# ARID

## Adaptation and Response in Drylands

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# Executive Summary

The NASA Terrestrial Ecology Program's **A**daptation and **R**esponse **i**n **D**rylands (ARID) scoping study provides a research agenda for the next generation of NASA's Terrestrial Ecology field campaigns. ARID will be an international research initiative bringing a global focus to dryland functioning and its critical role in climate mitigation and adaptation. Dryland ecosystems represent the planet's largest terrestrial biome, making up over 40% of the land surface and sustaining a third of the world's population, meaning one in three people in the world today lives in drylands. Defined by their aridity, dryland ecosystems provide vital services that include supplying 60% of global food production, supporting critical hotspots of biodiversity, representing 40% of terrestrial net primary production, and dominating the trend and the interannual variability in the terrestrial carbon sink. Dryland systems are also increasingly vulnerable to global change given compounded impacts from climate change and land use. Plant communities are shifting substantially in drylands around the world, with widespread observations of woody encroachment into grasslands and savannas, exotic grass invasion, large scale mortality events, lowered productivity, and losses of biodiversity in the face of exceptional drought, temperature, and wildfire. The fact that drylands have been identified as one of the most vulnerable global ecosystems to climate change has significant implications for food security, water availability, biodiversity, land degradation, geopolitical stability, as well as large potential feedbacks to future climate. ***Despite their global importance and high vulnerability to change, our scalable understanding and capacity to forecast dryland dynamics, as well as impacts to ecosystems and society, is notably poor.***

The ARID campaign would augment NASA's extensive current (e.g., ECOSTRESS, EMIT, SMAP, Landsat) and future (e.g., NISAR, SBG, and Landsat Next) satellites with a dedicated multi-scale field campaign using NASA airborne assets (e.g., AVIRIS, UAVSAR, and MASTER) and ground measurements. With these spaceborne, aircraft, and field sampling capabilities across scales, NASA is best positioned to bring the science and end-user communities together to address the ARID campaign's four interrelated science themes and overarching questions:

***Climate Variability and Drought***

*How are climate extremes like droughts, heatwaves, and large rain pulses impacting dryland systems and how do they interact with changing fire regimes, land cover change, and land-atmosphere interactions*?

***Ecosystem Structure, Function and Biodiversity***

*What are the main mechanisms driving the spatiotemporal distributions of dryland structure, function, and biodiversity and what is their vulnerability to change?*

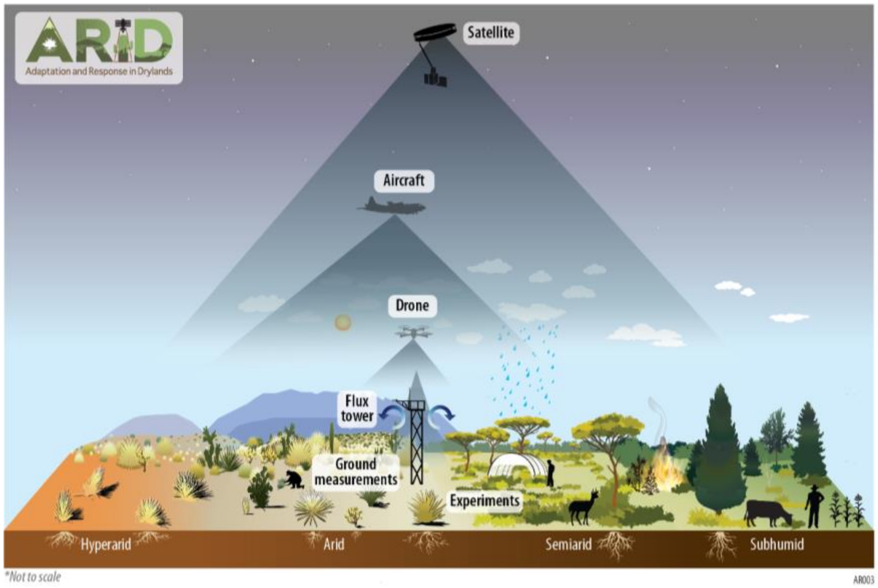
***Carbon Cycle Interannual Variability and Long-Term Trends***

*What is the contribution of drylands to the mean, trend, and interannual variability of terrestrial carbon uptake and what drives these patterns?*

***Social-Ecological Systems***

*What are the consequences of changes in drylands for social-ecological systems and what management (e.g., mitigation and adaptation) solutions can maintain the critical services provided by drylands even in the face of change?*

The interacting pressures of climate and land-use change are dramatically altering the structure and function of Earth’s drylands. Although global efforts recognize the crisis these changes portend for social-ecological systems, recent research exposes a significant lack of knowledge regarding the mechanisms behind and consequences of dryland transformation. To date, there has been no sustained research and monitoring campaign targeting dryland systems to fill this gap. Research in these heterogeneous ecosystems requires an understanding contextualized within larger planetary scale biogeophysical dynamics and variability. As such, NASA Terrestrial Ecology field campaigns are the ideal mechanism for gathering the cross-scale, transdisciplinary knowledge needed to understand, quantify, and predict change in these critical ecosystems. The ARID scoping study provides an intensive research plan consistent with the mandate of NASA Earth Science Division's Earth System Observatory to "*create a 3D, holistic view of Earth, from bedrock to atmosphere*." Furthermore, ARID is well aligned with NASA's Earth Science to Action (ES2A) strategy, which has the goal of innovating and collaborating across multiple research and end-user sectors “*to explore and understand the Earth system, make new discoveries, and enable solutions for the benefit of all*”.



*ARID will vastly improve the quantitative and predictive understanding of Earth’s drylands using a nested approach that coordinates in-situ measurements, existing and new networks, and with drone and aircraft data that harmonize with and inform satellite observations. The datasets and new knowledge will cross disciplines and scales.*

The ARID framework was co-created by a large and diverse community of scientists, data users, and practitioners who together informed an actionable study design to dramatically advance our understanding and capacity to monitor, forecast, and inform decisions for Earth’s rapidly changing drylands. Specifically, the scoping study provides a rationale for the importance of better understanding Earth’s dryland ecosystems, poses key scientific questions around the foundational interconnected research themes, offers a conceptual campaign framework to address them, and underscores the necessary role of NASA in achieving these important goals. ARID integrates multiple observations and analytical methods (e.g., proximal, drone, airborne, and satellite remote sensing observations, ground-based measurements, tower-based fluxes, and multi-scale modeling), leveraging the wealth of archived, current, and future multi-mission NASA data. During scoping, the ARID team secured strategic, multi-sectoral partnerships for facilitating the research, for co-developing science-based information products with decision makers, and for supporting and training the next generations of interdisciplinary Earth system scientists. ARID is co-designed with diverse end-users and knowledge providers (e.g., United States [US] Bureau of Land Management, Tribal authorities, Department of Defense, Department of Energy, US Geological Survey, Department of Agriculture, National Science Foundation) - as well as academic institutions and non-governmental organizations around the world - through high-level involvement, workshops, Town Halls, Round Tables, individual discussions, Working Groups, and webinars. ARID is responsive to and was developed with Native American perspectives during the co-design process, integrating Tribal Nations' expertise and viewpoints as part of the scoping study.

ARID is an international campaign, outlining strong research needs, partnerships, and synergistic field campaign initiatives for Australia, northern Mexico, southern Africa, and South America. At the same time there is a significant focus on the United States (US) due the strong national need for actionable dryland science. Drylands are of particular importance to US national resources and security, covering ~83% of the western US and under stress from the ongoing North American megadrought. Within the US, the Bureau of Land Management, US Forest Service, and Tribal authorities together manage >2 million km$^2$ of drylands for multisectoral land uses (rangeland, cultivation, forestry, conservation, energy), most of which are experiencing changes in vegetation and productivity relating to climate and land use change, including shrub encroachment and loss of grazing resources, invasive grasses, and changing fire regimes. Moreover, alternative energy siting and ambitious nature-based climate solutions (NbCS) programs frequently target drylands for development, restoration, and/or afforestation to enhance carbon sequestration and the human environment, but critical tradeoffs for biodiversity, water consumption, surface albedo, and social-ecological outcomes must be fully considered prior to acting on such recommendations. Yet the tools and scalable information to evaluate these actions, and for quantifying the intended and unintended consequences, remain remarkably limited.

By investigating how ecosystems are responding to climate change, weather extremes, management practices, and land-use change, ARID aims to better understand the shifting role of drylands in the Earth System, including global carbon and water cycles, thereby advancing our predictive capacity to support end-user decision making and improve forecasts of current and future feedbacks to climate change at the global scale. This white paper provides a broad research agenda based on engagement with the scientific community and end-users. The first three science themes - Climate Variability and Drought, Ecosystem Structure, Function, and Biodiversity, and Carbon Cycle Dynamics - focus mainly on the fundamental interactions between the *drivers of change* and *ecosystem responses*. The fourth theme, Social-Ecological Systems: Natural Resource Management and Adaptation-Mitigation, is related to *human systems*. Taken together, the white paper embraces drylands as multi-faceted, complex systems, meriting broad interdisciplinary approaches including terrestrial ecology, hydrology, biogeochemistry, remote sensing, and modeling. ***We stress that drylands represent a critical set of systems that – due to their global importance, responsiveness to perturbation, and poor representation in models – induce large uncertainties in our global understanding of anthropogenic change and feedbacks on Earth system processes*.**

The white paper also provides an implementation plan to address central science questions using a set of multi-scaled remote sensing approaches, ground networks, and process models, with NASA assets at the forefront of these approaches. A core portion of ARID is proposed to be carried out in the western US, taking advantage of natural gradients of aridity, practitioner interest, and the opportunity to leverage existing NASA data, partner airborne campaigns, and ground assets (e.g., NASA-USGS GEMx campaigns, the AmeriFlux network, the NSF NEON network and LTER networks, the USDA LTAR networks, etc.). In this way, **ARID provides a nexus of collaboration across existing institutions, researchers, and end-users, that require the diverse satellite observations, Airborne Science Program, and leadership of a coordinated leaf-to-orbit research project only NASA and a Terrestrial Ecology Field Campaign can provide**. The domestic focal areas include the southwestern US, Great Plains, Mountain West, and Great Basin. We provide detailed motivations of the science questions and end-user management challenges in each of these areas. While the US focal domain represents a large portion of the aridity range of global drylands, international sites are necessary to address science questions at a global scale and to represent the diversity of dryland ecosystems across which models and hypotheses are tested. Designated candidate international sites were selected based on queried community needs, scientific track record, and assets of local partners (long-term field data and instrumentation), as well as logistical feasibility, dependability of plans, and safety and security. Candidate sites are located in southern Africa, northern Mexico, Australia, and the Cerrado and Caatinga regions of South America. Leading international partner institutions (e.g., TERN - Australia; SAEON - South Africa) are members of Global Ecosystem Research Infrastructure (GERI), along with the US's NEON, where they coordinate research on global issues such as ecological drought.

Guiding principles of the ARID campaign strategy are to utilize NASA's ground, aircraft, and spaceborne instruments and missions for: (i) ensuring observations and modeling at scales appropriate to the spatio-temporal variability and cross-scale feedbacks of drylands, (ii) leveraging existing assets (data and infrastructure) and investments by partners, (iii) capitalizing on existing international networks, including the use of supersites for coordinated, synergistic field data collection, (iv) multi-temporal airborne and UAS acquisitions, (v) supporting ongoing and upcoming NASA missions, and (vi) balancing operational risk with scientific reward. The implementation plan is modular and can follow a phased approach where the logistically straightforward study regions within the US can be targeted first, while more complex international campaigns are planned.

ARID aims to use its research to support end-user goals and is thus fully aligned with NASA's ES2A strategy to "*advance and integrate Earth science knowledge to empower humanity to create a more resilient world*". The ARID field campaign will support algorithm development and uncertainty estimation of fundamental remote sensing products that feed directly into existing workflows of agencies. The ARID field campaign is the embodiment of ES2A as it directly addresses science questions and informs both existing applications and future adaptation strategies for federal agencies and Tribal authorities. **The NASA ARID campaign will deliver actionable, high-impact information and insights to many US land managers and a suite of national and international end-users**.

ARID’s scoping efforts and white paper formulation build on co-development and knowledge sharing frameworks that are specific to science and practitioner needs as informed through over 120 community engagement events, which included workshops, webinars, technical Working Group meetings, individual discussions, roundtables and in-person visits, Tribal consultations, and conference town halls with a diverse range of data end-user groups. ARID events included larger workshops in Arizona (October 2023), New Mexico (May 2024), and Washington D.C. (July 2024) that brought together research partners, end-users, Tribal Nations, and agency partners (BLM, USGS, DoD, DOE, NSF, NPS, USFWS, USFS). In addition, the ARID scoping team has directly worked with end-users representing a suite of managers and decision-makers responsible for stewardship of dryland ecosystems and natural resources. We have interacted closely with Tribal groups in recognition of indigenous connections to drylands, and the powerful opportunities to co-create and share knowledge, as well as to support diverse capacity building and the meeting of critical Tribal information needs. Finally, the white paper provides details of international engagements, partners, and their support and commitment to the ARID campaign, and ARID has strong international commitments and connections across nations and continents.

The ARID mission arrives at a critical juncture, as climate change impacts intensify and the need for sustainable management of dryland regions becomes more urgent than ever. While fine-scale spatial variability and rapid temporal dynamics of drylands have largely eluded prior Earth Observation (EO) technologies, ARID’s tiered observing plan, using multi-sensor airborne, uncrewed aircraft system (UAS), and in-situ data, will fill critical observation gaps, improving remote sensing and modeling capabilities. ARID will transform applications of remote sensing and Earth System Models to assess the current and future dynamics and sustainability of dryland ecosystems and communities in the face of changing climate and land use. By leveraging existing data and strong research-management partnerships, ARID can build critically needed actionable understanding through the use of transdisciplinary science in locations that are logistically dependable, safe for researchers, and with exceptional relevance for US and international priorities, making ARID a low risk and high return proposition.

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# A. Dryland Motivation

## A.1 Introduction and Motivation

### *A.1.1 Dryland Importance and Change*

"*Traditionally neglected at the policy level, drylands are gaining importance…Globally, the most important emerging issues are: climate change, food security, biodiversity and human security including water scarcity. Such forces are highlighting the value of healthy drylands to the world, and their role in a secure global future*." - United Nations Environmental Management Group (United Nations, 2011).

In October 2011, the United Nations (UN) Environmental Management Group published "*Global Drylands: A UN System-Wide Response*" (United Nations, 2011), which recognized that drylands have been historically neglected, and which acknowledged drylands' high value in the Earth System, as well as the large climatic and land use change threats faced by these ecosystems worldwide. The extent to which drylands have been subjected to desertification/land degradation – defined as the loss of biodiversity ecosystem function and ecosystem services caused by anthropogenic and natural drivers (D'Odorico et al., 2013) – has long been of significant global concern. Land degradation in drylands inspired the UN Convention to Combat Desertification (UNCCD) in 1994, to which the United States (US) is a signatory, along with 197 other countries. More recently, UN Sustainable Development Goal (SDG) 15.3 was created, which states and aspires to accomplish: "*By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world*" (UN, 2017)." The science themes of Adaptation and Response in Drylands (ARID) are closely tied to numerous US and international goals, and ARID could directly inform and assess the indicators countries are asked to evaluate (e.g., trends in carbon stocks, resilience to drought, impacts to ecosystem function (Johnson et al., 2017). In this way, **the new knowledge and datasets ARID would deliver are extremely well-aligned with the targets and information needs outlined by multiple US and international policy efforts, which recognize the importance and high levels of change occurring in drylands, as well as the consequences for social-ecological systems**.

Drylands, defined as systems where annual potential evaporative demand is at least 1.5 times greater than precipitation (Barrow, 1992), encompass a diverse array of ecosystem types, all unified by a scarcity of water (Figs. A.1, A.2). They span hyperarid to subhumid biomes and contain vegetation types from grasses, to shrubs, to forests amongst bare soil and biological soil crusts (Figs. A.1, A.2). In fact, the landscapes of these ecosystems vary greatly in vegetation and soil composition, including green forested areas to sparsely vegetated, with the only commonality that they are water-limited (Fig. A.2). Dryland ecosystems represent the planet's largest terrestrial biome (~60 million km2), making up over 40% of the global land surface (Safriel et al., 2005; Wang et al., 2022). This area is projected to increase 11%–23% by the end of the century due to climate change (Huang et al., 2016), partly in response to drying conditions advecting into downwind wetter transitional regions (Koppa et al., 2024). Drylands also directly support more than two billion people, or about 35% of the global human population, meaning drylands are the home to one in three people in the world today (Maestre et al., 2012; Reynolds et al., 2007; Wang et al., 2022). These water-limited ecosystems have the highest population growth rate of any ecological zone (Gaur & Squires, 2018; L. Wang et al., 2012), supporting livelihoods that are commonly tightly coupled to local ecosystem services. Overall, due to the location of vast croplands and rangelands, drylands produce 60% of the world's food supply (van der Esch et al., 2022; Wang et al., 2022) and account for up to 44% of cultivated lands (Burrell et al., 2020a; Cherlet et al., 2018). They also contain substantial mineral and energy resources, are areas of rapidly growing alternative energy installations, and support unique biological and cultural diversity across flora, fauna, and human communities (Alikhanova & Bull, 2023; Cartereau et al., 2023). Importantly, the distinct mechanisms regulating drylands are expected to control other ecosystem types in a warmer, drier world (Grünzweig et al., 2022). Drylands are, therefore, of great economic, cultural, and ecological global importance.

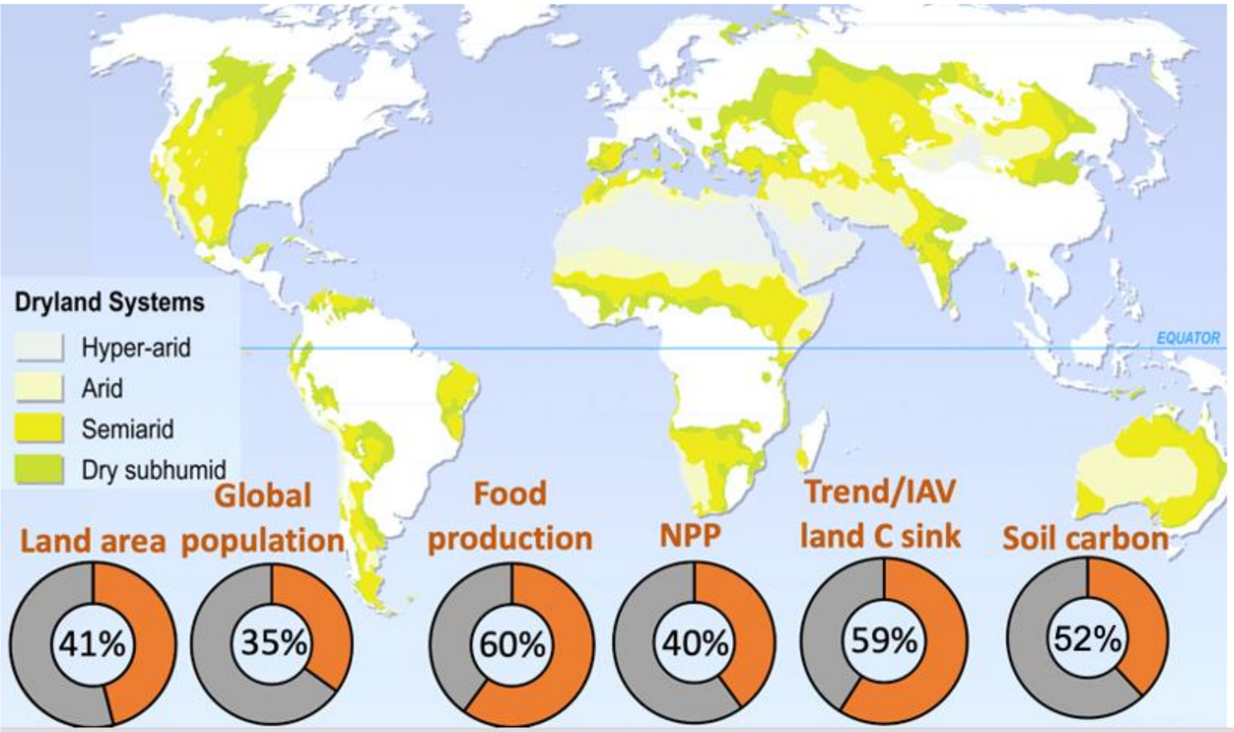


***Figure A.1.*** *Map of global drylands and their role in Earth's structure, function, and provision of services. Orange fractions of the circles show dryland contributions to global land area, population, food production, net primary production, the trend and interannual variability in the terrestrial carbon sink, and soil carbon (drylands store 32% of soil organic carbon and 79% of soil inorganic carbon to a 2m depth, combining to represent 52% of Earth's soil carbon to 2m).*

As mitigation options for climate change become an increasing focus, there is more interest than ever before in understanding, quantifying, and managing ecosystem carbon cycles (Díaz-Martínez et al., 2024). Although long considered an insignificant part of the global carbon cycle, in part due to misconceptions of these ecosystems as unproductive "wastelands" (Hoover et al., 2020; Mortimore et al., 2009), drylands represent 40% of terrestrial net primary productivity (NPP), largely dominate the interannual variability (IAV) in atmospheric CO2 concentrations, and store a third of the planet's soil organic carbon and 79% of its soil inorganic carbon (Plaza et al., 2018; together these pools make up 52% of Earth's total soil carbon to 2 m depth; Fig. 1). Drylands are estimated to provide an annual $CO_2$ drawdown on the order of 35 PgC through plant photosynthesis (Yao et al., 2020)– roughly on par with the tropics (including tropical forests, wetlands, and agricultural lands) – as well as additional significant drawdown through drylands' expansive photosynthetic soil communities (i.e., biological soil crusts; Elbert et al., 2012; Maestre et al., 2013; Wilske et al., 2008). Drylands also exert the greatest influence of any biome on the IAV of the global terrestrial carbon sink (Ahlström et al., 2015; Fan et al., 2019; Poulter et al., 2014; Sitch et al., 2024; X. Zhang et al., 2018). Because drylands are so responsive to changes in water availability, large year-to-year moisture changes (from ENSO, for example) can greatly affect surface carbon fluxes and substantially influence atmospheric carbon concentrations (Metz et al., 2023; Poulter et al., 2014). The lack of understanding of this dryland control on the carbon cycle IAV reduces our capability to quantify country-level emission reductions. Drylands also strongly contribute to the mean uptake trend (Ahlström et al., 2015; L. Wang et al., 2022), and have much greater tree carbon storage than formerly assumed (Brandt et al., 2020; Tucker et al., 2023a). Thus, although drylands have previously incorrectly been considered relatively unimportant in regulating Earth's carbon cycle and climate, we now know these ecosystems dominate core aspects of the planet's terrestrial carbon storage and flux. Nevertheless, our scalable and mechanistic understandings, and our model representation of the drivers and feedbacks for dryland contributions to the global carbon cycle remain notably poor.

Drylands also have remarkably high biodiversity, including maintaining 35% and 20% of global biodiversity and plant diversity, respectively (Gross et al., 2024; Maestre et al., 2021). The long evolutionary history of dryland ecosystems and their role as the origin of many unique plant lineages has given rise to multiple dryland biodiversity hotspots around the world (Maestre et al., 2021). Moreover, new work indicates that drylands act as a global reservoir of plant phenotypic diversity, challenging the pervasive view that harsh environmental conditions reduce plant trait diversity (Gross et al., 2024). Thus efforts to describe and monitor the unique diversity of species, form, and function found in drylands are critical (Reynolds et al., 2011). However, anthropogenic impacts, for example, livestock grazing pressure and changing wildfire regimes, can cause rapid species decline and loss (Cartereau et al., 2023). We may lose key aspects of dryland biodiversity before they've been discovered (Cowie et al., 2011; Lewin et al., 2024).

Rapidly expanding our knowledge of dryland structure and function is critical not only because of the biome's large and increasing global importance, but also because drylands are responding dramatically and rapidly to anthropogenic change. Many dryland ecosystems have passed or are believed to be close to passing tipping points, which, when crossed, lead to abrupt system transitions and persistent degraded states. Numerous dryland ecosystem services are under immediate threat, which, in turn, threatens global carbon cycles, climate feedbacks, and the well-being of myriad societies (Fraser et al., 2011; Gaur & Squires, 2018; M. W. Jones et al., 2022). Specifically, drylands are experiencing more extreme heatwaves, droughts, and fires; for example, in the western US, where the most severe drought in more than a thousand years is currently taking place, and record-high temperatures are putting pressure on the region's inhabitants, ecosystems, and their services (Dannenberg et al., 2022; Williams et al., 2022). Many drylands are drying in terms of annual mean water availability, including in the western US (F. Zhang et al., 2021). While increased evaporative demand through warming is causing higher humidity in most global ecosystems, drylands are not experiencing this higher atmospheric humidity due to already low surface soil moisture (F.

Zhang et al., 2021). These climate changes are resulting in rapid ecosystem vegetation shifts, such as mass dryland forest mortality in the face of “hot drought” (Allen et al., 2010; Anderegg et al., 2013) and large increases in the extent and severity of wildfire (M. W. Jones et al., 2022).

Effects of extreme events on drylands have been extensively highlighted by the media of late, especially in the US. The southwestern US was struck with an extreme drought in 2020 which depleted the Colorado River flow to unprecedented lows (Fountain, 2020). This drought is a part of a multi-decadal megadrought that started in the early 2000s and is the most extreme in this region in over one thousand years (Williams et al., 2022). Furthermore, one of the largest heat waves struck the western US in 2021 with temperatures reported over 120 degrees Fahrenheit and with over one thousand heat-related deaths (Bartusek et al., 2022). Additionally, with unprecedented heat in summer 2024, many western US cities are breaking records for the amount of time spent above 110 degrees Fahrenheit, especially in Phoenix, AZ (Golembo & El-Baweb, 2024). These hot conditions are causing hundreds of fatalities (Ramirez, 2024), and are a part of the drying conditions that have interacted with large scale exotic plant invasion to result in enormous increases in wildfire and changes in fire seasonality. Numerous articles document how fires in the western US, in turn, are destroying homes, causing landslides, imperiling wildlife, and resulting in wholesale changes to plant communities. While only providing a brief sampling of these recent events, it is clear that the changes and consequences observed in drylands are extreme, and that they will continue in western US drylands and across the globe. Because of drylands’ vulnerability, these changes will put pressure on water resources, ecosystem function, and human well-being for decades to come. Our ability to understand, monitor, forecast, and make decisions for these rapidly changing ecosystems must evolve now to keep pace with exceptional rates of change.

In recent decades, major land-use change has occurred in global drylands, with agriculture expanding to meet local and global demands for food, feed, and energy. For example, ~225,000 km2 of tree-covered drylands were converted to other land-cover types between 1992 and 2015; 56% of that area transitioned to shrubland, while 40% was converted to cropland (L. Wang et al., 2022). These are expansive shifts in land cover type, with critical implications for carbon storage, land health, and energy exchange with the atmosphere. Drylands are also the source of a large proportion of the food and fiber used around the world (e.g., grasslands alone produce 27% and 23% of the world's milk and meat, respectively), meaning that what happens in drylands does not only affect those who live in drylands. For both climate- and land use-induced change, vegetation transitions will have far-reaching consequences for biodiversity, carbon, water, and energy budgets, as well as the provision of vital ecosystem services. **Improved quantification of these changes and effects are critically needed to refine model forecasts, inform management decisions, and evaluate mitigation and adaptation options**. Yet, drylands’ heterogeneous landscapes with sparse canopy cover and pulse-driven activity have historically presented significant remote sensing and modeling challenges for estimating water and carbon flux, land cover classification, aboveground biomass, and many other crucial applications.

This white paper outlines a targeted plan to deploy field and NASA airborne instruments to vastly augment data derived from satellite observations that, when joined, will substantially advance quantification of drylands’ large and changing role in the Earth system. There are numerous management and conservation options for addressing the challenges of land use and climate change in drylands, but their utility at relevant scales requires an advanced generation of remote sensing tools, sensors, and dryland-specific algorithm development. This need is underscored by the fact that dryland ecology and remote sensing are understudied (Bond-Lamberty & Thomson, 2010; Ciais et al., 2011; Maestre, Quero, et al., 2012; W. K. Smith et al., 2019a). **We urgently need a NASA-driven field campaign to advance the science and technology that can provide a data-informed understanding of dryland processes and feedbacks to inform global resilience efforts**.

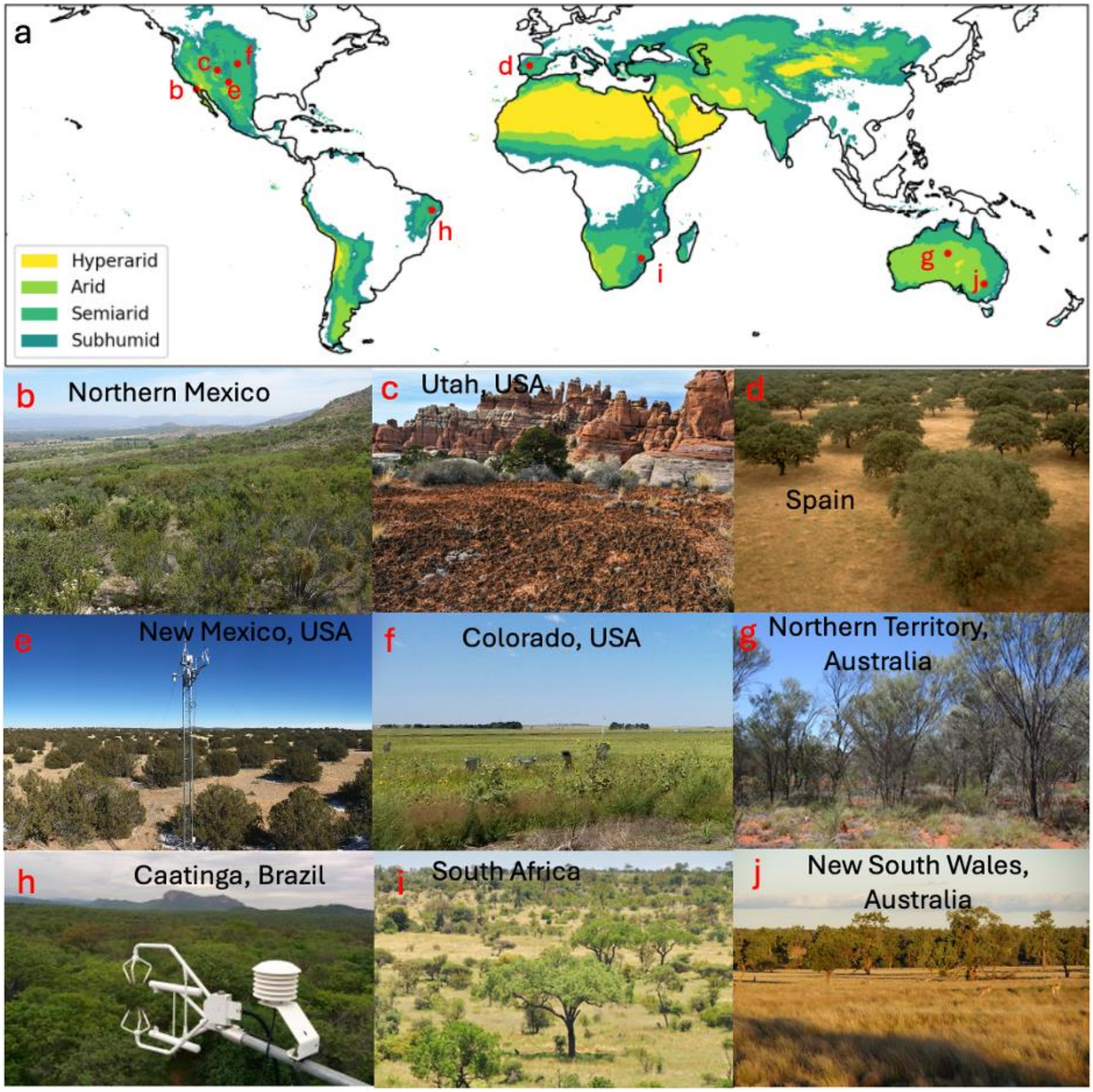


***Figure A.2.*** *(a) Global dryland distribution based on aridity index computed from TerraClimate precipitation and radiation data (Abatzoglou et al., 2018). Aridity index (AI) is defined as in Wang et al. (2022) as precipitation/potential evapotranspiration with hyperarid as AI < 0.05, arid as AI = 0.05-0.2, semiarid as AI = 0.2-0.5, and subhumid as AI = 0.5-0.65. (b-f) Sample pictures of different dryland landscapes (mainly arid and semi-arid, as defined by TerraClimate), which can vary substantially in structure and composition within the same regions and across the globe. (b) Arid shrubland site in Northern Mexico (MX-EMg MexFlux site; photo obtained from https://ameriflux.lbl.gov/sites/siteinfo/MX-*

*EMg#image-gallery with permission to reuse from the site investigators (Cueva et al., 2020)). (c) Arid desert ecosystem with dominant biological soil crust coverage in Utah, United States of America (U.S.; photo used with permission from Bill Bowman). (d) Semi-arid grassland and evergreen broadleaf forest site in central Spain (eslm1 PhenoCam site, photo obtained from https://phenocam.nau.edu/webcam/sites/eslm1/ with permission to reuse from the site investigators (Seyednasrollah et al., 2019)). (e) Semi-arid juniper savanna site in central New Mexico, U.S. (US-Wjs AmeriFlux site; photo owned by the authors). (f) Semi-arid cropland site in central Colorado, U.S. (US-xSL AmeriFlux and NEON site; photo obtained from https://ameriflux.lbl.gov/sites/siteinfo/US-xSL with permission to reuse from the site investigators (Metzger et al., 2019)). (g) Arid woodland site in Northern Territory, Australia (AU-ASM OzFlux site; photo obtained from https://www.ozflux.org.au/monitoringsites/alicesprings/alicesprings_pictures.html with permission to reuse from the site investigators (Cleverly et al., 2013). (h) Semi-arid needleleaf forest site in the Caatinga region of Brazil (BR-CST AmeriFlux; photo obtained from https://ameriflux.lbl.gov/sites/siteinfo/BR-CST with permission to reuse from the site investigators (Antonino, 2019)). (i) Semi-arid savanna ecosystem in Kruger National Park, South Africa (photo owned by the authors).*

*(j) Arid savanna site in Yathong Nature Reserve in New South Wales, Australia (photo owned by the authors).*

### *A.1.2 Uncertainties in Dryland Processes and their Role in the Earth System*

While new measurements and modeling show the large importance of drylands in the global system, substantial uncertainties remain regarding the drivers, magnitude, and vulnerability of these contributions. Dryland systems are characterized by large interannual variability in weather conditions and heterogeneous vegetation coverage (Fig. A.2), which have hindered past estimates of their role in the Earth system. Current trends in climate and land use changes translate into dryland ecosystem dynamics becoming more variable and trajectories more uncertain. For instance, long-term drought conditions are resulting in vegetation mortality that further impacts numerous ecosystem services (Jiao et al., 2021). Such changes from forests to grasslands or from grasslands to shrublands (Eldridge et al., 2015) have large consequences, for example, on carbon and energy feedbacks to climate change. Yet the magnitude and even the sign of these feedbacks remains highly uncertain. Weather variability is being experienced through pulsed dynamics of periods of extreme dryness and heat stress (Bradford et al., 2020) interspersed with large rainfall events that result in flooding, gully erosion, and the movement of soils to create landslides, fill reservoirs, induce dust storms (Luo et al., 2020), and reduce soil health of these dryland systems.

Water resources are further stressed due to the rapid emergence of high levels of evaporative demand pulling moisture from the vegetation and soils (Ojima, 2021; Hobbins et al., 2016). In fact, many dryland regions, such as the western US, are experiencing longer dry spells and less annual rainfall (F. Zhang et al., 2021). At the same time, there is increased water use and consumption to meet food, potable water, and energy needs to support rapidly growing dryland urban centers. In addition, water resources in dryland regions that sit in the rain-shadow of mountain regions are experiencing warming that has accelerated snow melt and glacier loss that feed rivers and aquifers. The future availability of water for dryland inhabitants, ecosystems, and agriculture remains highly uncertain, with severe implications for society.

These water resource uncertainties translate to concerns for global food security. ~90% of the world's dryland population lives in developing countries, which are facing developmental pressure to increase food production under water-limited conditions (L. Wang et al., 2012)and which do not have the resources to withstand reductions in food. Rangelands constitute the world's largest land use, and the majority of these fall in drylands, which have a large contribution to beef production (Maestre et al., 2022a). Global rangelands are experiencing significant changes to community composition (e.g., from shrub encroachment) and to forage productivity due to current and future climate change (Boone et al., 2018; Godde et al., 2020), with significant impacts on the livelihoods of more than a billion people (Maestre et al., 2022a). Relatedly, there is significant likelihood that climatic change will result in agricultural abandonment of crops in drylands as irrigation water becomes more limiting (ref). Yet the effects of these changes on food security, dust production, and feedbacks to climate change remain unclear.

