (Rusli and Booth, 2018).

2.4.4. *Lizards (Aspidoscelis tigris, Callisaurus draconoides, and Uta stansburiana)*

A geomorphic landform lizard habitat model, LizLand, found relationships between soil geomorphic features (e.g, sandy washes, rockiness; desert pavement; alluvial fans) and the distribution of 3 lizard species (*Aspidoscelis tigris, Callisaurus draconoides, Uta stansburiana*) in the Mojave Desert, where each species had preferences for distinct soil microhabitats (Heaton et al., 2006).

2.5. *Collaborative opportunities*

There is great potential for improved collaborations among soil scientists, conservation organizations, and government agencies overseeing the protection of threatened and endangered organisms that live underground or those relying on vegetation or other soil-dependent characteristics for survival (Fig. 5). Soil scientists, specifically pedologists, routinely assess soil-landscape relationships in the field and collect samples for biological, chemical, physical, and/or mineralogical analysis. Pedologists analyze soil texture (percent sand, silt, clay), rock fragment content and surface cover, soil moisture, soil temperature, percent carbon, aspect, slope, bulk density, among other soil properties. The data are assessed in combination with soil descriptions and other field observations to present an in-depth understanding of the processes influencing soil formation at a site. Habitat preference modeling and conservation planning would be strengthened through partnerships with soil scientists by coordinating the sampling and analysis of soils with ecologists and wildlife biologists working in a particular region. Aridland soil scientists, for example, specializing in salt-cemented soils would be well-equipped to partner on assessments of tortoise habitat by examining the genesis and geochemistry of constructed soil burrows or caliche caves (e.g., petrocalcic soil horizons).

3. Nutrient cycling and mineral weathering

"Weathering describes the breaking down or dissolving of rocks and minerals on the surface of the Earth. Water, ice, acids, salts, plants, animals, and changes in temperature are all agents of weathering" (National Geographic Resource Library, 2022).

3.1. *Mineral weathering: an overview*

Mineral weathering sustains terrestrial life on Earth by regulating the supply of nutrients (C, N, S) and metals (Ca, Na, Mg, K, Fe, Mn) released from soil minerals and rocks (Fig. 6; Bormann et al., 1998; Nezat et al., 2004; Frings and Buss, 2019). Assessing the drivers of mineral weathering is critical for addressing the global challenge of climate change and for estimating ecosystem level nutrient status- where biological contributions represent a serious gap in nutrient cycling models and assessments of rock-derived nutrients on a global scale. The weathering of silicate minerals stabilizes global climate over geologic timescales by consuming atmospheric acidity as carbon dioxide (Bormann et al., 1998; Nezat et al., 2004). Lithology type and distribution, climate, and ecosystem activity are predictors of silicate weathering rates and long-term carbon cycling (Gaillardet et al., 1999; Dessert et al., 2003;

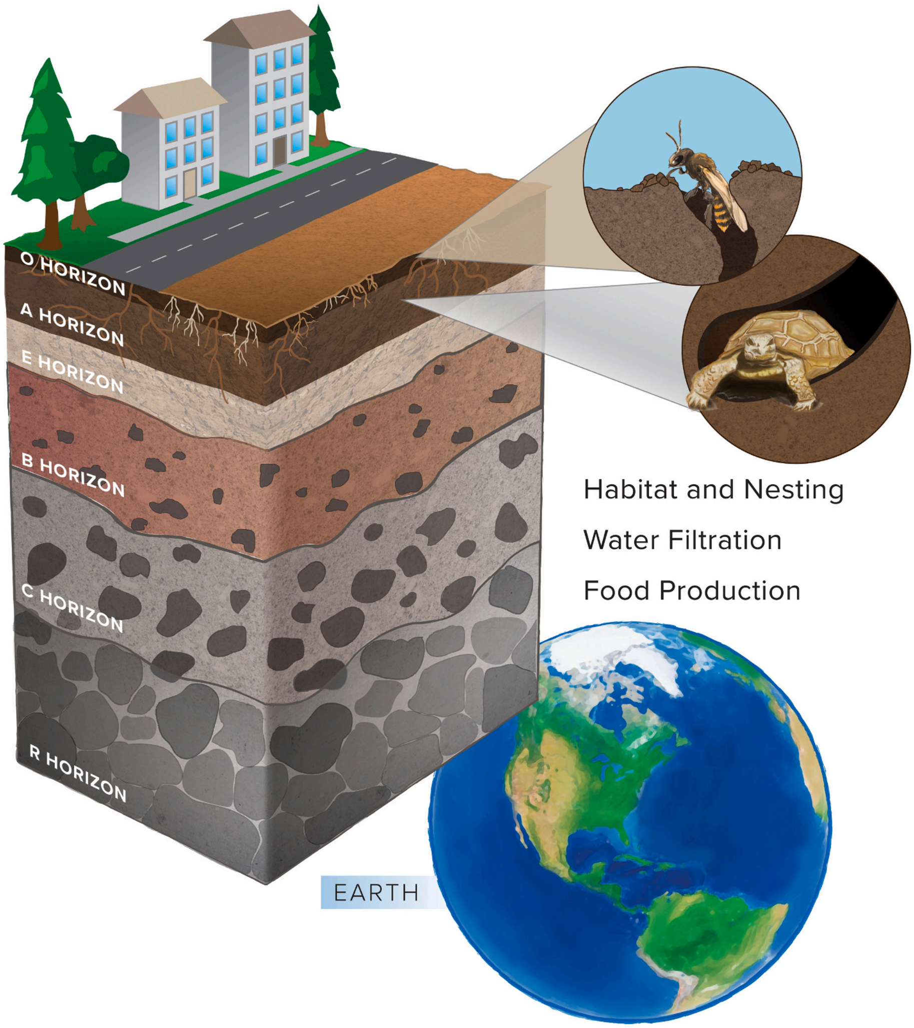

Fig. 5. A three-dimensional representation of a soil environment on Earth with an emphasis on the underrecognized role of soils in providing habitat and nesting space for ground-dwelling organisms. Illustration created by Rob Riedel and Matthew Verdolivo, UC Davis IET Academic Technology Services.

Suchet et al., 2003; Ibarr et al., 2016). Mineral weathering has been quantified across scales and disciplines given its global significance, from assessing weathering in global biogeochemical cycling (Von Blanckenburg et al., 2015; Winnick and Maher, 2018), to determining weatherability along environmental gradients with co-varying climate and overlaying ecosystem parameters (Dahlgren et al., 1997; Khomo et al., 2011, 2013; Rasmussen et al., 2007, 2010, 2011; Lybrand and Rasmussen, 2015; Buss et al., 2017), to examining microbial and abiotic controls on mineral dissolution and the formation of secondary weathering products at nano- to microscale scale resolutions (Bonneville et al., 2009, 2011; Gazzè et al., 2012; Saccone et al., 2012).

Importantly, a wide breadth of societal challenges aligns with ongoing questions pertaining to mineral weathering including how biota may influence or transform rock and mineral materials. As summarized by Lybrand et al. (2022), "How does (a)biotic mineral weathering drive nutrient cycling, the persistence of soil carbon, and ultimately, soil formation, in terrestrial environments on Earth and beyond? What mechanisms will securely preserve spent nuclear fuel to ensure the safe, geological storage of radioactive waste? How can we best preserve and conserve glass artifacts, such as medieval stained glass, or other cultural heritage materials? These questions reiterate the need to continue disentangling the heterogeneity of weathering processes in natural soils (Figs. 7-9), such as the foraging and mining of grain surfaces by fungi (Fig. 7a,b), and how weathering differs between simulations or controlled settings in the laboratory compared to the complex, intricate nature of field environments."

3.2. *Nanolandscapes of weathering: intersection of microbes and minerals*

Microorganisms (bacteria and fungi; referred to herein as microbes) inhabit and contribute substantial biomass to most subsurface terrestrial environments in addition to driving the decomposition and weathering processes that regulate the cycling of carbon, nitrogen, and other nutrients in the soil (Fig. 7; Taylor et al., 2009; Thorley et al., 2015; Bar-On et al., 2018; Zaharescu et al., 2020). Biological weathering has become recognized as a catalyst for mineral weathering and represents a driving force in nutrient cycling even amid the challenges associated with quantifying and distinguishing biological inputs from chemical or physical processes (Jongmans et al., 1997; Bormann et al., 1998; Banfield et al., 1999; Aghamiri and Schwartzman, 2002; Hoffland et al., 2004; Rosling et al., 2004; Balogh-Brunstad et al., 2008; Frings and Buss, 2019; Porder, 2019; Finlay et al., 2020; McCutcheon et al., 2021). As a result, biological weathering has been studied under laboratory conditions (e.g., Leake et al., 2004, 2008; Quirk et al., 2014, 2015; Burghelea et al., 2015; Bonneville et al., 2016; Zaharescu et al., 2017, 2019) and in natural soil systems (e.g., White and Brantley, 2003; Nezat et al., 2004; Wallander et al., 2006; Mahaney et al., 2013; Pawlik et al., 2016; Lybrand et al., 2019, 2022). Ongoing research questions focus on the relative influence of weathering mechanisms, including biochemical versus biomechanical weathering, in addition to addressing whether

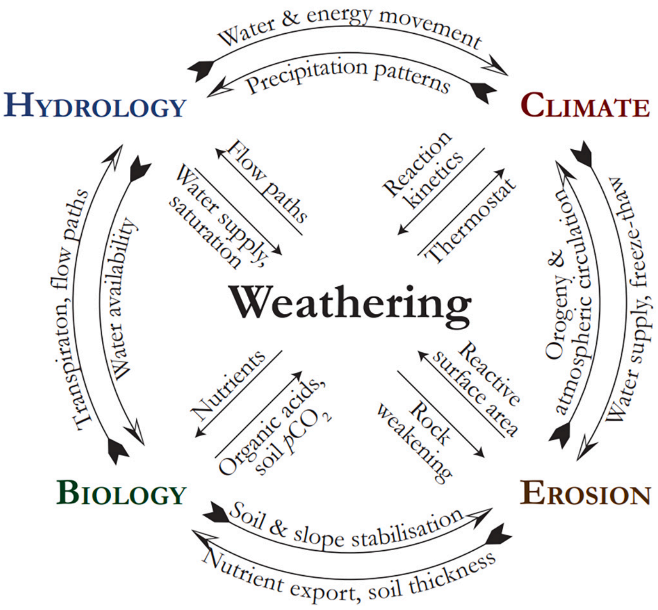

Fig. 6. "Weathering involves processes that span many orders of magnitude in spatial and temporal scales, from global geochemical budgets operating over billions of years, to sub-micrometre mineral fabrics and reactions. Therefore, 'weathering' means different things to different people, to the point that this familiar word may even impede discussions between scientific disciplines (Hall et al., 2012)." Figure from Frings and Buss (2019) with permission.

direct or indirect interactions between microbes and minerals contribute most substantially to mineral weathering in natural soils (Lee and Parsons, 1999; Buss et al., 2007; Mahaney et al., 2013; Bonneville et al., 2016; Austin et al., 2018). Furthermore, researchers also question whether microbes enhance or slow the dissolution of minerals and whether this varies by species or environment (Gadd, 2007; Pawlik et al., 2016). Given the complexities of microbe-mineral interactions and biological weathering research, much of the work has required the use of laboratory-controlled studies performed at the microscale (Kendall and Hochella, 2003; Perdrial et al., 2009). However, we need to understand the complex biogeochemical interactions driving weathering in natural systems to better equip climate and nutrient cycling models (Dontsova et al., 2020) and to broaden understanding of mineral weathering pathways.