Dryland carbon fluxes and stocks are some of the most uncertain of any biome (Fawcett et al., 2022; Rodriguez-Veiga et al., 2019). Many global scale land surface models are unable to replicate the mean net or gross carbon uptake or its year-to-year variability observed at in-situ flux tower sites (MacBean et al., 2021; Teckentrup et al., 2021; L. Wang et al., 2022). It is critical to reduce the uncertainty of dryland contribution to the global carbon cycle with measurements given their large demonstrated role in carbon cycling at the global scale. *In-situ* water stores (soil moisture) and fluxes (evapotranspiration) are more accurately represented in models, but relationships between these variables are poorly represented (Short Gianotti et al., 2019). Additionally, water flux partitioning between plant transpiration and bare soil evaporation is poorly represented, suggesting that compensating errors are present (MacBean et al., 2020). Challenges for modeling drylands include their daily-timescale pulse-lag dynamics with often lagged surface responses to rainfall events and multiple day-to-week responses that models do not yet capture (Feldman, 2024a; Ogle et al., 2004; Post & Knapp, 2021). The complexity of varied and asynchronous dryland plant responses to limited and changing water availability is not represented in global scale models. This is partly due to limited data used in the models' development, evaluation, and calibration, and partly because of limited cross-scale model activities that could be leveraged to facilitate global scale model development. Additionally, most modeling activities were developed using process understanding from mesic ecosystems, which often does not translate to sufficiently represent drylands.

Surprisingly, despite increasing atmospheric aridity and often declining soil moisture trends, many drylands are greening (Dardel et al., 2014; Gonsamo et al., 2021; Lian et al., 2021; Song et al., 2018), highlighting the complicated uncertainties for this biome. While CO2 fertilization is likely playing a large role in these trends (Zhu et al., 2016), it is uncertain how much and for how long the greening will continue (Burrell et al., 2020, Lian et al., 2021). Such greening might ultimately mitigate some of the dryland expansion effects (Berg & McColl, 2021) and the state changes observed in non-greening dryland ecosystems. However, current modeling approaches often do not explicitly account for rapid ecosystem change in their proportioning of the relative contributions of different drivers of greening (e.g., elevated CO2 versus land-use change), which means they can miss or underestimate the rapid changes driven by processes like extreme fires and changes in land use (Burrell et al., 2020b; K. J. Wessels et al., 2012). Disentangling the roles of temperature, CO2, and land use in dryland productivity has been identified as a key knowledge gap by the UNCCD, IPCC, and the Intergovernmental Science–Policy Platform on Biodiversity and Ecosystem Services (ref). At the same time, drylands and, in particular, rangelands are being discussed as a focal location to store carbon for climate mitigation, and ranchers are already being paid for carbon sequestration in the US and internationally (Briske et al. 2023). Yet improvements to remote sensing and modeling will certainly be required to quantify the carbon stored or lost and to inform any carbon payment or credit system.

Carbon sequestration is only one area where drylands are explicitly targeted as climate mitigation or nature based solutions, and for which uncertainties in dryland contributions create challenges for decision making. Given their large land area, drylands are viewed for their afforestation and renewable energy potential as a natural climate solution. However, poor understanding of the dryland carbon and energy balance greatly limits the ability to quantify potential benefits (or unintended consequences) and prevents prediction of benefits under future climate and land cover conditions (Barron-Gafford et al., 2016; Liu et al., 2022; Novick et al., 2024). Indeed, in many instances in the wet tropics and temperate ecosystems, tree planting can increase carbon uptake and cool the surface (Duveiller et al., 2018). As such, the African Great Green Wall - a colossal initiative to restore 100 million hectares of degraded ecosystems across 11 countries in the Sahel region - is proposed as a major natural climate solution for increased terrestrial carbon uptake and surface cooling benefits (Mirzabaev et al., 2021). However, given water limitation in drylands, these benefits may only be conferred in some instances (Rohatyn et al., 2022; L. Wang & D'Odorico, 2019), and increasing vegetation may even *warm* the surface through reduced albedo without a sufficient compensating evaporative cooling (Rotenberg and Yakir 2010, Williams et al. 2021, *Sci. Adv.*, Feldman et al. 2023). Thus, uncertainties in how drylands will respond to management, including management intended as a climate solution - results in significant challenges for decision making in these regions.

Historically remote sensing efforts to monitor drylands and land degradation were largely limited to time-series analysis of vegetation index data from low spatial resolution sensors (e.g., MODIS), using trends in greenness as a proxy for ecosystem function and overall vegetation cover (Fensholt 2007, Wessels 2013, Wessels 2007). However, monitoring greenness alone could not differentiate changes in vegetation structure and composition of plant functional types the trees, shrubs, and grasses to understand the nature of the ecological changes (Smith 2018). These past remote sensing challenges have meant that, despite their global importance and high vulnerability to change, our scalable understanding and capacity to forecast dryland dynamics, as well as impacts to ecosystems and society, is notably poor.

These limitations are now greatly reduced with the enhanced resolution and diversity of current and planned ground based, airborne, and spaceborne sensors. ARID airborne and UAS data in combination with advanced process models and new satellite sensors enable us to characterize vegetation composition, structure, and function at the appropriate scales. Accordingly, drylands represent a large but now addressable uncertainty in our understanding of terrestrial ecosystems. The ARID field campaign will investigate process level changes in ecosystem functions and services to further understand the impacts of these changes and potentially reduce uncertainties of dryland ecosystems.

### *A.1.3 Dryland Social-Ecological Systems and Connection to End-Users*

Those who manage dryland ecosystems have the increasingly challenging task of making decisions for vulnerable social-ecological systems that are experiencing substantial change. In the US, drylands are managed by federal and state agencies, Tribal nations, major corporations such as mining and cement industries, non-governmental organizations, and private landowners. Lands managed by federal and tribal entities are particularly expansive, and there is high overlap between the location of these lands and the occurrence of drylands (Fig. A.3). For example, the US Bureau of Land Management (BLM) alone manages nearly 10% of all land within the US, with dominant lands in western drylands. This represents a sizable challenge -

drylands are notoriously difficult to manage due to their dry climates, low soil fertility, and responsiveness to perturbation - but also a substantial opportunity. The ARID Terrestrial Ecology field campaign would provide urgently needed information on the status, trends, and management options of drylands. An improved understanding of the drivers of change, ecosystem responses, and adaptation and mitigation potential for drylands can inform decisions and improve outcomes for vast areas of the US and globe. Land managers and decision makers are asking for this information and a coordinated campaign can meet these needs.

A powerful component of ARID is the exceptionally strong partnerships with land managers in federal agencies and tribal authorities who were integral in producing ARID's research framework and themes. The NASA ARID campaign will bring sharp focus to the natural resources that decision-makers are struggling to manage across diverse sectors in the face of change. In addition to addressing key science questions, ARID has collaborated with diverse end-user communities, including numerous U.S. agencies motivated to improve science-based decision making, who are enthusiastic about the new knowledge and predictive understanding ARID will provide (Fig. A.3). Our approach is informed by and is extremely well aligned with NASA's Earth Science to Action initiative, and we have convened a global community of science, policy, and management practitioners to design a targeted field campaign addressing the most pressing questions facing drylands.

**A project such as ARID that improves the understanding of current and future dryland conditions, quantifies the drivers and consequences of global change, and informs the options for improved and adaptive decision making will support science-based land management at an astounding scale**. **We stress that ARID's framework and approach are designed based on substantial input from both the scientific and data end-user communities**.

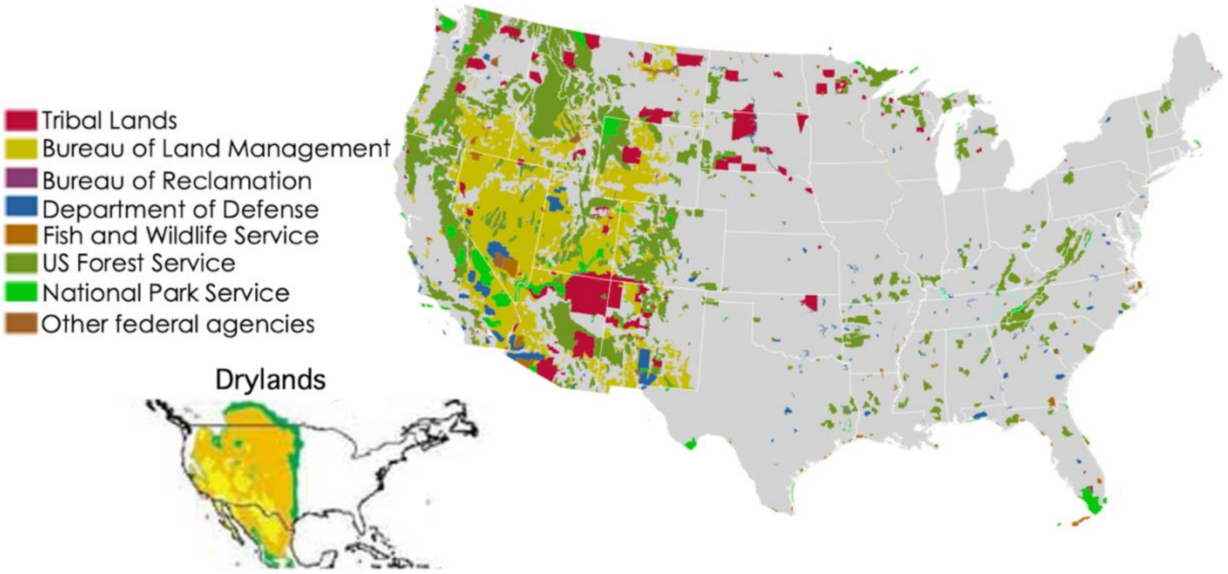


***Figure A.3.*** *Comparisons of U.S. federal and tribal lands with the location of drylands (lower left inset) highlights the vast area of drylands managed by public and tribal land managers in western North America. Due to low precipitation and soil fertility, drylands are notoriously difficult to manage, and they are transforming rapidly in the face of global change. These conditions result in*

> *exceptional challenges for land managers, who have co-produced ARID to meet their information needs. ARID will support a diverse range of federal and tribal land managers in providing actionable science to inform decision making in drylands.*

### *A.1.4 The need for a NASA Campaign in Drylands*

Drylands present key uncertainties in estimates of ecosystem processes and state variables that can only be quantified and disentangled through coordinated field, airborne, satellite-based, and modeling analysis. Drylands pose unique remote sensing and modeling challenges, as they are characterized by high spatial heterogeneity and high temporal variability caused by low and irregular precipitation. Only NASA can provide the satellite capability to evaluate ecosystem structure and function at the scale needed for Earth's heterogeneous drylands. A long-term NASA field and airborne campaign will fill multiple observation gaps (physical parameters) at the necessary spatio-temporal resolutions within a multi-scale framework to address critical science questions in drylands (see modified SATM E.1 for details). Previous NASA large-scale Terrestrial Ecology field campaigns have demonstrated the value of long-term field campaigns in addressing fundamental ecological questions. Like these previous campaigns, ARID will implement a multi-scaled approach to integrate remote sensing observations, ground-based observations, and modeling approaches to quantify and assess ecosystem drivers, responses, vulnerabilities, and consequences in the context of global change. We explicitly consider how dryland measurements must link across scales and address the considerable spatial and temporal heterogeneity found in these systems (see section B.2.1), as well as plan for the substantial leveraging of existing data, experimental field sites, global networks, cross-institution partnerships, and a wide range of research infrastructure (e.g., eddy covariance networks, global change experiments, natural aridity gradients).

Due to drylands' high spatial and temporal heterogeneity, vast spatial expanse, and dramatic rates of change, satellite data are key to an accurate understanding of dryland trajectories under global change. However, **remote sensing has been challenged by drylands' low vegetation signals, soil contribution to observations, and very high spatial (often meter scale soil-plant variability) and temporal variability (hourly to daily ecosystem responses), which make it hard to track or predict short- and long-term key variable changes and attribute them to specific drivers** (W. K. Smith et al., 2019b). For example, estimating the fractional cover of different vegetation types in spatially heterogeneous and sparsely vegetated tree-grass-shrub ecosystems is challenging (Pervin et al., 2022), resulting in considerable global land surface model uncertainty in predicted carbon, water, and energy budgets (Hartley et al., 2017a). There is a need to join satellite data with high-resolution data from airborne and UAS data acquisition to support plot to regional scale analyses (W. K. Smith et al., 2019b). Moreover, photosynthetic soils (biological soil crusts) characteristic of drylands are thought to make up 12% of Earth's land surface, but these organisms are typically not included in fractional cover classification algorithms or models. Their impacts on ecosystem carbon, water, and energy budgets, therefore, cannot be predicted, nor can their contribution to satellite observation data, representing a potentially important source of error.

Furthermore, drylands are driven by periodic precipitation pulses interspersed with extended dry periods (Collins et al., 2014; Feldman, Feng, et al., 2024a; F. Zhang et al., 2021) and experience irregular growing seasons (Cawse-Nicholson et al., 2021). Global scale process base land surface models are not capturing such responses (MacBean et al., 2021; Renwick et al., 2019; Teckentrup et al., 2021; Whitley et al., 2016). There is, thus, a need for continuous or higher-frequency measurements to capture ecological responses and better parameterize models (W. K. Smith et al., 2019b). Capturing the data at the appropriate spatiotemporal scales will require a coordinated multi-sensor field campaign that allows the research community to address observation gaps (linked to poor process understanding and predictive capability) and linkages across scales. **NASA is the clear lead for such an endeavor to scale observations and processes from leaf to orbit in drylands**

In addition to improving our understanding of these important water-limited ecosystems, drylands provide a rigorous test of the ability of modern remote sensing to capture highly dynamic, spatially complex, and globally significant ecosystems. Drylands have consistently played impactful roles in remote sensing development and evaluation. Due to lower cloud cover and higher likelihoods of favorable atmospheric conditions, many remote sensing techniques were developed in drylands, including early retrievals of surface reflectance and estimates of vegetation condition using red and near-infrared bands, which would later become the Normalized Difference Vegetation Index (NDVI). Increased spatial resolution and the ever-expanding array of current and future space-based NASA missions provide ideal conditions for testing and innovating drylands.

The recent advances in the spectral, spatial, and temporal capabilities of remote sensing and ground-based technologies mean a NASA Terrestrial Ecology field campaign focused on drylands can now provide the same exceptional advances in our understanding and support of our planet's dry ecosystems**. Now is the ideal time for a NASA Terrestrial Ecology field campaign focused on drylands (Fig. A.4), and only NASA can deliver the "leaf to orbit" perspective required to address the complexity, dynamics, and diversity of these critical ecosystems**. ARID was developed based on the ideas and information needs of scientific and data end user communities, and represents a strategic way forward for facilitating NASA's ability to revolutionize the quantitative understanding and management options for drylands in the Earth System.

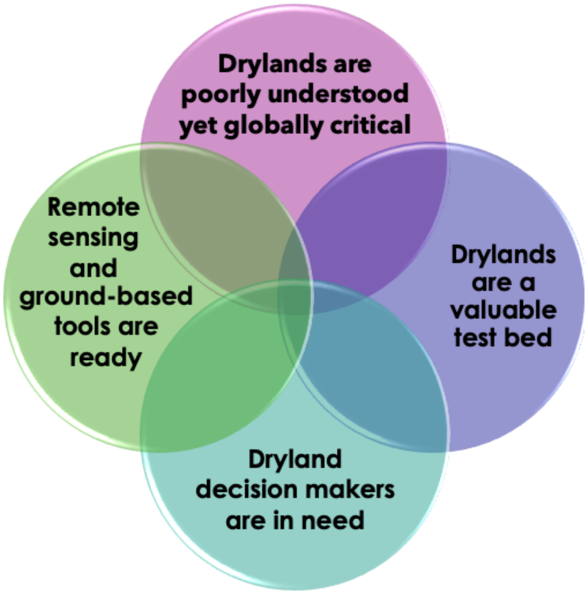


***Figure A.4.*** *Now is the ideal time for a dryland-focused NASA terrestrial Ecology field campaign. Emerging data show the critical contributions of drylands to the Earth system, as well as their responsiveness to change. Remote sensing and ground-based tools finally have the spatial and temporal resolution needed to assess heterogeneous drylands, and these systems represent a valuable testbed for evaluating and improving the accuracy and utility of satellite data. Finally, land managers and other decision makers in drylands are asking for this research. They need the cross-scale, actionable science that can inform management, adaptation, and mitigation solutions for Earth's drylands.*

We propose the Adaptation and Response in Drylands (ARID) field experiment, based on our scoping study between 2023-2024. We describe activities for an interdisciplinary project that addresses critical scientific questions and observation gaps by integrating novel airborne and space-based remote sensing with ground-based measurements and modeling. The proposed four focal study areas within the U.S., as well as an additional four international sites that include northern Mexico, drylands across southern Africa and Australia, and the Cerrado, Caatinga, and Gran Chaco in South America.

## A.2 Potential for a major scientific advancement

Effective Earth Observation for the entire planet is within reach. Advances in remote sensing technologies have dramatically increased our ability to observe rapid changes at fine scales. Drylands provide a rigorous test of the ability of modern remote sensing to capture highly dynamic, spatially complex, and globally significant ecosystems.

Over the past four decades, NASA's Terrestrial Ecology Field Campaigns have focused on temperate ecosystems (FIFE), boreal ecosystems (BOREAS), tropical forests (LBA), and Arctic-Boreal systems (ABoVE), and these efforts have demonstrated the power of coordinated field campaigns to vastly advance our understanding of complex systems, to build long lasting collaborations, and to train the next generation of Earth system scientists. While other ecosystems, such as boreal and tropical forests, have received long duration coordinated research efforts, drylands have not yet received this level of scientific attention. NASA has invested in dryland campaigns like NEESPI, SHIFT, EOS, HAPEX-Sahel and SAFARI-2000. However, they were shorter in duration, more limited in spatial domain, and/or did not involve personnel at the scale a NASA Terrestrial Ecology Field Campaign can support in ARID. Additionally, other agencies like the U.S. Department of Energy have invested in Arctic and tropical forest ecosystems through the Next Generation Ecosystem Experiments (NGEE), which have brought together diverse members of the science community. **Such a scale of effort and degree of community building has not yet occurred for dryland ecosystems and represents a substantial and timely research opportunity.** The remote sensing, modeling, and ground-based tools are also now much more capable of capturing the large spatial and temporal heterogeneity in dryland systems. Thus, **for the first time, ARID can provide a large-scale research effort to make substantial progress toward addressing critical dryland research and land management knowledge gaps**.

A NASA dryland terrestrial field campaign would result in major scientific advancement in five core areas. First, ARID will provide a substantially improved understanding of dryland contributions to global processes and how they respond to change. Drylands are understudied despite being globally extensive, with growing evidence showing they play a disproportionate role in the climate system. Joining remote sensing approaches with ground-based measurements and monitoring, as well as with statistical and process-based modeling and data analysis, will dramatically clarify the role of drylands in the Earth system. Second, the current generation of space-based, aircraft, and UAS remote sensing sensors offers unprecedented potential to scale processes and services across areas that cannot be measured on the ground in heterogeneous drylands. ARID would advance our spatio-temporal understanding of how drylands have already changed - including their growth into more mesic areas, and identify the main drivers that determine the size and direction of change. Third, ARID would directly support model development and evaluation. Ecosystem and Land/Earth System Models are currently woefully poor at capturing dryland drivers and responses to change, which drive large uncertainties in our understanding of global biogeochemical cycles and forecasts of future climate (Humphrey et al., 2018; Simpson et al., 2024a; Teckentrup et al., 2021). ARID would directly address this critical knowledge gap by supplying the datasets needed to parameterize and evaluate dryland mechanisms, processes, and patterns across scales and into the future.

Fourth, ARID will offer a powerful opportunity for calibration and validation of current and planned NASA satellite missions. Given a relative lack of focus on drylands throughout satellite missions, there are large uncertainties in satellite retrievals of dryland geophysical properties. For example, retrievals across measurement frequencies are hindered by mixed bare soil, biocrust, and plant fractions, which creates errors in retrievals of dryland infrared VIs and LST. Fifth, remote sensing tools in drylands offer impactful opportunities to support science-informed decision making and for monitoring, evaluating, and prioritizing mitigation and adaptation solutions .

Water scarcity is a key concern in drylands, but the exact mechanisms that govern water distribution—the partitioning of precipitation into evaporation, transpiration, runoff, and groundwater recharge—remain complex and not entirely predictable. The spatial and temporal variability of soil moisture, influenced by factors like vegetation patchiness and proximity to water sources, adds further layers of uncertainty. By employing NASA's cutting-edge remote sensing technologies and refining models, there is significant potential to uncover new insights into these processes and controls, improving our ability to predict and manage water resources in these fragile environments.

Climate change is expected to exacerbate the challenges facing drylands, with increasing frequency and intensity of droughts, heatwaves, and wildfires. Yet, many questions remain about how these changes will alter the structure and function of dryland ecosystems. For instance, the feedback loops between vegetation changes, fire regimes, and climate are not fully understood, and current models often struggle to capture the rapid, non-linear responses typical of these systems. Exploring these dynamics through innovative research approaches could lead to breakthroughs in our understanding of dryland resilience and the development of more effective management strategies.

Moreover, drylands represent a complex interplay between ecological processes and human activities, with land use practices such as grazing, agriculture, and energy production deeply intertwined with ecosystem health. The impacts of these practices under changing climatic conditions are still not fully known, particularly in terms of how they might affect the long-term sustainability of both the environment and the communities that depend on it. This uncertainty underscores the need for integrated research that not only addresses ecological questions but also explores the socio-economic dimensions of dryland management, opening up possibilities for new strategies that enhance resilience and sustainability in these vital regions.

Our proposed field campaign aims to address scientific questions spanning themes including water availability, dryland climate variability, fire, land atmosphere interactions, carbon stocks and fluxes, vegetation structure, heterogeneity and biodiversity, geology and soil processes, and land management to inform adaptation and mitigation strategies (Table A.1). The scientific advancements that would be enabled by the ARID campaign are summarized in Table A.1.

***Table A.1*** *Expected advances in dryland science themes within the ARID campaign.*

| Topic | Scientific discovery enabled by ARID |
|---|---|
| 1.1.1. Water Availability | Key controls of water availability in drylands |
| 1.1.2. Dryland Climate Variability: Pulses, Deluges, and Droughts | The impact of heterogeneous rainfall pulses on carbon, water and energy exchange and feedback to synoptic weather. |

| | |
|---|---|
| 1.1.3. Fire | The impacts of fire on the composition, structure, and function of drylands at various time scales and feedbacks to the fire regime. |
| 1.1.4. Land Atmosphere Interactions | Connecting the drivers of carbon, water, and energy exchange from local to global scales |
| 1.2.1. Vegetation Structure | The controls and impacts of climate on three-dimensional vegetation structure and its spatial heterogeneity |
| 1.2.2. Dryland Biodiversity | Quantification of vegetation biodiversity and identification of hotspots in drylands |
| 1.2.3. Ecosystem Function | The magnitude and duration of plant hydraulic and photosynthetic response to climate |
| 1.2.4. Dryland Geology and Soil Processes | Novel spectral descriptors of soil type and function, enabling new discovery |
| 1.3.1. Carbon Stocks and Fluxes | Direct, observational quantification of the role of drylands in the variability of global carbon sink. |
| 1.4.1. Land Management | Ability to monitor and forecast impacts of land management choices on biogeochemical and hydrological cycles |
| 1.4.2. Adaptation and Mitigation Strategies: a Socio-Ecological System Perspective | Holistic information needed to understand social-ecological interactions and feedbacks. |

## A.3 ARID Objectives

ARID's core mission is to reduce human and ecosystem vulnerability to environmental change through groundbreaking research using multi-scale remote sensing, in-situ measurements, and modeling. While we know drylands are critical in the Earth system and that the interacting pressures of climate and land use change are dramatically altering these ecosystems, there are significant knowledge and observation gaps that limit the ability to predict the manner, magnitude, and options for mitigating/adapting to current and future changes in drylands. These gaps are the focus of ARID’s research framework. The four themes and overarching science questions to be addressed by ARID are based on the need to develop a quantitative understanding of drylands and their responses to change, to predict future changes and feedback, and to inform decision making strategies to sustain drylands and the vital ecosystem services they provide. With this approach, ARID represents both cutting edge and actionable science.

To address shared foundational and applied science goals, ARID worked extensively with the research and end-user communities to develop four main science themes and associated overarching questions (see Section B.1 for more details):

***Climate Variability and Drought***

*How are climate extremes like droughts, heatwaves, and large rain pulses impacting dryland systems and how do they interact with changing fire regimes, land cover change, and land-atmosphere interactions*?

***Ecosystem Structure, Function, and Biodiversity***

*What are the main mechanisms driving the spatiotemporal distributions of dryland structure, function, and biodiversity and what is their vulnerability to change?*

***Carbon Cycle Interannual Variability and Long-Term Trends***

*What is the contribution of drylands to the mean, trend, and interannual variability of terrestrial carbon uptake and what drives these patterns?*

***Social-Ecological Systems***

*What are the consequences of changes in drylands for social-ecological systems and what management (e.g., mitigation and adaptation) solutions can maintain the critical services provided by drylands even in the face of change?*

Using these questions and themes, ARID aims to elucidate the **drivers** of change within drylands, the **responses** of ecosystems and social-ecological **consequences** of those responses, as well as the options **mitigation and adaptation** could provide for maintaining dryland ecosystem structure and function (Fig. A.5). The interconnections between ARID's questions, themes, and approach allow for an iterative strategy that synergistically informs our larger understanding of drylands in the Earth system.

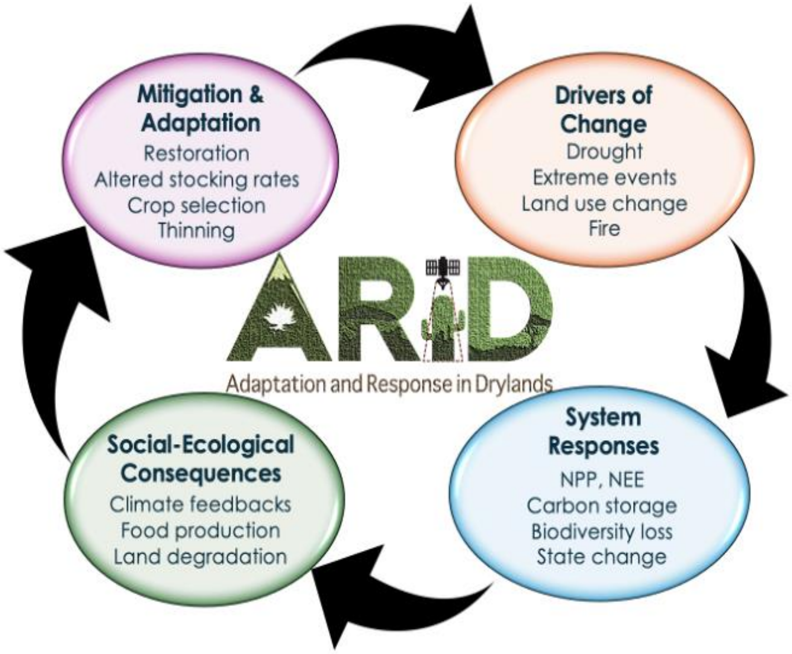


*Figure A.5. ARID is structured to the cycles of change in Earth's drylands, elucidating the causes, consequences, and solutions. This includes determining the **Drivers** of patterns and change for dryland structure and function; the types and magnitude of **Systems' Responses**; the **Social-Ecological Consequences** of system responses; and the options science-informed **Mitigation and Adaptation** options could play in maintaining drylands.*

**ARID will blend its science goals with critical NASA Terrestrial Ecology mandates for community and capacity building using the following joined objectives**:

***<u>Advance</u>*** the quantitative and scalable understanding of drylands' contributions to the Earth system

***__Transform__*** knowledge and model representation of the mechanisms behind and the consequences of the changes now observed in drylands and those yet to come

***__Build__*** a diverse and collaborative international community focused on multidisciplinary dryland science

***__Collaborate__*** with decision makers to determine and evaluate mitigation and adaptation solutions that sustain and build resilience in drylands in the face of change

***__Train and support__*** the next generation of diverse dryland researchers through multidisciplinary education, training, and network building

***__Revolutionize__*** multi-scale, multi-sensor remote sensing of dryland processes and utilize the unique attributes of drylands to improve and inform current and future NASA missions and effective interpretation and analysis of space-based data

***__Develop__*** data products and tools to inform science-based decision making and create a fully harmonized, accessible database for the global community

## A.4 Relevance to Solicitation and NASA

The timing of ARID is particularly beneficial for NASA fueled scientific discovery. The advent of higher-resolution satellites and emerging technologies, such as UAVs, coupled with existing satellites and aircraft, offers a high chance of gaining new knowledge about drylands through a NASA field campaign. ARID addresses all components of the A.4 scoping study solicitation, as well as NASA's Earth System Directorate science and applications mission, including those within the NASA Terrestrial Ecology Program. With respect to the 2017 NASA Earth Science Decadal Survey, ARID addresses numerous "important", "very important", and "most important" questions within the hydrology, climate, solid-earth, weather, and ecosystems science focal areas. The ARID framework integrates observations from NASA's current program of record (PoR), including decommissioned missions, (e.g., HYSPIRI, Aqua and Terra) and planned Decadal missions. Observations from ground instruments, NASA airborne payloads, and spaceborne missions are evaluated through SATM processes, and explicitly link the science questions with geophysical parameter requirements. We also align completely with NASA guidelines for recent initiatives such as the Transform to Open Science (TOPS) initiative and the Science Mission Directorate's SPD-41a directive.

### *A.4.1 NASA Terrestrial Ecology Program and A.4 Solicitation Relevance*

The NASA Terrestrial Ecology Program's Goal is to: "*Improve understanding of the structure and function of global terrestrial ecosystems, their interactions with the atmosphere and hydrosphere, and their role in the cycling of the major biogeochemical elements and water.*" With this goal in mind, ARID is addressing major science themes of "vegetation structure and biodiversity" and "carbon cycle interannual variability" (see Section B.1). Since drylands intimately link water and carbon cycles through water-limitation, the major hydrosphere theme of "climate variability and drought" is also evaluated within ARID's campaign. These science themes and research questions are ultimately interdisciplinary and cover topics in other NASA programs including those in Carbon Cycle and Ecosystems, Terrestrial Hydrology, as well as many programs across Applied Sciences. ARID is also highly relevant to the NASA SERVIR and LCLUC programs which aim to address climate change, food security, water and related disasters, land use, and air quality issues in predominantly dryland regions.

The A.4 field campaign solicitation also strives to "*identify **new** ecosystems, biomes or regions that merit intensive investigation*". While the global importance and vulnerability of drylands are evident (section A), limited research resources have been dedicated to the study of these ecosystems. *We therefore assert that drylands are indeed a "new ecosystem" when it comes to coordinated long-term ecological investigations by a NASA field campaign.* While there have been aircraft campaigns conducted in the drylands of western US (GEMx, SHIFT, WDTS), their scope was limited to generating a specific dataset or technologically motivated to develop or validate a NASA campaign. Due to the goals of those campaigns, there was not significant investment in understanding dryland ecosystem processes or collecting contemporaneous ecological field data. As a result, very few scientists or end-users within the ARID working groups have used these datasets (see Section B.2.5 and working group queries in Appendix F.10). Accordingly, ARID can be considered a new, large-scale effort to spearhead intensive investigations in direct response to the solicitation, and can powerfully leverage the data collected in past distributed campaigns. Given the importance and vulnerability of drylands, the dominance of drylands in the western US, and the overwhelming engagement response by the research and end-user communities, we argue ARID is in fact, long overdue.

As encouraged by the A.4 solicitation, the ARID field campaign will bring together diverse expertise across fields of study, spatial scales of focus, geographical locations, contributor demographics, and career stages. A broad range of expertise was engaged throughout the scoping, as exemplified by the diversity of participants making up the ARID community. ARID's engagement reached early, middle, and later career scientists and we were particularly enthused to see significant engagement with early career researchers. One of the powerful aspects of NASA's Terrestrial Ecology field campaigns is their relatively long time span, which not only allows for deep and iterative research, but which means early career scientists may participate in the same campaign as a student, post-doc, and PI. With this in mind it is imperative that early career researcher ideas and perspectives be included in scoping and project design. More than half of individual inputs and working group participants (>80, >175 people respectively) were at a career stage less than ten years beyond receiving their PhD (Appendix F.5, F.9).

### *A.4.2 NASA Earth Science Relevance*

The ARID scoping study provides a research plan consistent with the mandate of NASA Earth Science Division's Earth System Observatory to "create a 3D, holistic view of Earth, from bedrock to atmosphere." ARID addresses key components of NASA's Earth System Directorate science and applications mission. ARID will integrate observations from NASA's current program of record (PoR), including decommissioned missions (e.g., HYSPIRI, Aqua and Terra), and planned Decadal missions (e.g., Surface Biology Geology). ARID will support validation and science application using ongoing NASA satellite missions like SMAP, OCO-2, EMIT, ECOSTRESS, and GEDI, especially in some of the most complex ecosystems for these platforms to observe. It will also support the development and validation of upcoming NASA missions like SBG and NISAR and incubator missions like PBL and STV. Observations from ground instruments, NASA airborne payloads, and spaceborne missions are evaluated through Science and Application Traceability Matrix (SATM) processes, explicitly linking the ARID science questions with geophysical parameter requirements. ARID also follows guidelines of NASA's recent open data initiatives, including the Transform to Open Science (TOPS) initiative and the Science Mission Directorate's SPD-41a directive.

ARID addresses all four of NASA's Earth Science Directorate questions. ARID specifically addresses understanding the role of drylands in how the Earth system is changing now and, in the future, and what causes the changes (see section A.2). ARID also addresses the Earth Action-related ESD question of how Earth system science can provide societal benefit, specifically, within the social ecological systems focus in section B.1 in understanding dryland ecosystem services and land management.

With respect to the 2017 NASEM Earth Science Decadal Survey, "Thriving on our Changing Planet: A Decadal Strategy for Earth Observation from Space", which drives NASA ESD questions and goals, ARID addresses numerous "important", "very important", and "most important" questions within the hydrology, climate, solid-earth, weather, and ecosystems science focal areas. ARID is also being developed following key messages from the most recent United States National Climate Assessment (NCA5) and in coordination with the United States Global Change Strategic Plan (USGCRP) four pillars that guide how we respond to change and manage critical risks including: (1) Advancing Science, (2) Engaging the Nation, (3) Informing Decisions, and (4) Collaborating Internationally.

### *A.4.3 Relevance to Earth Science to Action Strategy*

ARID is directly aligned with the 2024 launch of the NASA Earth Science to Action strategy (ES2A) by bringing together scientists with end-user communities including public and private end-users, tribal nations, industries with large land-bases, and representatives from government agencies in the implementation of a dedicated NASA dryland field campaign. In accordance with the field campaign plan, the ARID scoping phase demonstrated this scientist and end-user community engagement in several overarching ways:

1) Engagement with end-user communities guided our research questions and plan development with land management and conservation of ecosystem services in mind such that the data collected can be implemented at higher application readiness levels.
2) Both ARID workshops in Arizona and New Mexico included intensive discussions with end-user communities that manage and own land across the western US. The Arizona meeting (October 2023) included discussing with end-users across public and private domains in the southwest US. The New Mexico meeting (May 2024) focused on engagement with tribal communities that own and manage land in the southwest US and

Great Plains as well as hold traditional ecological knowledge (TEK) about managing their land.

3) ARID's inter-agency partnerships with USGS, BLM, and USDA are built upon using the ARID field campaign data to support land management, especially throughout the western US (see section B.2.7 for further details).
4) The ARID field campaign will improve the algorithm development and uncertainty estimation of fundamental remote sensing products that feed directly into existing workflows of agencies with established user-basis and decision-making frameworks. These applications will facilitate adaptation and mitigation to changes in drylands.
5) The ARID team leadership included researchers that regularly work with end-users including USDA ARS members (Joel Biederman, Russ Scott)

ARID also drives the ES2A strategy virtuous cycle by foremost providing foundational data that can be used across a range of technical and societally beneficial uses (Fig. A.6). Additionally, with the ES2A rollout in 2024, it is expected that the Terrestrial Ecology program can fund work directly with end-users within ARID that can inform and directly impact aspects higher on the pyramid (see Fig. A.6).

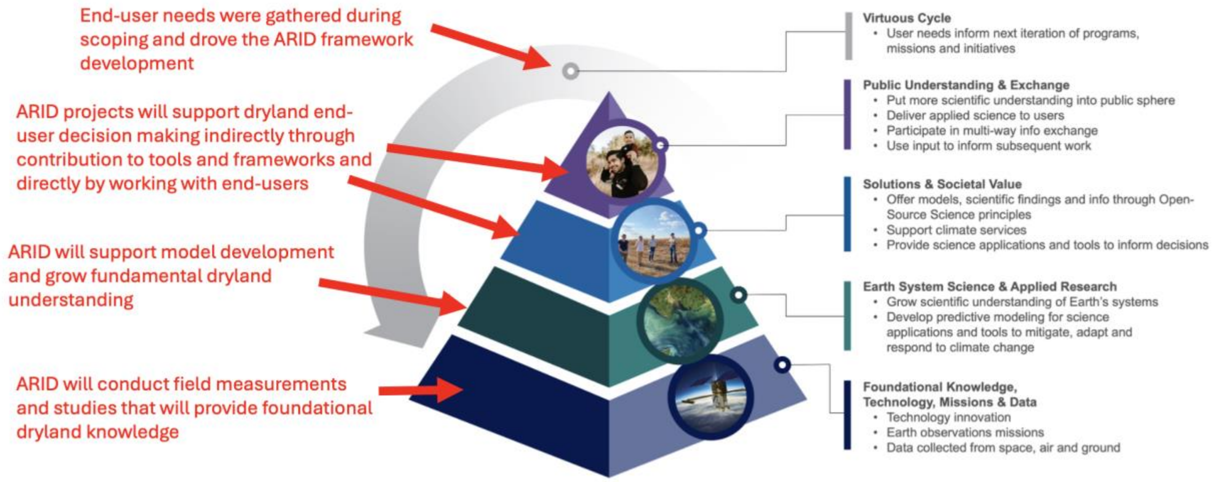


***Figure A.6.*** *The Earth Science to Action (ES2A) Virtuous Cycle obtained from [https://science.nasa.gov/earth-science/earth-science-to-action/](https://science.nasa.gov/earth-science/earth-science-to-action/). ARID informs each level of the pyramid to varying degrees.*

ARID has the potential to be a flagship program leading the ES2A ten-year strategy by being a means to directly support projects that "discover and demonstrate innovative and practical uses of NASA Earth Science observations and research through applied research and applications projects carried out in partnership with end user organizations." The ARID initiative will provide ES2A with the opportunity to directly engage operational agencies as well as rural and tribal communities, united around fundamental dryland science questions to address science-based decision making. This will clearly demonstrate the societal value of NASA's science to a large population of diverse users and garner inter-agency support for ES2A.