High-resolution microscopy represents a long-standing resource used by mineralogists; however, soil scientists, among other geoscientists, have also utilized high-resolution microscopy (e.g., scanning electron microscopy; transmission electron microscopy) for decades to identify secondary weathering products, dissolution pitting, and other weathering features (Berner and Holdren, 1979; Holdren and Berner, 1979; Eggleton and Buseck, 1980; Velde, 1984; Berner and Cochran, 1998; Banfield et al., 1999; Zhu et al., 2006; Graham et al., 2010; Gazzè et al., 2012; Lybrand and Rasmussen, 2014; Horgan et al., 2017) in addition to integrating techniques new to the earth and environmental sciences (e.g., helium ion microscopy; Dohnalkova et al., 2017; Lybrand et al., 2019; Balogh-Brunstad et al., 2020). Collaborations among soil scientists, mineralogists, microbiologists, microscopists, and geoscientists would enhance the study of microbe-mineral interactions given the intricacies of the nanoenvironment. Key partnerships would contribute to clearer, broadened perspectives on how microbes disrupt, dissolve, and extract nutrients from soil minerals (Fig. 7a,b) or how top predators in the microbial food web, such as soil testate amoeba, may influence nutrient cycling in contrasting environments (Fig. 7c-f; Marcisz et al., 2020). Furthermore, knowledge deficits exist in our ability to assess how coupled biological, geochemical, and physical processes interact to transform mineral surfaces, including physical mechanisms common to landscape surfaces, such as freeze thaw. ***How do we disentangle the heterogeneity of abiotic and biotic processes that drive mineral transformation and nutrient cycling processes in soil, especially at the nano- to microscale where mineral-water-microbe interactions occur?***

3.2.1. *Fungal-driven weathering*

Soil fungi transform minerals and cycle nutrients across spatial scales in field and laboratory settings (Simard et al., 1997; Wallander et al., 2001; Burford et al., 2003; Wallander et al., 2004; Leake et al., 2008; Finlay et al., 2009; Quirk et al., 2012; Ahmed and Holmstrom, 2015; Bonneville et al., 2016; Klein et al., 2016; Leake and Read, 2017; Lybrand et al., 2019; Pokharel et al., 2019; Finlay et al., 2020). Soil fungi contribute to nutrient cycling and mineral weathering pathways in many ways which include: acting as biosensors and allocating growth towards certain mineral types and size fractions (Leake et al., 2008; Bonneville et al., 2009); applying biomechanical forces during fungal growth that can disrupt the mineral lattice (Li et al., 2016); accelerating the dissolution of minerals through indirect, biochemical weathering (Balogh-Brunstad et al., 2008); increasing elemental dissolution rates using chemical energy transferred from plants to mycorrhizal associations (Quirk et al., 2014); and transferring carbon and nutrients between plants through the "underground highway" facilitated by mycorrhiza (Klein et al., 2016). The "Hyphae Move Matter and Microbes to Mineral Microsites" (HMMMMMs) framework brings attention to the importance of fungi and the hyphosphere for contributing to the formation of mineral-associated organic matter (MAOM) in the bulk soil environment in addition to the rhizosphere (See et al., 2022). The authors emphasize "an urgent need for fine-scale estimates of hyphal exploration and functional community composition within and across mineral soils" (See et al., 2022). Soil fungi contribute substantial carbon inputs to both the rhizosphere and the bulk soil environment; disperse bacteria associated with the fungi to the same mineral microsites being explored, selected, and colonized by the soil fungi; and influence the chemical composition and nature of the organics being deposited on the surfaces of mineral grains (See et al., 2022).

Recent work at the fungal-grain interface demonstrated the heterogeneity of processes at the nano- to microscale using laboratory and field approaches (Fig. 8; Bonneville et al., 2009, 2011; Saccone et al., 2012; Li et al., 2016; Lybrand et al., 2019; Finlay et al., 2020; Lybrand et al., 2022; See et al., 2022). Fig. 8 highlights the heterogenous nature of the fungal-grain interface as observed in a multi-disciplinary study that combined an in-soil mineral substrate mesh bag field study with subsequent analyses performed using transmission electron microscopy and diffraction, focused ion beam, and atomic probe tomography techniques (Lybrand et al., 2022). Here, fungi interacted with individual grains of ground basalt rock that were buried in a mixed hardwood forest soil for three years. Fungal growth on grains coincided with regions of the basalt glass matrix that contained magnetite inclusions. The presence of magnetite enhanced the accessibility of the glass matrix and provided a source of iron at or near the surface of basaltic grains, which likely created an advantageous environment for fungi to forage and mine mineral nutrients. The fungal-grain interface presented evidence for abiotic enrichment of elements (i.e., Ca), biotic aggregation, redox, and hydrolysis processes occurring across only 3–4 μm (Fig. 8).

Nano- to micron scale investigations strengthen our ability to understand how soil fungi drive nutrient cycling in soils by capturing the intricate, heterogenous mechanisms associated with fungal-mineral interactions and the release of rock-derived nutrients (Fig. 8; Smits et al., 2009; Reddy et al., 2020). The ability for soil fungi to interact with and transform rock and soil substrates in field and lab settings is central to understanding the rates and pathways of biogeochemical reactions related to nutrient cycling, soil formation processes, geologic carbon storage, cultural artifact preservation, and nuclear waste disposal (Totsche et al., 2010; Leake and Read, 2017; Finlay et al., 2020; Lybrand et al., 2022).

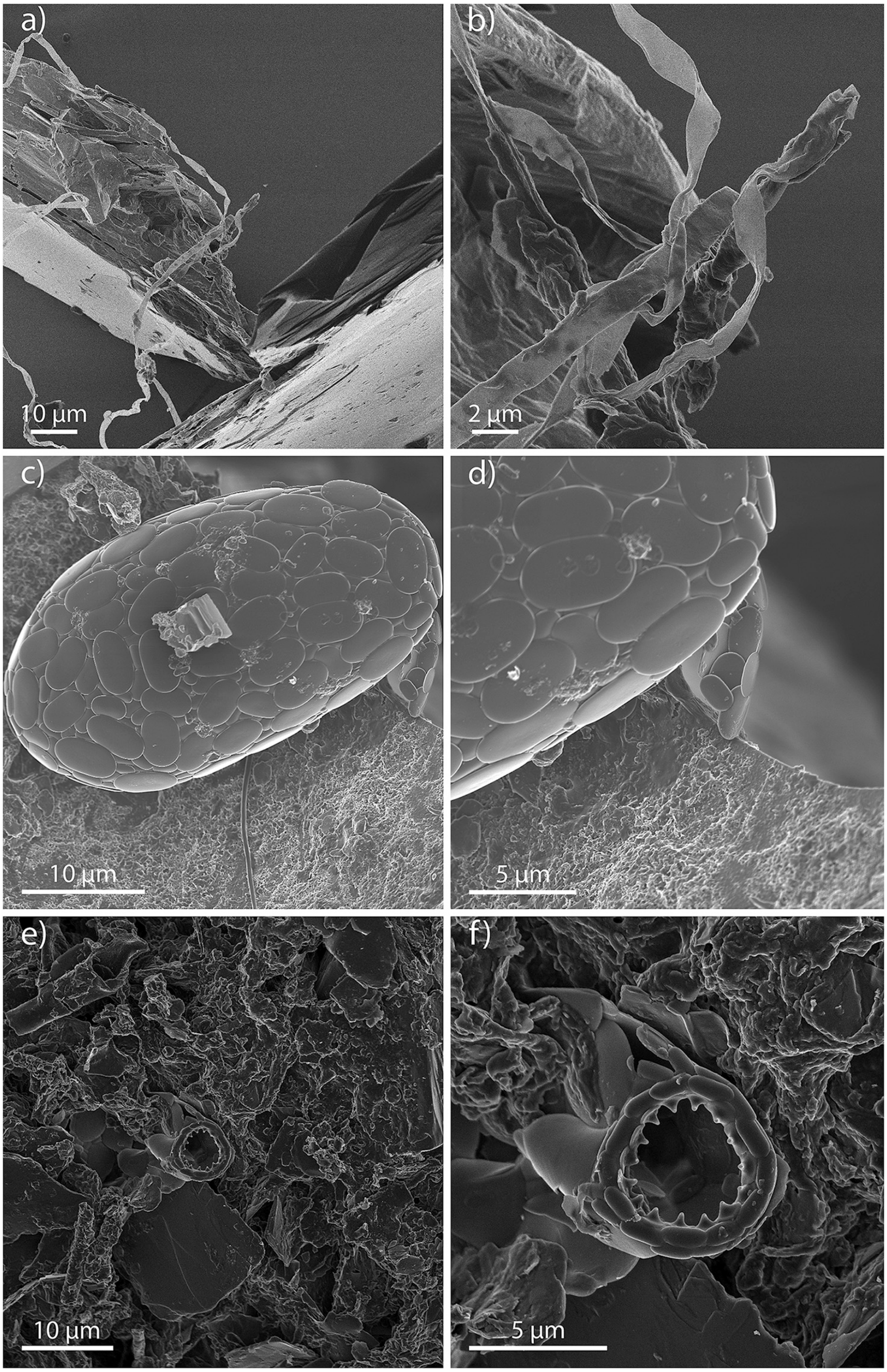

Fig. 7. Examples of how micro- nanoscale studies encompass a range of microbes (i.e., soil fungi, testate amoeba), mineral features, and organo-mineral interactions. a-b) A helium ion micrograph of a fungal-mineral interface detected on a basaltic grain (53–250 μm) from a bulk granular sample deployed at 10 cm depth in a desert scrub ecosystem (Tucson, AZ). (Modified from Lybrand et al., 2019; Imagery captured by Shuttha Shutthanandan (a-b) and Odeta Qafoku (c-f). c-d) A soil testate amoeba observed via scanning electron microscopy from a granular sample that was deployed in a humid, mixed hardwood forest soil in South Carolina. e-f) Scanning electron micrographs of a soil testate amoeba identified in a free light carbon fraction obtained from a coastal rainforest soil (Juneau, Alaska).

3.3. *Nanolandscapes of weathering: intersection of ice, minerals, and organics*

Freeze-thaw is a prevalent mechanism in our natural and built environments that influences the physical structure and composition of rock, soil, and organic materials (Schmitt et al., 2008). Freeze-thaw weathering, or frost weathering, has been the focus of much investigation in cold regions given that the process enhances weathering by breaking consolidated rock down into smaller, more weatherable blocks at the macroscale (e.g., talus slopes). Freeze-thaw also results in microcracks and other features in mineral grains at the submicron scale (Nicholson and Nicholson, 2000; Weiss et al., 2001; Luckman, 2013; Jia et al., 2017; Holbrook et al., 2019); deteriorates stone statues and historical buildings (Grossi and Brimblecombe, 2007; Siegesmund et al., 2008; Ruedrich et al., 2011); and presents crucial engineering challenges by affecting the structural integrity of natural building stones, concrete, and buildings (Thomachot and Matsuoka, 2007; Dewanckele et al., 2013; Jamshidi et al., 2013; Rodriguez et al., 2020). Assessing the microscale processes associated with freeze-thaw is critical for understanding controls on the stability of natural or built materials (Watanabe and Kugisaki, 2017; Dong et al., 2018; Xu et al., 2018; Wang et al., 2019; Wang et al., 2020; Zeinali and Abdelaziz, 2020; Leuther and Schlüter,

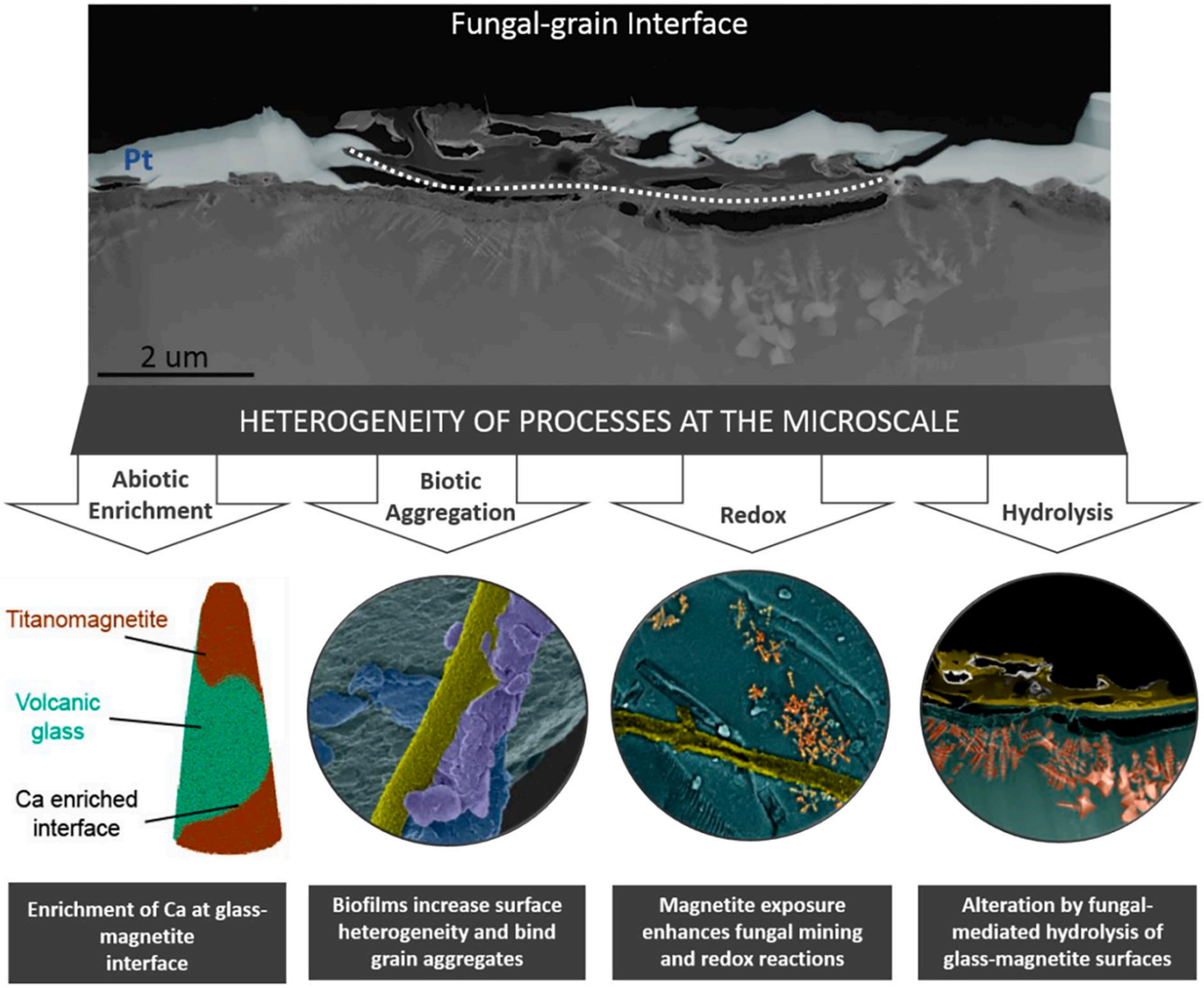

Fig. 8. An example showing the heterogeneity of microscale processes as observed along a basaltic glass-fungal interface. The research addressed questions pertaining to microscale interactions at the interface by combining atomic probe tomography with scanning electron microscopy, focused ion beam, and transmission electron microscopy. (Figure referenced from Lybrand et al., 2022).

2021) and for improving early-warning systems associated with macroscopic natural hazards, such as landslides, debris flows, or extensive surface runoff and flooding (Descroix and Mathys, 2003; Ravankhah et al., 2019; Baselt and Heinze, 2021). Extending frost weathering research to encompass warmer, temperate environments is needed, especially in regions experiencing more frequent and/or extensive freeze-thaw activity as a result of climate change (Hall et al., 2002; Schmitt et al., 2008).

Hall et al. (2002) ***put forth the question, "Are 'cold region' weathering processes truly zonal, might they be azonal?" since "the only fundamental zonal limitation is that sub-zero temperatures occur, and such a situation extends the role of freeze-thaw action well beyond polar or alpine zones?"*** Scientists and government agencies have dedicated time, research strategies, and funding to examine soil microbes as microscale drivers of mineral weathering and nutrient cycling processes (e.g., BERAC, 2010; Gaskill, 2019). Micro-nanoscale physical mechanisms have not been examined to the same extent even though freeze-thaw is actively transforming, and likely weakening, mineral grains across scales and climates as well as influencing the quality of organic matter in soil (Schmitt et al., 2008).

To date, some of the most prominent bodies of literature on ice-microbe-mineral interactions and freeze-thaw are found in atmospheric chemistry through the study of ice nucleation (Schnell and Vali, 1972; DeMott et al., 2003; Zimmermann et al., 2008; Conen et al., 2011; Hoose and Mohler, 2012; O'Sullivan et al., 2014; Tobo et al., 2014; Hiranuma et al., 2014; Kiselev et al., 2016; Coluzza et al., 2017; Conen and Yakutin, 2018; Knopf et al., 2018) and in cold weather regions (Smith et al., 1991; Hofle et al., 2013; Gentsch et al., 2015; Szymanski et al., 2015; Gillespie et al., 2014; Mueller et al., 2017; Gao et al., 2021; McCutcheon et al., 2021; Polyakov and Abakumov, 2021). The same tools and techniques (e.g., scanning electron microscopy) are used by and available to soil scientists, geoscientists, and atmospheric chemists alike. For example, an interdisciplinary team recently performed microscale investigations on in-situ ice formation on unreacted mineral particles and particles containing fungal-mineral interfaces and organic coatings following exposure to natural soil and laboratory weathering conditions (Lybrand et al., 2021). The experiments were performed with an ice nucleation chamber interfaced with an environmental scanning electron microscope; an innovative, relatively new (e.g., Kiselev et al., 2016) approach where in-situ ice formation was assessed via rapid imaging of individual mineral particles at sub-micron resolutions. The results from the work indicated that mineral coatings, presumably from soil microbes, influence where and how ice forms in natural soils whereas fungal-mineral contacts did not impact ice nucleation activity (Fig. 9a). Mineral grains exposed to biological activity in natural soil conditions showed enhanced ice formation at significantly lower relative humidity with respect to ice formation when compared to unreacted grains (Fig. 9b). This study contributes to a growing body of evidence suggesting the importance of organic matter for promoting ice nucleation activity on particles suspended in the atmosphere and those in soil.

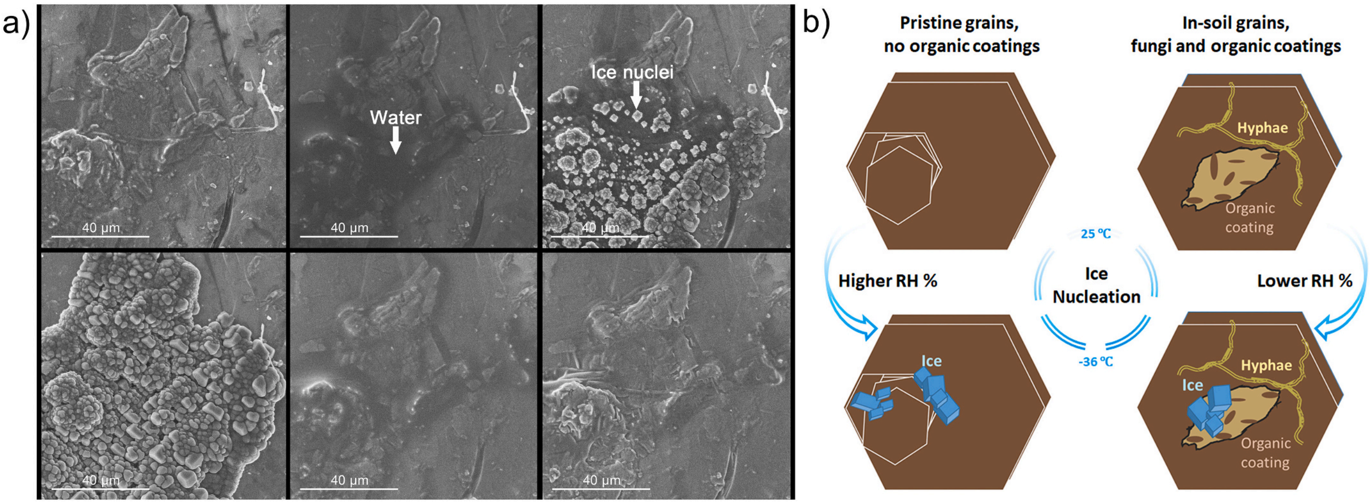

Fig. 9. a) Scanning electron micrographs of ice formation occurring on an organic coating versus mineral defects as observed on grains with no biological inputs. The top row of images shows the grain prior to exposure to ice nucleation and the sublimation cycle (left) followed by water uptake (middle) and the initial stages of ice nucleation on the organic coating (right). Images on the bottom row show the progression of ice crystal growth on the organic coating (left), ice sublimation (middle), and the grain surface after exposure to the full ice sublimation process (right). b) General schematic summarizing the differences in ice formation on pristine grains compared to those with mineral coatings following burial in a forest soil environment. This work found that grains deployed in the forest soil displayed ice formation at lower relative humidity (RH) percentages with respect to ice formation compared to pristine grains (Images and modified captions reproduced with permission from Lybrand et al., 2021).