# B. Technical Approach and Methodology

## B.1 Science Themes and Questions

The ARID mission is designed around four scientific themes (Fig. B.1) drawn from an extensive consultation process with scientists and end-users, a synthesis of the scientific literature, and assessment of technological challenges and opportunities.

1. Science Theme 1: Climate Variability and Drought
2. Science Theme 2: Ecosystem Structure, Function, and Biodiversity
3. Science Theme 3: Carbon Cycle Interannual Variability and Long-Term Trends
4. Science Theme 4: Social-Ecological Systems

Addressing these science themes contributes to understanding and managing the vast ecosystem services that drylands provide. These include, but are not limited to, water supply, carbon storage, crop/rangeland/livestock/forestry management, and biodiversity. Enabling research into dryland social-ecological systems connects the fundamental scientific discoveries from the first three science themes to the broader priorities in Earth Science to Action (Fig. B.1). Specifically, with a high population of humans living in dryland environments, social-ecological systems research evaluates the human interactions with the first three themes, including humans managing these ecosystems and adapting to them as they change. We envision research that not only represents cutting-edge discovery about drylands and their responses to change, but that creates usable information to support decisions and adaptations, and to promote resilience of drylands.

In this section we briefly outline the context of each science theme and sub-themes, along with overarching and specific science questions. We highlight that these science themes are interlinked, and each theme contributes to understanding the larger integrated system dynamics of dryland ecosystems (Fig. B.1). We briefly identify the approaches the ARID campaign would use to address these science themes and questions, noting that the associated ARID technical approaches are described in Section B.2.

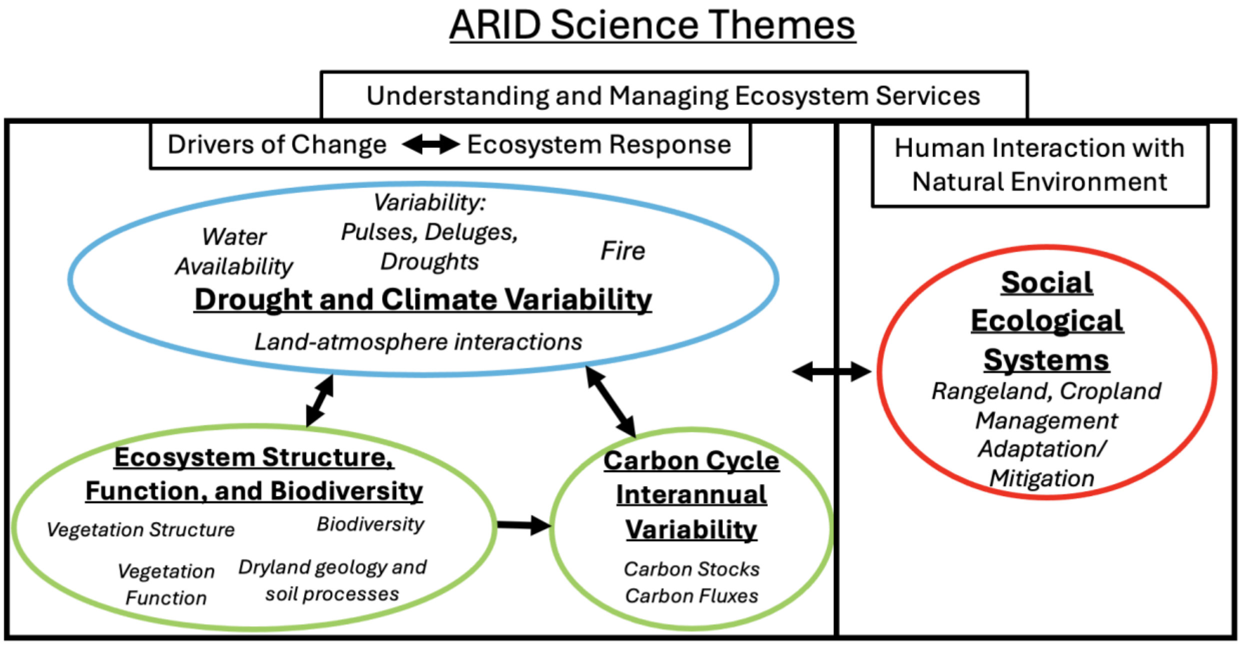


***Figure B.1.*** *Interactive components of ARID science themes. Linkage between the different ARID science themes as well as several main objectives of ARID. The first three science themes (green and blue ellipses) aim to understand the interaction between drivers of change and ecosystem responses. Dryland drivers are impacting biodiversity and ecosystem responses that feedback and further reinforce or suppress the climatic drivers, under land-atmosphere interactions. The fourth theme (red ellipse) aims to understand the interaction of humans with these three fundamental science themes. Altogether, they contribute to understanding dryland ecosystem services. The dryland biodiversity and ecological structure and function itself provides ecosystem services including water purification, forage and browse, grains, habitat, fuel wood, carbon storage, cultural settings, and many others. Research findings from a field campaign can quantify how ecosystem services are being impacted under global environmental changes, and work in partnership with land managers and other communities to co-develop usable information products to support decisions and adaptations in drylands.*

***Table B.1.*** *Summary table of ARID research questions discussed throughout Section B.1. These include the four main theme questions and select questions from each of the sub-themes.*

| Research Theme | Theme Questions | |
|---|---|---|
| **Theme 1: Climate Variability and Drought** | ***How are extremes like droughts, heatwaves, and large rain pulses across drylands impacting water availability, and are these extremes amplified by changing fire regimes, land cover change, and land-atmosphere interactions?*** | |
| **Sub-Theme** | **Central Sub-Theme Question** | **Select Process-level Questions** |

| | | |
|---|---|---|
| **1.1 Water Availability** | How do changes in the amount, timing, intensity and phase of water inputs affect surface water partitioning among evaporation, transpiration, runoff, and groundwater recharge, thereby regulating the amount of water that is available to humans and ecosystems? | How do changes in atmospheric conditions, such as CO2, VPD, and energy balance, alter the fate and temporal variability of **soil moisture**?<br>How can remote sensing detect, and Earth System Models predict, key physical parameters (e.g., precipitation, evapotranspiration, soil moisture, plant water status and runoff) to address these questions? |
| **1.2 Dryland Climate Variability: Pulses and Droughts** | How do dryland ecosystems process heterogeneous, highly dynamic moisture pulses?<br>How does the timing and duration of lack of rainfall impact dryland function, structure, composition, and water availability and how is drought intensity, severity, and duration changing in drylands? | How are moisture pulses changing?<br>How can Earth observation adequately capture pulse dynamics at the appropriate diurnal and daily-scale frequency?<br>Do process models capture rain/non-rainfall pulses and ecosystem responses?<br>How do higher temperatures and heatwaves influence drought onset and duration in drylands?<br>Which dryland ecosystem components respond most to drought? |
| **1.3 Fire** | How do fire regimes on both rangeland, open woodland, and forested landscapes change the composition, structure, and function of drylands at various time scales? | How do changes in dryland composition, structure, and function feedback to impact fire regimes?<br>What role does fire play in the expansion of invasive species, shrub encroachment, and the loss of ecosystem services as observed across multiple continents?<br>How does fire impact carbon stocks and fluxes across diverse dryland ecosystem types and across spatio-temporal scales? |
| **1.4 Land-atmosphere Interactions** | How do land-atmosphere interactions influence climate extremes, water availability, and dryland ecosystem responses, including changes in air temperature, changes in the frequency and intensity of extreme events, as well as land use change? | To what degree are land-atmosphere interactions driving drylands' contribution to water, carbon, and energy fluxes?<br>How much are climate extremes playing a role in these interactions?<br>How does dryland heterogeneity of soil conditions (e.g., soil moisture, soil texture) and vegetation (structure and types) influence landscape-scale land-atmosphere interactions (like convection)? |
| **Theme 2: Ecosystem Structure, Function, and Biodiversity** | ***What are the main mechanisms driving the spatiotemporal distributions of dryland structure, function, and biodiversity?*** | |
| **Sub-Theme** | **Central Sub-Theme Question** | **Select Process-level Questions** |

| | | |
|---|---|---|
| **2.1 Vegetation Structure and Heterogeneity** | How are ongoing changes in climate (rising CO2, increases in drought frequency and intensity, long-term changes in mean rainfall and changing fire regimes) and land use (changing fire regimes grazing and other land uses) impacting vegetation structure, function and habitat in drylands? | What are the rates and underlying causes of woody plant encroachment (WPE) in global drylands?<br>How do invasions by exotic shrubs and grasses observed in drylands around the world impact ecosystem function and disturbance regimes?<br>How are changes in structure and function impacting essential ecosystem services, including changes in water, carbon and nutrient cycling in drylands and provision of forage for livestock? |
| **2.2 Dryland Biodiversity** | What are the drivers of biodiversity (functional, phylogenetic, taxonomic) in drylands and how will these be changing? | What is the relationship between biodiversity, ecosystem function, carbon stocks and resilience to disturbances (drought and fire)?<br>What are the impacts of climate change (increased aridity) and continued grazing pressure on biodiversity (functional, phylogenetic, taxonomic, etc.)?<br>What is the impact of land cover transformation, land degradation, and cultivation on dryland biodiversity and species of special interest (e.g. endangered species)?<br>What are the impacts of invasive plant species on biodiversity, rangeland condition and water-availability? |
| **2.3 Ecosystem Function** | Across different timescales, what are the dominant mechanisms driving dryland function such as plant hydraulics, leaf level photosynthesis, respiration, and nutrient cycling? | What role has CO2 fertilization played in driving changes in the SPAC and dryland functions GPP, NEE, ET, and WUE?<br>What role has the timing and intensity of precipitation and temperature-driven increases in VPD played in driving changes in the SPAC and dryland functions GPP, NEE, ET, and WUE?<br>Can we utilize remote sensing data to improve the estimation of dryland vegetation physiological status (e.g. photosynthetic quantum yield, nutrient, pigment and enzyme concentrations, canopy stomatal and hydraulic properties, vegetation and soil water status, drought stress) for distinct PFT and biocrust communities?<br>Can we improve retrievals of vegetation function (e.g. carbon, water, and energy fluxes) in drylands, either directly (e.g. thermal estimation of energy balance), or via use of improved structural, physiological, and phenological retrievals in process-based models?<br>Can improvements of decomposition of soil organic matter be improved by night-time monitoring of carbon exchanges and soil moisture levels? |

| | | |
|---|---|---|
| **2.4 Dryland Geology and Soils** | How do soil communities and physicochemical characteristics drive and respond to climate variability and ecosystem change? | What is the extent, composition, and function of dryland biological soil crusts (biocrusts)?<br>What roles do soils play in dictating aboveground structure, function, and response to change?<br>How much inorganic carbon is stored in dryland soils across different soil types, aridity index gradients, and natural vs. managed systems, and how vulnerable is the carbon to environmental shifts?<br>What contribution do soil signals play in space-based observations of all terrestrial ecosystems?<br>What are the sources, sinks, causes, and consequences of accelerated topsoil loss and dust in Earth's drylands? |
| **Theme 3: Carbon Cycle Interannual Variability and Long-Term Trends** | ***What is the contribution of drylands to the mean, trend, and particularly the interannual variability of terrestrial carbon dynamics?*** | |
| **Sub-Theme** | **Central Sub-Theme Question** | **Select Process-level Questions** |
| **3.1 Carbon Stocks and Fluxes** | How large are the carbon stocks and fluxes in drylands, how do they vary at sub-annual to decadal timescales, and what is their response through space and time, to drivers of global change? | How vulnerable are dryland carbon stocks and fluxes to global and regional changes in water availability and atmospheric demand, combined with asynchronous plant responses to periods of water stress (B.1.2.1)?<br>How do woody encroachment and desertification change dryland carbon cycling and feedbacks?<br>What is the relative contribution of different plant functional types to carbon stocks and how are these changing along environmental gradients?<br>What influence do rooting strategies and belowground carbon allocation play in ecosystem carbon storage?<br>What is the potential of carbon capture in dryland vegetation and soils to work as a nature-based climate solution (NCS)?<br>How can remote and in-situ observations be best used to model and quantify carbon stocks and fluxes? |
| **Theme 4: Social Ecological Systems** | ***What are the consequences of changes in drylands for social-ecological and what management (e.g., mitigation and adaptation) solutions can maintain the critical services provided by drylands even in the face of change?*** | |
| **Sub-Theme** | **Central Sub-Theme Question** | **Select Process-level Questions** |
| **4.1 Land Management** | How are land and water resources and resource management being affected by drought and aridity changes? | How is the composition and productivity of rangelands changing under various management regimes and how are they predicted to change due to climate?<br>How will remote sensing and modeling enhance assessment and forecasting of land resources (e.g., |

| | | |
|---|---|---|
| | | soil moisture, productivity, water use, carbon storage) for various land uses?<br>How will land use further impair wildlife corridors and migratory pathways?<br>How will further fragmentation of conservation and rangeland areas affect biodiversity and conservation goals?<br>How will reduced water availability impact forage production, cropping yields, livestock conditions, and habitat conditions?<br>How will increased thermal stress affect agricultural production of rangelands, cropland, forests, livestock, wildlife, and wildlands systems?<br>How will renewable energy deployment affect ecosystem services?<br>Can multi-sensor observations and modeling improve our ability to assess land management effectiveness? |
| **4.2 Adaptation and Mitigation Strategies** | ***Adaptation and resilience of dryland social ecological systems***<br>How can dryland ecosystems enhance their resilience in the face of environmental stressors, and what adaptive strategies can local communities implement to build resilience?<br>***Mitigation options for different dryland livelihood strategies***<br>How will climate variability and water limitations hinder carbon sequestration efforts? | ***Adaptation and resilience of dryland social ecological systems***<br>What factors and information can enhance adaptive capacity of dryland social-ecological systems to meet the challenges to increased aridity?<br>How can ecological forecasting of drought conditions enable decision making of dryland operators and natural resource managers?<br>Have land managers needed to change their strategies in drylands in the past few decades to accommodate change? What drives these changes?<br>***Mitigation options for different dryland livelihood strategies***<br>What impact will renewable energy development and carbon sequestration practices have on dryland livelihood strategies and ecosystem services in different dryland regions?<br>How can improved observations enhance our assessment of renewable energy systems and carbon sequestration practices?<br>What increased information can be provided related to changes in ecosystem processes and ecosystem services related to mitigation practices? |

### *B.1.1 Science Theme 1: Climate Variability and Drought*

A dominant climate feature across dryland regions of the world is the low precipitation levels and high evaporative demand. These climate drivers are leading to reduced water availability and increased drought impacts resulting in economic losses, altered levels of ecosystem services, damage to natural resources, and reduced capacity to maintain livelihoods. Dryland regions are facing increases in climate variability that further exacerbate conditions, including more frequent droughts and heatwaves, pulses of extreme rainfall events, increased frequency and intensity of fire, and sustained, stronger extremes through land-atmosphere interactions.

Droughts in dryland systems are not uncommon, however, recent increases in climate variability and exposure to extreme events are affecting local hydrological systems to further exacerbate drought conditions and severity of droughts. Droughts are characterized by meteorological droughts (e.g., when dry weather conditions persist) and hydrological droughts (e.g., when water availability is low) (Fig. B.2). In dryland systems these two conditions often coexist due to climate and human related causes. Future scenarios across the region suggest that elevated seasonal temperatures and increases in the atmospheric evaporative demand will exacerbate drought effects, through increased evapotranspiration, for example, despite the level of changes in precipitation taking place.

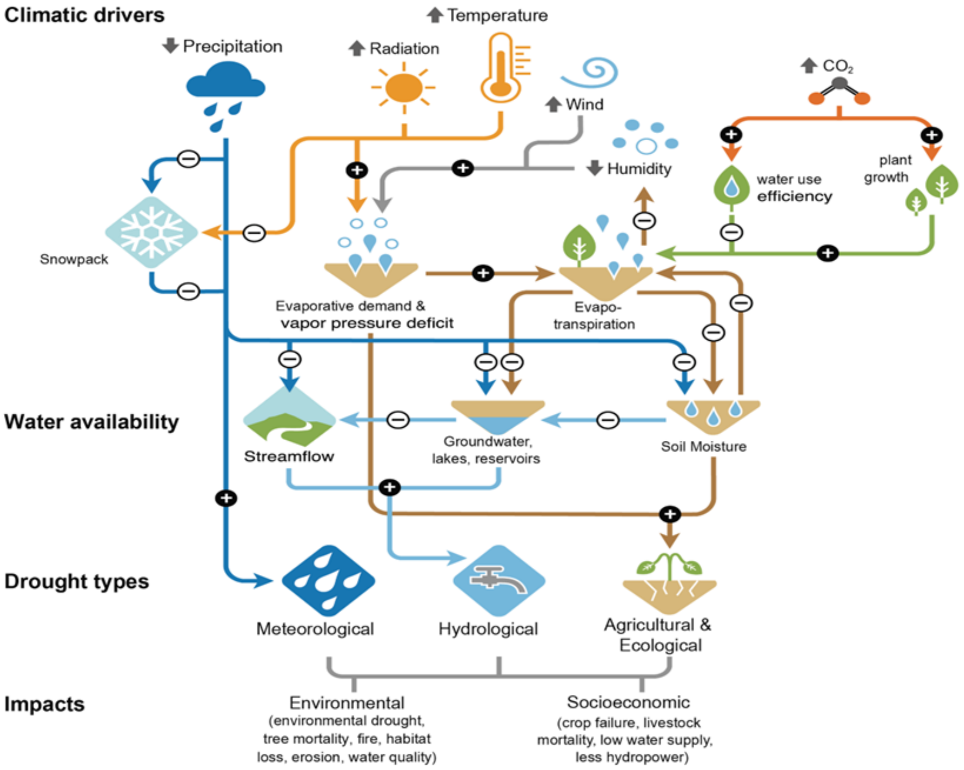


***Figure B.2.*** *Conceptual diagram describing climate, land use, and atmospheric* $CO_2$ *effects on water availability and resulting drought conditions, including water consumption under various land uses such as irrigation for cropping systems. Considerations of diurnal pattern of dew formation also needs consideration in these dryland landscapes (from IPCC WG1 Chapter 8, 2021)*

The consequences of these climate driven changes, human-caused changes in water allocation and usage for cropping and other consumptive activities, such as mining, has reduced the natural flows of water in many dryland systems. Extraction of groundwater supplies to meet demands of local communities for drinking water supply and irrigation as well as reservoir usage for power generation and irrigation have impacted water availability across drylands. In addition, other extreme events are associated with increasing climate variability such as dust storms, flooding following drought conditions contributing to landscape deformation through erosion or gully formation, and enhanced fire danger as fuel loads are persisting in flammable stages for longer periods of time.

Our overall question we ask in this theme is: *How are climate extremes like droughts, heatwaves, and large rain pulses impacting dryland systems and how do they interact with changing fire regimes, land cover change, and land-atmosphere interactions?*? This major science theme, drought and climate variability, is further defined in four sub-themes: 1) water availability, 2) pulses and extreme events, 3) fires, and 4) land-atmosphere interactions in dryland systems.

#### *B.1.1.1 Sub-Theme: Water Availability*

*Motivation*

Water is the key limiting factor for ecosystems and societies in drylands. Quantifying how water availability is changing due to climate change and through land use activities is critical to understanding and predicting how dryland ecosystem structure and function will be altered (e.g., structure, composition, vegetation productivity, water partitioning, carbon cycling) in the future (Fig. B.2). This understanding is essential to inform decision makers of how to adapt management practices to conserve and enhance dryland resources.

Dryland water availability is controlled by the amount, timing, and fate of water inputs (frozen or liquid and mainly through precipitation) at the land surface (Fig. B.2). Precipitation may evaporate from wet leaves and surfaces, run off laterally, or infiltrate into soil locally, recharging soil moisture. Soil moisture is subsequently partitioned among abiotic evaporation, root uptake, and subsequent transpiration by plants. Typically, recharge to groundwater is small in drylands except in and along mountain fronts, where precipitation is higher and runoff is concentrated (Scanlon et al. 2006).

Snowmelt is an important moisture source in many drylands at higher latitudes and/or higher elevations. In some drylands, especially those near large water bodies, fog and dew can contribute important fractions of the water budget (L. Wang et al., 2017). Soil water availability is often spatially heterogeneous in drylands, due to soil/geologic variability, topography, and variable, infrequent, patchy precipitation. Water availability at the land surface is further modified by ecosystem structure, biodiversity, and functioning that controls the land surface energy balance and regulates evapotranspiration (ET). Thus, changes in dryland land cover (e.g., woody plant encroachment) and land use (e.g., urbanization, grazing) could have dramatic effects on precipitation partitioning and change the amount of water that is available for ecosystems and human needs.

Climate change is affecting water availability, with general predictions that dry locations are becoming drier from warming temperatures and higher evaporative demand (Held and Soden 2006). The western US is also drying with trends toward reducing mean rainfall amounts (F. Zhang et al., 2021). While many ecosystems have higher atmospheric humidity due to increased ET from higher evaporative demand, the atmosphere above drylands is not becoming more humid (Simpson et al., 2024a).

*Questions*

In seeking to quantify water availability as a key driver of change in drylands, we identify several key questions to be addressed by ARID. First, how do changes in the amount, timing, intensity and phase of water inputs affect surface water partitioning among evaporation, transpiration, runoff, and groundwater recharge, thereby regulating the amount of water that is available to humans and ecosystems? Second, how do changes in atmospheric conditions, such as CO2, VPD, and energy balance, alter the fate and temporal variability of **soil moisture**? Finally, how can remote sensing detect, and Earth System Models predict, key physical parameters (e.g., precipitation, evapotranspiration, soil moisture, plant water status and runoff) to address these questions?

### *B.1.1.2 Sub-Theme: Dryland Climate Variability: Pulses and Droughts*

Two controls particularly powerful in regulating dryland structure and function are rainfall pulse dynamics and dry spells or drought between pulses (large changes in dryland resource availability and process rates across short timescales). Many dryland regions are currently experiencing more rainfall variability and extreme heat waves. Nominally, this includes longer dry spells and more intense rainfall (Pendergrass et al. 2017), as well as “hot droughts”, where drought conditions co-occur with warmer temperatures. The precipitation pulse dynamics of drylands are poorly understood, particularly how the rain pulse inputs influence the soil-vegetation system at hourly-to-daily timescales and consequently the water, carbon, energy cycles and erosion rates. With most terrestrial biosphere models developed to understand forests of more humid regions, they may not include dynamics at these daily timescales and how their impacts accumulate to influence annual flux estimates (Feldman, Feng, et al., 2024a). This increase in rainfall variability also extends to extreme events, with more frequent and intense droughts, heatwaves, dust storms, and severe weather events. We outline pulse dynamics and drought dynamics separately within this subtheme.

#### <u>*Pulses of moisture and ecosystem responses*</u>

*Motivation*

Pulsed events, both nominal and extreme, have major consequences on dryland water availability, landscape structure, and ecosystem dynamics. Pulse dynamics refers to the tendency of dryland biological activity to be controlled by relatively infrequent moisture pulses, and while it has long been known drylands can respond quickly to precipitation, the mechanisms behind pulsed controls and the expectations for their change with climate change, remain highly uncertain. Dryland moisture inputs may include rainfall, snowmelt, and in some cases, meaningful amounts of fog, dew, or water vapor adsorption. Pulse dynamics are a key feature of dryland ecosystems. Because of the strong moisture limitation in these systems, periodic moisture inputs result in rapid changes in ecological activity which are dynamic over time scales of hours to days. Discrete moisture pulses temporarily alleviate the effects of water stress on plant and microbial activities, allowing higher rates of photosynthesis, evapotranspiration, and ecosystem respiration (Huxman et al., 2004; Noy-Meir, 1973). High-intensity rainfall events can also trigger flooding and/or erosion. The frequency and intensity of precipitation pulses is changing (Demaria et al., 2019; F. Zhang et al., 2021) and the impact of this change is highly uncertain.

*Questions*

The main question we seek to understand is: How do dryland ecosystems process heterogeneous, highly dynamic moisture pulses?  Some more specific questions to consider are: How are moisture pulses changing? How can Earth observation adequately capture pulse dynamics at the appropriate diurnal and daily-scale frequency? What are the key determinants of the functional form of the pulse response (diurnal and daily-scale)? Do process models capture rain/non-rainfall pulses and ecosystem responses?

### *Drought*

*Motivation*

In contrast to pulses, droughts may occur as discrete short-term events or persist for years to decades or longer. Droughts may be characterized as meteorological (e.g., when dry weather conditions persist), hydrological (e.g., when surface water systems are relatively dry) or ecological (when plant and soil water availability are low) (Figure B.2). In dryland systems, these three conditions often coexist due to climate and human related causes. In addition to types of droughts, drought can manifest over a variety of temporal scales including flash droughts at weekly scales to decadal scale deficits. Future scenarios across the western US drylands suggest that increasing mean aridity conditions, like increasing temperature (and associated evaporative demand) and declining winter rainfall totals (e.g.(F. Zhang et al., 2021)), will lead to greater drought effects. Droughts are common in dryland systems. However, with recent climate change, the frequency and intensity of droughts are predicted to increase in most drylands (Dai, 2011). Climate and land use change are also affecting local hydrological systems to further exacerbate drought severity and duration. The recent severe drought in the western US is unprecedented for thousand-year timescales and has exposed the vulnerability of agricultural livelihoods with significant socio-economic impacts. These drought effects substantially impact dryland productivity and biogeochemical processes. However, the ecosystem responses to drought in drylands are poorly understood and poorly modeled in terrestrial biosphere models (De Kauwe et al. 2015).

*Questions*

The main question we seek to understand is: how does the timing and duration of lack of rainfall impact dryland function, structure, composition, and water availability and how is drought intensity, severity, and duration changing in drylands? More specific questions to consider include: How do higher temperatures and heat waves influence drought onset and duration in drylands? Which dryland ecosystem components respond most to drought? How can modeling of ecosystem responses to drought be improved? How does remote sensing help to monitor the drought onset, development, and drought impacts? How can we project changes in ecosystem structure with increased persistence of drought conditions?

### *B.1.1.3 Sub-Theme: Fire*

*Motivation*

Climate change - specifically seasonal and interannual warming temperatures, increased evaporative demand, and declining water availability - is driving unprecedented increases in wildfire across dryland ecosystems globally, including increases in fire intensity and frequency (Senande-Rivera et al., 2022). While fire is a natural part of dryland ecosystems, persistent and repeated events and/or novel vegetation-fire feedbacks can cause threshold responses and ecosystem state changes as tipping points are crossed (Hoover et al., 2020). For instance, in rangeland and woodland ecosystems, invasive annual grasses are transforming natural fire regimes and displacing native grass and shrub species leading to large reductions in forage production and quality (Balch et al., 2013; Fusco et al., 2019; J. T. Smith et al., 2022; J. T. Smith, Allred, Boyd, Davies, Kleinhesselink, et al., 2023). Conversely, fire management that traditionally aimed to prevent or extinguish natural fire regimes has had unintended consequences, such as rapid shrub encroachment of large areas of natural grasslands with associated reductions in forage yields (Briggs et al., 2002; Keeley, 2006), as well as the unnatural accumulation of surface fuels (Barbero et al., 2015; Littell et al., 2009; Mueller et al., 2020).

Rangelands including grassland, shrubland, and open woodland ecosystems, experience the largest extent of burned area in the western US and globally (Crist, 2023). Rangeland wildfire is increasing with climate change due to the aridification of these ecosystems and changes in community composition (Fig. B.3; Balch et al., 2013). The most at-risk areas in the western US, such as low resistance and resilience sagebrush ecosystems, are quickly being converted to invasive annual grass-dominated ecosystems that further elevate fire risk (J. T. Smith et al., 2022).

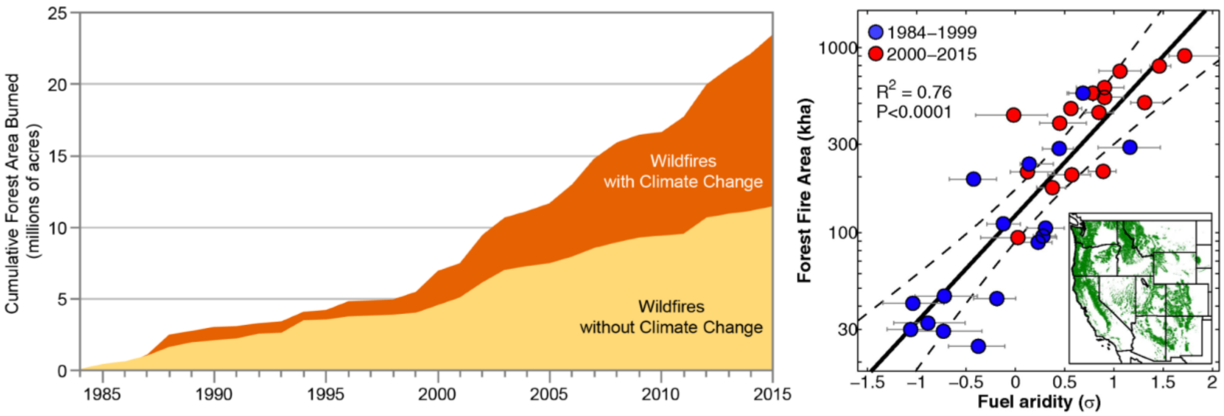


***Figure B.3.*** *(a) The cumulative forest area burned by wildfires has greatly increased between 1984 and 2015, with analyses estimating that the area* *burned by wildfire across the western continental US over that period was twice what would have burned had climate change not occurred (Garfin et al., 2018, 4th National Climate Assessment, Southwest Chapter adapted from Abatzoglou & Williams, 2016). (b) A strong correlation has been observed to fuel aridity since 2000 and seems to be a key driver related to the area burned (Abatzoglou & Williams, 2016a).*

Fire management on woodland and forested ecosystems has heavily targeted vulnerable dry mixed conifer forest that are fully within the ARID domain (Fig. B.3). Fire exclusion management on forest ecosystems was largely successful for much of the 20th century, but the confluence of accumulated surface fuels, unnaturally dense forests, and climate change has rapidly increased wildfire frequency and severity (Fig. B.3) (Abatzoglou & Williams, 2016b; Barbero et al., 2015; Garfin et al., 2018; Mueller et al., 2020). Landscape-scale, stand-replacing fires have the potential to push western US woodland and forest ecosystems beyond tipping points and thereby cause lasting changes in vegetation structure, composition, and succession (Batllori et al., 2020). Recognizing this threat, the forest management paradigm rapidly shifted to widespread deployment of forest restoration treatments, including mechanical thinning and managed or prescribed fire, aimed at reducing canopy cover and fuel loads to reduce wildfire frequency and severity (Fulé et al., 2012). Through ARID, we can further integrate multi-scale remote sensing observations, and coordinate with land managers to inform land management strategies towards increased forest resilience to wildfire without unintended negative consequences.

We have the opportunity to explore cutting-edge rangeland and wildfire management strategies that leverage novel multi-scale remote sensing technologies. For instance, with very high spatiotemporal resolution optical data (e.g., daily, 3-meter data from PlanetScope) and virtually fencing (Wätzold et al., 2024), we can determine where targeted grazing opportunities exist as a potential tool for managing fine fuels on rangeland ecosystems. Novel science-informed management approaches can be pioneered on western US rangelands and then knowledge can be tested on transferred to global rangeland socio-ecological systems through ARID international partnerships.

*Questions*

In seeking to understand how dryland fire regimes respond to climate change and in-turn drives change in dryland community composition, structure, and function, we have identified key overarching questions to be addressed by the ARID terrestrial campaign: How do fire regimes on both rangeland, open woodland, and forested landscapes change the composition, structure, and function of drylands at various time scales?; and how do these changes in dryland composition, structure, and function feedback to impact fire regimes?

We have further identified key sub-questions with direct management implications that could also be targeted as part of the ARID campaign that include: What role does fire play in the expansion of invasive species, shrub encroachment, and the loss of ecosystem services as observed across multiple continents? How does fire impact carbon stocks and fluxes across diverse dryland ecosystem types and across spatio-temporal scales? To what extent can grazing be used as a management tool to reduce fire frequency and intensity in drylands? How is a changing snowpack and a shift from snow to rain in winter impacting fire dynamics across diverse dryland ecosystem types? How can management (e.g., forest thinning, prescribed fire, invasive removals, grazing) be deployed to reduce fuels and increase dryland ecosystem resilience to fire? What management options (e.g., aerially seeding for restoration) could help ecosystems recover from fire when it does occur?

#### *B.1.1.4 Sub-Theme: Land-Atmosphere Interactions*

#### *Motivation*

Land-atmosphere interactions strongly influence dryland carbon, water, energy, and other biogeochemical fluxes, and are shifting with changes in large-scale atmospheric circulation under climate change (Zhou et al., 2021). These interactions also contribute to rainfall initiation in drylands as well as intensification of droughts and heatwaves. For example, soil moisture spatial heterogeneity, the amount of soil moisture, and the ET rates from different vegetation types can contribute to rainfall initiation in drylands (De Kauwe et al., 2013; Green et al., 2017; Koster et al., 2004; Taylor et al., 2011). Similarly, low soil moisture availability can reduce terrestrial carbon uptake and prolong drought conditions (Dannenberg et al., 2022; Williams et al., 2022). It is essential to understand this feedback between the land surface and atmosphere to accurately predict climate and weather patterns as well as the associated impacts on precipitation, soil moisture, ET, runoff, dust storms, and vegetation productivity and dynamics (e.g., stress response, phenology, vegetation mortality).

#### *Questions*

We seek to address: How do land-atmosphere interactions influence climate extremes, water availability, and dryland ecosystem responses, including changes in air temperature, changes in the frequency and intensity of extreme events, as well as land use change? More specific questions to consider include: To what degree are land-atmosphere interactions driving drylands' contribution to water, carbon, and energy fluxes? How much are climate extremes playing a role in these interactions? How does dryland heterogeneity of soil conditions (e.g., soil moisture, soil texture) and vegetation (structure and types) influence landscape-scale land-atmosphere interactions (like convection)? Do land-atmosphere interactions amplify the effects of extreme weather in drylands? Do changed dryland land uses and rangeland management influence land-atmosphere interactions, and if so, at which scales? How does shrub encroachment, vegetation composition change, or reduced vegetation cover influence land-atmosphere interactions?

### *B1.1.5 Approaches to Studying Drought and Climate Variability*

To address these scientific questions, challenges quantifying and modeling the key physical parameters of the water cycle must be overcome. Key parameters include precipitation, surface temperature, topography, relative humidity, evaporative demand, evapotranspiration, vegetation structure and status, vegetation water status, fractional cover, wind speed, water use efficiency, surface roughness, groundwater, and soil moisture (W. K. Smith et al., 2019b). Additionally, non-rainfall inputs such as fog and dew are challenging to quantify. For soil moisture, only shallow (5 cm and potentially deeper), coarse resolution (~ 10's km) measurements are detectable by current satellites. In addition, geostationary data can provide greater temporal resolution to estimate soil moisture, surface temperature, and water availability in dryland systems.

Meanwhile, high spatial resolution (<0.1 km) shallow soil moisture from satellite synthetic aperture radar (SAR) is available, but it is typically measured too infrequently (~weekly) to detect important features of rainfall pulses and drying dynamics, which often dominate the function of dryland ecosystems. Recent advances in estimating evaporation and transpiration with remote sensing observations and various modeling techniques provide useful starting points to evaluate dryland ET rates (Awada et al., 2022; Pan et al., 2020; Senay et al., 2017; K. Zhang et al., 2016). In addition, partitioning evapotranspiration into its evaporation and transpiration components can be difficult due to sparse vegetation, and thus mixed pixels of bare soil and vegetation need to be partitioned with the aid of very high resolution UAS and airborne data from the ARID campaign.

Groundwater, which greatly improves the productivity and diversity of both ecosystems and human activities, monitoring gravity storage changes from orbiting satellites has led to innovative global and large regional-scale understanding (Scanlon et al. 2021), though these analyses are often too large in scale to be useful to water resource managers. Estimates of groundwater can be improved with data fusion techniques to produce finer spatial resolution products as well as provide measurement continuity, which are critical to determine future groundwater availability in drylands. For example, the next generation GRACE satellite combined with well data via models and data assimilation shows great promise in improving the spatial and temporal resolutions of these measurements, enhancing their utility for decision-making. Additionally, supersites and some soil moisture networks (USCRN, SCAN) include soil moisture measurements at intervals between 5 cm and 100 cm and sometimes deeper, which can provide an understanding of the role of some of the deeper moisture sources have on ecosystem function.

New approaches are needed to better understand how changing water availability alters water movement and use at 1) throughout the soil-plant-atmosphere and how this translates to 2) structural change of the individuals and ecosystems, 3) ecosystem composition across the landscape, and 4) landscape to regional scale carbon, water, energy exchange. To address precipitation-related challenges, ARID will need to develop and test new high-temporal and spatial precipitation estimates by combining ground radar and gauges, aircraft measurements, existing satellites, algorithms, and modeling techniques.

To better measure plant available water related to soil moisture and soil water potential, new techniques based on remote sensing of water along the atmosphere-plant-soil continuum can be developed using microwave observations, which can be validated using GNSS sensors measuring VOD frequently at the site level (Feldman, 2024a). Such plant water status information is especially useful for integration with plant hydraulic schemes in terrestrial biosphere models. Information from models and remote sensing products, such as soil moisture and rainfall distribution, can be merged to provide finer spatial resolution measurements deeper into the soil of soil moisture, especially when combining high temporal frequency passive and high spatial resolution active microwave sensors. When combining this information with soil characteristics, it can be used to estimate soil water potential. For improved estimates of ET, new soil moisture products and higher resolution (<100m) thermal data from aircraft and spaceborne instruments can be integrated into ET models as a constraint, with improved ET partitioning schemes. These can be further validated using the network of flux tower sites dispersed across dryland ecosystems.

To capture the pulse dynamics of extreme precipitation events or infrequent flooding events, opportunistic observational strategy is needed to follow these events and to monitor impacts of these events on landscape deformation and vegetation structures. Being able to monitor long term ecosystem responses to these pulse events will be a key feature of ARID research approach. In addition, experimentally imposing moisture pulses and then monitoring responses, and pulse chasing such as deploying aircraft, drone, mobile flux towers, and personnel for field measurements during and immediately following naturally occurring moisture pulses. It also includes utilizing high temporal frequency satellite measurements such as passive microwave remote sensing, which measure at near daily timescales in all-weather conditions, and geostationary satellites that measure across infrared spectra at sub-hourly scales. Finally, using these data, it is essential to develop characteristic responses of states and fluxes to pulse events for model development.

As increasing aridity across dryland regions affect vegetation condition and fuel moisture levels, new techniques are primed to rapidly accelerate our understanding of these vegetation-fire interactions with novel ecohydrologic applications. In particular, advances in active remote sensing techniques include light detection and ranging (LIDAR) and synthetic aperture radar (SAR) are enabling more accurate monitoring of forest structure and water content; while advances in visible to shortwave infrared (VSWIR; ~400 to 2500 nm) imaging spectroscopy (also known as hyperspectral imaging and hyperspectral remote sensing), thermal infrared, and solar-induced fluorescence remote sensing are enabling more accurate monitoring of ecosystem composition and function (W. K. Smith et al., 2019b).

In addition, LiDAR data from field to satellite (e.g., NASA GEDI) scale are increasingly being used to monitor key predictors of fire occurrence and severity including ecosystem surface fuels and forest density in forest and rangeland ecosystems. Wintertime LiDAR data can also be applied to monitor changes in winter snowpack, a key early indicator of ecosystem drought and critical fuel moisture conditions (Duncanson et al., 2022; Dwivedi et al., 2024; Painter et al., 2010). Microwave data from field to satellite (e.g., NASA SMAP) and the deployment of Landsat Next in 2030 are very complimentary to LiDAR data and can be used to explicitly track changes in ecosystem fuel moisture dynamics over seasonal timescales (Humphrey & Frankenberg, 2023; Rao et al., 2020; Yao et al., 2020). Active microwave techniques, e.g., synthetic aperture radar (SAR), can be applied to achieve very high spatial resolution measurements for enhanced fuel moisture monitoring along fuel treatment gradients (e.g., NASA NISAR) (Rao et al., 2020; Santoro et al., 2021). Thermal infrared (e.g., NASA ECOSTRESS) and solar-induced fluorescence (e.g., NASA OCO-3) observations can also be applied as an early indicator of ecosystem drought stress and for active fire monitoring for improved fire response times and management (Farella et al., 2022). Imaging spectrometer observations from field to satellite scales (e.g., NASA EMIT) can be used to determine species composition dynamics both pre- and post-fire to better understand complex vegetation-fire feedbacks and to monitor ecosystem state changes following fire events (W. K. Smith et al., 2019b).

In addition, additional field, aircraft/drone, and remote sensing observations will enhance characterization of land-atmosphere interactions related to drought and climate variability dynamics. Several key approaches to address these science questions and challenges include: (1) Isolate the driving factors of land surface behavior using techniques such as (a) experimental setups to isolate variables and interactions (i.e., using rainout shelters to keep soil moisture dry/constant compared to ambient conditions and measure ET or GPP differences), (b) model experiment isolations (like GLACE-CMIP5) where driving processes are isolated within the model scheme (Koster et al. 2004), and (c) statistical analyses using observational data (Granger Causality/convergent cross mapping/Sugihara causality) (Green et al. 2017, Sugihara et al. 2012). (2) Examine the role of land management and patchiness of vegetation and/or soil moisture on ET and GPP fluxes. (3) Simulate drought experiments or monitor natural ones to determine role of extremes on dryland ET and GPP fluxes and their recovery. (4) Quantify the sensitivity of dryland GPP and ET fluxes to soil water availability variations, which is currently an uncertain model parameter. These approaches can all be addressed using simultaneous soil moisture and flux measurements (or flux proxies) at any scale and using observed or modeled data. Importantly, many of these approaches require measuring land and atmosphere properties at hourly or daily scales where weekly timescales will miss these rapid dryland dynamics. Similarly, high spatial resolution measurements will be needed to distinguish between signals from soil and vegetation in remote sensing and flux tower footprints.

### *B.1.2 Science Theme 2: Ecosystem Structure, Function, and Biodiversity*

Drylands in the US and globally have experienced significant change in structure, composition, and productivity and more significant change is predicted under climate change and land management practices (Boone et al. 2017; Godde et al., 2020; Joyce et al., 2013; Kleinhesselink et al., 2023). Conventional remote sensing and modeling approaches have poorly represented vegetation structure in drylands characterized by low cover and density of woody plants across spatially heterogeneous landscapes. These landscapes are characterized by their horizontal, vertical, and temporal heterogeneity in the cover and density of bare soil, biocrust, and distinct plant functional types (PFTs) (W. K. Smith et al., 2018). The fine spatial and temporal scale of dryland variability has meant that historical remote sensing and modeling of drylands has represented vegetation structure, composition and function at aggregate scales not well-suited to actual dryland systems. Indeed, many remote sensing and modeling approaches assume full cover and dominance by a single PFT. Even in models representing distinct C3 and C4 photosynthetic pathways, the uncertainty in PFT fractional cover leads to higher uncertainty in modeled carbon, water, and energy fluxes than in more homogeneous ecosystems (Hartley et al., 2017b).

Drylands also have remarkably high biodiversity, including 35% and 20% of global diversity and plant diversity hotspots, respectively (Maestre et al., 2021). The long evolutionary history of dryland ecosystems and their role as the origin of many unique plant lineages have given rise to multiple biodiversity hotspots around the world (e.g. Succulent Karoo in South Africa, and Sonoran Desert in North America, Gran Chaco and Caatinga in South America, dry forests of Meso-America and Australia) (Maestre et al., 2021). The high diversity of drylands adds to the complexity of measuring and modeling vegetation structure and function, while highlighting the critical need for improved EO in global drylands.

The biodiversity and range of PFT’s that characterizes the dryland systems also contributes to the variability in ecosystem functions and processes rates that respond to alternating periods of dryness and wetness, responses to extreme climate conditions, and diurnal cycles of water and carbon dynamics. Understanding the ecosystem responses to climate variability as changes to ecosystem structures change will be a key focus of ARID.

Our overall question we ask in this theme is: *What are the main mechanisms driving the spatiotemporal distributions of dryland structure, function, and biodiversity and what is their vulnerability to change?*

#### *B.1.2.1 Sub-Theme: Vegetation Structure and Heterogeneity*

##### *Motivation*

While recent NASA Terrestrial Ecology field campaigns have greatly advanced Earth observation and modeling of vegetation processes in mesic ecosystems (tropical, boreal and arctic), a new focus on dryland remote sensing, including improved detection and quantification of horizontal and vertical vegetation structure as well as PFT diversity, will pave the way towards greater structural and functional realism in remote sensing retrievals. Improvements in our ability to measure dryland vegetation structure and composition will enhance our understanding of dryland biodiversity and representation of dryland vegetation type and cover (and associated carbon, water and ecosystem services) in Earth system models.

##### *Questions*

We seek to address: How are ongoing changes in climate (rising CO2, increases in drought frequency and intensity, long-term changes in mean rainfall and changing fire regimes) and land use (changing fire regimes grazing and other land uses) impacting vegetation structure, function and habitat in drylands? More specifically, what are the rates and underlying causes of woody plant encroachment (WPE) in global drylands? How do invasions by exotic shrubs and grasses observed in drylands around the world impact ecosystem function and disturbance regimes? How are changes in structure and function impacting essential ecosystem services, including changes in water, carbon and nutrient cycling in drylands and provision of forage for livestock?

These primary questions give rise to a series of sub-questions that will enhance our earth system observation capabilities and ecosystem understanding of drylands, including: (i) Can we optimize new sensors and sensor-synergies to retrieve separate biophysical/structural data (e.g. cover, height, biomass, leaf area, light interception, etc.) for distinct woody and herbaceous, grass, forb and succulents, C3 and C4 PFTs, biocrust and bare soil in drylands? (ii) Can we utilize remote sensing data to improve the estimation of dryland vegetation physiological status (e.g. photosynthetic quantum yield, nutrient, pigment and enzyme concentrations, canopy stomatal and hydraulic properties, vegetation and soil water status, drought stress) for distinct PFT and biocrust communities? (iii) Can we improve retrievals of vegetation function (e.g. carbon, water, and energy fluxes) in drylands, either directly (e.g. thermal estimation of energy balance), or via use of improved structural, physiological, and phenological retrievals in process-based models? (iv) Can we use enhanced remote sensing to detect changes in vegetation structure and function associated with management and disturbance events in drylands, including fire, wood harvest, agricultural clearance, grazing, and invasive species? (v) Can we improve predictions of future changes in vegetation composition, structure and function under climate change using novel datasets and data fusion for model development, initialization, evaluation, and data assimilation to optimize parameters related to vegetation processes?

#### *B.1.2.2 Sub-Theme: Dryland Biodiversity*

*Motivation*

While harsh environmental constraints have been hypothesized to limit functional diversity in drylands, these dry ecosystems host a higher-than-expected functional diversity. This “functional paradox” could be attributed to unpredictable environmental conditions allowing alternative plant strategies to coexist, leading to high functional, trait, and species diversity (Gross et al., 2024). Horizontal, vertical, and temporal heterogeneity in plant functional types (woody perennials, annual and perennial C3 and C4 grasses, annual and perennial forbs), and diverse biocrust communities make for diverse autotrophic communities in drylands. High spatiotemporal variability in water availability has driven unprecedented species diversity across global drylands, including dynamic mixtures of C3 and C4 grasses, shallow-rooted CAM cacti and agaves, and deep-rooted C3 shrub and tree species, each with specialized water acquisition strategies (Gross et al., 2024). Diverse dryland plant communities in turn support significant diversity in invertebrate and vertebrate herbivore and predator populations. However, the scale-dependent processes through which structural heterogeneity (MacArthur and MacArthur 1961; Wu 2004) and temporal variability due to disturbances (fire and rainfall pulses) drive dryland biodiversity is poorly understood.

Drylands are amongst the most vulnerable ecosystems to climate change (D. Li et al., 2018) with serious impacts on dryland biodiversity. For example, 44-88% of global dryland tree species face significant decline under predicted increases in aridity (Cartereau et al., 2023) along with cascading effects on other taxa. It is furthermore widely established that land degradation in drylands results in substantial loss in biodiversity and ecosystem services (Davies et al., 2012; Lewin et al., 2024; Montanarella et al., 2018.). Grazing, the dominant land use in drylands, can have major impacts on biodiversity that become more pronounced in rangelands with higher aridity, and a drier future (Gross et al., 2024; Maestre et al., 2022b). In addition, US rangelands have experienced significant changes in vegetation species composition with the cover and production of annual plants now exceed that of perennials on > 21 million ha of rangeland managed by BLM, marking a fundamental shift in the ecology of these lands (Kleinhesselink et al., 2023). BLM furthermore needs species-specific products on the extent of Sagebrush (primarily for conservation of endangered Greater sage-grouse, *Centrocercus urophasianus*) and pinyon juniper cover, as well as invasive annual grass cover specifically.

*Questions*

We ask: What are the drivers of biodiversity (functional, phylogenetic, taxonomic) in drylands and how will these be changing? More specifically, we ask: what is the relationship between biodiversity, ecosystem function, carbon stocks and resilience to disturbances (drought and fire)? What are the impacts of climate change (increased aridity) and continued grazing pressure on biodiversity (functional, phylogenetic, taxonomic, etc.)? What is the impact of land cover transformation, land degradation, and cultivation on dryland biodiversity and species of special interest (e.g. endangered species)? What are the impacts of invasive plant species on biodiversity, rangeland condition and water-availability?

#### *B.1.2.3 Sub-Theme: Ecosystem Function*

*Motivation*

As a result of the complexity in community composition and ecosystem structure, dryland ecosystem function is also a complex mosaic of multiple functional groups moving between dormancy and activity over unique diurnal, daily, seasonal, and interannual time scales. The changing ecosystem functional dynamics of dryland ecosystems are affecting large-scale energy, water, and biogeochemical cycles (e.g., carbon, nitrogen, and phosphorus). The rates of change in these ecosystem processes are regulated by biodiversity and ecosystem conditions operating in response to climate anomalies, land and water use practices, and altered intensity and duration of disturbance events.

Drylands can be in a state of relative dormancy following dry events that endure for weeks to several months, until a rain event recharges surface soil moisture driving an initial pulse of heterotrophic respiration and loss of carbon from the ecosystem (Roby et al., 2022; Throop et al., 2020). Depending on the timing and intensity of the rain event and the depth and texture of the soil, root zone soil moisture (RZSM) will next recharged, driving a pulse of ecosystem carbon uptake through photosynthesis or gross primary productivity (GPP) that can continue until critical soil moisture thresholds are reached (Feldman, Feng, et al., 2024b; Z. Fu et al., 2024). Dryland GPP and ecosystem respiration can be co-limited by nutrients such as the macronutrient nitrogen, which can be regulated by nitrogen-fixing biocrusts and C3 tree species (Reed et al., 2011; Vitousek et al., 2013).The balance between GPP, total ecosystem respiration (heterotrophic and autotrophic), and carbon losses through disturbances such as fire, grazing, and erosion ultimately determine the net ecosystem exchange of carbon (NEE) - a critical measure of the contribution of drylands to the global carbon cycle (Ahlström et al., 2015; Poulter et al., 2014).

Dryland vegetation is fundamentally controlled by plant hydraulic considerations through the soil-plant-atmosphere water continuum (SPAC), such as root water uptake and leaf and xylem conductances. Ultimately, leaf water potential, influenced by both soil water availability and vapor pressure deficit, is a strong control of photosynthesis and evapotranspiration rates. For instance, hydraulic and photosynthetic strategies differ greatly between isohydric species that close their stomata relatively quickly under drought, while anisohydric species can keep their stomata open under drought and endure much more negative water potential (Martínez-Vilalta & Garcia-Forner, 2017). Additionally, CAM plants such as dryland succulents avoid stressful atmospheric conditions during the day by photosynthesizing at night and by storing more water to maintain function under stressful conditions. Understanding the complex SPAC in different dryland plants as it controls dryland carbon (C) dynamics is of particularly high priority since we know drylands play a disproportionately large regulator of global trends and variability in atmospheric $CO_2$ concentrations (Ahlström et al., 2015; Humphrey et al., 2018; Poulter et al., 2014) (see section B.1.3). As determined by the SPAC, dryland GPP is predominantly water limited and has been found to be tightly coupled with anomalies in RZSM and ET (Biederman et al., 2017a; Scott et al., 2015). Slight changes in the balance between GPP, NEE, and ET, i.e., ecosystem water use efficiency (WUE), can have large consequences for dryland carbon and water cycling (F. Li et al., 2023).

*Questions*

In seeking to understand how dryland GPP, NEE, and ET dynamics respond to climate change and in-turn contribute to global carbon and water cycling, we have identified key overarching research questions to be addressed by the ARID terrestrial campaign: 1) Across different timescales, what are the dominant mechanisms driving dryland function such as plant hydraulics, leaf level photosynthesis, respiration, and nutrient cycling? 2) To what extent can we use novel remote sensing techniques to track changes in the SPAC and resulting changes in ecosystem function including GPP, NEE, ET, and WUE?; and 3) How has dryland functioning related to GPP, NEE, ET, and WUE changed over time and by functional type and what are the major driving factors (e.g., atmospheric CO2, RZSM, VPD, nutrients)?

We have further identified key sub-questions with direct management implications that could also be targeted as part of the ARID campaign that include: (i) What role has CO2 fertilization played in driving changes in the SPAC and dryland functions GPP, NEE, ET, and WUE? (ii) What role has the timing and intensity of precipitation and temperature-driven increases in VPD played in driving changes in the SPAC and dryland functions GPP, NEE, ET, and WUE? (iii) Can we utilize remote sensing data to improve the estimation of dryland vegetation physiological status (e.g. photosynthetic quantum yield, nutrient, pigment and enzyme concentrations, canopy stomatal and hydraulic properties, vegetation and soil water status, drought stress) for distinct PFT and biocrust communities? (iv) Can we improve retrievals of vegetation function (e.g. carbon, water, and energy fluxes) in drylands, either directly (e.g., thermal estimation of energy balance), or via use of improved structural, physiological, and phenological retrievals in process-based models? (v) Can improvements of decomposition of soil organic matter be improved by night-time monitoring of carbon exchanges and soil moisture levels?

### *B.1.2.4 Sub-Theme: Dryland Geology and Soils*

#### *Motivation*

In drylands, bare rock, sediments, and soils strongly affect remotely sensed signals, facilitating characterization of geologic processes along with measurement of biologic functions. Exposed geology in drylands strongly connects to the wellbeing of humans, wildlife, natural and agricultural ecosystems.

Soils play critical roles in all terrestrial ecosystems, but the capacity to observe large amounts of soil from space-based sensors is rare outside of drylands. Because dryland soils are visible from space and the air, they provide exceptional opportunities to use coupled sensor space-, airborne, and ground-based approaches to 1) improve our quantitative and predictive understanding of dryland soil structure, function, and responsiveness to change and 2) improve our interpretation of soils' contribution to all space- and airborne based terrestrial data. Currently, 10-20% of drylands worldwide are classified as degraded or marginal. When considering that drylands also have the highest growth rate of any ecological zone (18.5%; Gaur & Squires, 2018), these statistics are concerning, as productive soils are a nonrenewable resource on human time scales, and recovery rates are notoriously slow in drylands.

Another way drylands are different from many wetter ecosystems is that they maintain extensive and diverse communities of photosynthetic soils, called biological soil crusts (biocrusts; Fig. B.4). Biocrusts are soil surface communities of mosses, lichens, and cyanobacteria that cover vast expanses of the terrestrial surface and play critical roles in soil stabilization, fertility, water cycling, and carbon exchange with the atmosphere (Elbert et al., 2012; Weber et al., 2022). Biocrusts are found on all of Earth's continents and global estimates suggest biocrusts make up

12% of Earth's land surface and represent up to 10% of desert NPP and > 25% of nitrogen fixation (Elbert et al., 2012; Weber et al., 2022). However, the estimates of biocrust coverage and quantitative understanding of biocrust contributions to global biogeochemical cycles remain highly uncertain, in large part due to a relative lack of options for remotely sensing biocrusts. Increased spatial resolution and advances in sensor diversity can build on past biocrust remote sensing (Havrilla et al., 2020; Karnieli et al., 1999; Potter, 2016; Rodríguez-Caballero et al., 2017; Rozenstein & Adamowski, 2017; W. K. Smith et al., 2019b; Yan et al., 2024), to substantially improve quantitative assessments that monitor, track change, and scale composition and function in biocrusts.

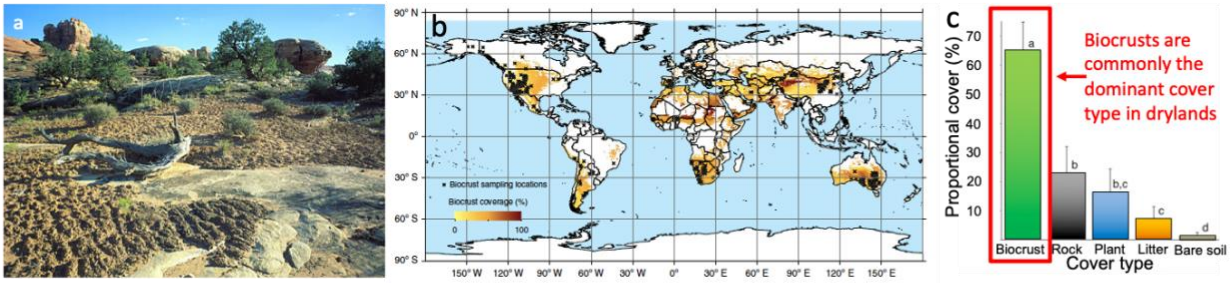


***Figure B.4.*** *(a) Landscape photograph showing biocrusts amidst shrubs, trees, coarse woody debris, and bedrock. Biocrusts are the bumpy, brown and black soil in the interspaces. (b) Estimated biocrust coverage (in %) within each 0.5° × 0.5° - black X's are sampling locations. Biocrusts cover 17.9 million km2: 12.2% of the global terrestrial surface (Rodriguez-Caballero et al., 2018). Spatial coverage was estimated with environmental modeling based on 911-point measurements. (c) Surface cover of the main components of many drylands at a site on the Colorado Plateau USA, showing biocrusts represent the dominant cover type (Torres-Cruz et al., 2018).*

The major global dust sources are found in arid regions. The role of dust in radiative forcing (heating or cooling) is a major uncertainty in Earth System Models (Miller et al, 2006; Mahowald et al, 2011). To address this gap in knowledge, the Earth Surface Mineral Dust Investigation (EMIT) is collecting VSWIR imaging spectrometer data from the International Space Station across the arid regions of the world (Thompson et al., 2023). Field studies of mineral composition and abundance are needed on a more widespread basis for the validation of EMIT results. Dust also contributes to the productivity (Swap et al., 1992) and water balance (Painter et al., 2010) of non-dryland systems and represents an unquantified component of the global carbon cycle (Webb et al., 2012). Climate shifts and land use intensification affect the production of dust, yet the ecological importance of dust remains understudied (Field et al., 2010; Mahowald et al., 2005).

In drylands, heavy rainfall over bare geologic parent material, rock outcrops and sediments, can impart pulses of metallic element concentrations to hydrologic and biologic systems and result in gully erosion events (Nordstrom 2009). Natural sources of acid rock drainage and heavy metal contamination may be amplified in areas of legacy and active mining. Over 500,000 legacy mined areas are estimated in the U.S. with a significant fraction in the arid west; however, no comprehensive or large regional assessments of the impact of natural acidic rock and mined areas to stream water quality have yet been made.

Human activities affecting land, water, and air quality are starkly evident in arid regions. Population growth and shifts in national economies to sustainable energy systems are driving demands for mineral resources, such as the projected needs for lithium to enable a global movement from fossil fuels to electric vehicles and grid-level energy storage (Graham et al.,2021). The largest producers of lithium are in arid regions of Australia and Chile. Competition for such resources to make a “Green Energy Transition” is one example of recent trends in mineral extraction from drylands. Critical minerals, those important to national economies and security and subject to supply disruption, are being identified by national level studies (USGS, 2022) and driving exploration from new sources and studies of extraction from mine waste (Sarker et al, 2022).

*Questions*

We ask: how do soil communities and physicochemical characteristics drive and respond to climate variability and ecosystem change? Further sub-questions capture the specific aspects of soil and geological interactions in dryland systems. These include: What is the extent, composition, and function of dryland biological soil crusts (biocrusts)? What roles do soils play in dictating aboveground structure, function, and response to change? How much inorganic carbon is stored in dryland soils across different soil types, aridity index gradients, and natural versus managed systems, and how vulnerable is the carbon to environmental shifts? What contribution do soil signals play in space-based observations of all terrestrial ecosystems? What are the sources, sinks, causes, and consequences of accelerated topsoil loss and dust in Earth’s drylands? What is the contribution of erosional (aeolian and hydrological) processes to dryland carbon cycling? How do changes in soil reflectance feedback to global climate (e.g., albedo)? How does soil health contribute to dryland ecosystem resilience to change? How do soil environment changes affect the diversity and functions of soil microbial communities?

### *B.1.2.5 Approaches for Ecosystem Structure, Function, and Biodiversity*

Historical remote sensing technologies generally did not provide data with sufficient spatial, spectral and temporal resolution to reliably separate different PFT in measurement of dryland vegetation structure, function, or species composition. However, new sensors and sensor-synergies on airborne and AUS platforms have significant new potential to retrieve separate structural metrics (e.g., density, height and size of individual woody plants, fractional cover, leaf area index, height and biomass of herbaceous PFT), enabling the separation of annual/perennial herbaceous grasses and forbs, woody plants, and biocrust. More work is needed using very high-resolution imagery and diverse passive and active sensors (LiDAR, Radar, VSWIR imaging spectroscopy) to retrieve these structural metrics. Hyperspatial approaches from very high-resolution remote sensing (cm scale) allows quantification of individual tree/shrub biomass, which can be calibrated with ground observations (e.g., TLS, tree rings, forest inventory) (Tucker et al., 2023a).

As a key implication of vegetation structure, wildfire characteristics in drylands (e.g., surface or crown fire) depend on fuel type (herbaceous, woody or litter), fuel amount, and flammability (Kahiu & Hanan, 2018). The challenge for remote sensing of fuels for fires in drylands is that changes in vegetation structure and productivity impacts the probability, propagation and type of fire and therefore needs to be estimated at fine spatial and temporal scales. However, improved remote sensing of productivity, biomass and water content of different PFT provides new opportunities to track fuel loads and thus potential for fire occurrence and type of fire. The ARID campaign will improve high spatial and temporal resolution vegetation structure and productivity retrievals, with green and dry biomass assessments, to provide improved inputs on fuel loads for fire monitoring and modeling.

The ARID field campaign will also focus on improved quantification of dryland vegetation physiological state and function in systems frequently limited by drought and heat stress. Orbiting and geostationary remote sensing assets can contribute to this effort, with geostationary satellites now providing opportunities for near-continuous monitoring of land surface temperatures and greenness and orbiting platforms providing both high resolution and high return-frequency VSWIR imaging. In particular, infrared and microwave retrievals of vegetation water status offer significant potential as input for modeling dryland vegetation dynamics and land surface models, while VSWIR imaging spectrometers can provide enhanced measurement of physiological capacities relating to photosynthesis, evapotranspiration, growth, and phenology.

Enhanced observational capabilities are providing improved characterization of biodiversity across various landscapes (BioSCape campaign 2023) with AVIRIS and LiDAR data. In addition, airborne and UAS image spectroscopy and LiDAR, accompanied with intensive field work during the ARID field campaign can capture plant diversity and structure of PFTs at fine scales. The long-term field data on plant species composition recorded at LTER, NEON, and new supersites will be used to train models to map functional and taxonomic diversity, as well as specific grass and shrub species with the airborne and UAS data. These models will be scaled-up to space-based image spectroscopy (EMIT, SBG, EnMap, Landsat Next) and LiDAR+SAR  (GEDI, NISAR, EDGE) to address science questions across vast drylands.

Satellite remote sensing has been used to estimate GPP, NEE, ET, and WUE dynamics across spatial scales back to the early 1980’s (Fisher et al., 2017; Ryu et al., 2019). These estimates have helped shape our current understanding of dryland function within the context of the broader Earth system (Ahlström et al., 2015; Humphrey et al., 2018; Poulter et al., 2014). However, these key ecosystem functions cannot be directly observed and while the spatial variability of these products is generally consistent with field measurements, their temporal variability suffers from substantial uncertainties and bias, particularly across dryland ecosystems (Biederman et al., 2017a; Verma et al., 2014). New remote sensing techniques including solar-induced fluorescence (SIF) – a factor closely related to GPP and NEE – and land surface temperature (LST) – a factor closely related to GPP, NEE, and ET offer exciting new opportunities to overcome past limitations. Space-borne SIF estimates are currently being provided by the ISS OCO-3, the polar-orbiting OCO-2, and the geostationary TEMPO mission. LST estimates have been provided historically by the polar-orbiting Landsat and MODIS missions and new estimates include the ISS ECOSTRESS and the geostationary GOES mission.

Furthermore, microwave-based measurements of soil moisture and vegetation optical depth (from SMAP) and radar backscatter (from NISAR) can provide insights into plant hydraulics and the various dryland plant water use strategies under water limitation. Ground-, UAS-, and aircraft based GNSS microwave instruments can be further used to investigate plant hydraulic and stomatal conductance strategies across C3, C4, and CAM plants (Feldman, 2024b).

Dryland systems often have heterogeneous vegetation coverage and resulting bare ground and rock surfaces interspersed. Biological soil crusts are also part of the landscape matrix of dryland systems. These surface properties such bare ground fraction, surface mineralogy, digital elevation data, as well as surface biophysical data mentioned in B1.1.5 will provide information to more accurately interpret the surface and soil characteristics from space borne sensors. Remote sensing will be used to identify indicators of soil properties (e.g., soil moisture, organic matter content, nutrients, texture, salt accumulation) along the replicated climatic and ecological gradients (Viscarra Rossel, 2016).

Advances in remote sensing capabilities now provide opportunities to integrate remote sensing data with high-resolution soil biogeochemistry datasets derived from field experiments (multiple temporal and vertical measurements) to identify biological, physical, and chemical indicators of soil health/degradation. Satellite remote sensing observations and advanced analysis techniques such as microwave polar orbit (1-3 days), thermal polar orbit (VIIRS, Landsat, etc.), thermal geostationary (15 minute) (GOES, Himawari, MSG), ISS instruments (ECOSTRESS, OCO3) (1-5 day), rainfall, satellite and ground data fusion (e.g., GPM, PERSIANN-CDR) all provide greater capacity to analyze surface characteristics that influence soil and geological processes.

Recent campaigns have provided information on enhanced mineral observations useful in dryland landscapes. Remote sensing data from NASA's Earth Surface Mineral Dust Source Investigation (EMIT) mission & NASA-USGS Geological Earth Mapping Experiment (GEMx) field campaign are imaging spectroscopy missions that provide spectral information at 8-10 nanometers from the visible to shortwave infrared wavelengths (VSWIR) at ~60 m and ≤15 m spatial resolution, respectively. The prime mission for EMIT and for GEMx (using AVIRIS instruments for the VSWIR and MASTER for the thermal infrared) is to map and understand mineral composition of dryland systems and the archive is available on the NASA Land Processes Distributed Active Archive Center (LPDAAC).

Given the role of drylands in providing forage for livestock and wildlife, quantifying the temporal phenology and spatial variability in green and senescent herbaceous and woody forage is challenging, but is a critical goal for ARID. New sensors and sensor-model fusion approaches have potential to estimate cover and biomass of green and senescent vegetation and thus graze and browse resources for domestic and wild herbivores. ARID will provide opportunities for development of growing season productivity and dry season decline using diverse remote sensing approaches, including high spatial resolution imagery for tree canopy characterization, high temporal resolution HLS or commercial data (e.g., Maxar, Planet) for sub-pixel unmixing.

### *B.1.3 Science Theme 3: Carbon Cycle Interannual Variability and Long-Term Trends*

The ARID field campaign has the potential to substantially increase our understanding of the role drylands play in the global carbon cycle. We ask, what is the contribution of drylands to the mean, trend, and particularly the interannual variability of terrestrial carbon dynamics? What are the underlying drivers of this dryland net carbon exchange? Can we improve quantification of dryland carbon stocks, fluxers, and controls? Addressing these issues is vital for near-term management and policy decisions aimed at climate change mitigation. Namely, it is challenging to distinguish the effects of rapid increases or decreases in anthropogenic carbon emissions, and thus any nation-level or global mitigation efforts, from the rapid increases or decreases in terrestrial net carbon exchange we see in drylands. Disentangling drylands' contributions from interannual climate variability is needed to quantify the effects of climate action.

Currently, about half of anthropogenic carbon emissions are removed from the atmosphere annually by natural carbon sinks, with roughly equal amounts taken up by the land and the ocean. Drylands are characterized as having low organic carbon stocks on a per-area basis - particularly above ground - but high, variable, and poorly predicted carbon fluxes (Biederman et al., 2017a). Many global scale land surface models are presently unable to replicate the mean net or gross carbon uptake or its year-to-year variability at in-situ flux towers (MacBean et al. 2021; Teckentrup et al., 2021; Wang et al., 2022). This is problematic because drylands are vast, and whether they act as a sink or a source of carbon in any given year can strongly influence the temporal variability in the global carbon cycle (Poulter et al. 2014, Ahlstrom et al. 2015; Zhang et al., 2018). Untangling the dryland carbon interannual variability issue will strongly depend on the integrated studies outlined above in the Ecosystem Structure and Function sections, as well as the Climate Variability and Drought section. Whether drylands act as a sink or a source of carbon in any given year strongly influences the interannual variability in the CO2 growth rate.

In addition, given their large land area, drylands are viewed for their potential for afforestation and renewable energy as natural climate solutions. However, poor understanding of the dryland carbon and energy balance prevents prediction of the benefits. Indeed, tree planting can increase carbon uptake and cool the surface (Duvieller et al. 2018), however in drylands, any additional evapotranspiration associated with tree planting efforts may result in unintended consequences such as salinization of soils or depletion of soil moisture. Further, creating dense tree canopies in drylands will increase the risk of fire and other disturbances through the creation of above-average fuel loads - and thus the rapid loss of gained carbon stocks in catastrophic events. Also, adding trees or more vegetation may even warm the surface through reduced albedo compared to the underlying soil (Rotenberg and Yakir 2010, Williams et al. 2021 Sci. Adv., Feldman et al. 2023). Therefore, given water-limitation in drylands, such carbon sequestration benefits of tree planting may only be conferred in some instances (Rohatyn et al. 2022) and the new knowledge created by ARID could help quantify, scale, and forecast the utility or potential problems with these national and global efforts.

The overall question we ask in this theme is: *What is the contribution of drylands to the mean, trend, and interannual variability of terrestrial carbon uptake and what drives these patterns?*

### *B.1.3.1 Sub-theme: Carbon Stocks and Fluxes*

*Motivation*

Persistent challenges remain in understanding the large dryland contribution to the global carbon cycle variability and its uncertainties, as well as in predicting the impacts of carbon cycle responses to climate and land use changes on vegetation biomass, structure, biodiversity and function. Global-scale, process-based land surface and dynamic vegetation models, which form the land component of earth system models, poorly capture dryland gross and net carbon fluxes, with considerable spread across model estimates (MacBean et al. 2021; Teckentrup et al., 2021; Fawcett et al., 2022). The combined effects of short-term pulse events, seasonal to interannual alterations of precipitation patterns, and changes in ecosystem structure, add to the complexity of dryland carbon cycle and fluxes. Furthermore, remote sensing-based production efficiency models that predict GPP and NEE perform notoriously poorly in drylands (Biederman et al., 2017a, Smith et al. 2019).

Although historically challenged by high heterogeneity, new remote sensing tools are revolutionizing the ability to quantify carbon above and belowground in drylands. For example, a recent joining of high-resolution satellite imagery, deep learning, and ground-based allometric relationships showed the power to map tall vegetation across vast areas and estimate carbon stocks in drylands at the individual tree scale (Fig. B.5) (Tucker et al., 2023b). In Africa, 9.9 billion trees were assessed for carbon, including wood, foliage, and root carbon. Comparisons with numerical simulation models for the area found that carbon stocks of trees were underestimated by some models and overestimated by others. Such high-resolution remote sensing of drylands, linked with modeling, has large potential for model benchmarking and for a much improved quantitative understanding of carbon storage and change in drylands. The increase in remote sensing observations that do not rely on greenness to assess carbon cycling, such as SIF, also bring new opportunities to improve estimates of carbon flux for dryland plants that often remain green even while their stomates are closed and carbon uptake is minimal (W. K. Smith et al., 2018; X. Wang et al., 2022; Y. Zhang et al., 2023). Dryland soils too store vast amounts of carbon in organic and inorganic forms and improving quantification of those stocks and their vulnerability to change will be critical in advancing estimates of carbon storage and flux in global drylands (see Section B.1.2.4). New capabilities for high temporal resolution assessment of soil dryland CO2 exchange provide unprecedented opportunities to assess biocrust and soil heterotroph contributions to overall exchange (Darrouzet-Nardi et al., 2015; e.g., as assessed by eddy covariance tower), allowing for the attribution of carbon sources and sinks at the within-ecosystem scale.