This affects weathering and nutrient release to the biosphere, with direct consequences for interactions between the atmosphere and geosphere. As we move forward in defining weathering pathways to constrain nutrient cycling models (Hartmann et al., 2014; Goll et al., 2017; Sun et al., 2021), the underpinning mechanisms of freeze-thaw impacts require additional consideration across spatial and temporal scales, from the Arctic, where permafrost thaw is becoming more frequent as a result of warming climate (e.g., Schuur et al., 2015; Chadburn et al., 2017), to more temperate environments where the role of freeze-thaw in enhancing weathering pathways may currently lack consideration altogether.

3.3.1. *Soil-landscape to microscale perspectives on organo-mineral associations in Arctic soils*

Arctic and boreal soils store more than 50% of Earth's soil organic carbon in permafrost (Jobbágy and Jackson, 2000; Tarnocai et al., 2009), making these landscapes a focal point for the study of warming and environmental change in the Arctic (Moni et al., 2015). Arctic air temperatures are exceeding previous predictions and increasing at a rate twice that of the global average (AMAP, 2017; Screen, 2017). Landscapes in the Arctic once stabilized for millennia by permafrost (soil, rock, or sediment frozen for over two consecutive years) are now more susceptible to thaw (Ping et al., 2015). As permafrost thaws, microbes decompose once-frozen organic matter and release methane, carbon dioxide, and other greenhouse gases to the atmosphere (Schuur et al., 2008; Chen et al., 2016). Releasing heat-trapping greenhouse gases presents the potential to drive unprecedented changes in global climate (Koven et al., 2015; Lawrence et al., 2015). Permafrost temperatures are rising worldwide with an associated thickening of the active layer, or the surface soil overlying permafrost that thaws and refreezes seasonally (Lawrence et al., 2015). Permafrost thaw under warming air temperatures alters carbon and nutrient cycling dynamics of Arctic ecosystems; poses as a threat to global climate goals; and impacts the structural integrity of urban infrastructure and rural communities (Schaefer et al., 2014; Gentsch et al., 2015; Turetsky et al., 2020; Natali et al., 2021; Schneider von Deimling et al., 2021). As a result, regional to global scale research efforts have centered on modeling permafrost distribution, the predictive response of permafrost soils to warming climate conditions, and future projections of permafrost dynamics (Turetsky et al., 2020). Integrating soil properties into global models has provided more realistic predictions of permafrost distribution, such as the refinement of freeze-thaw processes (e.g., Yokohata et al., 2020). Closer assessments of the belowground systems that contribute to the variability, stability, and/or degradation of permafrost are required across scales from soil-landscape relationships, to morphological observations and soil properties expressed in a pedon, to nano-microscale relationships of collected permafrost soil samples (Fig. 10; Baumann et al., 2009; Hofle et al., 2013; Gillespie et al., 2014; Shelef et al., 2017; Polyakov and Abakumov, 2021; Rooney et al., 2022).

Soil morphological descriptions and pedological investigations of permafrost landscapes are required to interpret the complex processes of soil formation (Fig. 10a,b; Smith et al., 1991; Tarnocai and Bockheim, 2011; Kovda and Lebedeva, 2013) and the heterogeneity of carbon distribution in Arctic soils (Fig. 10c,d; Ping et al., 1998, 2008). The expression of soil properties in permafrost soils varies based on differences in processes prevalent in the soil, which leads to distinct contrasts in Arctic soil profiles compared to more temperate environments where soil horizons are generally arranged in more systematic ways (Figs. 5, 10a,b). Permafrost soils present much complexity and heterogeneity in soil as a result of the dominant pedogenic processes in the Arctic. For example, the freezing and thawing of Arctic soils can lead to the formation of soils through cryogenic processes (i.e., freeze-thaw cycles, cryoturbation). Cryoturbation (denoted with a jj), or frost churning, moves organics from the landscape surface to depth and results in the subsurface accumulation of organic matter (i.e., Oejj) and the formation of irregular, broken, or distorted horizon boundaries (Fig. 10). The soil profile depicted in Fig. 10b presents pockets of "Oejjf" at >50 cm depth, or the presence of intermediately decomposed organics (i.e., Oe) that have been cryoturbated or moved downward in the profile by freezing (f) and freeze-thaw (i.e., jj). The example displayed in Fig. 10 represents the variability of describing and sampling permafrost soils at the pedon scale. Fig. 10 also highlights the need for Arctic pedologists skilled at making soil horizon differentiations and soil morphological observations to be included in the field descriptions, sampling, and research activities focused on the distribution of soil organic carbon in Arctic landscapes (Ping et al., 1998).

Soil micromorphology, the microscopic study of soil, has also been a useful approach for characterizing permafrost soils, particularly the

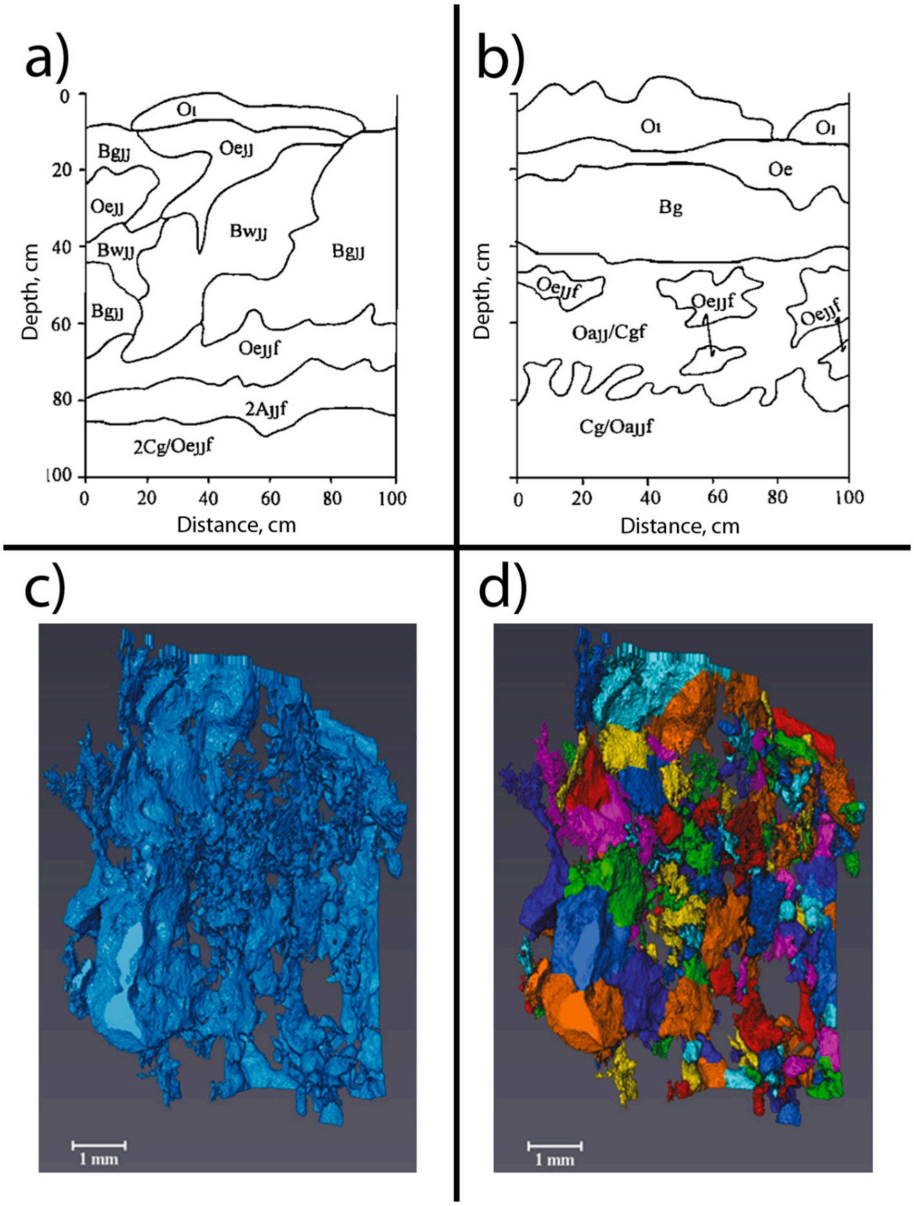

Fig. 10. The complexity of permafrost soil demonstrated in a-b) soil profiles for a) a moist nonacidic tundra soil and b) a moist acidic tundra soil. Both soil profiles represent cryoturbated soils from the Arctic Foothills, Alaska (Ping et al., 1998). Cryoturbation, also known as frost churning, occurs when materials from the soil horizons have been mixed by freeze-thaw processes. The intricacies of permafrost soils are also observed at the c-d) microscale where X-Ray computed tomography (XCT) was used to assess complex relationships among connected and unconnected pores. Here, an aggregate from a permafrost core sampled in Toolik, Alaska was visualized as c) an unseparated pore network and d) as connected objects using XCT. All figures were reproduced with permission (Ping et al., 1998; Rooney et al., 2022).

expression of soil structure (Van Vliet-Lanoe, 1985; Smith et al., 1991) and when considering cryoturbation as a mechanism for the redistribution of soil particles (Fox and Protz, 1981). Nano- to microscale investigations of organo-mineral associations and the distribution of organics in Arctic soils are still emerging in conjunction with advancements in the analytical approaches required to support such analyses (Prater et al., 2020; Gao et al., 2021). As global land surface models continue to improve and integrate the physical properties of soil to predict permafrost processes (e.g., Yokohata et al., 2020), there are opportunities to combine advanced analytical capabilities with soil morphological investigations to identify the micro- nanoscale controls on the distribution and persistence of soil organic carbon in Arctic soils (Gentsch et al., 2015; Mueller et al., 2015, 2017, 2019; Gao et al., 2021). Microscale analyses are especially critical for recognizing the dynamic nature of interactions at the mineral-organic interface (Kleber et al., 2021).

The importance of nano- to microscale investigations continues to be recognized (Hochella et al., 2019) including the need to differentiate among the degree of decomposition of organics and associations with coarse to fine-grained mineral particles (Fig. 10d; Mueller et al., 2017). NanoSIMS was used to examine interfaces among plant residues and mineral soils where organo-mineral associations were identified, such as evidence for the preliminary stages of soil aggregation or microstructure development (Mueller et al., 2017). The deepening of the active layer and exposure of previously frozen soil to freeze-thaw under warmer conditions also alter soil porosity characteristics at the nano-microscale (Rooney et al., 2022; Ma et al., 2021; Liu et al., 2021; Rempel, 2010). More work has since integrated the use of soil aggregates in microscale assessments of the influence of freeze-thaw on porosity in the active layer and permafrost as investigated along a gradient of discontinuous to continuous permafrost in Alaska (Rooney et al., 2022). X-ray computed tomography (XCT) has also been employed to compare soil macropore patterns between hummocks and interhummocks using intact soil columns excavated from alpine meadows in the northeastern Qinghai-Tibet Plateau (Gao et al., 2021). Soil morphological and micromorphological investigations require a stronger coupling to regional to global scale modeling activities and interdisciplinary research projects focused on the response of permafrost soils to climate change, especially for differentiating composition and the nature of buried/cryoturbated organic horizons.