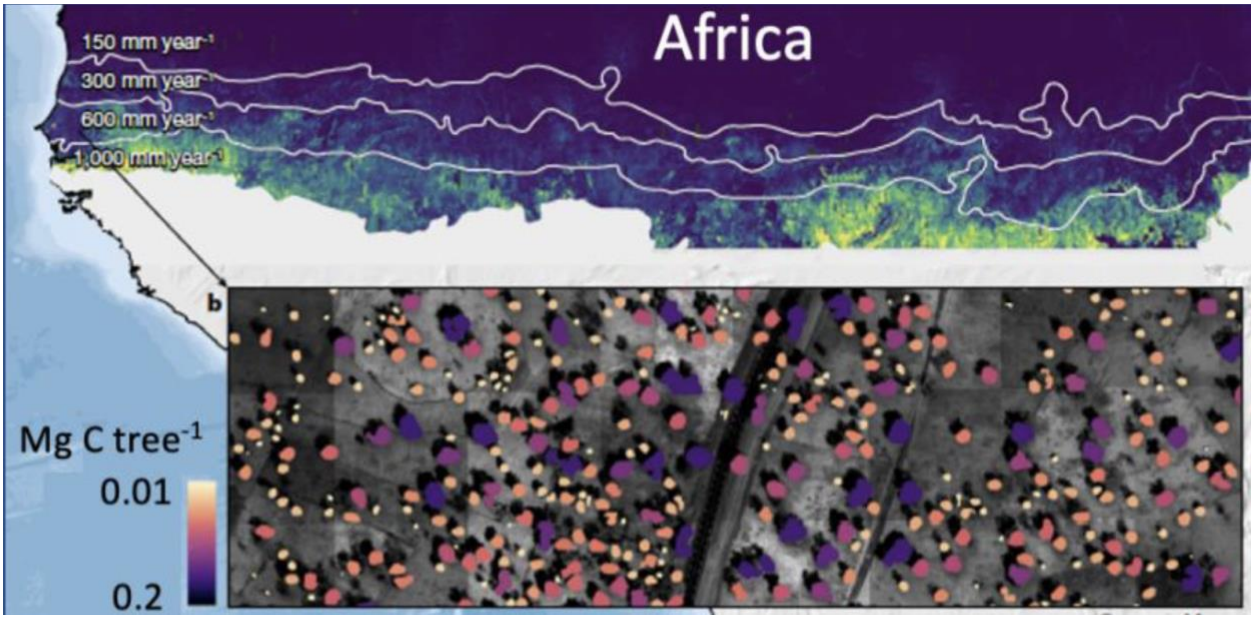


***Figure B.5.*** *Carbon estimates of 9,947,310,221 trees across 9.7 million km2. The study covered much of Africa and estimated woody carbon stock of single trees. Such remote sensing tools would be incredibly valuable not only for*

> *improving estimates and forecasts of carbon cycling in global drylands, but evaluating and prioritizing mitigation and adaptation efforts (Tucker et al., 2023b).*

*Questions*

We seek to answer the following questions: How large are the carbon stocks and fluxes in drylands, how do they vary at sub-annual to decadal timescales, and what is their response through space and time, to drivers of global change? Several more specific questions should be addressed: How vulnerable are dryland carbon stocks and fluxes to global and regional changes in water availability and atmospheric demand, combined with asynchronous plant responses to periods of water stress (B.1.2.1)? How do woody encroachment and desertification change dryland carbon cycling and feedback? What is the relative contribution of different plant functional types and biocrusts to carbon stocks and how are these changing along environmental gradients? What influence do rooting strategies and belowground carbon allocation play in ecosystem carbon storage? What is the potential of carbon capture in dryland vegetation and soils to work as a nature-based climate solution (NCS)? How can remote and in-situ observations be best used to model and quantify carbon stocks and fluxes?

### *B.1.3.2 Sub-theme: Integrated Approach to address Carbon Cycle Theme*

Estimating aboveground biomass in sparse, short stature, heterogenous drylands (e.g. savannas and shrublands) is challenging with space-based sensors and algorithms that are mainly designed for forests. This limits our ability to accurately quantify aboveground carbon stocks. However, new sensors and sensor-synergies offer unprecedented potential to retrieve separate structural metrics (e.g., density, height, and size of individual woody plants, fractional cover, leaf area index, height and biomass of herbaceous PFT), enabling the separation of annual/perennial herbaceous grasses and forbs, woody plants, and biocrust. More work is needed using very high-resolution imagery (Tucker et al., 2023) and diverse passive and active sensors (LiDAR, Radar, VSWIR imaging spectroscopy) to retrieve these structural metrics. Hyperspatial approaches from very high-resolution remote sensing (cm scale) allows quantification of individual tree/shrub biomass and thus high-resolution aboveground carbon storage, which can be calibrated with ground observations (e.g., terrestrial laser scanning, tree rings, forest inventory) (Babst et al. 2018, Tucker et al., 2023).

Production efficiency models that rely on satellite remote sensing inputs cannot partition GPP according to the fine scale plant functional type (PFT) heterogeneity. Satellite remote sensing has been used to estimate GPP, NEE, ET, and WUE dynamics across spatial scales since the early 1980’s (Fisher et al., 2017; Ryu et al., 2019). However, these key ecosystem functions need to be better linked to appropriate PFT’s and information on vegetation state (e.g., photosynthetic capacity), as well as physiological function (e.g., photosynthetic activity). There is co-location of NASA instruments on the ISS, including the OCO-3 and ECOSTRESS, as well as Landsat Next missions and enhanced capabilities of geostationary platforms. These instruments together offer an exciting new opportunity to overcome past limitations, by providing first-time insights into the diurnal to seasonal dynamics of SIF and LST, factors closely related to GPP, NEE, and ET.

In addition, coupling these satellite-based observations with more detailed ground based tower flux data deployed over the diverse dryland landscapes will greatly improve ecosystem process understanding of these observations. Spaceborne instruments such as OCO-2 and 3 can retrieve atmospheric columnar CO2 (XCO2), which can be directly linked to net CO2 exchange via atmospheric inversions. OCO-2 MIP is a useful top-down inversion that uses these satellite retrievals and can estimate the carbon cycle and its variability (Byrne et al., 2023).

Tower flux studies in combination with machine learning approaches can also be used to scale up carbon flux measurements. The NASA ARID campaign provides a unique opportunity to coordinate high resolution airborne and UAV campaigns with in-situ networks of towers and field sites to (i) validate spaceborne biomass and CO2 flux data from current and future satellite missions (e.g. SBG, NISAR, OCO, EDGE candidate explorer mission), and (ii) to better test, develop, and optimize models so that they can more accurately represent and estimate dryland carbon stocks and fluxes. Modeling of carbon stocks and fluxes will be further improved by more accurate quantification of above- vs. belowground biomass ratios and of PFT fraction using satellite and airborne observations (Section B.2.1), calibrated by extensive ground observations (Section B.1.2.1). Finally, focused regional evaluation of in-situ measurements, new aircraft measurements, and/or focused calibration of carbon flux-based remote sensing indices can all contribute to informing both machine learning approaches and top-down inversions (Byrne et al., 2023) that scale dryland carbon fluxes to larger scales. All these fields, airborne, and hyperspatial approaches allow model development, testing, and optimization to improve representation and accuracy of dryland carbon cycling in process-based models.

The ARID field campaign will also focus on improved quantification of dryland vegetation physiological state and function in systems frequently limited by drought and heat stress and affected by fire and other disturbances affecting carbon stocks. In addition, the ARID campaign will enhance our ability to study ecosystem recovery from disturbances that influence the level of carbon uptake across these high stress and frequently disturbed landscapes. Orbiting and geostationary remote sensing assets can contribute to this effort, with satellite constellations and geostationary satellites now providing opportunities for near-continuous monitoring of land surface reflectance and temperatures. Together VSWIR surface reflectance, thermal infrared and microwave retrievals of vegetation water status offer significant potential: (i) to enhance measurement of physiological capacities relating to photosynthesis, evapotranspiration, growth, and phenology; and (ii) as observational constraints to improve the representation of dryland vegetation dynamics in land surface models (W. K. Smith et al., 2019b).

### *B.1.4 Science Theme 4: Social Ecological Systems*

The ARID field campaign will support efforts to study dryland social ecological system dynamics and livelihoods. Many of the products and insights gained from ecosystem process studies, ecosystem structural observations, and climate variability analyses will greatly improve understanding of drivers of change to dryland social-ecological systems and potential impacts to dryland livelihood practices. Research in these social-ecological systems will be conducted jointly with research activities described in the previous sections.

Dryland systems serve as critical water and land resources and habitat for wildlife and livestock, dryland crops, energy production, and other critical ecosystem services supporting rural livelihoods (Briske et al., 2023; McNeeley et al., 2017; Ojima et al., 2015). Dryland systems support livelihoods associated with ranching, farming, forestry, conservation, recreation, cultural amenities, and renewable energy production; and are reliant on key ecosystem processes underlying habitat integrity, biological productivity, water resource quality and quantity, biodiversity, and soil health (White et al. 2000; Lund 2007; Fernández-Giménez et al. 2019; Briske et al. 2023). Dryland livelihoods and agricultural practices operate as tightly integrated social ecology systems (SES) (Havstad et al., 2007; Hruska et al., 2017; Mccollum et al., 2017).

Changes in climatic drivers, such as rainfall and growing season temperatures, influence biodiversity and ecosystem processes that include evapotranspiration, soil moisture retention, biogeochemical cycling (i.e., carbon, nitrogen, and phosphorus), and productivity (Ojima et al., 2015; Polley et al., 2013). Climate regimes within most dryland systems typically have low mean and high variability precipitation patterns associated with high evaporative demand (Asner et al. 2004; Zomer et al. 2006; Havstad et al. 2007; Reeves et al. 2014). Shorter-term climate variability and longer-term climate change in dryland systems are environmental factors that affect temperature ranges and extremes and the frequency, intensity, form, and duration of precipitation events (Holmgren et al. 2006; Polley et al. 2013). These changes in critical ecosystem services act to further constrain the ability of people to meet livelihood needs in these dryland regions. Concerns about these changes are shared across U.S. public entities (BLM, USFS, etc.), tribal land managers, and private land managers.

Land use practices in drylands have also altered ecosystems and have affected water availability, further exacerbating stresses to various livelihoods, such as rangeland management, cropping systems, and tourism (Briske et al. 2023). Extensive systems include pastoral management of various livestock types ranging from sheep and goats to horses, camels, and cattle. Agropastoral and dryland cropping practices are common in semiarid ecosystems supporting small grain cropping such as sorghum and wheat production. Extensive land use also includes wildlife reserves and conservation areas that provide critical habitats and other natural resources such as wood products, browse, and forage. In areas where adequate water resources are available, irrigated cropping systems can be highly productive, though these systems are vulnerable to rapidly decreasing water resources due to ground water depletion or stream flow reductions. Recent deployment of renewable energy projects, especially solar and wind power installations, have increased land competition for rangeland activities and compromised conservation efforts.

Here, we ask: *What are the consequences of changes in drylands for social-ecological systems and what management (e.g., mitigation and adaptation) solutions can maintain the critical services provided by drylands even in the face of change?* This question is addressed through two sub-themes of land management and adaptation and mitigation.

### *B.1.4.1 Sub-Theme: Land Management*

#### *Motivation*

Land-use management in drylands sustain ecosystems and their services, and can safeguard the future of rural livelihoods, agricultural economics, and communities who depend on drylands. Managed lands in drylands include rangelands, dryland cropping, as well as rainfed and irrigated croplands. Drylands also maintain both traditional and alternative energy production and use, mining, recreation, and forest management, including old growth forests. Land management thus encompasses a wide diversity of ecosystems, goals, and challenges. This includes natural resource management of wildlife, endangered species, exotic species, wildfire, and protection of our most cherished cultural resources.

Rangelands constitute the largest land use in the world and most of these fall in drylands (Maestre et al., 2022b). Global rangelands are experiencing significant changes in composition - notably shrub encroachment and invasive annual grasses - with impacts on forage production due to current and future climate changes and interactions with wildfire (Boone et al., 2018; Godde et al., 2020), with significant impacts on livelihoods of more than a billion people (Maestre et al., 2022b). Vast areas of rangelands in US drylands are managed by BLM (1 million km$^2$), USFS (781 000 km$^2$), Tribal authorities (283,000 km$^2$), and private landowners who require spatial data on their natural resources for informed decision making. In particular, US rangelands under BLM management have already recorded significant changes in vegetation composition and structure during the past 30 years with perennial grasses decreasing and shrubs increasing (Kleinhesselink et al., 2023). Wildfire is also a major issue for dryland land managers in the US and around the world and improved options for managing fuels, exotic plant invasion, and stabilization/restoration after fire is of considerable interest. Indeed, US rangelands are predicted to change significantly as the climate becomes warmer, drier, and more variable (Joyce et al., 2013). The ARID field campaign will help us understand the fundamental science behind the changes, the interactions with diverse land uses and management strategies, and the ways these could result in improved remote sensing monitoring capabilities.

Extensive land use also includes wildlife reserves, climate refugia, and conservation areas that provide critical habitat to maintain biodiversity and other natural resources such as wood products, browse, and forage. For example, numerous Tribal Nations are interested in buffalo population restoration and management throughout western US drylands. Many dryland systems also support agropastoral systems where small grain production is interspersed in rangeland systems.

In areas where adequate water resources are available, irrigated and rainfed cropping systems can be highly productive, though these systems are vulnerable to rapidly decreasing water resources due to ground water depletion or stream flow reductions. Irrigated cropland systems constitute the largest consumption of water in drylands worldwide and sustainable water use is imperative. Recent deployment of renewable energy projects, especially solar and wind power installations, have increased land competition for rangeland activities and compromised conservation efforts (Briske et al., 2023) and can also represent high water demand.

Land use management of dryland systems is faced with balancing multiple objectives to maintain biodiversity, land productivity, access to water, and soil health. As management challenges are compounded by climate change and variability of water availability, land managers are faced with limited options and information to support land management decision-making options. Improved ecological forecasting and now-casting of dryland conditions can greatly help practitioners and managers to deal with emerging stresses to ecosystem services.

*Questions:*

How are land and water resources and resource management being affected by drought and aridity changes? How is the composition and productivity of rangelands changing under various management regimes and how are they predicted to change due to climate? How will remote sensing and modeling enhance assessment and forecasting of land resources (e.g., soil moisture, productivity, water use, carbon storage) for various land uses?

Sub-questions include: How will land use further impair wildlife corridors and migratory pathways? How will further fragmentation of conservation and rangeland areas affect biodiversity and conservation goals? How will reduced water availability impact forage production, cropping yields, livestock conditions, and habitat conditions? How will increased thermal stress affect agricultural production of rangelands, cropland, forests, livestock, wildlife, and wildlands systems? How will changes in ecosystem structure affect various land uses across dryland ecosystems? How will cascading effects related to droughts, fires, and extreme rainfall events affect land system conditions? Can invasive species be more effectively managed and how is their extend and effects on ecosystems affected by global change? Can we improve wildfire management success with fuels treatments, managed fire use, and post-fire management activities? How will renewable energy deployment affect ecosystem services? Can multi-sensor observations and modeling improve our ability to assess land management effectiveness? How can land management support resilience and resistance in dryland ecosystems?

### *B.1.4.2 Sub-Theme: Adaptation and Mitigation Strategies*

As dryland systems continue to be affected by climate and land-use changes the need to consider adaptation and mitigation strategies for these regions is crucial and growing. Development of climate resilient management strategies that assess multiple stresses, such as droughts, extreme heat, erosional flooding, dust storms and fires, are needed to enhance coping responses, to develop place-based adaptation and mitigation strategies, and to enable transformative actions when needed. These climate resilient strategies need to incorporate a SES perspective that links ecosystem services to livelihood strategies and to utilize co-design and co-production practices to develop useful options and actions. For example, development of climate resilient management strategies in response to climate change focusing on the onset of rapid drought events that impact ecosystem services and adaptation of various livelihood enterprises to climate changes will provide a conceptual example of the needed transdisciplinary research needed. Providing new insights on how dryland ecosystems are changing will enable development of enhanced management activities to build resilience and sustain livelihoods that would contribute to long-term mitigation to climate change practices and adaptation practices to meet livelihood needs. Within this subtheme, we outline adaptation and mitigation strategies separately.

#### ***<u>Adaptation and resilience of dryland social ecological systems</u>***

*Motivation:*

As changing conditions in dryland regions affect the delivery and availability of key ecosystem services, such as forage, browse, fuel wood, grains, habitat, water resources, the need for adaptation strategies is becoming more urgent. ARID research, in partnership, with various practitioner and decision maker communities can enhance strategies for adapting to these changing conditions. For example, social-ecological systems research studies have incorporated improved drought assessments to enhance drought response strategies co-developed with natural resource managers (Fernández-Giménez et al., 2019; McNeeley et al., 2016). These analyses provide greater insight into the range of coping and adaptation choices to make under various levels of adaptive capacity and the importance for co-development practices to be employed for greater end-user usage. Institutional responses to climate change are often best suited for dealing with emergency situations and isolated events, rather than for slower onset, cumulative, or systemic climate-related problems leading to disruption of ecosystem services. Efforts to enhance resilience of social-ecological systems in these dryland situations are supporting communities to adapt to climatic changes, such as flash-drought, increased fire events, loss of land productivity by engaging with operators at the local scale to enhance delivery of more nuanced information needed to deal with these climate stresses given local adaptive capacity. ARID research observations provided if this field campaign is deployed will provide additional climate information and analytical tools to better inform and enable natural resource managers to cope with water shortages, droughts, and extreme events.

*Questions:*

Key questions related to adaptation and resilience of dryland social-ecological systems: How can dryland ecosystems enhance their resilience in the face of environmental stressors, and what adaptive strategies can local communities implement to build resilience? Several sub-questions include: What factors and information can enhance adaptive capacity of dryland social-ecological systems to meet the challenges to increased aridity? How can ecological forecasting of drought conditions enable decision making of dryland operators and natural resource managers? Have land managers needed to change their strategies in drylands in the past few decades to accommodate change? What drives these changes?

### ***Mitigation options for different dryland livelihood strategies***

*Motivation:*

Dryland systems are being evaluated for enhancing carbon sequestration, and establishing renewable energy sites, such as solar and wind. The land use practices when integrated into livelihood goals and strategies can enhance the socio-economic resilience of many communities. Considerations of impacts on wildlife habitat, water availability, and further fragmentation of landscapes should be addressed in permitting and siting of large-scale renewable energy facilities. Various natural resource management approaches need further development to take advantage of these potentials and to contribute to various livelihood systems, while not undermining cultural norms and needs.

Likewise, mitigation practices that enhance carbon stock stability and reduce carbon losses due to reduced primary productivity or losses due to disturbances such as fires and erosion of soils should benefit from the research conducted above. Including renewable energy siting with greater understanding of extreme events and pulse events will improve long-term suitability of renewable energy facilities.

*Questions:*

Related to human dimension issues in drylands: How will climate variability and water limitations hinder carbon sequestration efforts? What impact will renewable energy development and carbon sequestration practices have on dryland livelihood strategies and ecosystem services in different dryland regions? Sub questions include: How can improved observations enhance our assessment of renewable energy systems and carbon sequestration practices? What increased information can be provided related to changes in ecosystem processes and ecosystem services related to mitigation practices?

### *B.1.4.3 Research Approaches in Support of Social Ecological Systems*

Developing research efforts to address climate change impacts on dryland management practices, the research community will need to assess various land management activities from extensive practices associated with ranching and conservation efforts to more intensive levels associated with irrigated agriculture and other cropping systems. Land use practices in these dryland regions are determined by water availability. Sources of surface water and groundwater sources will often dictate the type of land use practices feasible. Surface water sources are critical for livestock and wildlife management, whereas sources of groundwater may allow for more intensive agricultural systems including irrigated farming. Connections to water sources, such as mountain snowmelt and runoff, that allow for recharge of the aquifers and surface flows are also important resources that are undergoing changes. These factors determine how effective land management practices can be, especially as emerging practices are needed to develop adaptation and mitigation options.

ARID research efforts related to land management practices will rely heavily on the research findings of the science foci described above, especially as enhanced understanding emerges from how climate variability will affect critical ecosystem services, such as water availability, carbon fluxes, ecosystem structure and biodiversity. Through these research efforts connections to land use management practices will be aided by integrative modeling and observations efforts to support assessment of current trends and projections of changes affecting ecosystem services critical to land management decision making.

Coordinated research efforts with natural resource agencies and other organizations will be needed to co-develop usable products for dryland resource managers, across public, tribal, and private entities. ARID research described above has the potential to support land management decision making by improved forecasts of drought events, soil moisture levels, forage and browse availability, land cover and land use patterns, plant functional types, fire monitoring, and ecosystem forecasts. These improvements can enhance the ability to develop integrated model-observation system to support now-casting to forecasting of cropland and forage production (see Grass-Cast model - USDA/ARS); assessment of landscape features that differentiate between active vs non-photosynthetically active vegetation using SiF technologies; integrating soil moisture and actual ET assessments to enable better forage and crop yield estimates; and characterizing the vulnerability of different agricultural practices and other land uses to changes in aridity. This information can be used to guide observational protocol to provide better information on the timing, duration, and intensity of drought conditions in different dryland regions of the world.

These advancements from better understanding of climate variability and water availability dynamics on ecosystem services will aid development of adaptation strategies and assess the effectiveness of mitigation strategies associated with renewable energy deployment and carbon sequestration activities.

## B.2 Overall Study Design

In order to address the critical fundamental and applied sciences questions and observation gaps in Section B.1, we have designed an interdisciplinary, multi-scale ARID field campaign based on our scoping study. The field campaign will leverage existing assets and provide new field and aircraft measurements to scale from point to pixel to plant across field to aircraft to satellite instruments (Fig. B.6). The study domain will span diverse drylands from hyperarid to subhumid, in the US and internationally. The approach includes measurements across spatial, temporal, and spectral axes to observe drylands' highly spatiotemporally heterogeneous landscapes. It also includes methods to inform and be informed by process modeling (Section B.2.2).

We first discuss approaches to address challenges with remote sensing, modeling, and ground observations in drylands in Sections B.2.1 to B.2.3. We emphasize the role of the proposed ARID campaign to address observation gaps. These approaches are general and can be applied across domains and focal areas. Next, in Section B.2.4., we motivate our main dryland domain across four focal study areas within the US, as well as an additional four international sites that include northern Mexico, drylands across southern Africa and Australia, and the Cerrado, Caatinga, and Gran Chaco in Brazil. We discuss specific existing field and aircraft assets we will leverage within these domains in Section B.2.5. We develop our field sampling strategy within these domains in Section B.2.6 using both new measurements and the existing assets. Finally, we discuss our proposed applied science activities in alignment with Earth Science to Action strategy in working with end-users to accomplish land management and mitigation goals.

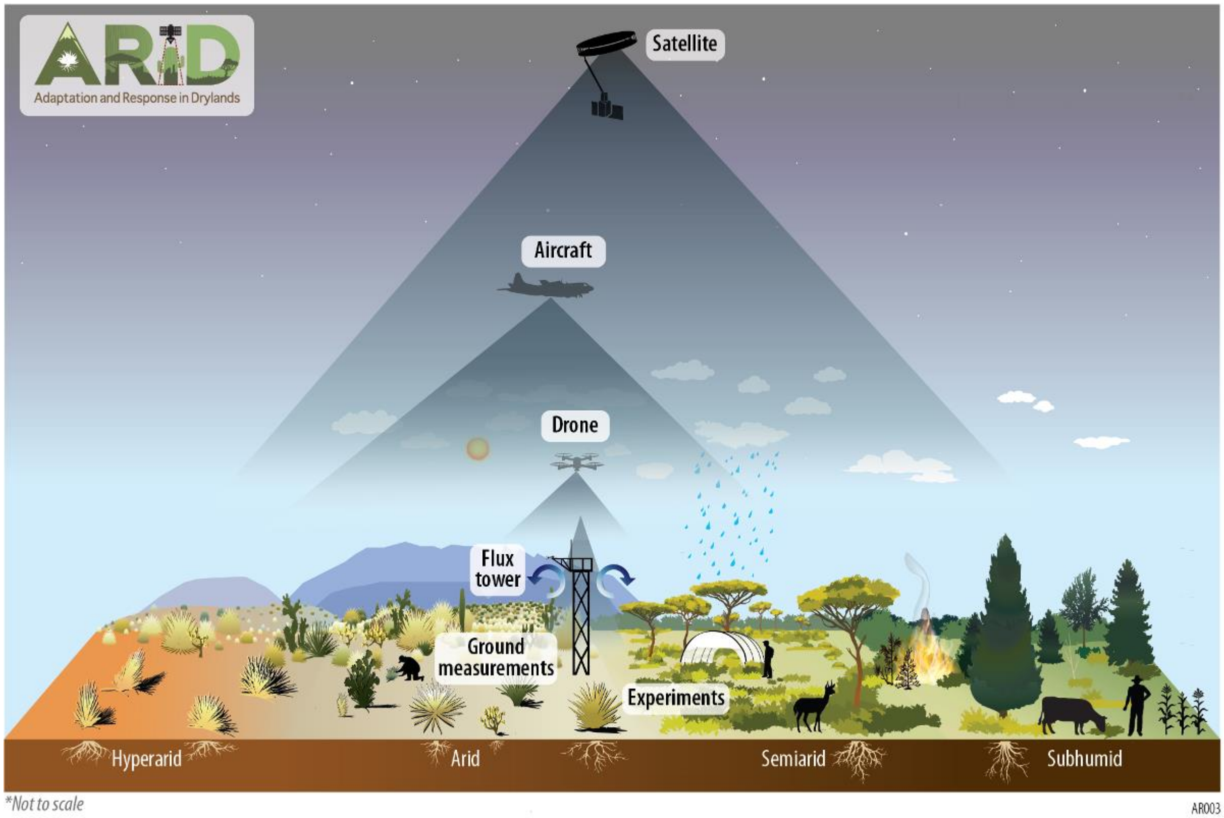


***Figure B.6.*** *ARID will include a nested approach of coordinating measurements in the field, existing and new networks, drones, and aircraft to inform satellite measurements and improve understanding of drylands alongside NASA satellite measurements. Figure B.10 shows how these measurements integrate into and are informed by dryland modeling efforts.*

### *B.2.1 Remote Sensing of Drylands and the critical role of NASA sensors*

Drylands are characterized by high spatial heterogeneity and high temporal variability which pose unique remote sensing challenges (outlined below). This demands fine resolution and frequent observations brought about by acquisitions at multiple scales, from multiple sensors and modalities (SAR, Hyperspectral, thermal) (W. K. Smith et al., 2019b). *NASA's airborne sensors along with the UAS and proximal sensing proposed by ARID will fill observation gaps of physical parameters at the scales required to address the science questions and applications.* For example, the recent Surface Biology and Geology (SBG) High-Frequency Time Series (SHIFT), an airborne and field campaign which took place in a California dryland, is investigating how the frequent acquisition of imaging spectrometer data within a growing season reveals the progression of ecosystem function (Chadwick et al., in revision, 2020a) by characterizing leaf density, leaf chemistry, plant health, vegetation type and other plant attributes, which are often conflated by multispectral proxies for greenness (Myneni et al., 1995).

The historical remote sensing literature on dryland ecosystems, especially on the topic of land degradation, is dominated by the time-series analysis of trends in vegetation greenness (Normalized Difference Vegetation Index - NDVI) (K. J. Wessels et al., 2012), with no differentiation of trees, shrubs, grasses, or biocrust. Such analyses cannot therefore explain the ecological causes of observed trends in greenness leading to speculative conclusions. Contradictory interpretations of "browning and greening" trends have been controversial in the context of desertification/land degradation monitoring (Fensholt et al., 2012; Prince et al., 2007). In contrast, the ARID campaign will use current and emerging airborne, UAS, proximal, and space-based sensors that can fully characterize dryland ecosystems to understand changes in their structure, composition and function, as well as soil moisture and evapotranspiration, extending well beyond only the focus of greenness and its trends. Moreover, accurate estimation of fractional cover of plant functional types (PFTs) at the appropriate scale are fundamental for achieving accurate carbon, water, and energy fluxes from process-based land surface and dynamic global vegetation models (Hartley et al., 2017a). *This will require novel combinations of UAS and airborne VSWIR imaging spectrometers, multispectral infrared sensors, LiDAR, and SAR sensing within a robust scaling framework.*

Addressing the ARID science questions will therefore require a fully integrated and coordinated approach that scales-up observations and process models "from leaf to orbit". This section of the white paper focuses on remote sensing and will (i) demonstrate the critical role of NASA remote sensing data in estimating parameters required to address the ARID science questions, (ii) demonstrate the need for airborne, UAS and in-situ data to sense the required physical parameters and processes at the appropriate higher spatial and temporal scales, (iii) emphasize the need for a multi-scale, multi-sensor, multi-modality approach, (iv) highlight opportunities for novel approaches using proximal sensors on towers and UAS, and (v) highlight the role of ARID in the calibration and validation of remote sensing algorithms to utilize new and future NASA missions.

#### *B.2.1.1 The challenges of remote sensing in Drylands*

Drylands have consistently played impactful roles in remote sensing development. Due to lower cloud cover and higher likelihoods of favorable atmospheric conditions, many remote sensing techniques were developed in drylands, including early retrievals of surface reflectance and estimates of vegetation condition using red and near-infrared bands, which would later become the Normalized Difference Vegetation Index (NDVI) (Tucker, 1979). Despite this important role, our remote sensing capacity for core measurements of ecosystem structure, composition, and function (e.g., productivity, water exchange, etc.) in drylands show severe deficiencies (Biederman et al., 2017b; W. K. Smith et al., 2019b). We highlight the fundamental challenges of dryland remote sensing below:

1. The characterization of dryland composition and function is difficult without very high-resolution imaging spectrometer data due to dynamic mixtures of mineral soil, non-vascular biocrusts, C3 and C4 annual grass and forbs, C3 and C4 perennial grass and forbs, C3 trees and shrubs, and CAM succulents and cacti (Fig. A.2).

2. Traditional remote sensing-based ET and GPP products rely on parameters derived from optical reflectance such as FAPAR, which captures changes in vegetation greenness and photosynthetic capacity and not photosynthesis efficiency. Low confidence in the accuracy of dryland GPP and ET products derived from remotely sensed data limits their use in understanding broad spatial patterns in dryland ecosystem function, as well as their use for benchmarking process-based models (see section B.2.2).
3. The characterization of dryland structure is difficult without very high resolution optical or LiDAR data due to low density and low-stature vegetation (shrubs and grass) and horizontally and vertically complex tree structure and cover.
4. Episodic vegetation activity due to irregular and patchy rainfall is not captured frequently enough by many remote sensing platforms, making it difficult to characterize temporal variability in key structural and functional traits.
5. High exposure of soils and varied geologic substrates often confounds our ability to retrieve biological contributions to spectral reflectance.
6. Photosynthetic soils (biocrusts) can significantly contribute to carbon, water, and nutrient flux in drylands, but these contributions are poorly known since biocrusts are intermixed with both the mineral soil and vascular plants at fine spatial scales.
7. Soil moisture estimates do not capture high spatial-temporal variability required to model water fluxes.

Drylands demand a fine and frequent observation approach using a multi-scale, multi-platform, and multi-sensor framework (Fig. B.7 Parameters and modalities, (W. K. Smith et al., 2019b). *The challenges of dryland remote sensing can be addressed by leveraging the ever-expanding array of current and future space-based NASA missions given reliable calibration and validation with in-situ, UAS, and airborne measurements planned for the ARID campaign (Fig. B.7)*. The multi-scale ARID campaign will also enable the development of improved algorithms and models for estimating essential physical parameters and reliable higher-level products (e.g. GPP, ET) that can be applied globally to more accurately account for drought impacts on dryland ecosystem processes and structure, biodiversity, and the global water and carbon cycle.

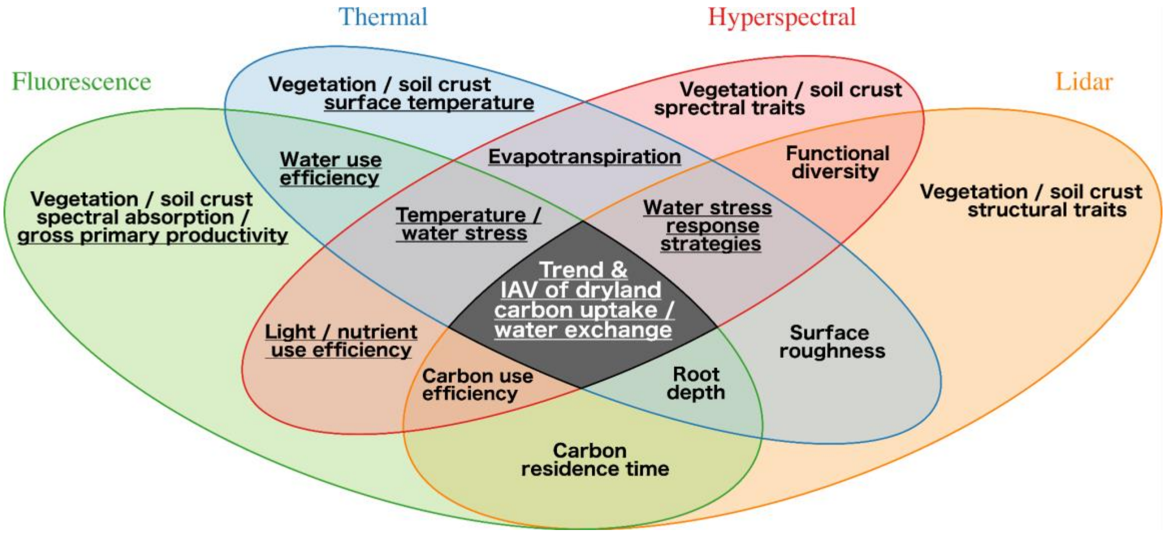


***Figure B.7.*** *Parameters and modalities. Note this figure does not include Microwave sensors which provide additional information related to soil moisture, ecosystem structure, and vegetation water content. This figure is used with permission from (W. K. Smith et al., 2019b).*

### *B.2.1.2 Physical parameters for science questions and applications*

The ARID science theme working groups listed physical parameters that are required to address science questions within each science theme and sub-theme. These are summarized in a modified Science and Application Traceability Matrix (SATM) along with the potential sensors on proximal (e.g. towers), UAS, airborne, and space-based satellite platforms (Appendix F.1). Table B.2 is a summary of the ARID SATM, listing the physical parameters most frequently required by the sub-theme science questions (indicated by subtheme numbers, Table B.1). Successfully observing these parameters during the ARID campaign at the appropriate resolutions would contribute to substantial advancement of dryland science across many focal areas. Some parameters have established remote sensing sensors and techniques (e.g. vegetation fractional cover), while others, such as, soil carbon and belowground biomass remain a significant challenge. Parameters such as GPP and ET are remote sensing-based model outputs requiring remotely sensed input parameters including chlorophyll fluorescence, surface temperature, precipitation, soil moisture, and PFT fractional cover (also included elsewhere in the SATM).

The estimation of most physical parameters requires multiple sensors on multiple platforms (Fig. B.6). Key to the scaling-up process are (i) proximal remote sensing instruments installed at field sites capable of provide near-continuous, high spatial resolution measurements; (ii) UASs that augment the field measurements and provide reference data beyond the extent of field plots; (iii) airborne NASA sensors covering larger areas for higher level product generation with fine spatial resolution; and (iv) satellite platforms that provide measurements that can be validated, trained, and integrated into models to provide global coverage of key physical parameters (Fig. B.7). The NASA drylands field campaign will enable an effective scaling-up process and uncertainty estimation to unlock the full potential of remote sensing data to address critical science questions. ***Below we highlight some of the critical physical parameters required to address ARID science questions and how the ARID field campaign will improve their estimation.***

***Table B.2.*** *Select rows of the ARID Science and Application Traceability Matrix (for full SATM, see Appendix F.1). Selected physical parameters required to address science sub-themes (numbered in footnotes) and the remote sensing sensors available on proximal (e.g. towers), UAS, airborne and spaceborne platforms. Names of sensors are given in the footnotes of this table. The table lists the current and future sensors that can make the most significant advances and does not list all available options. Science Sub-themes: 1.1 Water availability, 1.2 Dryland climate variability: Pulses and Drought, 1.3 Fire, 1.4 Land-Atmosphere interactions, 2.1 Vegetation structure and Heterogeneity, 2.2 Biodiversity, 2.3. Ecosystem Function, 2.4 Dryland Geology and Soil Processes,* *3.1 Carbon stocks and fluxes, 4.1 Land Management, 4.2 Adaptation and Mitigation.*

| **Physical Parameter or process / Observable** | **Science theme number** | **Comment: need and current status** | **Near surface and Proximal** | **UAS** | **Airborne** | **Spaceborne/ Satellite** |
|---|---|---|---|---|---|---|
| Soil Moisture (SM) | 1.1, 1.2, 2.1, 2.2, 2.3, 2.4, 3.1 | Poorly estimated for the subsurface/root zone; identified need for higher resolution (10 m to <1 km) estimates<br>Driver for local models<br>Validation/diagnostic for water cycle in LSMs/ESMs | Soil moisture network, GNSS receiver above and below canopy | Thermal | UAVSAR / AirMoss, SMAPEx; NOAA airborne gamma NOHRSC, AirSWOT, | SMAP, ECOSTRESS, Hydrosat, SBG, SMOS, NISAR, Sentinel1, |
| Evapotranspiration (ET) Level 4 model output | 1.1, 1.2, 1.3, 2.1, 2.2, 3.1 | Calibration/Validation for model estimates of ET, E and T. Open ET models can use multiple RS inputs | Infrared Thermometer (IRT): Apogee SI-111-SS<br>Thermal Camera: FLIR A700f; ICI P-Series | Thermal | HYTES, MASTER | ECOSTRESS, Landsat, Hydrosat, SBG |
| Surface temperature (ST) of soil vs. plants | 1.2, 1.4, 2.3, 3.1 | Input to ET, GPP, NEE, plant stress | Infrared Thermometer (IRT): Apogee SI-111-SS<br>Thermal Camera: FLIR A700f; ICI P-Series | Thermal | HYTES, MASTER | ECOSTRESS, Landsat, Hydrosat, SBG |
| Vegetation fractional cover of Plant functional types (PFT) | 1.3, 2.1, 2.2, 2.3, 3.1 | PFT: Trees, shrubs, grasses, forbs, biocrust. Grass biomass poorly estimated.<br>Local calibration/ initialization for models<br>DGVM constraint<br>Trait information | PhenoCam; Terrestrial Laser Scanning (TLS) | Multi-spectral Lidar | AVIRIS-NG, NEON-AOP, G-LiHT, LVIS | Landsat, SBG, EMIT |
| Vegetation height: Grass, shrubs, trees | 1.3, 2.1, 2.2, 3.1 | Shrub (<3m) biomass poorly estimated with optical and space-based LiDAR algorithms.<br>Individual tree heights can be extracted using SFM from airborne imagery.<br>Potential constraint for data assimilation | Terrestrial Laser Scanning (TLS) | Structure from motion (SfM); Lidar | Discrete Lidar, G-LiHT<br>LVIS, UAVSAR, AVIRIS-NG, NEON-AOP | NISAR, S1, GEDI, IceSat2, WorldView, |
| Above ground biomass: grass | 1.3, 2.1, 2.3, 2.2, 3.1 | Grass biomass poorly estimated with optical | Terrestrial Laser Scanning (TLS) | Multi-spectral; Lidar | AVIRIS-NG, G-LiHT, NEON-AOP | EMIT, Landsat NEXT, HLS, SBG, |
| Above ground biomass: shrubs and trees | 1.3, 2.1, 2.2, 3.1 | Shrub biomass is poorly estimated with optical and space-based LiDAR algorithms.<br>Calibration/Validation for model estimates of NPP<br>Potential constraint for data assimilation | Terrestrial Laser Scanning (TLS) | Lidar | Discrete Lidar, G-LiHT<br>LVIS, UAVSAR, AVIRIS-NG, NEON-AOP | NISAR, S1, GEDI, IceSat2, EDGE, STV |

| | | | | | | |
|---|---|---|---|---|---|---|
| Photosynthetically active vegetation fractions of PFT’s | 1.3,2.3, 3.1 | Essential to make a distinction between active and non-active components | Phenocams, spectrometer (e.g., Ocean Insight FLAME VNIR spectroradiometer) | Hyperspectral, Multi-spectral | AVIRIS-NG, LVIS | EMIt, EnMAP, SBG, Landsat |
| Vegetation moisture content | 1.3, 2.3 | | TLS; dual GNSS receivers installed above and below the canopy | Hyperspectral, Multi-spectral, SAR | AVIRIS-NG, UAVSAR | S1, NISAR, EMIT, EnMAP, SBG, Landsat 8,9,10, NEXT, HLS, PACE |
| Invasive species: tree, grass, shrub, forbs | 1.3, 2.1, 2.2 | Individual Invasive plants species could be spectrally distinguished | Hyperspectral: ASD FieldSpec; Spectra Evolution RS-3500, 8800, PSR+ | Hyperspectral | AVIRIS-NG | EMIT, EnMAP, SBG, |
| Solar-induced Fluorescence (SIF) | 1.2, 2.3, 3.1 | | Ultra-hyperspectral VNIR: PhotoSpec; FluoroSpec; FloX Box | Ultra-hyperspectral VNIR | FIREFLY, CFIS | OCO-2,3, TEMPO |
| Fraction of photosynthetically active radiation absorbed (FAPAR) per PFT | 2.3, 3.1 | Input to carbon-flux models | Hyperspectral, Multi-spectral | Hyperspectral, Multi-spectral | AVIRIS-NG | EMIT, EnMAP, SBG, GOES-R |
| Gross Primary Production: Trees, grass, shrubs. Level 4 model output | 1.2, 1.4, 2.3, 3.1 | Modeled variable, require FAPAR of PFT and meteorological variables as input | Hyperspectral; Thermal; SIF | FAPAR of PFTs derived above | FAPAR of PFTs derived above | FAPAR of PFTs derived above, GOES-R |

Abbreviations: S1: Sentinel1, SBG: Surface Biology Geology, AirMOSS: Airborne Microwave Observatory of Subcanopy and Subsurface, UAS-LS: Uncrewed AirborneSystem - Laser Scanner, FIREFLY: fluorescence imaging of red and far-red light yield, CFIS: Chlorophyll Fluorescence Imaging Spectrometer, FireSense is multi-band microwave, visible to thermal infrared observation program,, UAVSAR: Uninhabited aerial vehicle synthetic aperture radar, SMAP: Soil Moister Active Passive, SMAPEx: SMAP Experiments, NOHRSC: National Operational Hydrologic Remote Sensing Center, AirSWOT: Air Surface Water and Ocean Topography, HyTES: Hyperspectral Thermal Emission Spectrometer, MASTER: MODIS/ASTER airborne simulator, AVIRIS-NG: Airborne Visible-Infrared Imaging Spectrometer - Next Generation, NEON-AOP: National Ecological Observatory Network-Airborne Observation Platform, G-LiHT: Goddard's LiDAR, Hyperspectral & Thermal Imager, LVIS: Land, Vegetation, and Ice Sensor, ECOSTRESS: Ecosystem Spaceborne Thermal Radiometer Experiment on the International Space Station, SMOS: Soil Moisture and Ocean Salinity, NISAR: NASA-ISRO SAR, EMIT: Earth Surface Mineral Dust Source Investigation, GEDI: Global Ecosystem Dynamic Investigation, STV: Surface Topography and Vegetation EnMAP: Environmental Mapping and Analysis Program, GOES: Geostationary Operational Environmental Satellite

*Carbon stocks and fluxes partitioned among plant functional types (PFT)*

The reliable estimation of carbon stocks and fluxes, require their partitioning among plant functional types (PFT) including annual grasses and forbs, perennial grasses and forbs, shrubs, trees, biocrust and litter, as well as their photosynthetically active vs. inactive (e.g. litter) fractions. Accurate estimation of fractional cover of PFT at the appropriate scale is fundamental to parameterizing and reducing the uncertainty of carbon (GPP) and water (ET) flux models (Hartley et al., 2017a). In particular, assessing changes in the fractional cover and biomass of woody shrubs versus grass is essential for monitoring shrub encroachment in the US (Kleinhesselink et al., 2023) and across global rangelands, driven by a combination of $CO_2$ fertilization, changing rainfall frequency and intensity, and overgrazing (Stevens et al., 2017).

Aboveground woody biomass and carbon stocks have been poorly estimated for drylands by traditional remote sensing products originally developed for forests (Bastin et al., 2017). However, recent advances in AI, specifically deep learning, to extract individual trees from very high-resolution drone and airborne imagery, as well as continent-wide commercial satellite imagery (e.g. Maxar's WorldView and PlanetScopeLANET) are enabling the estimation of carbon in dryland trees (Tucker et al., 2023) (Fig. B.5). ARID's integration of airborne and UAS measurements can serve as training data to develop area-specific convolutional neural network models that will automatically extract individual trees (and show promise for shrubs) to estimate carbon density and its changes using commercial satellite imagery. Aircraft- and UAS-based assessment of ecosystem dynamics allow a more detailed spatial view than traditional satellites (Pervin et al., 2022; Villarreal et al., in review) and has shown utility for algorithmic development, particularly when paired with coordinated field campaigns (Chadwick et al., 2020). In a multiscale, multi-step process, PFT fraction can first be estimated with UAS-based LiDAR (ULS) combined with very-high resolution (5cm GSD) multi-spectral or imaging spectrometer data, assisted by AI and advanced image processing (Sankey et al., 2018). The UAS-based biomass and fractional cover estimates of the PFT's will be used as reference data to develop models that predict these variables using airborne imaging spectrometer (AVIRIS) and LiDAR data (LVIS and/or discrete LiDAR from NEON AOP) acquired contemporaneously over the UAS data and across the larger study sites. The airborne-derived estimates of biomass and fractional cover of the PFT's in turn serve as indispensable and reliable calibration and validation for model development to predict these variables with space-based imaging spectrometer data (e.g. EMIT, SBG) and SAR data (Sentinel 1, ALSO2/4 or NISAR). *The ARID field campaign will significantly improve the estimation of fine-scale fractional cover and biomass for different dryland PFTs which will transform the modeling of carbon fluxes (GPP and NPP) and stocks in drylands* (Hartley et al., 2017b; M. O. Jones et al., 2021; Kleinhesselink et al., 2023; Robinson et al., 2019; Shi et al., 2022).

Existing rangeland monitoring applications by partners BLM (e.g. Rangeland Analysis Platform, Climate Engine) and USGS (Rangeland Condition Monitoring Assessment and Projection, RCMAP) currently use estimates of PFT from Landsat to track rangeland condition (M. O. Jones et al., 2021; Kleinhesselink et al., 2023; Robinson et al., 2019; Shi et al., 2022). More accurate estimations of 16-day PFT and grass biomass with Landsat or SBG can feed directly into existing applications. In this manner, the ARID field campaign can revolutionize the PFT fractional cover products that are already embedded in decision making workflows of agencies and tribal authorities.

*Soil moisture (SM) and vegetation water content (VWC)*

Quantifying the amount of water stored within dryland soils, at plot-to-regional scales, is one of the most important aspects of ecosystem analysis and prediction, yet remains a considerable challenge for remote sensing and modeling communities. The NASA SMAP mission currently offers near daily retrievals of soil moisture, which is appropriate for evaluating pulse dynamics. It has two advantages in drylands, including lower retrieval error because of lack of an overlying vegetation layer and scattering (Chan et al. 2016, Colliander et al. 2019), as well as a deeper sensing depth due to drier soils and deeper emission (Moghaddam, Saatchi et al ; Feldman et al. 2023). However, its spatial resolution is particularly limited at 30km. It is therefore essential to leverage aircraft measurements, such as from NASA Scanning L-band Active/Passive (SLAP), flights to retrieve soil moisture over 100m scales to quantify its spatial distribution in relation to drylands' heterogeneous vegetation distributions, elevation, and proximity to other water sources. Such aircraft measurements can be co-located with soil moisture networks, such as measurements at Mesonet, NEON, and/or AmeriFlux stations, which allows validation and further understanding of soil moisture spatial dynamics. Furthermore, these measurements tend to be limited to the upper soil layers and new measurements of deeper soil layers should be explored in the field. Terrestrial water storage (TWS) provided by the NASA Gravity Recovery and Climate Experiment (GRACE) can provide deeper soil moisture information. GRACE indicates especially strong TWS losses in drylands resulting from climate change coupled with direct human activity including land cover changes and unsustainable irrigation practices (L. An et al., 2021). However, the vertical representation of TWS is uncertain and low spatial resolution can be prohibitive, thus requiring use of soil moisture stations with measurements at a range of depths (Rodell et al. 2001). NISAR will also provide a soil moisture product that will be calibrated and used in the ARID campaign.

Vegetation water content information can additionally be retrieved through microwave active and passive measurements such as from NISAR and SMAP, especially through the retrieved parameter vegetation optical depth (VOD) (Konings et al., 2019). These VWC retrievals experience some of the same challenges as soil moisture, with the addition that it is unclear how much sparse vegetation plays a role in the VOD retrieval. Such challenges can be tested with GNSS sensors and airborne measurements from SLAP that have finer resolution (Feldman, 2024a).

*Gross Primary Productivity (GPP), Evapotranspiration (ET) and Water Use Efficiency (WUE)*

GPP, ET, and WUE are key processes that link the water, carbon, and energy cycles, especially in drylands where water is the dominant constraint on vegetation productivity (Fisher et al., 2017). These parameters are key for addressing numerous ARID science questions related to the trends and interannual variability in carbon uptake, water availability along the soil-plant-atmosphere continuum (SPAC), rangeland resource availability, crop productivity and water stress, and dryland responses to drought and heatwave events (Table B.1). Satellite remote sensing is unmatched in spatiotemporal coverage and has been used to estimate GPP, ET, and WUE dynamics across spatial scales back to the early 1980's (Fisher et al., 2017; Ryu et al., 2019). These estimates have helped shape our current understanding of dryland function within the context of the broader Earth system (Ahlström et al., 2015; Humphrey et al., 2018; Poulter et al., 2014). However, these key ecosystem functions cannot be directly observed and thus rely heavily on physical parameters derived from the optical domain of the electromagnetic spectrum, such as the fraction of absorbed photosynthetically active radiation (FAPAR), which provide information on vegetation state (e.g., photosynthetic capacity), but not physiological function (e.g., photosynthetic activity). Operational GPP and ET products based on these data are widely used and include the NASA MODIS GPP and ET products, and more recently the NASA SMAP Level 4 C products. Although the spatial variability of these products is generally consistent with field measurements, their temporal variability suffers from substantial uncertainties and bias, particularly across dryland ecosystems (Biederman et al., 2017a; Verma et al., 2014). For example, across the drylands of southwestern North America the MODIS ET and GPP products were only able to account for 20–30% of the interannual variation in measured GPP (Biederman et al., 2017a).

Co-location of NASA instruments, including the NASA OCO-3 and ECOSTRESS missions, offers an exciting new opportunity to overcome past limitations, by providing first-time insights into the highly dynamic nature of solar-induced fluorescence (SIF) and land surface temperature (LST) – factors closely related to GPP and ET. By providing information directly related to vegetation physiological function, SIF and LST offer a significant advance relative to traditional reflectance-based parameters such as FAPAR (Farella et al., 2022; Y. Sun, Gu, et al., 2023; Y. Sun, Wen, et al., 2023). SIF is a direct measure of the light re-emitted from chlorophyll during photosynthesis and thus represents a direct proxy for photosynthetic activity (Y. Sun, Gu, et al., 2023; Y. Sun, Wen, et al., 2023). LST can be integrated with measurements of air temperature to infer changes in stomatal conductance and rates of canopy transpiration, processes fundamental to both GPP and ET (Fisher et al., 2017; Volk et al., 2024). Thermal sensors have been included on satellite platforms for decades, and LST has been used as a critical input to a variety of models including semi-empirical / physical or surface energy balance models that estimate ET, e.g., in the Open ET application managed by USDA (Volk et al., 2024). While these past missions continue to provide invaluable data, we need complementary sub-daily observations since SIF and LST vary at high temporal frequency – especially across drylands – in response to high temporal frequency changes in biophysical factors.

SIF and LST measurements from towers, airborne, and space-based platforms have tremendous potential for more direct measurements of dryland physiological function. Drylands are an ideal testbed to further explore SIF-GPP and LST-ET relationships across spatial and temporal scales. SIF can be measured near-continuously from towers, regularly with VSWIR imaging spectrometers on UAS and with FIREFLY and CFIS sensors on aircrafts, and at multiple times per day with OCO-2, OCO-3, and the geostationary TEMPO platform (Table B.2). LST can also be measured near-continuously from towers, regularly with thermal imagers on UAS and with MASTER and HyTES sensor on aircrafts, and multiple times per day from space with the ECOSTRESS, SBG, and the HydroSat platforms (Table B.2). The integration of these cutting-edge data can help to revolutionize the accuracy of space-based GPP, LST, and WUE estimates across various spatiotemporal scales required to address urgent dryland science questions.

### *B.2.1.3 Proximal Sensing*

Proximal sensing, or fixed plot to site scale sensors, provides high spatial, temporal, and spectral resolution measurements enabling a more direct link to dryland field measurements including flux measurements from eddy-covariance towers (Fig. B.8) (Gamon, 2015; Schimel et al., 2019). Proximal sensing can be used to validate satellite measurements and products (Y. Zhang et al., 2023), drive and test the representation of ecosystem processes in models (Magney et al., 2019; Raczka et al., 2019), reveal spatial heterogeneity in fluxes at the field level (Javadian et al., 2022, 2024; Magney et al., 2019) and scale field-level measurements to the landscape as observed by spaceborne instruments (Farella et al., 2022) thereby providing unprecedented insights into the processes that drive ecosystem fluxes (Pierrat, Z. et al., in review). Proximal sensing will be a critical component of the ARID campaign since we plan to deploy a suite of sensors across existing flux tower networks to fully link remote sensing and flux measurements in space and time and enable mechanistic insights into the link between remote sensing signals and biologic processes (Gamon, 2015; Schimel et al., 2019).

Specifically, as a part of the ARID field campaign, we propose five different types of proximal sensing that cover ecosystem structure, composition, and function: visible-to-shortwave infrared spectral reflectance (VSWIR), solar-induced chlorophyll fluorescence (SIF), thermal infrared emittance (TIR), microwave backscatter (WVB), and light detection and ranging (LiDAR) (Table parameters). Early efforts have effectively deployed: 1) proximal SIF and LiDAR measurements to show the direct connection between SIF and GPP at the AmeriFlux Niwot Ridge dry mixed conifer flux site (Magney et al., 2019); and 2) proximal thermal and structure from motion (SfM) measurements to show the direct connection between canopy temperature and water stress at the AmeriFlux Mount Bigelow dry mixed conifer flux site (Javadian et al., 2022, 2024). ARID also intends to deploy mobile, low-cost towers that combine the aforementioned spectral sensors and full suite of meteorological and eddy covariance (Wong et al., 2023a) measurements to capture pulse dynamics or experimental treatments. Such mobile towers will provide significant opportunities for innovation. These data have the potential to resolve three key questions: What is the scale dependence (spectral, spatial, temporal) of dryland ecological processes and fluxes?; What are the underlying physical and biological drivers of observed remote sensing signals?; How can new technologies, synergies, algorithms and models developed at the site advance our understanding of global dryland ecology at scale?

The ARID campaign should invest in proximal sensing to address many of the remaining barriers to entry, the standardization of products, and the coordination of efforts (Gamon, 2015; Schimel et al., 2019), following the example of the FLUXNET community (Pastorello et al., 2020). ARID can be the driving force in support of a first of its kind coordinated dryland proximal sensing network.

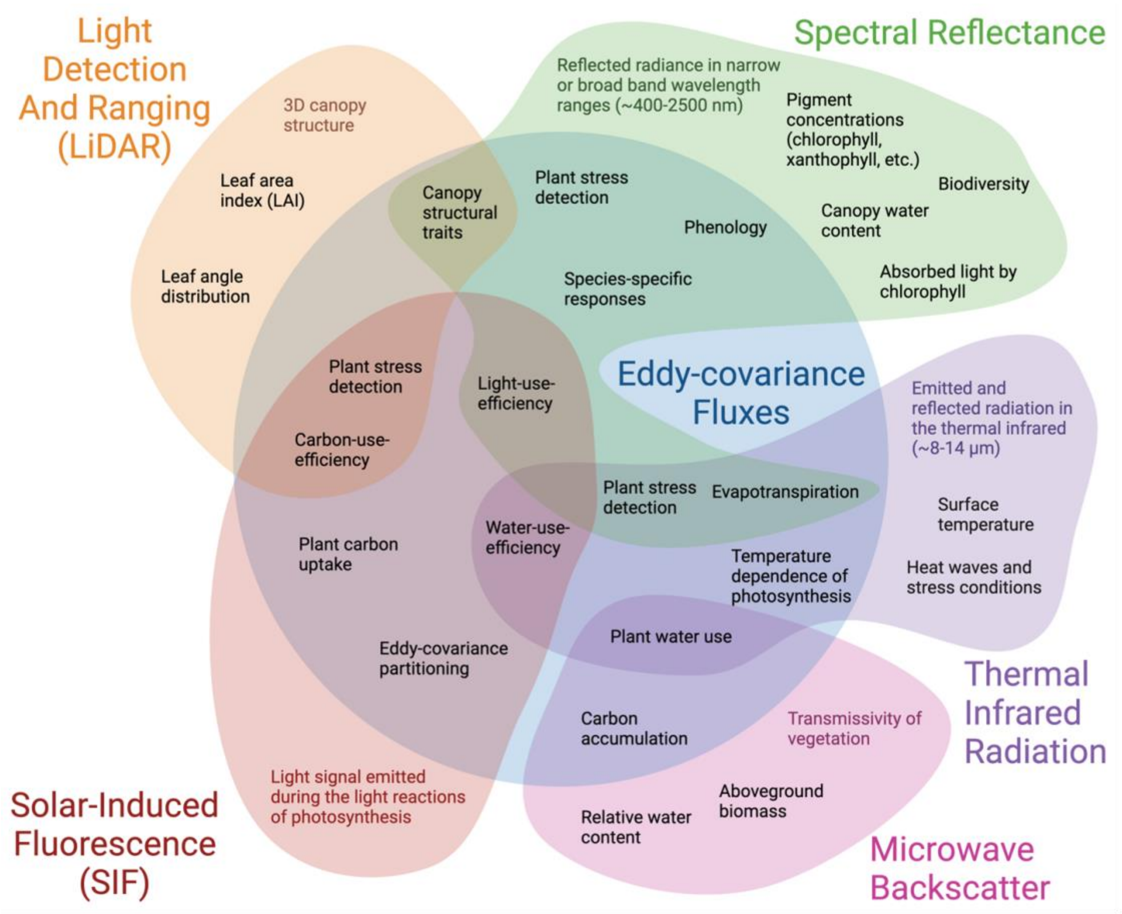


***Figure B.8.*** *Overview of synergies between proximal remote sensing and eddy-covariance flux data. Major proximal remote sensing techniques shown as different color overlapping polygons. A description of each technique is shown in colored text and key physical parameters associated with each technique and across multiple co-located techniques are listed in black text. Image from (Pierrat, Z. et al., in review).*

### *B.2.1.4 Uncrewed Aircraft Systems (UAS) Remote Sensing*

UAV-based assessments of ecosystems allow finer spatial scale and more frequent data acquisition than satellites (Z. Sun et al., 2021; Villarreal et al., In Review) and have shown utility for remote sensing algorithmic development, particularly when paired with coordinated field campaigns (Chadwick et al., 2020b). UAS platforms and sensors (multi-spectra, LiDAR, thermal, and image spectroscopy) are evolving very rapidly and providing scientifically robust data that fill an observation scaling gap between in-situ and airborne data, at ever-reducing costs.

With their extremely high spatial resolution (GSD 5 cm to 1m), UAS data will play a key role in scaling up field measurements to airborne (1-15m GSD) and space-based measurements (>10m GSD)(Fig. B.9). For example, the UAS-derived very high resolution fractional cover of various PFTs can be generated from the fusion of image spectroscopy and LiDAR data (Sankey et al., 2018), which will be used to develop mixture models that accurately estimate these fractional covers with AVIRIS data over vast areas (see details above) (Pervin et al., 2022; Villarreal et al., In Review) (Fig. B.9). Characterizing the distribution of PFTs in drylands is critical given these ecosystem's high spatial heterogeneity. During the ABoVE field campaign, researchers demonstrated the indispensable role of UAS in measuring fine-scale, low-stature vegetation structure (similar to dryland vegetation) using RGB cameras and "structure from motion" (SFM) photogrammetry, that could not be captured with airborne and satellite data (Assmann et al., 2020; Cunliffe et al., 2020; Yang et al., 2022). The other significant benefit of UAS is the flexibility of on-demand data acquisition which can be as frequently as required to capture rapidly-changing variables during diurnal cycles or pulse dynamics following rainfall events. *UAS will play a key role in the ARID field campaign to capture the high spatial heterogeneity at flexible on-demand intervals to investigate temporally variable PFT phenology and function during rapid green-up, senescence or pulse events.*

Other useful applications of note are using a combination of sensors mounted on UAS instruments to derive products like GPP and ET (Morgan & Caylor, 2023), which at the higher spatiotemporal resolutions of UAS, can advance GPP and ET retrievals from satellite platforms.

University PI's and commercial service providers have been using UAS with less restrictions to collect data on government sponsored projects, e.g. in ABOVE (Assmann et al., 2020; Cunliffe et al., 2020). However, UAS use within US government agencies has been heavily restricted, leading to the grounding of all BLM and USGS DJI drones in 2019. (However, indications are that these limitations may be resolved in the next few years as US-built UAS with sufficient capability become more affordable.) Other ARID partners, e.g. NEON managed by Battelle, have developed significant drone remote sensing capabilities (including sensor calibration) and are not impacted by the DJI security concerns and grounding.

The ARID mission plans to make extensive use of drone-based data collected by PI's, private service providers, and government partners (e.g. BLM and USGS). *We thus anticipate PI's and non-government partners (e.g. NEON managed by Battelle) will collect the majority of the UAS data with its limited administrative burden compared to federal government agencies.* We furthermore plan to use standardized drone data processing/calibration workflows and the ARID cloud environment to process all drone data, similar to recent airborne data processing developments (see Section D) (e.g. SHIFT, BioScape). ARID cloud environment will support hierarchical data storage, include file and archive version control, provide digital object identifiers (DOIs) for data and use an API for data search, discovery and retrieval, similarly to CyVerse Open Science Workspace (Yang et al., 2022).

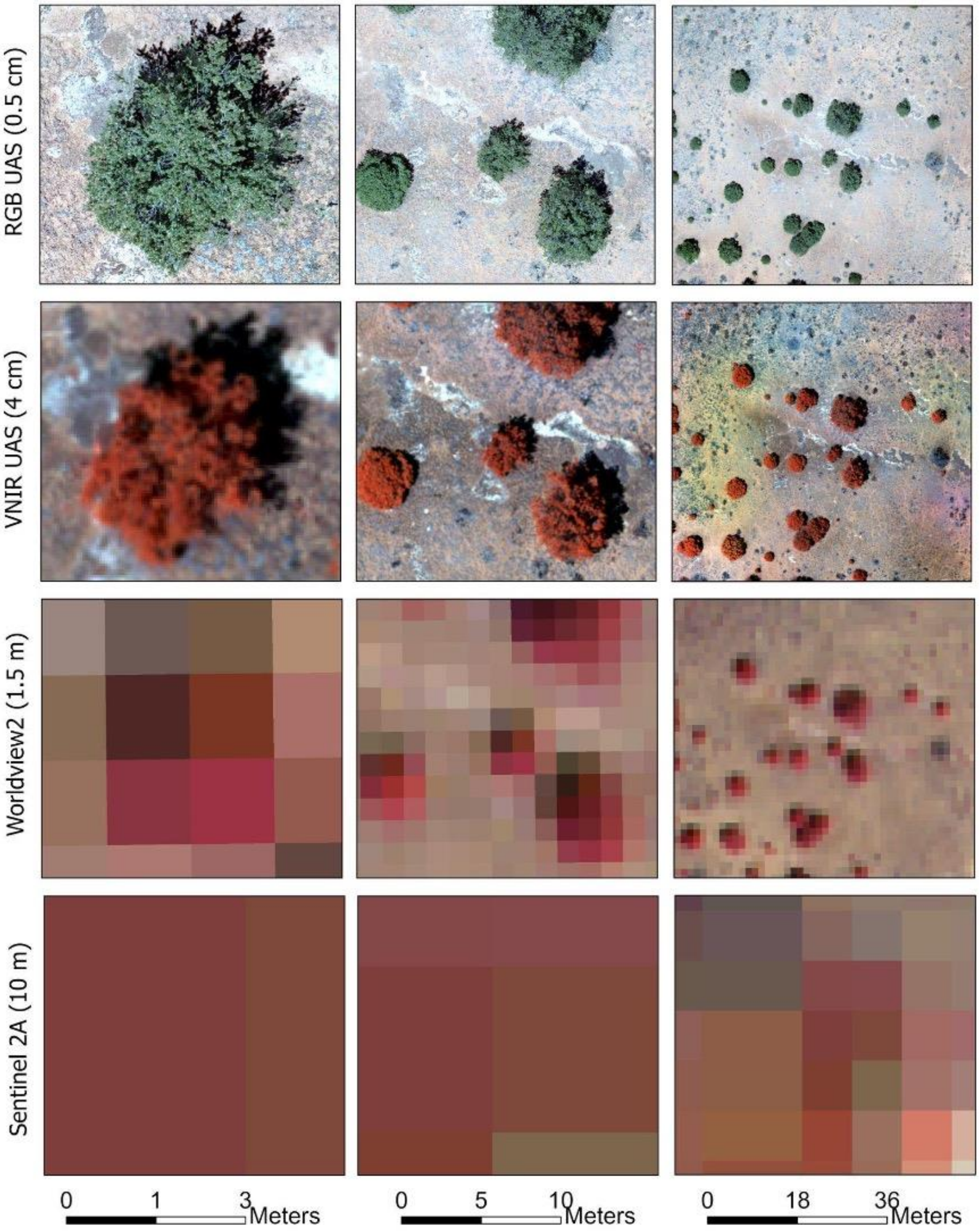


***Figure B.9.*** *Illustration of different pixel resolutions and scales of UAS imagery and satellite imagery. The top row shows an RGB UAS image at 0.5 cm resolution displayed at scales ranging from tree crown to landscape (left to right), followed by a 4 cm resolution visible near infrared (VNIR) UAS image displayed as a false color composite (vegetation is red), a 1.5 resolution Worldview2 false color composite satellite image and a 10 m resolution Sentinel 2A false color composite. Image from Villarreal et al., (In Review).*

### *B.2.1.5 Airborne Remote Sensing*

NASA's airborne Sensors will play a critical role in sensing essential biophysical parameters in order to address science questions, and scaling up to space-based sensors. The ABoVE campaign has illustrated how airborne observations have the potential to link field-based, process-level studies with geospatial data products derived from satellite remote sensing, spanning the critical intermediate space and time scales essential for a comprehensive scaling of ecosystems (Miller et al., 2019). Airborne sensors fill the crucial intermediate spatial scale between field or UAS data and space-based sensors. *While previous NASA airborne campaigns typically only involved a single overpass without a revisit, ARID's community clearly communicated that our science questions require multi-temporal, seasonal, and inter-annual repeat acquisitions to capture the high temporal variability of drylands (see aircraft remote sensing feedback in Appendix F.10).* This poses new challenges and opportunities, as addressed below.

A guiding principle of the ARID airborne acquisition strategy will be to leverage (i) existing complementary NASA campaigns (e.g. GEMx, FireSense; see Section B2.5), (ii) investments by other US institutions, notably our partner NEON, (iii) compatible airborne assets and capability of international partners and commercial service providers to manage costs and simplify logistics. While extensive airborne data (especially AVIRIS) have been acquired in parts of US drylands, these efforts were seldom focused on long-term terrestrial ecology science questions. However, we plan to leverage existing and on-going missions (e.g. GEMx) through coordination of complementary flights (Section B2.5).

The ARID science questions and ARID community feedback (Table B.1, Appendix F.9) highlights the need for multi-date airborne acquisitions to capture vegetation dynamics within one growing season, as well as pulse events. This could be achieved by (i) e.g. coordinating with NEON to complement their peak-greenness acquisitions of their dryland NEON sites with 2-3 additional acquisition of their NEON-AOP instruments, (ii) complementing other campaigns (e.g. GEMx, FireSense, Western Diversity Time Series) acquisitions for priority sites with 2-3 additional AVIRIS acquisitions and (iii) acquiring very frequent (e.g. weekly) drone-based imaging spectrometer data over field sites within footprints of AVIRIS overflights. While such frequent acquisitions pose financial and logistic challenges, the benefit to quantifying rapidly varying dryland dynamics cannot be overstated, motivating the community to develop innovative practical solutions rather than defaulting to traditional one-off acquisitions. The process of optimally selecting potential areas for airborne acquisitions in the US and overseas is outlined in the mission planning section B.2.4.

ARID will utilize a combination of foundational NASA sensors (LVIS, AVIRIS, UAVSAR, HYTES), PI-led NASA sensors (G-LiHT), and partner sensors (e.g. NEON-AOP). Multiple sensor modalities will be acquired and combined including, imaging spectroscopy, LiDAR and SAR, as briefly outlined below.

*Imaging Spectroscopy (hyperspectral image spectroscopy - HIS):* The *AVIRIS* sensors (Classic, Next generation (NG), and recent versions 3 and 5) are capable of deriving the largest number of required physical parameters and functional traits (Table B.2, Appendix F.1). AVIRIS will be a key workhorse for ARID given that the spectral signature will provide high resolution retrievals of carbon stock and fluxes (fractional cover of PFT), biocrust, vegetation composition, PFTs, vegetation, chlorophyll content, water content, and fuel loads (Pervin et al., 2022). All variables are otherwise challenging to retrieve with satellite sensors alone and will inform satellite-based algorithm development for EMIT and SBG. Adequately addressing dryland science questions will require multi-temporal acquisitions over selected “supersites” to capture changes vegetation during various phases of the growing season. The HIS data and field work will furthermore provide essential calibration/validation data for Landsat and SBG-based estimates of key variables in future updates to BLM’s and USGS’s rangeland monitoring applications (see Section B.2.7). NEON’s AOP sensors include an HSI that is very similar to AVIRIS-NG and can help meet measurement demands where necessary. NASA’s G-LiHT can also contribute HIS observations.

*SAR - UAVSAR:* SAR, in particular polarimetric L-band SAR, has proven effective at estimating woody vegetation biomass and structure changes in arid savannas and shrublands (Naidoo et al., 2015, 2016; K. Wessels et al., 2019, 2023). The airborne *UAVSAR* (L-band) has been effective at estimating biomass across a wide range of environments, from tundra to tropical forests (Z. Zhang et al., 2017). During ARID, the UAVSAR sensor could thus be employed to estimate tree and shrub biomass and cover and to scale up models to regional coverage with ALOS2/4 and the imminent NISAR mission. UAVSAR-L has furthermore proven essential to estimating fuel loads and fuel moisture content for wildfire risk prediction (K. An et al., 2024). The multi-band (L & P) UAVSAR (L-band and AirMoss) can furthermore contribute to the accurate estimation of soil moisture and differentiating soil moisture and vegetation or crop water content (Tobin et al., 2022), especially in combination with AVIRIS to help partition PTF. The multi-band UAVSAR will also enable innovative tomographic SAR (TomoSAR) PolInSAR methods for measuring vertical vegetation structure in woodlands and savannas. It will ultimately inform algorithm development for NISAR and applications for spatially heterogeneous drylands with mixed woody and non-woody vegetation landscapes.

LiDAR: LiDAR is essential for measuring woody vegetation height, 3D structure, biomass, carbon stocks, and their changes through time (Table B.2). Multiple discrete and waveform LiDAR sensors are available as part of various sensor payloads including LVIS (waveform 10 or 20m footprint), G-LiHt (Discrete), NEON-AOP (both discrete and small footprint waveform). The airborne LiDAR data will be used to calibrate models to estimate biomass with space-based SAR (e.g., NISAR) and LiDAR (e.g. GEDI, EDGE and IceSAT2).

Multi-sensor Observations: There is significant opportunity for innovation when combining various sensors and modalities within the ARID airborne acquisitions. These include LiDAR+UAVSAR or LiDAR+HSI for vegetation biomass estimation by PFTs.

SIF: Airborne SIF measurements can be correlated with tower-based SIF and GPP estimates and can assist in calibrating space-based SIF estimates with OCO-2/3 and TEMPO. SIF is being measured by the FIREFLY (Fluorescence Imaging of REd and Far-red Light Yield) which has been integrated with the multimodality NASA G-LiHT payload, as well as CFIS (Chlorophyll Fluorescence Imaging Spectrometer) built to validate OCO-2.

Atmospheric Carbon: CARAFE: The Carbon Airborne Flux Experiment (CARAFE) is a unique NASA asset that combines in-situ atmospheric sensors and wavelet transform eddy covariance to directly quantify surface-atmosphere exchange of carbon dioxide, methane, water vapor, and sensible heat at spatial scales of ~1 km (Wolfe et al., 2018). Airborne fluxes can constrain NEE and energy balance across gradients in modeled and remotely-sensed surface characteristics, extending beyond the reach of stationary towers and providing opportunities for upscaling and process studies (Hannun et al., 2020; Poulter et al., 2023). CARAFE will provide the opportunity to quantify the spatial distribution of carbon fluxes across heterogeneous drylands, especially when flown over flux towers.

MODIS/ASTER Airborne Simulator (MASTER): The MASTER instrument is maintained and operated by the Airborne Sensor Facility at NASA Ames Research Center. This sensor covers the midwave infrared with 15 bands, the thermal infrared with 10 bands, and the visible to shortwave infrared with 25 bands (Hook et al., 2001). This information across the optical and infrared regions facilitates the quantification of surface temperature, characterization of emissivity, derivation of ET, and mapping of surface cover elements and change (French et al., 2008). Use of MASTER data in conjunction with AVIRIS data has been shown to increase the accuracy of surface temperature quantification (Grigsby et al., 2015).

#### *B.2.1.6 The Central Role of NASA Space-based/Satellite Remote Sensing*

The current and future NASA space-based sensors will be key in continuously sensing a host of parameters at a sufficient spectral, spatial, and temporal resolution across vast global drylands (Table B.2). The ARID field and airborne campaign will enable multi-scale retrieval model development for accurately estimating key parameters from space-based sensors. A host of new sensors and missions provide exciting opportunities for innovations that combine multiple sensing modalities (e.g., optical and SAR) to address key science questions and applications (e.g., rangeland monitoring) at the appropriate spatio-temporal scales. The combination of diverse NASA satellites offers critical measurements for improving our predictive understanding of dryland processes, controls, variability, and adaptation potential. ***Given the high spatiotemporal complexity of dryland landscapes, a better understanding of drylands globally will require a full interpretation of current and future NASA spaceborne sensors and their increasingly high-resolution capabilities spectrally, spatially, and temporally.***

Key parameters estimated by NASA space-based sensors include Level 2 and 3 products such as land surface temperature (LST; Landsat, ECOSTRESS, SBG), solar-induced fluorescence (SIF; OCO-2, OCO-3, TEMPO), vegetation structure (GEDI, ICESat-2, NISAR) and composition (EMIT, HISUI, SBG), and soil moisture (SMAP, NISAR); and Level 4 products such as gross primary productivity (GPP; VIIRS, Landsat, OCO-2, OCO-3), aboveground carbon stocks (SMAP, GEDI, ICESat-2), evapotranspiration (ET; Landsat, ECOSTRESS), water use efficiency (WUE; Landsat, ECOSTRESS), root zone soil moisture (RZSM; SMAP, NISAR) (Table B.2, Appendix F.1). NASA's soil moisture (SMAP, NISAR), vegetation water content (SMAP, NISAR), terrestrial water storage (GRACE), water vapor (AIRS), and precipitation (GPM) estimates also provide an opportunity to capture a range of dryland mechanisms relevant to water availability and the soil-plant-atmosphere continuum (SPAC). Importantly, there is an urgent need to improve and expand upon these existing products through improved evaluation and calibration, integration of novel measurements and techniques, data fusion, algorithm advances, and data-model development (e.g., model benchmarking, parameterization, and data assimilation).