3.4. Collaborative opportunities

There are opportunities to expand the role of soil scientists working with research teams across spatial and temporal scales from nano-microscale processes to the global scale (see dotted yellow box in Fig. 11; e.g., Slessarev et al., 2016). Enhanced collaborations could improve understanding of the fungal hyphosphere in the soil environment including “spatially explicit, quantitative research characterizing the environmental drivers of hyphal exploration and hyphosphere community composition across systems” (See et al., 2022). Soil scientists would offer much expertise and insight on identifying landscape-, soil-, to micro-scale controls on factors driving environmental differences in the hyphosphere of the soil environment including how soil forming factors and processes may be influencing the composition and nature of the hyphosphere itself. As stated by Frings and Buss (2019), “Landscapes ultimately arise as the integrated result of processes that act at the mineral-grain scale.” We still need to identify and understand the mineral weathering pathways that promote habitability on Earth and potentially elsewhere. Soil scientists are poised to offer cross-scale expertise in the soil subdisciplines (e.g., soil physics, soil chemistry, soil mineralogy) whether that be examining nano- to microscale controls on rock-derived nutrient release using high-resolution microscopy (Fig. 12) or examining the soil properties at sites that support terrestrial organisms on Earth or beyond, whether those species live, nest, or dwell in the soil or rely on the vegetation supported by the soil (Figs. 2-5).

More active, integrated collaborations are required to address obstacles, challenges, and questions arising under the influence of anthropogenic factors and changing climate conditions as presented by Dontsova et al. (2020), Schwartzman (2013); and Brantley et al. (2011), some of which include:

“1. What are the impacts of human-induced land use change on biological weathering?

2. What is the impact of changing environment/climate on the dominant biological weathering processes?

3. What is the impact of extreme events (disturbances), such as hurricanes, fire, extended drought, etc. on the feedbacks between biological and geological processes?

4. How can increased knowledge of biogeochemical weathering processes be exploited to sequester atmospheric carbon dioxide?”

4. Linking soil to the space and planetary sciences

“Much of the neglect of soil science [in current space programs] is also due to the relative scientific anonymity of soil scientists [to space scientists].” Cameron (1963).

4.1. Overview: Is there soil on Mars or on other planetary bodies?

Soil has been referred to as a “frontier in extraterrestrial explorations” (Fig. 13; Lin, 2005). Bridging soil science with the planetary and space sciences has been discussed for decades (Cameron, 1963; Lin, 2005), with demonstrated success in research that has since paved the path forward (Ewing et al., 2006, 2007; Amundson et al., 2008). There have been questions on whether surficial materials on Mars and other planets truly meets the definition of “soil” given a lack of biota (e.g., Richter and Markevitz, 1995; Markewitz, 1997). Or whether soils include “any loose, unconsolidated materials that can be distinguished from rocks, bedrock, or strongly cohesive sediments” with “no implication of the presence or absence of organic materials or living matter is intended” as defined by the Mars Rover Exploration (MER) team (Bell et al., 2000; Gellert et al., 2004; Squyres and Knoll, 2005; Amundson et al., 2008). Amundson et al. (2008) emphasized that soils exist in Antarctica and elsewhere on Earth “where the climate is too harsh to support higher plant forms (Soil Survey Staff, 1999),” which therefore “fully includes generally abiotic soils within a standard pedological framework.” Extraterrestrial soils, sometimes referred to as Astrosols given abiotic formation pathways, have also been described as “historical entities that retain information on their climatic and geochemical history (Certini et al., 2009).” Most recently, the Soil Science Society of America presented a new definition of soil as, “the layer(s) of generally loose mineral and/or organic material that are affected by physical, chemical, and/or biological processes at or near the planetary surface and usually hold liquids, gases, and biota and support plants.” This definition was introduced by Van Es (2017) to address multiple concerns of inclusivity related to the previous definitions of soil, one of which was specifically focused on the “implicit message that soil science (and therefore research funding) would not be relevant outside planet Earth.”

Regardless of whether “soil” exists on Mars and other planetary bodies or not, soil scientists are positioned to contribute to collaborative opportunities in the planetary sciences by applying skillsets, expertise, technologies, and concepts from the discipline, such as pedogenesis or the formation of soil, to Mars (Fig. 13), entirely new worlds, or analogous environments on Earth. Conversely, the planetary and space science community would benefit from a more intricate connection with the discipline of soil science focused on a cross-disciplinary, three-dimensional perspective of the subsurface. Soil scientists already consider how interactive physical, biological, and chemical processes drive mineral weathering processes, with many who already work in

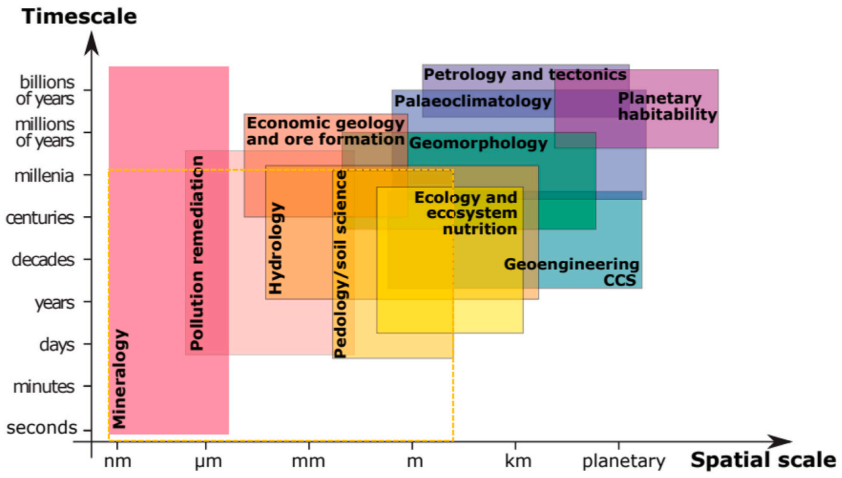

Fig. 11. A schematic highlighting the extensive range of mineral weathering research across scales and disciplines. This figure has been modified from Frings and Buss (2019) to emphasize that the scale and scope for Pedology/Soil Science research (as highlighted with yellow dashed line) could be expanded to include the wider range of research being conducted now and in the future.

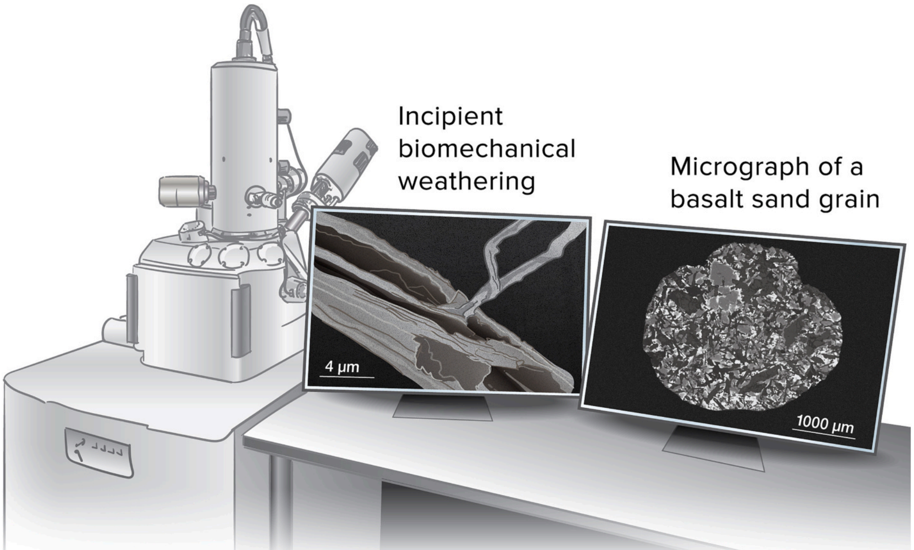

Fig. 12. An illustration of a Scanning Electron Microscope with the displays highlighting a fungal hypha transforming the edge of a mica grain (left) through a biomechanical weathering interaction and an electron micrograph of a basalt sand grain collected from a Mars analog landscape in Iceland (right). High-resolution microscopy is a critical resource for expanding our understanding of microscale processes that control nutrient cycling in soil. Illustration created by Rob Riedel, UC Davis IET Academic Technology Services.

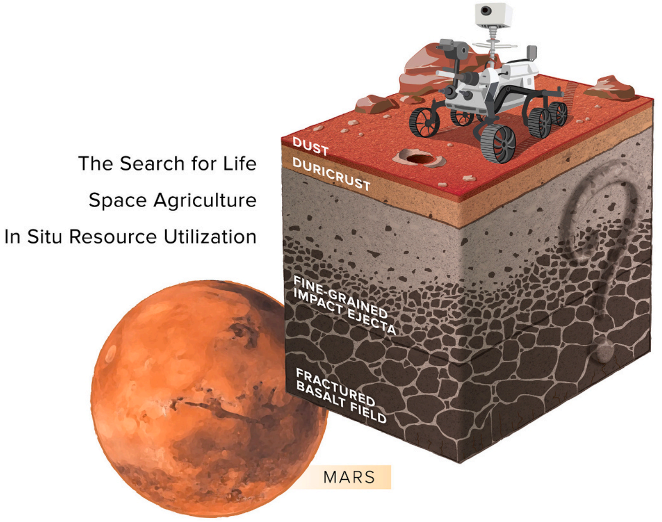

Fig. 13. An illustration presenting a hypothesized soil depth profile for the subsurface on Mars including a thin dust layer, duricrust, fine-grained impact ejecta, and a fractured basalt field. The field of soil science offers opportunities for partnerships with planetary and space scientists to better understand processes related to the search for life, space agriculture, and in situ resource utilization. Illustration created by Rob Riedel, UC Davis IET Academic Technology Services.

extreme environments that serve as analogs to Mars (Bockheim, 1997; Arnalds and Kimble, 2001; Bockheim, 2002; Arnalds, 2004; Graham et al., 2008; Ewing et al., 2006, 2007, 2008; Owen et al., 2011; Balks et al., 2013; Arnalds, 2015; Arnalds et al., 2016; Amundson, 2018). More specifically, the CheMin instrument aboard Curiosity has discovered an abundance of X-ray amorphous materials in all Martian rocks and soils analyzed to date from Gale Crater, Mars (i.e., Rampe et al., 2020); a topic being explored at the microscale by soil scientists and geoscientists for analog studies on Earth (Minitti et al., 2007; Hausrath et al., 2008; Tamppari et al., 2012; Dorn et al., 2013; Schindler et al., 2019; Yesavage et al., 2015; Broz, 2020). Future space exploration missions for landers and rovers would benefit from the continued incorporation of instruments that investigate soil properties (i.e., Sample Analysis at Mars suite; Chemistry and Mineralogy instrument; Alpha Particle X-Ray spectrometer instrument; Mars Hand Lens Imager camera). The science would also be advanced by integrating nano- to microscale microscopy capabilities specifically for soil particles that would build upon current capabilities, such as the Planetary Instrument for X-Ray Lithochemistry (PIXL) on the Perseverance rover mission. The PIXL instrument is a micro-X-Ray fluorescence spectrometer that analyzes the elemental chemistry of rocks and sand-sized grains with a 120 μm-diameter X-ray beam (Allwood et al., 2020). An ever-present need exists to dig deeper on Mars, which requires the engineering tools and capabilities required to dig, observe, and sample soils at greater depths including the ability to observe and analyze points within intact soil profiles. New technologies are presently being developed to dig deeper during planetary exploration (MapX, CheMinX; Sarrazin et al., 2018). Soil scientists are also designing and implementing approaches that support the in-situ analysis of soil properties in field excavated walls of soil profiles, such as the use of multistripe laser triangulation scanning to quantitatively assess soil structure (Eck et al., 2013; Hirmas et al., 2016). Establishing new partnerships and continuing to strengthen existing collaborations between soil scientists and planetary scientists is required to embrace the diverse perspectives and disciplines needed to address challenges of future missions and human exploration activities.

Both disciplines would also be enhanced by a stronger integration and engagement with students, the public, and stakeholders. Investing the energy to establish these connections is especially relevant in a world where scientific communities are striving to recruit students and a diverse workforce while justifying relevance and funding to our broader society. For example, exposing geoscience students to the importance of soil science in the planetary and space science context would capture an audience who already want to see more widespread applications of soil science and the geosciences apart from agriculture, mining, or oil extraction (Baveye et al., 2006). Incorporating growers into discussions on space agriculture would engage individuals with years of expertise and experience in the agricultural industry; stakeholders who value strong collaborative community networks and the co-production of knowledge in shared spaces (e.g., Nocco et al., 2020). Integrating a broader, more diverse approach to space travel, research, and exploration activities would be enhanced by the neighborliness frames identified by Carlisle (2020), “Farmers had learned to see the world as a neighborhood, in which residents relied on one another and flourished through cooperation.” Opportunities to create collaborative pathways between the broader soil science and the planetary and space science communities remain underutilized yet prevalent (Cameron, 1963).

Soil continues to be studied as a medium for conducting research on Martian landscapes as well as extending agriculture and engineering applications with respect to establishing human settlements on Mars

(Fig. 13; Bugbee and Salisbury, 1988; Ming and Henninger, 1989; Wamelink et al., 2014; Chow et al., 2017; Karl et al., 2018; Cannon and Britt, 2019). Martian analog soils have been developed for conducting relevant experiments and research (e.g., Cannon et al., 2019); and to assess how soils could be used to construct building materials for structures on Mars (e.g., Naser, 2019). As for basic applications in research, overlapping topic areas on the formation of rock varnish, polygonal terrain, weathering rinds, and other features have been studied by geoscientists for decades (Engel and Sharp, 1958; Perry and Adams, 1978; Krinsley, 1998; Sak et al., 2004; Thiagarajan and Lee, 2004; Sak et al., 2010) and continue to be assessed from a planetary science perspective (e.g., Seibert and Kargel, 2001; Bishop et al., 2002; Knoll et al., 2008; Lanza et al., 2012; El-Maarry et al., 2014). In situ microscopy of Martian soil samples has provided support for a historically dry climate on the surface of Mars through an analysis of particle size distribution using optical microscopy and atomic force-microscopy (Pike et al., 2011). The Phoenix spacecraft landed at high northern latitudes in periglacial terrain in 2007. The spacecraft was equipped with an optical microscope used to classify soil particles based on color, size, and other optical and magnetic properties (Goetz et al., 2010).

The expanding realm of Critical Zone Science has presented the prospect for Solar System Critical Zones (SSCZ), including Proto-Critical Zones (abiotic CZs). Examples of planetary CZs include Mars, comets, asteroids, and planet(oids), all of which present boundary zones that qualify as Proto-CZs (Ashley and Delaney, 2017). In the context of addressing interdisciplinary questions in soil science that align with concepts of extraterrestrial CZ science and NASA's mission to find life on other planets, *How can soil science advance the search for life and habitable environments on Mars and beyond- from distinguishing biosignatures to better utilizing terrestrial analogs on Earth for planetary exploration?*

4.2. *The search for life…and false positives*

"A 'biosignature' is an object, substance, and/or pattern whose origin

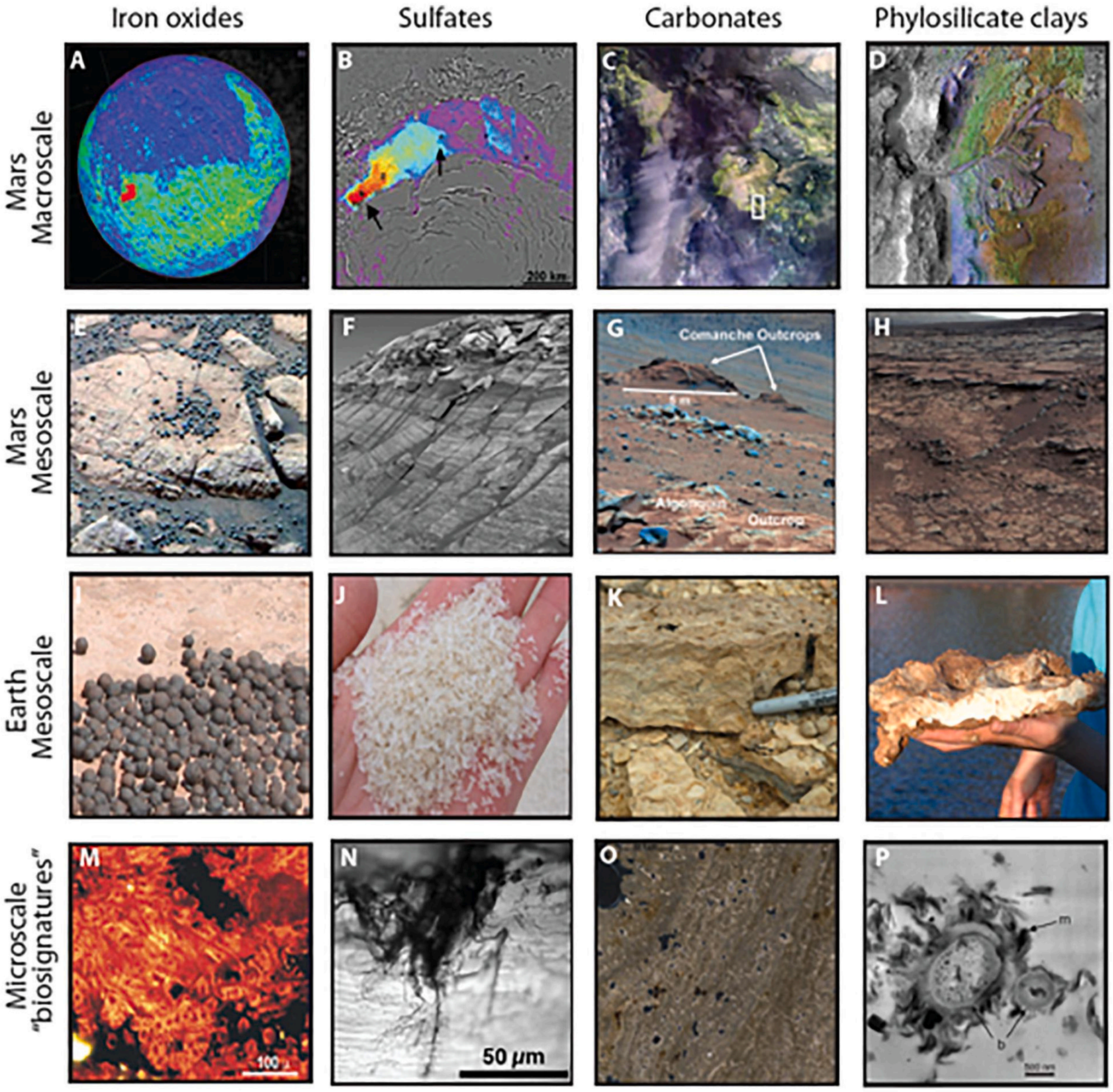

Fig. 14. A cross-scale perspective on the types of landscapes and minerals on a-h) Mars where "false positive" biosignatures have been identified and also where missions continue to focus on the goal to identify evidence for morphological biosignatures. i-p) Examples of mesoscale to microscale biosignatures that have been identified on Earth. The figure displays biosignatures that are directly relevant to subdisciplines of soil science including soil biology, chemistry, mineralogy, and pedology. Image reproduced with permission from Chan et al. (2019).

specifically requires a biological agent" (Fig. 14; Hays et al., 2017). "The usefulness of a biosignature is determined not only by the probability of life creating it but also by the improbability of nonbiological processes producing it" (Des Marais et al., 2008; Des Marais, 2013; Hays et al., 2017).

"Did life ever exist on Mars?" is a key question driving the Mars Sample Return Mission; a joint partnership between NASA and the European Space Agency that would bring the first Martian rock, dust, and soil samples back to Earth in the 2030s. The search for life on Mars is an overarching goal of the Mars Exploration Program with emphasis on identifying biosignatures or recognizing the activities of microbial groups preserved in rock, soil, and sediment materials on Mars and in terrestrial analogs (Cuadros, 2017; Vago et al., 2017). Extensive evidence for the presence of water has been documented for ancient Martian landscapes (i.e., Nazari-Sharabian et al., 2020). Water on present-day Mars has also been detected, such as modern water ice confirmed at the Phoenix landing site (Renno et al., 2009). Conversely, much less is known about how direct evidence for life, if present, was preserved on Mars.

Biological weathering mechanisms present the potential to form distinct, long-lasting mineral biosignatures whether that be through microbes imprinting unique morphological features at biotic-abiotic interfaces or by producing biominerals, microstructures, and microfossils that are preserved in the soil or regolith matrix. Research on the potential for biosignatures formation has spanned landed Mars missions (Goetz et al., 2016), spectral studies of Mars (Villanueva et al., 2013), and the use of terrestrial analogs on Earth that emphasize: the study of terrestrial fossils in clay deposits, anaerobic, and volcanic terrestrial environments (Orofino et al., 2010; Westall et al., 2015); morphological biosignatures (Cady et al., 2003; Fisk et al., 2003); and mineral biosignatures preserved through the formation of biominerals (Banfield et al., 2001). Microbially produced minerals retain isotopic signatures indicative of biotic activity (Boston et al., 2001), present unique structural characteristics attributed to biological origins (Cady and Farmer, 1996; Farmer and Des Marais, 1999; Konhauser et al., 2002) or even capture biological compounds in the mineral precipitation process (Hays et al., 2017). The expertise of soil scientists extends to spatial and temporal scales beyond the confines generally recognized for the discipline (Figs. 11, 12).