*Capturing long-term trends and variability of global drylands:* Long-term satellite records from NASA polar orbit platforms provide invaluable baseline information across a diverse range of techniques. This includes 20-40 years of estimates of NDVI (MODIS, VIIRS, Landsat), LST (MODIS, VIIRS, Landsat), soil and vegetation moisture content (AMSR, SMAP), and, more recently, vegetation structure (ICESat) and SIF (OCO-2). These platforms provide critical observations at a fixed overpass time and are ideal for evaluating vegetation function, phenology, and long-term trends in vegetation dynamics (e.g., the global greening of semiarid areas) (Fensholt et al., 2012). The long-term NDVI record has played a central role in the controversial debate around human-induced desertification versus the impact of rainfall variability (Prince et al., 2007; K. J. Wessels et al., 2012). NASA’s soil moisture (SMAP), terrestrial water storage (GRACE), water vapor (AIRS), and precipitation (GPM) estimates will play a crucial role in hydrological modeling at the fine temporal scales needed to capture pulse dynamics of dryland systems. More recent higher resolution remote sensing datasets and modeling will allow an ARID campaign to unpack the politicized, umbrella term of “desertification” into changes in composition, structure and function (e.g., water use efficiency) of dryland ecosystems (Brandt et al., 2020; Mugabowindekwe et al., 2023; Tucker et al., 2023).

*Capturing high temporal variability of global drylands:* Satellite-based sensors can help address the challenge of capturing the high temporal variability of dryland ecosystems through novel data fusion techniques and better integration of measurements from geostationary satellite platforms. Advanced data fusion techniques are revolutionizing our ability to seamlessly integrate multiple satellite records towards monitoring drylands in unprecedented temporal detail. Leading the way, the NASA Harmonized Landsat and Sentinel-2 (HLS) initiative is integrating observation from  Landsat 8, Landsat 9, Sentinel-2A, and Sentinel-2B satellites to generate a harmonized, analysis-ready surface reflectance data product at 30-meter spatial resolution and with observations every two to three days. There is also the emerging opportunity to better utilize high temporal frequency observations from geostationary satellites, which have served primarily as inputs for weather forecasting, and overcome many of the temporal limitations of orbital sensors. The geostationary constellation provides almost complete coverage of global drylands in North/South America (GOES-R, TEMPO), Central Asia/Australia (Himawari-8/9) and Africa/the Middle East/Southern Europe (SEVIRI). Of note, the TEMPO mission (Earth Ventures class platform) is providing first-time hourly SIF measurements over the entire US that can be used to track the diurnal cycle and pulse dynamics of dryland vegetation productivity. Emerging initiatives to fuse measurements across multiple low orbit and geostationary sensors is enabling the monitoring of key ecosystem variables such as GPP and ET at unprecedented spatial and temporal resolutions (Khan et al., 2022; Stisen et al., 2007).

For instance, the NASA GeoNEX project through data fusion is now providing harmonized, analysis-ready surface reflectance and LST products at hourly, daily, and sub-weekly temporal resolution at a near-global scale. Together these novel platforms and initiatives offer invaluable yet underexplored insight into pulse dynamics of dryland ecosystems and offer potential to revolutionize our understanding and informing critical societal decisions regarding our planet's drylands.

*Capturing unique high spatial and temporal variability of global drylands from NASA's Venture class sensors on the ISS:* The NASA Ventures class sensors and missions operated by other national space agencies on the International Space Station (ISS) could transform our understanding of dryland structure (e.g., tree, shrub canopy height) and function (e.g., GPP and ET). While these sensors provide high temporal resolution in some cases, they have high capacity to evaluate dryland's heterogeneous surfaces with their mostly higher spatial resolutions (<100m). ECOSTRESS (70-m) measurements of  LST (Level 2) and ET (Level 3) which can be combined with co-occurring OCO-3 (2-km) measurements of SIF (Level 2) and GPP (Level 3) to derive first-time integrated estimates of WUE (Level 4). These observationally-constrained estimates of ET, GPP, and WUE have the potential to fully overcome limitations of previous products and revolutionize our understanding of dryland function from the individual rainfall pulse to annual timescales. EMIT, DESIS and HISUI are providing first-time space-borne hyperspectral measurements that can be used to map dryland spectral traits across diverse functional groups (e.g., C3, C4, and CAM plants, diverse biocrust species). Additionally, these hyperspectral missions will revolutionize our knowledge of geological surface composition, as well as vascular and non-vascular plant fractional cover across global drylands. Finally, the GEDI mission is providing novel structural traits (e.g., vegetation height, plant area index, and total aboveground biomass) that will for the first time capture the true high structural biodiversity of drylands and enable first time assessments of how dryland structure relates to and potentially regulated dryland function. These instruments offer observations at variable overpass times and thus can be jointly used to gain insights into diurnal dynamics at high spatial resolution. We acknowledge that it is possible that several of the sensors listed here will no longer be available during ARID (e.g., DESIS). However, several like EMIT, ECOSTRESS, GEDI are likely to continue collecting data from the ISS for several more years during the ARID campaign, depending on various factors. Continued acquisitions from these three sensors during the ARID study is strongly desired and will allow synergistic use of these different data types and preparation for SBG (Stavros et al., 2017).

*Capturing high spatial and temporal variability of global drylands with commercial small satellite constellations:*  Emerging polar-orbiting small satellite constellations have the potential to provide first-time high spectral and spatial resolution observations in the optical and thermal regions of the electromagnetic spectrum. The PlanetScope constellation is providing surface reflectance across key optical bands at 3-m spatial resolution and a daily revisit frequency. The newly launched Hydrosat constellation will provide complementary observations in the thermal infrared region of the electromagnetic spectrum, which can be used to estimate LST, surface water availability, and the evolution of drought dynamics across drylands at 20-m spatial resolution and a daily revisit frequency. Through ARID, we will partner with these initiatives and explore options to continue and expand the NASA NextView License to make these data fully available to the ARID research community (Neigh et al., 2013).

*Key Future Sensors:* NASA's Surface Biology Geology (SBG) Designated Observable mission objectives are strongly aligned with ARID's objectives by focusing on terrestrial vegetation physiology, functional traits, and health (Cawse-Nicholson et al., 2021), as well as wildfire ecology and risk applications, at high spatial resolution. Specifically, the SATM in Appendix F.1 indicates that SBG Thermal and VSWIR components will play a key role in estimation of multiple parameters related to fractional cover of PFTs, and other vegetation and fuel characteristics in drylands. SBG's hyperspectral component will be especially important for parsing vegetation and soil. The airborne AVIRIS data will enable the development of accurate spectral unmixing models with which these parameters can be estimated, and methods applied using Landsat and SBG (Cawse-Nicholson et al., 2021). These spaceborne instruments in combination with structural parameters and woody vegetation biomass estimated with NISAR and space-based LiDAR (GEDI, EDGE) will revolutionize the estimation of dryland vegetation composition, structure, and biomass (Duncanson et al., 2022; X. Li et al., 2024), especially in spatially heterogeneous drylands. This will include dryland applications related to rangeland condition, shrub encroachment, invasive grasses, fuel moisture and fuel loads. Additionally, the ARID campaign will be critical to the calibration and validation of SBG and NISAR observations and derived products, including soil moisture, vegetation water content, and fuel moisture products from NISAR. Landsat-NEXT will also provide 26-bands of multi-spectral bands including 5 bands in TIR wavelengths at 10- to 60-m resolution with a very high temporal 6-daily frequency provided by the triplet of satellites. With a planned launch year of 2030, ARID and its follow-on applications may still provide benefit to, and, in turn, benefit from Landsat NEXT.

The Decadal Survey (2017) (Medicine et al., 2019), highlighted three Explorer mission observables, including Terrestrial Ecosystem Structure, and a mission called EDGE (Earth Dynamics Geodetic Explorer) has just been approved for Phase A development. The space-based waveform LiDAR on EDGE is specifically tailored to have the ability to characterize dryland ecosystems with discontinuous, short stature vegetation structure, in addition to forested ecosystems. The Surface Topography and Vegetation (STV) designated observable is currently in incubation phase, but could enter the next development phase during the course of the ARID campaign. If successful, both STV and EDGE have clear science objectives (see SATM) to accurately measure short stature vegetation structure and biomass in drylands. ARID will contribute to their calibration and validation efforts while the science community will benefit from the accurate measurements of dryland carbon stocks and PFTs.

*Sensors from other Agencies and commercial companies*

While this section mainly aimed to highlight the contribution of NASA sensors, it is clear that ARID will greatly benefit from the sensors made available by other agencies and commercial companies. The European Space Agency's (ESA) series of Copernicus satellites will contribute in several ways including (i) increasing the temporal frequency of wide area observations through the Harmonized LandSat Sentinel-2 (HLS) which will achieve a nominal 3 daily observation rate, (ii) providing hyperspectral data via EnMAP at 30 x 30m and Copernicus

Hyperspectral Imaging Mission for the Environment (CHIME) scheduled to launch before the end of the decade, (iii) providing SIF observations from TROPOMI and the upcoming FLEX mission, (iv) providing microwave data from ALOS4 L-band and SAR from JAXA,  and (v) as discussed above, providing high frequency and fine-scale GOES observations which are being used to develop GPP and ET products at a sub-hourly temporal resolution (Khan et al., 2021). We will also continue to build collaborations with commercial platforms including WorldView, PlanetScope, and Hydrospec under the NASA NextView License framework and explore ways in which we can make these data freely available to the ARID research community (Neigh et al., 2013).

### *B.2.2 Dryland Ecosystem Modeling and Model-Data Synthesis*

We envisage two key roles for models as part of the ARID field campaign. First, the ARID field campaign will provide critical opportunities to address long-standing scientific questions regarding dryland functioning and improve representation of processes within models. Data on vegetation structure and composition, vegetation phenology, water availability and plant water use, and fire dynamics will allow us to improve model parameterizations, enabling more accurate predictions of dryland carbon and water flux variability, plant responses to pulsed rainfall and extreme climate events, and long-term vegetation shifts. These efforts will significantly enhance our ability to predict dryland ecosystem responses to global change, as well as dryland ecosystem feedbacks to the climate system, and ensure models can better support land management and policy decisions.

Second, models provide useful direction for data collection efforts and in the design of remote sensing instruments. In underrepresented dryland ecosystems, where our process understanding, mapping, and modeling all remain poor, models can play a crucial role in supporting hypothesis testing, planning for data collection, in evaluating the precision and resolution of emerging remote sensing technologies, and in aiding development of algorithms for retrieving land surface parameters through Observing System Simulation Experiments (OSSEs).

Overall, ARID provides an opportunity to systematically link ground observations of important ecosystem process responses to climate variability, water availability, and ecosystem structure, involving remote sensing observations across different spatial, spectral, and temporal scales, to process-based models via comprehensive and extensive data-model synthesis. The linkage between models and different scales of observation serves as a bridge between ecosystem theory and multiscale observational platforms to better understand, as well as predict, how dryland systems respond to emerging climate and land use changes across dryland regions of the world.

#### *B.2.2.1 Interfacing Dryland Modeling and Dryland Remote Sensing*

Process-based models at all scales generally do not fully represent the complex structure, functioning, and dynamics that are characteristic of dryland ecosystems. This includes models from smaller scale ecological (process-specific models), to landscape or habitat scales, to global-scale dynamic vegetation models and land surface models implemented within Earth system models. Such lack of representation is in part because models were largely developed and tested for more mesic, homogeneous forested ecosystems where data and experiments are more numerous and understanding of relevant processes more advanced. We outline several dryland modeling limitations here.

First, the representation of the spatial complexity of mixed woody-herbaceous ecosystems and associated processes (e.g., shrub-grass competition for water) is largely absent from all modeling frameworks. For example, the radiative and aerodynamic transfer schemes implemented in most global-scale land surface models (LSM) assume homogeneous vertical distribution of leaf area, causing overestimation of light interception (Bégué et al., 1996), and incorrect parameterization of surface layer aerodynamic conductance (Dolman & Wallace, 1991; Kabat et al., 1997; Young et al., 2021), with implications for carbon and water cycling and energy balance calculations. Many models also lack representation of dryland specific plant functional types (PFTs), including biocrusts, annual and perennial grasses, and forbs, and shrubs. In addition, while both C3 and C4 photosynthetic pathways are included in many models, fractional cover of these key PFTs are likely poorly estimated and not well validated and there is generally no representation of warm versus cool season types, both of which are pivotal for understanding drylands such as in the western US. The methods used to create global scale PFT fractional cover maps used in LSMs have the highest uncertainties in heterogeneous, sparsely vegetated dryland regions, which results in a large spread in modeled carbon, water, and energy fluxes due to uncertainties in PFT fractional cover (and notably is larger than the inter-model spread due to differences in model structures) (Hartley et al., 2017b).

Second, key processes for modeling dryland ecosystem responses to rainfall pulses, carbon flux variability, woody plant encroachment, or vegetation recovery from disturbance (e.g., fires) and climate extremes (e.g., severe drought) are either only recently under development and have not yet been widely tested for drylands, or missing in models altogether. Such processes include dryland plant specific phenology schemes, fire dynamics and vegetation responses to fire, mechanistic descriptions of plant water uptake and use (e.g., plant hydraulics or stomatal optimization; dryland plant specific rooting profiles and competitive interactions), hydraulic redistribution, and groundwater recharge. Most phenology schemes have been developed for boreal and temperate mesic, forested ecosystems (MacBean et al., 2015) and therefore dryland specific PFT phenology schemes need to be developed (Dahlin et al., 2017; Hufkens et al., 2016; Renwick et al., 2019), which will require new data collection and analysis efforts (B.2.1 and B.2.3) and harmonization of existing data. Most models still only include an empirical water stress function that performs poorly in capturing plant water stress (De Kauwe et al., 2015). New mechanistic approaches to modeling plant water uptake and use (e.g., plant hydraulics and stomatal optimization) are currently being developed for LSMs (Paschalis et al., 2024; Sabot et al., 2022), but have not yet been widely tested in dryland ecosystems (though see Hawkins et al., 2022). Other processes and model parameterizations relevant for capturing plant responses to water stress, such as dryland plant specific rooting profiles and groundwater have not widely been implemented in models. While recent studies have implemented hydraulic redistribution (HR) by roots in LSMs (C. Fu et al., 2018; Niu et al., 2020), further research is needed to assess the consequent impacts on simulations of carbon and water fluxes, vegetation dynamics, and plant responses to drought across a range of dryland ecosystem types, and how well these new HR schemes perform when applied in conjunction to other developments in modeled ecohydrological functioning (e.g., plant hydraulics). Fire modules are often not activated, or even included, in LSMs and where they are used can perform poorly (Baudena et al., 2015; Hantson et al., 2020; Teckentrup et al., 2021). Even where fire processes are included in models, the parameterizations are often too simple to represent the complex interactions between fuel types and fuel flammability controlling the probability of ignition and spread of crown fires, common in dry forests, relative to surface fires, common in open herbaceous systems, the duration of fires in dryland regions, and the role of human activities in fire ignition (Hantson et al., 2020; Teckentrup et al., 2019; Thavhana et al., 2024).

Third, model performance is poor where dryland-specific processes should in theory be represented in the models. These processes include asynchronous dryland plant responses (e.g., PFT-specific leaf phenology and physiological activation) to large seasonal changes in water availability, periods of water stress, or pulsed rainfall dynamics, (De Kauwe et al., 2017; MacBean et al., 2021; Whitley et al., 2016). Unsurprisingly given these three factors, dryland model evaluations have shown that vegetation dynamics (e.g. phenology, long-term trends), carbon, and water fluxes (including partitioning between transpiration and bare soil evaporation) and the response of these processes to warming and elevated $CO_2$ are not well represented in models (Dahlin et al., 2015; Dashti et al., 2021; Fawcett et al., 2022; MacBean et al., 2015, 2020, 2021; Renwick et al., 2019; Teckentrup et al., 2021; Traore et al., 2014; Whitley et al., 2016) with implications for predictions of land-atmospheric feedbacks (Humphrey et al., 2018; (Simpson et al., 2024b).

Models should play a vital role in improving our knowledge of the role of drylands in global carbon and water cycles and land-atmosphere feedbacks, and for forecasting the effects of climate change on ecosystems that underpin provisioning of vital ecosystem services for a range of livelihoods in both developed and developing countries. However, we cannot currently rely on process-based models either for attributing observed changes in dryland ecosystems (shrub encroachment as one example) to environmental change drivers, or for accurately predicting dryland ecosystem responses to changing climate variability, extremes, and land management. *There is an urgent need to assess where and why models are not performing well in drylands, and to use new data to improve our understanding of dryland ecosystems.*

ARID is of vital importance for improving our ability within the ecological and Earth system science communities to model drylands. *Integrating field and satellite data from the ARID campaign will provide an unprecedented opportunity to develop models that can reliably address a number of ecosystem challenges in the dryland system.* The field campaign proposed in ARID will provide the requisite synthesis and harmonization of existing data together with new datasets and analyses that are sorely needed to improve modeling of dryland ecosystems. Additionally, modeling itself fosters collaboration among dryland scientists, remote sensing scientists, and land managers, all with a goal of driving innovative projects to fill significant knowledge gaps. In this section, we outline the scope of model improvements that could be made with the ARID field campaign (aligning with planned data collection efforts), how we envisage such a model improvement effort could be organized, and the technical and scientific questions we plan to answer with ARID modeling activities.

#### *B.2.2.2 How ARID can co-improve dryland modeling and model-data synthesis for improved process understanding*

Modeling and model-data fusion techniques enhance the utility of remote sensing data for improving process understanding by integrating observations with model predictions to estimate quantities that cannot be observed remotely. By fusing process models with remote sensing data, models can be constrained and adjusted, improving the accuracy of predictions related to ecosystem processes such as below ground processes, carbon fluxes, and water use. For example, the NASA ABoVE domain estimates of above ground biomass or leaf area derived from remote sensing were used to reduce bias in model biomass and improve estimates of regional carbon flux and belowground carbon pools (Huo *et al*. 2024). This approach not only improves model performance but also allows for better understanding of complex ecosystem dynamics, particularly in heterogeneous environments where direct measurements are limited.

A dryland focused remote sensing field and satellite campaign will also provide much needed datasets with which we can improve modeling of dryland ecosystems. The ARID field campaign will allow for coordinated data collection to address multiple different facets of poor dryland ecosystem process representation (i.e., simultaneously evaluate and constrain processes related to vegetation dynamics, carbon and water fluxes with multiple datasets). New data collection together with ARID supported synthesis and harmonization of existing datasets will support dryland model initialisation (e.g., PFT maps), process development, and testing.

Four core processes that are key for modeling dryland ecosystem responses to climate variability and extremes (Section B.1.1 to B.1.3) will be targeted for improvement based on new data collection and harmonization in ARID. These include inaccurate representation of: 1) vegetation and biocrust composition and structure in sparsely vegetated, heterogeneous ecosystems; 2) dryland plant specific phenologies; 3) processes related to water availability, uptake and use (including groundwater, hydraulic redistribution, plant hydraulics or stomatal optimization schemes and dryland plant specific rooting structures); and 4) fire and recovery from fire. If we can improve model representation of these four core processes we should be able to better predict plant responses to pulses and droughts (from improvements to modeled plant water use and phenology) (B.1.1.2), carbon cycle inter-annual variability (related to interactions between pulsed ecosystem responses and seasonal dynamics (B.1.1.1 and B.1.3.1), and long-term changes in vegetation composition and carbon sequestration (related to responses to disturbance and competition for resources between different PFTs and biocrusts) (B.1.2 and B.1.3). All four of these categories are closely aligned with data collection efforts planned in the ARID field campaign, outlined in the remote sensing approach in B.2.1 and SATM Table B.2 as well as in the science theme approaches in Section B.1. For example, data collected during the ARID campaign on vegetation fractional cover and height will assist in initializing land surface models with static vegetation or in testing shifting vegetation composition and competition predicted by vegetation demographic models; LAI, FAPAR, SIF, NIRv, and PRI data for specific dryland PFTs will help develop new dryland PFT phenology schemes with impacts on our ability to simulate dryland energy balance, carbon and water fluxes; biomass and burnt area data will help to test and develop fire models; and soil moisture, hydrogeodesic (groundwater), VOD, and leaf water potential measurements together with partitioned ET data will help to assess new plant hydraulics and hydraulic redistribution schemes that in turn will enable models to better represent drought stress (with feedbacks on simulations of phenology, pulsed responses, and drought induced mortality). All above mentioned datasets, together with Level 4 remote sensing and upscaled in-situ flux products (e.g., GPP and ET) will be utilized to quantify and constrain uncertainties in models across scales via data assimilation and emerging machine learning methods for parameter and state estimation.

*B.2.2.3 Plan for modeling activities within ARID*

We envisage a four-phase modeling effort within ARID, with a continuous flow of information between modeling and data/experimental communities at each stage (Table B.3):

***Phase 1: Data Model Fusion Framework:*** Development of a framework that can support the linkage between various observations of dryland ecosystem structure and processes to the various ecosystem process representation available in different modeling schemes will enable better information exchange. This DMF framework will provide additional guidance on how ecosystem processes can be better inferred by remote sensing observations. Estimates of ecosystem dynamics based on modeling analysis can be cross referenced to remote sensing or ground-based observations.

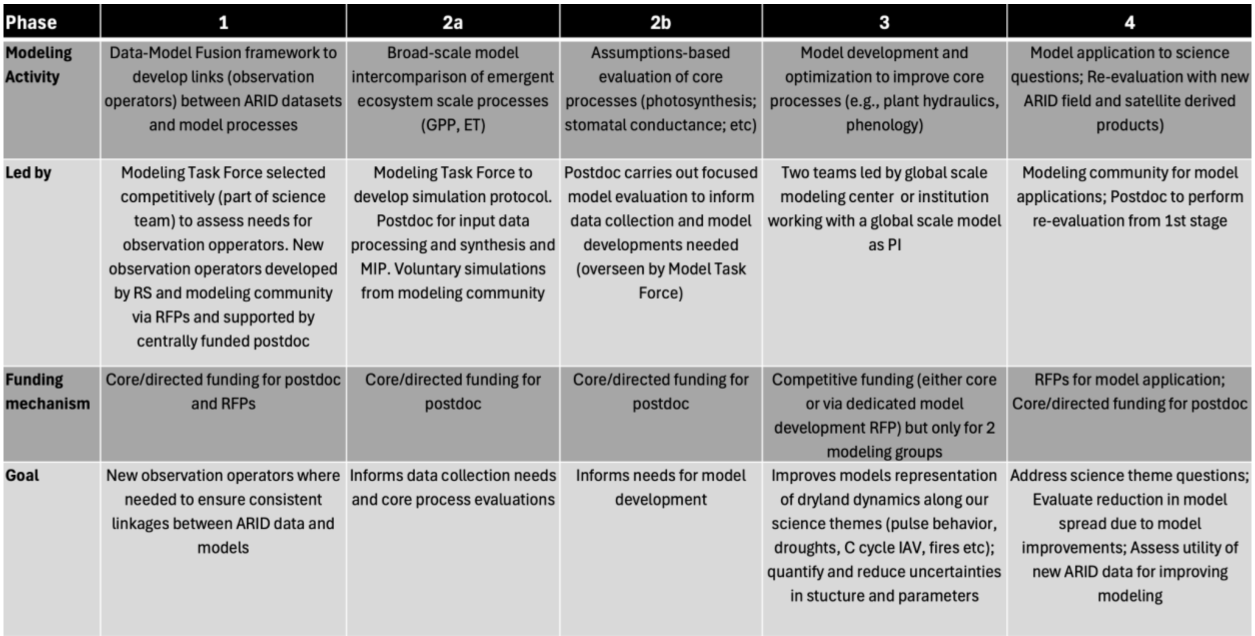
***Phase 2a: Model inter-comparison***. Modeling of dryland ecosystems is unique in that the processes needed to accurately represent dryland ecosystem structure, functioning, and dynamics are not necessarily included in the models, and knowing which processes are important is a considerable challenge. Therefore, the goal of the initial model-intercomparison should be to benchmarking multiple emergent dryland ecosystem variables at broad spatial scales (e.g., model-data comparison of GPP, ET, above- and belowground carbon stocks, and soil moisture using iLAMB or other available tools) to identify where/when models agree or disagree and better understand possible causes of poor dryland model performance.

***Phase 2b: Detailed, assumptions-based process-evaluation***. Building on Phase 2a, in Phase 2b centrally funded personnel (see below) would coordinate a voluntary multi-model inter-comparison comprising a suite of site-based simulations (including experimental manipulations) in order to perform tests and assessments of model assumptions used to simulate various variables in an assumption-based evaluation (Medlyn et al., 2015) of *core* processes (for example, carbon assimilation, phenology, root water uptake, litter input quantity and quality) that contribute to emergent ecosystem level responses. The results of these analyses will be published in a journal article detailing the  “roadmap” of dryland model developments that are needed and that will be supported by ARID.

***Phase 3: Model developments and optimization***: Based on our existing knowledge of what processes are misrepresented or missing in models, we expect that new model developments will be needed. We anticipate that dryland model developments will be incorporated into many NASA Requests for Proposals (RFP). However, we advocate that the roadmap of model developments resulting from Phase 2a,b efforts should be the target of dedicated core funding. Given the significant resources and continuity of personnel efforts that are required for rigorous model developments and model optimization, we suggest targeted global scale modeling groups (with different core structures – e.g., land surface model and dynamic vegetation/vegetation demographic models) be funded for a specific, competitive RFP. This funding should include a requirement that these modeling groups collaborate with individual or smaller groups of scientists with expertise on specific processes – i.e., those working finer scale, process-specific models, and/or datasets that can help test hypotheses and guide model developments. We also advocate that teams submitting proposals for this dedicated RFP include experts on data assimilation and model integration. We envisage this dedicated RFP will help to build teams involving strong collaborations between empirical scientists and modelers to develop new mathematical functions of missing processes (e.g., dryland specific plant phenology, biocrusts, etc.). The goal of funding only 2-3 modeling groups is that each new development can be carefully tested and evaluated so that other modeling groups can benefit directly from knowledge gained about which processes improve dryland ecosystem modeling, and how to best parameterize those processes in their models. We believe this framework is the most optimal for maximizing limiting resources for the whole modeling community.

***Phase 4: Regional to global scale modeling to address ARID science themes***. The ultimate goal of the ARID modeling effort will be to use the new state-of-the-art dryland modeling schemes developed throughout the 10-year field campaign to make more reliable predictions of the impact that climate and environmental change will have on dryland ecosystems from near term to decadal and centennial time scales, and from ecosystem to global spatial scales (see more detailed science questions below). This fourth and final phase will include model implementations and output interpretation of the several main models designated for development within ARID. This phase, which will start in the final stages of ARID and last well beyond the planned field campaign, will also see the re-evaluation of models within a global benchmarking framework, using new airborne, upscaled, and satellite data products developed within the ARID field campaign.

*Table B.3. Three phase modeling framework envisaged for ARID describing the 3 phases, who the work would be led by, the funding required, and the overall goal for that Phase.*



| Phase | 1 | 2a | 2b | 3 | 4 |
|---|---|---|---|---|---|
| **Modeling Activity** | Data-Model Fusion framework to develop links (observation operators) between ARID datasets and model processes | Broad-scale model intercomparison of emergent ecosystem scale processes (GPP, ET) | Assumptions-based evaluation of core processes (photosynthesis; stomatal conductance; etc) | Model development and optimization to improve core processes (e.g., plant hydraulics, phenology) | Model application to science questions; Re-evaluation with new ARID field and satellite derived products) |
| **Led by** | Modeling Task Force selected competitively (part of science team) to assess needs for observation opperators. New observation operators developed by RS and modeling community via RFPs and supported by centrally funded postdoc | Modeling Task Force to develop simulation protocol. Postdoc for input data processing and synthesis and MIP. Voluntary simulations from modeling community | Postdoc carries out focused model evaluation to inform data collection and model developments needed (overseen by Model Task Force) | Two teams led by global scale modeling center or institution working with a global scale model as PI | Modeling community for model applications; Postdoc to perform re-evaluation from 1st stage |
| **Funding mechanism** | Core/directed funding for postdoc and RFPs | Core/directed funding for postdoc | Core/directed funding for postdoc | Competitive funding (either core or via dedicated model development RFP) but only for 2 modeling groups | RFPs for model application; Core/directed funding for postdoc |
| **Goal** | New observation operators where needed to ensure consistent linkages between ARID data and models | Informs data collection needs and core process evaluations | Informs needs for model development | Improves models representation of dryland dynamics along our science themes (pulse behavior, droughts, C cycle IAV, fires etc); quantify and reduce uncertainties in stucture and parameters | Address science theme questions; Evaluate reduction in model spread due to model improvements; Assess utility of new ARID data for improving modeling |

In addition to model evaluation and developments, the wealth of new and existing dryland datasets collected and/or synthesized within ARID will be utilized by all modeling groups for model parameter optimization and state estimation using traditional data assimilation and emerging machine learning methods. Currently, most parameters in global scale models have been calibrated for more mesic ecosystems and likely do not represent dryland plant and soil traits. Literature and trait database reviews combined with parameter sensitivity analyses are needed to assess what new trait data collection efforts are needed and to inform prior bounds for parameter data assimilation experiments. This work will predominantly be funded via RFPs to individual modeling groups. A large part of this research will need to be devoted to developing the technical expertise to assimilate diverse, multi-variable dryland datasets into process-based models, and thus needs to occur in parallel to model developments (see B.2.2.4 Technical Questions). We anticipate that machine learning and artificial intelligence methods applied to ARID data should be used in some cases where process understanding is still lacking – for example, in understanding fire occurrence and spread (see B.2.2.4 Technical Questions).

As indicated in Phase 4, ARID data collection efforts across multiple scales enables our multi-scale modeling framework (Fig. B.10). It is crucial that we leverage data from field and airborne remote sensing through to space-borne observations including those from geo-stationary observations. Ecophysiological, ecohydrological, process-specific models at ecosystem scales, landscape and habitat models, and land surface and dynamic vegetation models working in concert will provide enhanced analytical capacity to integrate information of ecosystem dynamics gained from multiple sources of remote sensing observations in terms of spatial, temporal, and spectral scales. Process-specific field or high resolution airborne and satellite datasets will enable hypothesis testing with smaller scale, more process-oriented models, from which process understanding will be implemented into larger scaled models. Higher level, coarser resolution data products will be used to evaluate and calibrate ecosystem scale fluxes at broader spatial scales.

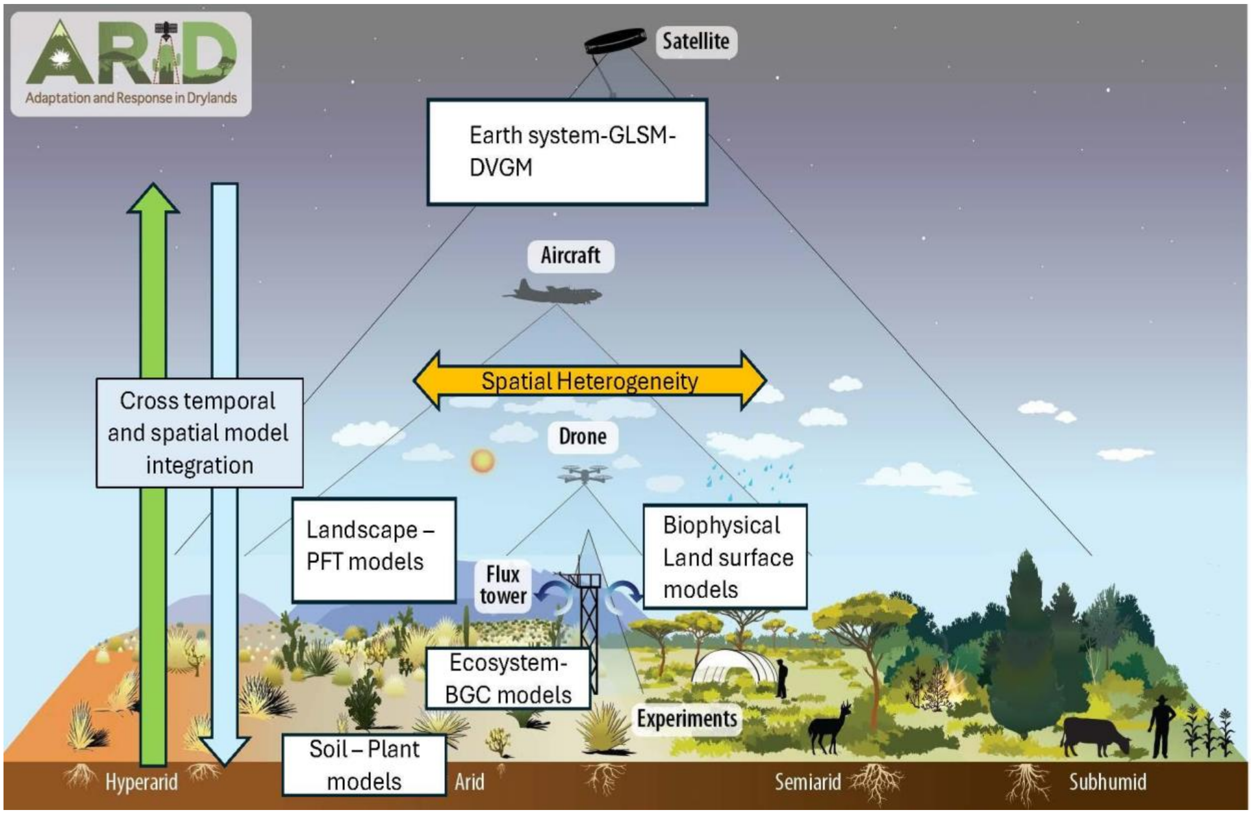


***Figure B.10.*** *The role of multi-scale modeling within ARID.*

While we have targeted four key processes for model development in ARID (vegetation and biocrust composition and structure, phenology, plant water use, and fire), we note that challenges exist in modeling belowground dynamics, such as soil $CO_2$ pulses following rainfall (i.e., the “Birch Effect”), nutrient cycling, and inorganic carbon dynamics (not currently represented in any global scale land surface or dynamic vegetation model). These are important issues that need to be addressed for adequately modeling carbon cycle variability and long-term carbon sequestration potentials of dryland ecosystems. Field data of relevance for testing and improving modeled belowground processes will be collected as part of the ARID field campaign (Section B.2.3). However, given the challenges measuring these quantities, these goals are more aspirational, and we encourage individual research groups to pursue them.

### *B.2.2.4 Technical modeling and science questions addressed by ARID modeling activities*

*Technical modeling related questions we hope to answer within ARID in collaboration with remote sensing and field data scientists:*

- Can models capture pulse dynamics (fast plant and soil responses to changing rainfall)? If not, what is missing in the models to be able to better simulate this key characteristic of dryland ecosystems?
- How can we better characterize dryland vegetation and biocrust fractional cover and dynamic vegetation change over time (e.g., shrub encroachment)?
- How much (species) diversity do we need to account for in order to accurately predict surface fluxes and ecosystem resilience in drylands?
- Which data (and data characteristics) are needed to constrain dryland model parameters and initial conditions via Bayesian data assimilation and novel machine learning-based parameter estimation techniques?
- Are PFT specific parameters useful in dryland ecosystems, or is spatialization of dryland PFT parameters needed (Dahlin et al., 2017)?
- In what ways do demography based dynamic vegetation models need to be adapted to improve representation of vegetation and biocrust composition, structure and competition in drylands?
- Can machine/deep learning methods be used to identify patterns and relationships that could help improve modeling of fire occurrence, spread and burn severity?
- What dryland management practices are currently missing in models? How can we best represent these management practices?
- Could state data assimilation be used to update dryland carbon stocks and water stores following disturbance or management in cases when adequate process-based modeling of these processes cannot be achieved?
- How can important facets of terrain complexity that exert important controls on dryland ecosystem composition and functions be better represented or parameterized in LSMs?
- How can groundwater and lateral water flow processes be better represented for drylands with complex terrains?

*Science questions we hope to answer with data-constrained, newly improved models within ARID:*

- Will all dryland regions experience continued declines in water availability, and what will be the impact on dryland vegetation-carbon-water interactions?
- Will increased drought and fire frequency lead to widespread mortality in dryland ecosystems? What would be the consequences for dryland species composition, carbon sequestration, soil quality and water retention?
- What are the mechanisms of dryland plant adaptation to the changing climate (warming, water stress)?
- Is $CO_2$ fertilization causing enhanced productivity and/or water use efficiency in dryland ecosystems? If so, are increases in WUE enough to offset declines in water availability in drought stressed periods?
- Which processes contribute to high inter-annual variability in dryland carbon cycling? And which dryland regions are “hotspots” of global carbon cycle inter-annual variability?

- What are the causes of shrub encroachment in drylands, and are they the same in all dryland regions? How does shrub encroachment alter dryland productivity and water use?
- How do shifting patterns of trees versus grasses impact land-atmosphere coupling? Conversely, how is changing atmospheric circulation affecting vegetation composition and ecosystem functioning in drylands?
- How does topographic complexity (elevation, aspect, slope) serve to buffer or exacerbate changes in the composition and functioning of dryland ecosystems?
- How do different dryland management practices impact above- and belowground carbon stocks, surface and groundwater storage and the surface energy balance?
- What nature-based solutions can be utilized in drylands to combat dryland degradation?