A wealth of soil science and earth surface literature focuses specifically on weathering mechanisms (Jackson et al., 1948; Tardy et al., 1973; Berner and Holdren, 1979; White and Blum, 1995; Banfield et al., 1999; Frazier and Graham, 2000; Kendrick and Graham, 2004; Dixon et al., 2009; Rasmussen et al., 2010, 2011; Nakao et al., 2012), including the micromorphology of soils and the formation of secondary minerals as assessed at the nano- to microscale of study using high-resolution microscopy (e.g., Allen, 1978; Banfield and Eggleton, 1988, 1990; Banfield et al., 1995; Buck et al., 2006; Lee et al., 2007, 2008; Minyard et al., 2011). Given that a primary research area emphasizes the need to distinguish biosignatures from "false positive" abiotic signatures, we need to forge interdisciplinary partnerships that integrate experts on abiotic weathering processes or equip soil scientists with the opportunities to employ tools that, for example, differentiate biominerals from secondary minerals produced through abiotic pathways (Gadd et al., 2014; Byrne et al., 2016; Grant et al., 2016; Li et al., 2020).

4.3. Soils of terrestrial analogs

The Encyclopedia of Astrobiology has defined a terrestrial analog as, "a field site, which bears an analogy or similarity in some way to other planetary bodies of the solar system. Similarities can be related with physicochemical conditions, such as dryness, low water activity, mineralogy, or chemical composition of the environment. (Fig. 15)." Terrestrial analogs represent "places on Earth that approximate, in some respect, the geological, environmental and putative biological conditions on a particular planetary body, either at the present-day or sometime in the past. Analog studies are driven by the need to understand processes on Earth in order to interpret and groundtruth data sent back from Mars and other planetary bodies by unmanned orbiters and rovers" (Osinski et al., 2006).

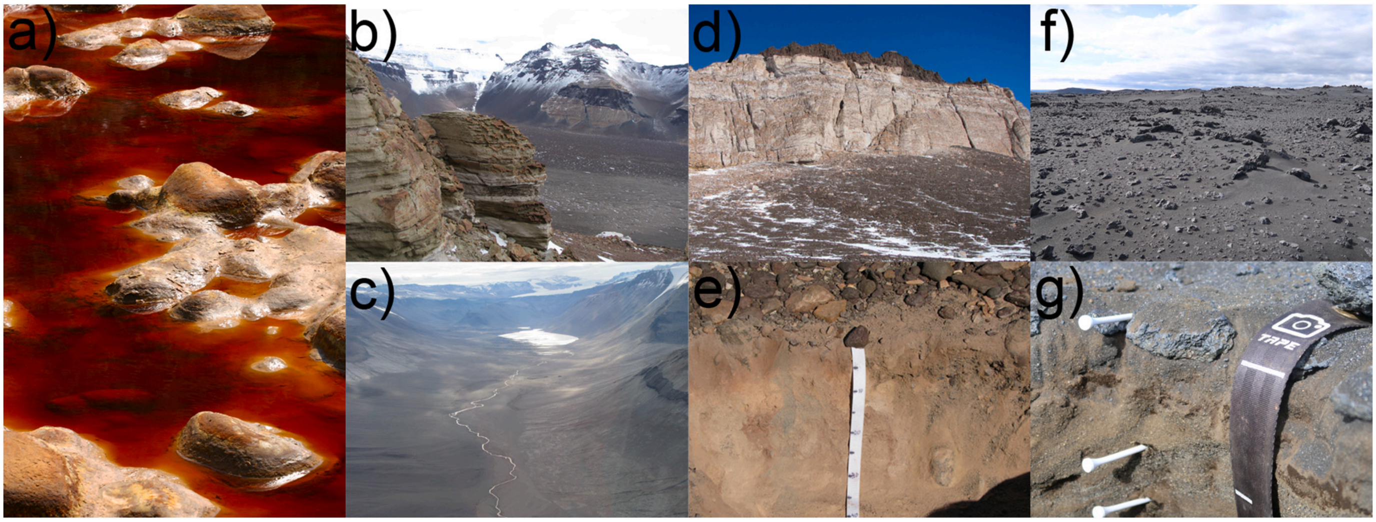

Fig. 15. The diversity of terrestrial analogs on Earth relate to different environments that could have existed on Early Mars including hydrothermal spring systems as well as subsurface, subaerial, and subaqueous environments (Hays et al., 2017). The figure contains examples of the diverse types of terrestrial analog environments found on Earth including a) Rio Tinto River near Berrocal, Spain, b) Beacon Sandstone in Antarctica presenting evidence of surface weathering and biological alteration by cyanobacteria, c) Lake Vanda and the Onyx River in Wright Valley, Antarctica, d) University Valley in Antarctica with e) soils that showed evidence of salt accumulation at depth, and f) the barren landscapes in the highlands of Iceland g) with evidence for incipient soil development at depth. Photographs from 13a-d used with permission from Doug Ming and those in 13f,g were taken by Rebecca Lybrand. The Field of View (FOV) for the panels has been estimated based on features in each photograph including: a) FOV of ~1.5 m for the rocks in the Rio Tinto; b) The distance between the Beacon Sandstone featured in the foreground is ~6 km from the cliffs pictured on the opposite side of Beacon Valley; c) the FOV for the Onyx River is ~10 km across at the upper end of Lake Vanda (inlet of the Onyx River); d) The University Valley image is ~50 m FOV width in the foreground and ~300 m to the base of the valley wall; e) the University Valley soil profile is about 60 cm FOV width; f) the rocks in the foreground of the Iceland landscape panel are approximately 0.5–1 m in size; and g) The photograph is focused on the surficial soil horizons where each white line on the soil profile measuring tape denotes a 10 cm increment.

Research utilizing terrestrial analogs for Mars and other planetary bodies are a high priority in the international planetary science communities (Fig. 15; Pollard, 2001; Farr, 2004; Osinski et al., 2006) and present opportunities to expand interdisciplinary collaborations among earth, planetary, and biological scientists (Osinski et al., 2006). Studies in terrestrial analogs center on astrobiology, exploration science (e.g., instrument testing, astronaut training), and a process-based approach to assess analogous landscapes and materials from a comparative planetary geology perspective (Osinski et al., 2006); all of which encompass strong, and sometimes already demonstrated, links to soil science.

We entered a new era of research on Mars focused on "regional to outcrop level" analyses versus work solely on global mapping (Farr, 2004). Soil scientists, especially those specializing in terrestrial analog environments, could contribute greatly to upcoming missions through data and site interpretation given that soil science naturally integrates a three-dimensional, multidisciplinary view of the subsurface—one of the most challenging dimensions to capture in the planetary and space sciences to date. NASA highlighted the need to dig deeper on Mars in a news article stating that, "NASA has barely scratched the surface of Mars – literally. While past rovers have dug inches into the rusty soils of the Red Planet, NASA is testing out a drill that can go feet deep and operate autonomously with minimal human guidance. Probing that far down below the harsh Martian surface will reveal a world we've never seen up close before – one where scientists believe there's a chance for life" (Tavares, 2019).

Furthermore, a NASA-requested survey conducted by the U.S. National Resource Council received the following recommendations from the Terrestrial Analogs to Mars community panel: "process studies at analog sites, field workshops, instrument and operations tests, and laboratory measurements" and the need to expand the "collection and wide dissemination of terrestrial analog data." The Canadian Space Agency recognized the need for expanded interdisciplinary connections by identifying enhanced collaborations between earth and planetary scientists as a primary goal when forming the Canadian Analogue Research Network (CARN) under the theme of "Exploring other worlds begins with exploring our own." Research teams would benefit from the inclusion of soil scientists in resulting workshops and discussions as many actively engage in research at extreme environments, termed extreme pedology (Goryachkin et al., 2019).

Ongoing work in terrestrial analog sites has focused on applications in astrobiology and comparative planetary geology where Earth-based analogs provide environments for the study of Mars and beyond. The Atacama Desert is a well-recognized, longstanding analog for hyperarid conditions on Mars and has been explored from numerous comparative perspectives including: to examine soil formation and soil carbon cycling along an arid-hyperarid climate transition (Ewing et al., 2006, 2008); to demonstrate the importance of depth profile sampling on Mars to understand salt and water mobility, where geochemical data suggests the formation of a Typic Petrogypsid (an arid soil cemented by sulfates) at Meridiani Planum, Mars based on soil sampling and data interpretation in the Atacama (Amundson, 2018); to show that viable bacteria and fungi are transported on particles of wind-blown dust to the Atacama's hyperarid core and that Martian dust should be analyzed for potential biosignatures given the occurrence of similar dust transport mechanisms on Mars (Azua-Bustos, 2019); to assess how analogous environments may support life in hygroscopic habitats provided by soluble salts (Davila and Schulze-Makuch, 2016) and the importance of assessing microbial fingerprints in salty, subsurface soils preserved over thousand-to million-year timescales (Wilhelm et al., 2017).

The Antarctic Dry Valleys represent another established terrestrial analog where dominant soil-forming processes are likely comparable to Mars, such as salinization, or the accumulation of soluble salts. Soluble salt composition, abundance, and preservation mechanisms vary along climo- and chronosequences in Antarctica with the most abundant and mobile salts (e.g., nitrate) concentrating in surface soils and nearsurface salt pans in the driest, and often oldest, ultraxerous soils (Claridge and Campbell, 1977; Bockheim, 1982; Bockheim, 1990; Bockheim, 1997). The high elevation Antarctic Dry Valleys serve as an ideal analog site for subsurface ice on Mars given that this may be the only location on Earth to contain dry permafrost (Heldmann et al., 2013). Permanently frozen soils in Antarctica provide analogous materials to Mars for assessing landscapes containing ice-cemented soil versus massive subsurface ice (Heldmann et al., 2013). Microbial diversity, distribution, and abundance have also been analyzed as a function of Antarctic soil properties that are comparable to conditions on Mars (Smith et al., 2006; Cary et al., 2010; Lee et al., 2012; Richter et al., 2014).

Above, examples are provided from two prominent analogs for Mars, namely Antarctica and the Atacama Desert. Potential connections among the biological, soil, geologic, and planetary sciences remain underexplored for established terrestrial analogs elsewhere on Earth as identified by Farr (2004) and others. Examples include the accumulation and preservation of subsurface salts or the distribution of salts as dust in arid landscapes of the Mojave Desert (Wells et al., 1985; Reheis et al., 1995, 2009; Reynolds et al., 2006, 2007; Graham et al., 2008; Hirmas and Graham, 2011; Lybrand et al., 2013, 2016). Or the study of soils in icy, cold analogs for Mars, including the Canadian Arctic (e.g., Osinski et al., 2006), Svalbard (Hausrath et al., 2008), or the Icelandic Deserts (Arnalds, 2004, 2015; Arnalds et al., 2016). Overall, we need to better connect the study of soils to the planetary sciences as emphasized by Amundson (2018): "The knowledge of the soils of Mars is very fragmentary, but it will expand if soils continue to become part of the suite of targets for future planetary research."

4.3.1. *Connections to Mars exploration and human settlement*

Linking soil science and the geosciences to exploration science activities in terrestrial analogs presents opportunities to identify and solve challenges in mission design, operations, and the development of technologies needed to explore and settle on Mars (Snook and Mendell, 2004). Planetary exploration requires that rovers, drills, and other technologies are tested at sites that encompass properties of rocks, soils, and terrain, among other factors likely to be encountered during surface mission operations on the Moon or other planetary bodies (Snook and Mendell, 2004). Soil scientists with expertise in the spatial distribution of soils and associated properties in extreme analog environments would offer insight and guidance on soil-landscape relationships that may present challenges to planetary exploration and research. For example, evidence for thinly indurated crusts ('duricrust') has been detected at multiple landing sites on Mars (Arvidson et al., 2004a, 2004b, 2008; Herkenhoff et al., 2008; Golombek et al., 2020; Piqueux et al., 2021) and created challenges for deep drilling activities at the Insight landing site (e.g., Witze, 2019; Dorminey, 2021; Spohn et al., 2022). Indurated soils are a common phenomenon on Earth and form as the result of contrasting processes occurring under different climate, geologic, or topographic conditions (e.g., Gile et al., 1966; Flach et al., 1969; Torrent et al., 1980; Boulet et al., 1998; Chadwick et al., 1989; Boettinger and Southard, 1990; Harden et al., 1991; Hollingsworth and Fitzpatrick, 1993; Blank et al., 1998; Hobson and Dahlgren, 1998; Van Breemen and Buurman, 2002; Duniway, 2006; Duniway et al., 2007; Brock and Buck, 2007; Lybrand et al., 2013; Salari et al., 2019). Soil scientists working in extreme environments may be well-versed to contribute to discussions on landing site locations or to identify analogs that may present similarities in terrain or geochemical evolution of the landscape.

A second example pertains to addressing potential human health and plant growth challenges on Mars given the abundance of salts distributed in Martian surficial materials. Perchlorate, a soluble salt and human health contaminant, has been detected in the surface and nearsurface at multiple landing sites on Mars (Fig. 16a; Hecht et al., 2009; Cull et al., 2010; Navarro-Gonzalez et al., 2010; Glavin et al., 2013; Ojha et al., 2015). Perchlorate represents both a resource and hazard to consider in human exploration and settlement activities on the Martian surface (Davila et al., 2013; Fig. 16). Perchlorate is a resource given that the compound is a strong oxidizer and potential fuel source (e.g., solid

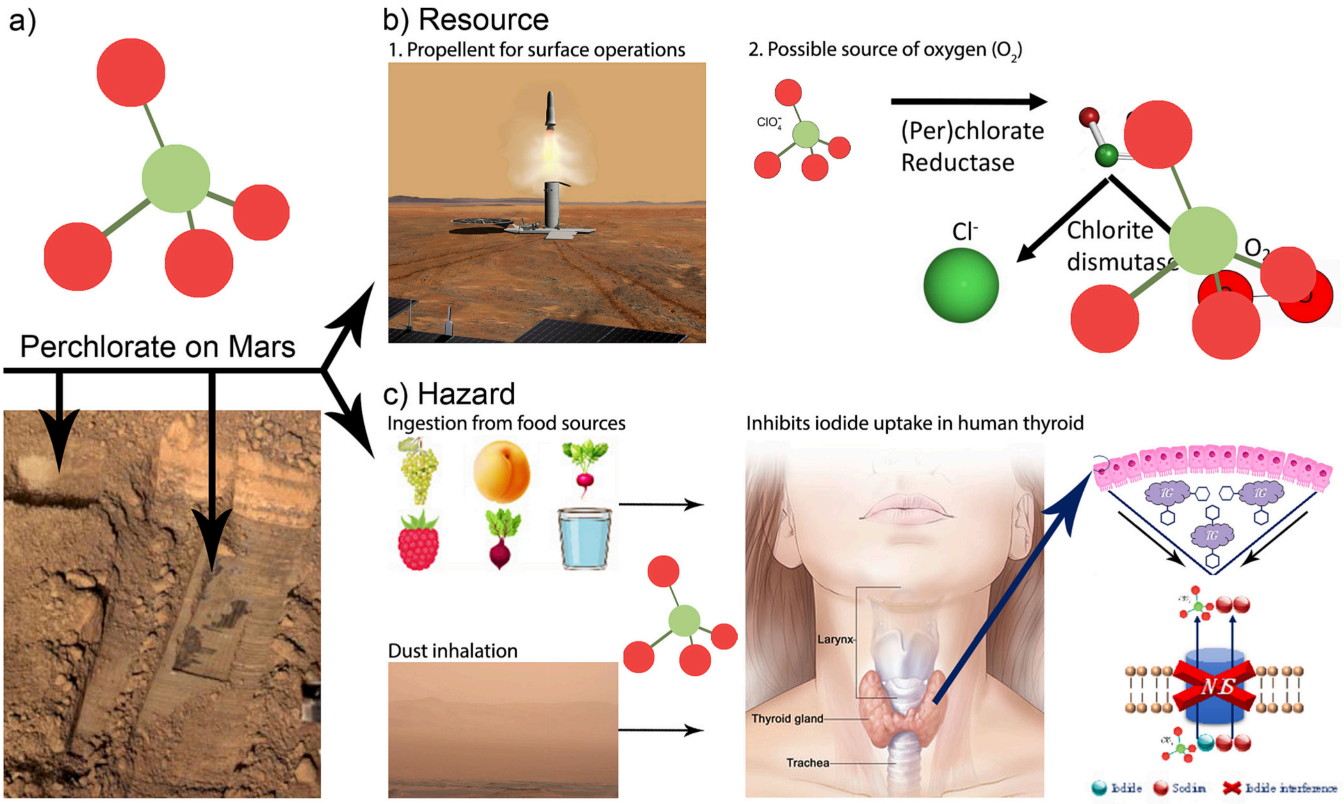

Fig. 16. Martian perchlorate has been described as a hazard and a resource (Davila et al., 2013), which makes identifying the controls on the distribution and variation of perchlorate and other soluble salts on Mars and in Earth-based analogs an important research priority. a) Perchlorate has been detected at multiple landing sites on Mars as evidenced at the Phoenix Landing Site in the analysis of the Rosy Red, Sorceress 1, and Sorceress 2 Wet Chemistry Lab (WCL) samples (Hecht et al., 2009). Image credit: NASA/JPL-Caltech/University of Arizona. b) Perchlorate is a resource given its role as a strong oxidizer and potential fuel source, as a possible in situ supply of oxygen on Mars, and as a geochemical marker for understanding liquid water contents and the migration of salts solubilized in water under both present-day climate and paleoclimate conditions (Davila et al., 2010, Ojha et al., 2015; Davila and Schulze-Makuch, 2016). Image credit: NASA/JPL-Caltech. c) Perchlorate is a well-known health contaminant on Earth that interferes with iodide uptake in the human thyroid and thereby impacts thyroid hormone synthesis in infants, adolescents, and adults (Lisco et al., 2020). The widespread distribution of perchlorate on Mars is also therefore a hazard given that perchlorate is found in water and accumulates in some food products (e.g., leafy greens, fruits, vegetables). Plans for human settlement activities on Mars would need to account for the strong likelihood of encountering perchlorate and other salts in the dust, in the Martian soil materials used to grow food, or in the subsurface ground ice used as source(s) of water (Davila et al., 2013). Images modified and used with permission from Lisco et al. (2020) and the medical illustration of the human thyroid was provided with permission from Terese Winslow (tereswindslow.com).

rocket fuel) in addition to serving as a possible source of oxygen on Mars (Fig. 16; Davila et al., 2013). The abundance and spatial variation of perchlorate is an important research topic in both the geosciences communities and those working in exploration science. Perchlorate provides information about liquid water contents and migration under present-day climate and paleoclimate conditions while also presenting the potential to support or preserve signs of life in the Martian subsurface (Davila et al., 2010, Ojha et al., 2015; Davila and Schulze-Makuch, 2016). Perchlorate also serves as a hazard since the contaminant impacts human health by interfering with iodide uptake in the human thyroid. Perchlorate exposure commonly occurs through the ingestion of contaminated water given the high solubility of the compound and through the consumption of food products, such as fruits and vegetables. Astronauts could therefore potentially be exposed to perchlorate through dust or by ingesting foods grown in Martian materials or through water obtained from subsurface ice (Davila et al., 2013; Berliner et al., 2021; Duri et al., 2022).

The Curiosity Rover has confirmed the ubiquitous nature of perchlorate on Mars, with its detection of perchlorate approximately 5000 km from the Phoenix Mission site in environments of contrasting geology, mineralogy, and landforms (Leshin et al., 2013; Ming et al., 2014). The widespread occurrence of Martian perchlorate led to its inclusion in NASA's Strategic Knowledge Gaps (SKGs) given that perchlorate represents both a potential hazard to human health and a resource by supplying a source of oxygen for life support or fuel (Fig. 16; Davila et al., 2013). There is a need to understand the strong spatial variation of perchlorate observed both on Mars and in Earth-based hyperarid analogs where perchlorate salts occur naturally (Jackson et al., 2010; Kounaves et al., 2010; Lybrand et al., 2013; Andraski et al., 2014; Ming et al., 2014; Jackson et al., 2015; Lybrand et al., 2016). This is an example of one path forward that would enhance collaborations among soil scientists who work on salt-rich soils in arid to hyperarid systems on Earth as well as the scientists and engineers working in the space exploration science community.

4.4. Collaborative opportunities

Research partnerships among NASA, universities, and private sector organizations are already prevalent in the planetary and space science community and represent potential areas of collaboration with soil scientists. There are also established teams of soil scientists and geoscientists based at the NASA Space Centers (e.g., Johnson Space Center, Goddard Space Flight Center). Soil scientists and geoscientists interested in pursuing research opportunities in the space and planetary sciences are able to pursue external funding through NASA's solicitations with applicable soils-relevant programs ranging from Habitable Worlds, Solar System Workings, Exobiology or even Human Exploration depending on the nature of the proposed research topic or project idea. The National

Space Grant College and Fellowship Program was also established by Congress in 1988 to "broaden the base of universities and individuals contributing to and benefiting from aerospace science and technology and ultimately to the development and utilization of space resources" (California Space Grant Consortium, 2022). Space Grant Consortiums operating at the state level offer educational and/or research opportunities for students, faculty, and additional interested individuals depending on the state and funding available. Promoting relevant educational, research, and career opportunities to students and early career scientists serves to encourage the next generation of soil/geoscientists to think freely about applications of soils research on Mars and other planetary bodies.

Declaration of Competing Interest

The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data synthesized and presented in this work are from published literature that have been cited accordingly.

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