### *B.2.3 Coordinated Ground Measurements*

In-situ observations of surface states and fluxes aligned with airborne campaigns and satellite observations are essential to addressing ARID scientific questions. One of ARID’s strengths is the ability to leverage rich networks of available ground measurements of soil moisture, water fluxes, carbon fluxes, and vegetation states, all of which are targets of remote sensing platforms. Observational and manipulative experimental data offer direct means to address long-standing knowledge gaps for dryland ecosystems at representative sites, and for improving interpretation and use of remote sensing data. ARID will take the essential step of systematically combining ground measurements with proximal, aerial, and satellite remote sensing and modeling efforts to quantify dryland functioning and forecast future responses across dryland regions (MacBean et al., 2021). ARID’s approach to incorporate ground networks will closely follow the blueprint that NASA Terrestrial Ecology Program campaigns have followed since FIFE and continuing through ABoVE by using distributed field observations in representative land cover types and across environmental gradients of key forcing variables (e.g., mean annual temperature and precipitation, time since disturbance). Here, we discuss our vision and approaches for how existing ground networks and new ground measurements will be used within ARID to address dryland-specific challenges and opportunities. Note that while several ground networks are mentioned in this section, a more comprehensive list of ground networks that will be leveraged in our domains is presented in Section 2.5.

Unique challenges in drylands include the ability to monitor key parameters and processes to understand mechanisms across vast landscapes that have large spatial complexity and heterogeneity. ARID will leverage the richness of existing infrastructure, including weather stations, flux towers, manipulative experiments, and other in-situ networks, as well as a wealth of existing datasets including soil assessments and long-term vegetation monitoring. However, critical new components proposed here will facilitate effective coordination of ground measurements with modeling and remote sensing efforts. These include: 1) augmenting existing sites deployed across identified environmental gradient transects (see potential locations in Fig. B.11) with proximal remote sensing instruments, and enhanced sensor networks to facilitate upscaling efforts (Super Sites described in B.2.3.2 below); 2) making use of relocatable flux towers for short-term campaigns to increase measurements in ecosystem types and disturbance regimes that are not well represented in the existing networks; 3) facilitating contemporaneous measurements with ground based LiDAR, UAS, and airborne flyover campaigns to understand spatial scale heterogeneity and link high resolution fractional cover, thermal drone imagery, and SIF to carbon, water, and energy fluxes with multitemporal and airborne data at flux towers and Super Sites; and 4) utilizing ground campaigns, experimental manipulations, and in-situ sensor networks to fill in the gaps between long-term sites along airborne transects and enhance measurement capability at those sites (e.g., sapflux, tree growth, soil moisture down to 1 m, belowground carbon, rooting depth, plant water status, and direct measures of net primary productivity).

#### *B.2.3.1 Vision for Effective Upscaling Strategies and Improving Sensing Capabilities*

ARID's ground-based measurements are ultimately the highest resolution and thus most essential for upscaling our dryland processing understanding across the globe and testing our remote sensing capabilities. This is especially important for observing drylands' complex landscapes. Using the ground measurements in our domains, ARID will use several strategies for upscaling process understanding and sensing techniques. (1) As perhaps the primary technique, UAS and aircraft fly-overs of in-situ networks, experiments, and particularly ARID Super Sites, present unique opportunities to calibrate and validate retrieval methods of target physical parameters using the in-situ knowledge, as well as understand the spatial scales of representation of the target physical parameters. (2) Gaining an understanding of spatial variability and representation of target physical variables from these ground measurements (augmented with UAS and aircraft measurements) presents an opportunity to develop quantitative frameworks for optimal placement of new sensors in existing measurement networks. (3) The ground measurements leveraged in ARID present a unique opportunity to test sensing capabilities and innovative development of proxies for remotely sensing particularly challenging variables to observe. These variables include evapotranspiration, carbon uptake of both soil and vegetation, soil carbon, soil types, deeper soil moisture, and other belowground variables. (4) Experimental manipulation sites provide opportunities to test whether observation-based approaches with satellites (often using statistical models) can replicate results from manipulations, such as rainfall mean and variability manipulations (e.g., DroughtNet) (Beier et al., 2012).

#### *B.2.3.2 Super Sites and Distributed Flux Towers*

We propose targeted augmentation of a coordinated subset of existing eddy covariance tower sites to be designated as ARID Super Sites that are strategically located to provide multi-year, data-intensive time series across environmental gradients. Most existing flux towers in dryland sites across the globe make ground-based observations, including local meteorology, land-surface water vapor, CO2 and energy exchanges, and soil moisture and temperature states (Baldocchi et al., 2001; Novick et al., 2018). Sites will be selected from among long-term flux towers already operating in the following networks to be designated as ARID Super Sites, with an inclination towards sites with more feasibility of access and that contain a high amount of instrumentation. These will be chosen from existing networks within the ARID domain including AmeriFlux, MexFlux, OzFlux, ICOS, NEON, LTER, USDA LTAR, NPS, BLM (AIM), USFS, NEON, TERN. In addition to standard instrumentation to quantify land-atmosphere exchange of carbon, water and energy, augmentations at Super Sites will include RGB imagery, hyper/multi-spectral data, thermal data, biocrust and vegetation composition, cover, and structure (Table B.2 SATM). Given the key role of soil moisture in drylands (Novick et al., 2024), Super Sites will be augmented with multi-depth soil sensor profiles of volumetric water content and soil water potential, spatially distributed to capture the dominant cover types of each site. Within the flux tower footprint, we suggest installing soil autochambers to make continuous measurements of soil CO2 efflux to the atmosphere, capturing biocrust, root, soil heterotroph, and inorganic carbon cycling contributions. We will partition soil exchange of CO2 among these dryland sources (i.e., heterotrophs, autotrophs, inorganic carbon) with isotopic assessment, including in-line measurements of 13C:12C ratios for CO2, and targeted measurements of 14CO2 to determine the age and sources of respired carbon, as well as the turnover times of soil organic carbon. We will assess the biocrust community composition and spectral properties of the soil within the autochambers to link carbon cycling to the soil microclimate, weather, and remote sensing data concurrently collected at the Super Site. On soils adjacent to but outside of the tower footprint, we will manipulate the biocrust cover, for example mimicking climate and physical disturbance, to quantify the effect on overall soil CO2 exchange. These in-situ measurements will be coupled with laboratory incubations that allow assessment of the mechanisms, vulnerability, and potential future contributions of soil microbial heterotrophs and soil inorganic carbon cycling to dryland carbon.

#### *B.2.3.3 In-Situ Networks and New Relocatable Towers*

In addition to regular distribute sites and Super Sites, both modeling and remote sensing efforts will take advantage of a number of existing in-situ measurement networks in drylands. For example, these include networks SPECNET (optical measurements linked with surface fluxes), SNOTEL and SNOWPIX (for snowpack dynamics), the National Soil Moisture Network (standardized, distributed soil moisture), the Phenocam network (ecosystem greenness), etc. There are similar in-situ networks in ARID's international drylands domains; for example, Brazil has a national network of 360 soil moisture and rainfall stations in semi-arid sites.

To test specific hypotheses, field-based research can greatly benefit from the use of relocatable towers. Relocatable towers will be used for short-term deployments of diverse instrument suites, including eddy covariance, spectrometry, and RGB camera systems using scanning point measurements of user-specified targets (i.e., vegetation, ground, sky, etc.). Relocatable towers will thereby monitor hyperspectral reflectance in the visible and NIR regions and have capability to resolve far-red SIF, coupled with RGB imagery (Wong et al., 2023b). These deployments will: 1) assist with mapping key parameters required to address process-based questions and knowledge gaps across environmental, land use, and disturbance gradients and 2) augment testing the ability of remote sensing platforms to accurately quantify and represent variability in these key parameters (e.g., soil water availability, belowground carbon profiles to depths of 1 m, and rooting depths. (For more detail see section B 2.1.3 Proximal Sensing)

#### *B.2.3.4 Manipulative Field Experiments and Long-term Ecological Field Sites*

We will leverage existing field-scale manipulative experiments where key environmental variables such as precipitation amount, timing, temperature, and nutrients are manipulated to directly test and observe how and why these variables alter dryland function (M. D. Smith et al., 2024). Existing precipitation manipulations in drylands across the US alone include RainMan (Javadian et al., 2023; Y. Zhang et al., 2023), DroughtNet (Knapp et al., 2017), and Mean Variance Experiment at the Sevilleta LTER). Augmenting existing manipulations with additional ground-based remote sensing measurements, (e.g. thermal imagery, spectral measurements, relationships among surface states and fluxes) will provide a direct link to the airborne and remote sensing campaigns. These leveraged manipulative field experiments will provide the means to test the ability of remote sensing platforms to detect and quantify change, and develop a more process-based understanding for model parameterization/characterization of processes that are challenging to observe from remote sensing. As learned from extensive scoping with practitioners, ARID can also coordinate with large land management treatments that can act as experiments for researchers. For example, land management agencies such as the BLM and US Forest Service will be applying large scale restoration treatments that can be assessed and tracked through time. These ‘experiments’ allow scientists and managers to work together to improve understanding of the drivers of treatment outcomes to advance success in future management efforts, including in the context of climate change.

#### *B.2.3.5 Vegetation Surveys*

Within the US and internationally there is a wealth of long-term data assessing plant and biocrust community composition and cover across time and space in drylands. For example, the BLM’s Assessment, Inventory, and Monitoring (AIM) program and the National Park Service’s Inventory and Monitoring program have thousands of sites in the western US where plant and biocrust data are collected. These existing datasets can be blended with past remote sensing data and with the collection of new data, including ground-based, UAS, and airplane remote sensing, to improve the understanding of the controls over and changes to vegetation patterns and to build predictions for future change. This includes assessment of changes to biodiversity, increases in the abundance of exotic invasive plants, and losses or gains of functional types that lend insight into the kinds of vegetation most likely to be successful in a warmer, drier world. The sites also allow for improvement of remote sensing interpretation, as remotely sensed data can be ground truthed with vegetation survey data, as well as informing emerging new opportunities for remotely sensing biocrusts. More information can be found in B.2.5.2.

#### *B.2.3.6 Soil Properties*

Advancing our understanding of dryland controls and resilience must include consideration of the roles soils play in regulating ecosystem function and response to change. Soil maps and field-based studies can join with remote sensing tools to provide a much improved assessment of soil controls over dryland structure and function. Remote sensing of soils is challenging, and since drylands have a large coverage of soils, ARID presents a unique opportunity to both understand their role in dryland processes from rich networks of in-situ measurements as well as develop and test techniques to remotely sense soil types and soil carbon.

Although deeper soils and integrated soil carbon stocks are not currently able to be assessed with remote sensing, we can link remotely sensed to field based soil collections using models, as well as inform emerging soil-focused remote sensing tools. ARID can strategically conduct field studies across common land cover types (i.e., grassland, shrubland, woodland) and aridity classes to elucidate climate, plant community, and edaphic controls over soil carbon. ARID will collaborate with and contribute to ongoing US and international mapping efforts by the USGS, NRCS, and USDA, and can stratify the landscape according to vegetation cover and composition, mapped soil characteristics, parent material, topography, surface hydrology, and disturbance history. An improved understanding of the relationship between these potential controls and soil organic and inorganic carbon will provide insight into the determinants of soil carbon and its spatial distribution, over the vulnerability of organic and inorganic carbon to climate and land cover change, and to the potential management actions that could protect or even increase soil carbon in drylands. Large scale disturbances and land management treatments (e.g., wildfire, landscape restoration) could be targeted for assessment, as could research manipulations (e.g., DroughtNet) and time-since-disturbance/treatments, in order to reveal the longer-term consequences of change and/or management. To elucidate soil contributions to dryland ecosystem carbon exchange with the atmosphere, we will use a relocatable automated soil efflux system that can be deployed in areas that have experienced relevant change (e.g., after fire) or that are undergoing scientific manipulation (e.g., DroughtNet) to complement the same system being used in Super Site tower footprints (see Section B.2.3.1).

There are also emerging capabilities for assessing soil organic and soil inorganic carbon using remote sensing tools. For example, although, remote sensing has rarely been used for estimating soil inorganic carbon and monitoring its changes - because optical remote sensing cannot penetrate the land surface and radar-based remote sensing is often too coarse in spatial resolution (Jarmer et al., 2005) - small-scale exploration in the use of satellite remote sensing (e.g., Landsat, Sentinel) for regional soil inorganic mapping has recently emerged and does provide useful new insight for new approaches designed to quantify and monitor soil inorganic dynamics (Jarmer et al., 2005; Kusumo 2018). ARID can build on these advances with an explicit assessment of soil carbon at Super Sites and associated linkages to remote sensing measurements.

### *B.2.4 Study Domain and Selection Criteria*

The ARID field campaign will adopt a strategy for detailed, geographically focused and comprehensive field, airborne and orbiting data collection in an *Intensive* (threshold) research region of the western US, with complementary programs at internationally *Distributed* (baseline) field sites representing global drylands. This strategy will promote the synergies and efficiencies inherent in the concentration of resources and research teams in the *Intensive* region, while *Distributed* sites will sample the large range of structural, physiological, bioclimatic, edaphic and land use diversity in global drylands. Thus, where the *Intensive* sites may be the primary locus of technological advances in dryland processes, remote sensing science, and modeling during ARID, the *Distributed* sites will provide opportunities for application, parameterization and validation of new EO technologies across globally diverse drylands.

***Intensive* Study Region:** Given the global representativeness of drylands in the western US (Figure B.11; see below), the western U.S. is ARID's threshold (or required) domain. Thus, ARID science questions and themes (Section B.1) can be largely addressed in this domain if descoping is necessary. While all shaded areas in Figure B.11 are a part of ARID's domain, we recommend focused studies in four locations: grasslands, shrublands and dry deciduous woodlands of the southwest US; rangelands and croplands of the western Great Plains; Mojave Desert in the Great Basin; and cold, higher elevation deserts of the Mountain West (see Implementation Plan in Section B.2.6). Given the high density of AmeriFlux, NEON, LTER, and LTAR sites in the region, we anticipate that airborne campaigns would be anchored by existing (and potentially new) field data, while sampling the larger heterogeneity characteristic of dryland regions.

***Distributed*** **International Study Regions:** To ensure ARID science represents global drylands, we propose several baseline (desired) study regions, that would provide additional insight into variability with different vegetation types, a wider range of hyperarid to subhumid climatic conditions, and possibly different forcing from extreme events (Fig. B.12). We anticipate that final *Distributed* site selections will occur during the initial planning stages of the ARID field experiment, based on cost, logistics, and local collaborator contributions. However, we recommend core baseline regions including four rotating regions in the Chihuahuan and Sonoran desert of northern Mexico, dry-wet transect of southeastern Australia, desert to subhumid woodland gradients in southern Africa, and dry regions of the Caatinga, Cerrado and Gran Chaco in South America (Fig. B.12) (We note that some of the Cerrado is not classified as drylands, but some parts are, and the ecosystem represents critical transition point for drylands and thus, based on community input, it is a focal ecosystem). This list is not exclusive, and international sites will be added based on local interest and PI-led proposals. See our implementation plan in Section 2.6 for more details.

**Dryland Definition:** ARID can ultimately support projects across all global drylands. Our ARID dryland definition is based on aridity index (AI; Wang et al., 2022) of regions where aridity index (precipitation/potential ET) is less than 0.65, including hyperarid (AI<0.05), arid (AI = 0.05-0.2), semi-arid (AI=0.2-0.5), and sub-humid (AI=0.5-0.65). Other dryland definitions were explored, including alternative rainfall and water availability metrics, and classifications based on dominant vegetation/biome. However, aridity index is the most widely accepted, given its inclusion of both precipitation and radiation.

**Selection Criteria and Domain Motivation:** Such an *Intensive* ARID domain that is focused on drylands of the western US and several distributed international sites is chosen for several reasons:

*Representativeness*: The western US drylands represent global drylands in terms of mean aridity level. Additionally, it has an extensive representative distribution of semi-arid sites with some arid and sub-humid regions. Vegetation includes grasses (C3 and C4), shrubs, trees, and CAM plants. It contains hot-cold gradients from north to south as well as along elevation gradients that include wet-dry and hot-cold seasonalities. A dry to wet gradient exists generally from west to east between hyperarid to subhumid ecosystems. Land cover gradients also exist between rangelands throughout western US eastward into croplands of the dry western half of the Great Plains. All of these gradients allow for climate changes assessments in evaluating spatial relationships that can indicate changes in time. The western US also includes the contribution of mountains to climate both with orographic effects and snowpack impacts on dryland water availability. International sites add several elements. For example, southern Africa includes gradients between hyperarid and sub-humid tropical woodlands, which is wider climatic gradient than that observed in the western US. It is fog-driven and highly seasonally rainfall driven. Australia also provides a testbed for understanding strongly ENSO driven dryland systems and its contribution to the interannual variability of the carbon cycle.

*Previous Measurement/Existing Infrastructure*: The western US includes a vast amount of existing field network infrastructure and previous measurements and airborne campaigns to leverage within the ARID campaign. Namely, ARID airborne campaigns can leverage airborne campaigns conducted by USGS (GEMx), NEON, and NASA (Western Diversity Time Series, SHIFT) to create multiple overpasses of locations within a year. More detailed coverage of this topic can be found in Section 2.5. International baseline domains were also selected based on the existence of measurement infrastructure, interested partners, and ongoing research.

*Supporting Personnel*: ARID will support an extensive community in its domestic domain of U.S.-based researchers, rights holders, and end-users who live in, manage land in, and/or study drylands. International candidate domains were also selected based on proximity to research partners that are studying drylands or working with end-users on land management needs and that would continue to build on the ARID funded work after the campaign has ended.

*Community Input*: Community feedback across over 100 engagement events and over 350 written inputs (see Section C) revealed a strong interest in ARID having both domestic and international domains, with suggestions showing almost equal interest in each. The community showed broad interest across the dryland western United States as a whole (Fig. B.11), including many suggestions to consider the Great Basin and Great Plains. The strongest international interest was in Africa, particularly Southern Africa. Mexico is also of disproportionately high interest to the community given the Chihuahuan and Sonoran deserts are shared by the U.S. and northern Mexico.

*Feasibility*: Conducting NASA research and field campaigns domestically is simplified by lower cost, less time, and logistical ease of instrument transportation (relative to international transport of instruments, personnel, etc.), ease of use of NASA funds domestically on researchers at U.S. institutions, safety, and high density of airports with feasible air traffic permissions. Several examples of successful domestic campaigns, and particularly those ARID will leverage, are discussed in Section 2.5. International sites are also selected partly based on research partner availability and their ability to augment deployment of NASA campaign components.

### Further Motivation of ARID Distributed International Domains

*Southern Africa:* In addition to strong interest from the community, southern Africa includes gradients between hyper-arid ecosystems in Namibia to dry tropical forests in Mozambique. There are existing efforts by USAID, NASA SERVIR, university partners in Mozambique, and Conservation International in Botswana to augment sustainable land management practices. These are opportunities for NASA to assist with co-development efforts. There are also opportunities to build on former NASA field campaigns (BioSCape) in South Africa. Additionally, the ARID team has connected with Gobabeb-Namib Research Institute and University of Namibia leadership in Namibia and Okavango Research Institute in Botswana, providing further opportunities to co-conduct field campaigns with in-place knowledge holders and field sites as well as contribute to co-training students (see letters of support).

*Australia:* Australia is likely a strong driver of carbon cycle interannual variability (Metz et al., 2023; Poulter et al., 2014) especially with its strong sensitivity to ENSO events. There is also strong technical ecosystem science experience among Australian researchers and high potential for co-development of work. For example, ARID team members are well connected with and have partnered with TERN and OzFlux site networks, as well as government institutions like CSIRO. Additionally, the ARID team has partnered with leadership of a proposed Centre of Excellence to be funded through Australia's Research Council focused on effects of heatwaves on terrestrial ecosystems that would have a similar timeframe and scale as ARID.

*Northern Mexico:* Northern Mexico was commonly mentioned by the community to consider given it shares the Sonoran and Chihuahuan Deserts with the US and might provide an opportunity for US-Mexico transects. These include gradients between arid desert and semi-arid croplands. Agencies like Mexico's SAGARHPA and Institute for Forestry, Agriculture and Livestock Research (INIFAP) assist farming, ranching, and forest industries, and there are opportunities to assist end-users. Co-development of dryland ecosystem function is likely with ARID partners including site networks MexFlux and NEON and partners at Universidad Nacional Autonoma de Mexico (UNAM) and the Instituto Technologica de Sonora (ITSON). There are also opportunities to co-produce with the Mexican National Council of Humanities, Science and Technology (CONAHCYT), which is a funding ministry for Mexican researchers that funds networks like Network of Social-Ecological Participatory Observatories (SEPO) and International Network for Drylands Sustainability (RIZA).

*South America:* ARID also received a high proportion of community feedback with written inputs to include South America, and particularly to include existing efforts in the Gran Chaco, Cerrado, and Caatinga (i.e., the South American Dry Diagonal). NASA has conducted work particularly in Brazil during the LBA campaign, but not in drylands east and south of the Amazon tropical forest. These areas are experiencing dramatic change due to climate and land use changes. While an arid region was registered for the first time in northeast Brazil, the semi-arid region is expanding at a rate of 75,000 km2 per decade (Tomasella et al., 2023). There are vast ongoing research efforts for ARID to complement including NeoTropTree, DryFlor, SECO, FAPESP e-phenology, among others, which are established communities and measurement networks*.* In fact, in September 2024, ARID leadership held a workshop with about 50 researchers in South America or those who conduct work with these networks to understand research needs. There was interest in participation of all dryland sites across South America, which **more than 30% of South America is drylands**, and including research in seasonally semi-arid regions like the Cerrado which are experiencing increased atmosphere aridity and land transformation may be a proxy and testbed for understanding expansion of drylands, also in direction of tropical and subtropical moist forests. Furthermore, ARID has partnered with the Organization of American States, which will be pivotal for connecting the work ARID does with end-users and land managers in South America.

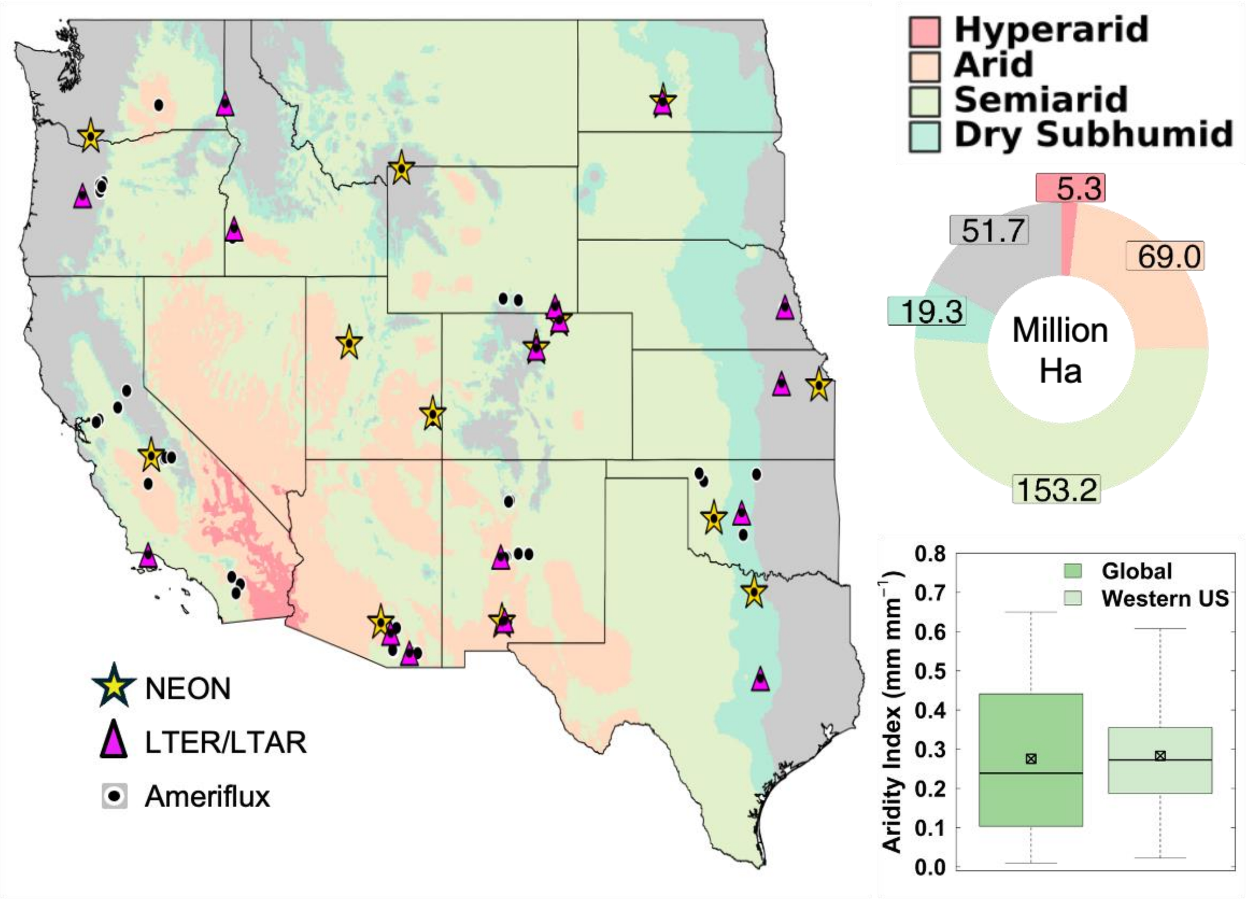


***Figure B.11.*** *ARID's proposed intensive, threshold domain as shown in the colored shading. Most of the region is arid and semi-arid (pie-chart) and its mean aridity is approximately the same as the global dryland mean aridity (see boxplots).*

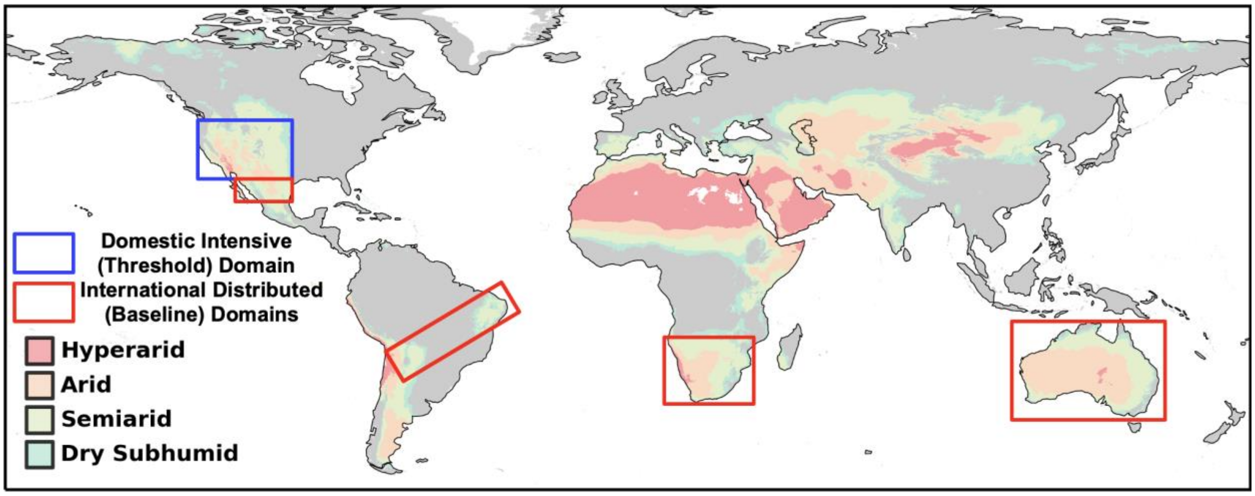


***Figure B.12.*** *Global dryland distribution based on aridity index. Potential ARID field domains are outlined by borders and include shaded dryland regions (based on aridity index) within those borders. A core intensive domain includes shaded drylands within the western US highlighted approximately by the blue borders. Candidate distributed international domains are shown as shaded regions outlined by the red borders. More specific proposed transects and sites are proposed in Section B.2.6. These are ultimately focal areas that ARID will focus, and are not meant to be exclusive. Research and measurements can be proposed and included within ARID outside of these focal areas during the campaign.*

### B.2.5 Leveraging Existing Field Campaigns and Networks

A defining feature of the ARID field campaign is a strong ability to leverage previous and ongoing field (including airborne) campaigns. While NASA and other agencies (i.e., USGS) have invested in airborne campaigns in drylands, and particularly in the western US, these datasets have not been used substantially to advance understanding of dryland ecosystem processes. In fact, the ARID team queried their working group members about their use and need for airborne measurements (see Appendix F.10 for more details). The 67 members queried included scientists at varying career stages that have worked to varying degrees in drylands. Of these researchers, very few had any knowledge of the range of aircraft campaigns that NASA was involved in (including GEMx, Western Diversity Time Series, SHIFT, etc.). This might be attributable to the campaigns addressing a specific set of research questions (often unrelated to dryland ecosystem science), limited community engagement, and/or being focused on technical readiness level demonstration for upcoming satellite sensors. This also may be due to the fact that previous NASA airborne acquisitions were not coordinated with field measurements and optimally timed within a cohesive dryland ecosystem field campaign as proposed by ARID. Despite the apparent lack of awareness of previous NASA campaigns, all respondents indicated that future aircraft measurements across VSWIR imaging spectroscopy, lidar, microwave, infrared, etc. would be useful to their work in dryland ecosystems. Furthermore, the respondents overwhelmingly indicated that temporal revisits, especially at seasonal timescales, would be most useful for addressing their research questions. This feedback creates a strong case for multi-temporal, multi-sensor, strategically located airborne acquisitions that complement existing and on-going to address ARID science questions. It is clear that the existing airborne campaigns by themselves cannot sufficiently advance our understanding of dryland processes.

We describe several campaigns here that ARID should specifically leverage in its intensive domestic domain in the western US and in some cases internationally. These include both airborne and ground measurement networks. This list is not exhaustive, and we anticipate a wide array of data will be leveraged within ARID, though we anticipate that the campaigns and networks mentioned here are critical to leverage to address ARID’s research questions. For example, we anticipate that several AmeriFlux and/or NEON sites will serve as ARID Super Sites (see Section 2.3).

#### *B.2.5.1 Ongoing Aircraft Campaigns ARID will leverage*

***Geological Earth Mapping Experiment (GEMx) (2023-2026):*** GEMx is an interagency effort by USGS and NASA to collect VSWIR imaging spectrometer and multispectral infrared data for surface mineral identification and mapping across a large portion of the western US using NASA's ER-2 high altitude aircraft. GEMx runs through 2026 with funding up to $4M per year provided by the USGS Earth Mapping Resources Initiative (Earth MRI). Flights occur between April and September each year. GEMx goals include improving knowledge of the nation's geology, in particular critical mineral resources. Sensor's flown have been AVIRIS-Classic and MASTER (MODIS/Aster Airborne Simulator) in 2025 and 2026, the sensor suite is expected to include AVIRIS-3. Lower altitude collections of AVIRIS-NG and HyTES (Hyperspectral Thermal Emission Spectrometer) are also possible in the coming years. GEMx activities complement the Earth Surface Mineral Dust Source Investigation (EMIT) mission. To date, 480,000 sq. km of the western US have been covered, with plans for further coverage throughout 2025-2026 across all of the southwestern US states (Fig. B.13). Given that GEMx is ongoing, and GEMx leadership is also on the ARID leadership team (Raymond Kokaly), it is possible to plan timing and location of GEMx flights to benefit both ARID's and GEMx goals.

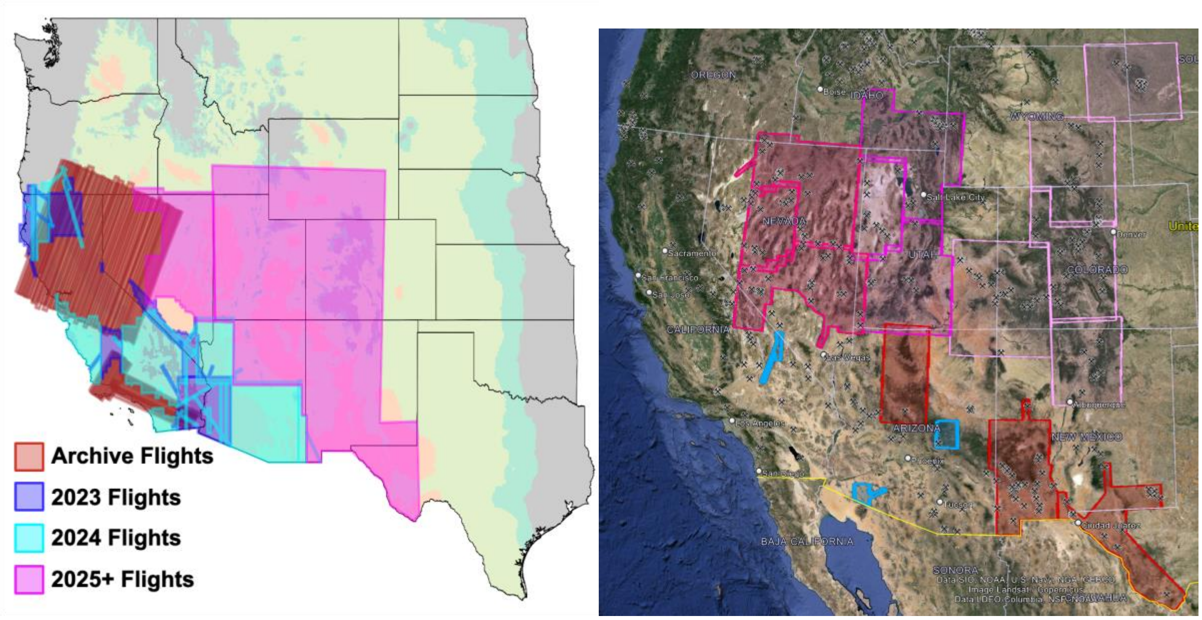


*__Figure B.13. (A)__ left, GEMx flight coverage compared to ARID domain using AVIRIS-Classic and MASTER instruments. __(B)__ right, Prospective GEMx coverage in 2025 to 2027 with red boxes indicating flights for April to June 2025, dark magenta boxes (NV) for flights in June-Sep 2025, and pink boxes for flights in 2026/2027. Blue boxes include a re-fly in 2025 for areas that were cloudy.*

***Hyperspectral Infrared Imager (HyspIRI) and Western Diversity Time Series (WDTS) (2004-present):*** HyspIRI was a NASA satellite mission to study global vegetation state and monitor natural disasters (drought, volcano, wildfire) with imaging spectrometer and multispectral infrared data. It has included several airborne campaigns since 2004 with AVIRIS-Classic and MASTER mainly in southern California and parts of Nevada (Lee et al., 2015). As a continuation, WDTS is a NASA field campaign in California starting in 2013 and continuing to provide critical information on natural disasters like volcanoes, wildfires, and droughts. The initial HyspIRI-based airborne campaign was mainly used to demonstrate technical readiness for upcoming satellite missions (Lee et al., 2015). WDTS is aiming to establish a time series of repeated collection in areas of the western US. To date and to our knowledge, these data have not yet been widely used to address dryland science questions as proposed by ARID. Flights include MASTER, AVIRIS-Classic, HyTES, and PICARD sensors flown on ER-2 aircraft. The

ARID team connected with WDTS leadership at University of Wisconsin (Prof. Phil Townsend) and, in stating a need for more scientific use of the datasets and ongoing dataset development efforts, they encouraged the use of the datasets within ARID.

***Goddard's LiDAR, Hyperspectral & Thermal Imager (G-LiHT) (2011-Present)***: G-LiHT is a NASA airborne campaign ongoing since 2011 including many flight paths across the western US (Cook et al., 2013). It measures Lidar, thermal, and VNIR imaging spectrometer data. With ongoing funding through NASA Headquarters, it is expected to continue into the timeframe of the proposed ARID field campaign.

***FireSense (2023-2028)***: FireSense is an annual NASA airborne campaign starting in late 2023 to improve US wildfire management. Previous and planned flights include AVIRIS-3, MASTER, UAVSAR, and SLAP throughout the western U.S mostly in Colorado, Arizona, Utah, and California.

***NEON***: These are NSF funded sites operated by Batelle, with many sites throughout the US (Fig. B.11). These sites include associated aircraft flights during peak greenness at all sites annually or bi-annually including from hyperspectral, thermal, and LiDAR instruments. Flight schedules can be found at https://www.neonscience.org/data-collection/flight-schedules-coverage.

***Other noteworthy airborne campaigns***: There are other campaigns ARID can leverage in specific cases including WHyMSIE airborne campaign includes flights across the western US and Great Plains in 2024, SMAPVEX flights in 2015 in Tucson, AZ, the SBG SHIFT campaign in California in 2022, FarmFlux across the Great Plains and western US beyond 2027, and upcoming Catalyst. More information about other campaigns is provided in Appendix F.12.

#### *B.2.5.2 Field Networks ARID will directly leverage*

***NEON***: These sites provide typically a range of field measurements including water and carbon fluxes, soil moisture, temperature, and radiation. There are approximately 13 of these sites across the western U.S. that ARID can leverage.

**GERI:** Leading international partners institutions (e.g. TERN - Australia, SAEON - South Africa) are members of Global Ecosystem Research Infrastructure (GERI), along with NEON. Together, they are coordinating research on global ecological drought.

***AmeriFlux***: These sites provide a standardized set of measurements including water and carbon fluxes, soil moisture, temperature, humidity, wind speed and radiation across the U.S. (Fig. B.11). With AmeriFlux as an ARID partner, obtaining datasets from site PI is more streamlined and there are opportunities to install new instruments at these sites within the ARID campaign. Of particular interest are use of the net ecosystem exchange and evapotranspiration measurements which can be used to develop and scale remote sensing products of these quantities.

***LTAR/LTER***: These sites are often coupled with AmeriFlux towers, but also integrate strategic research, coordinated experimentation, and common measurements to address ecological and agricultural challenges within and across major US ecoclimate zones. LTAR sites particularly focus on agricultural lands including croplands, grazing lands, and integrated agroecosystems.

***NOAA Fire Prediction Sites:*** NOAA received funding to set up four fixed field sites in Flagstaff, Arizona, Berkeley, California, Boise, Idaho, and Gunnison, Colorado. These sites will include soil moisture and temperature, doppler and LiDAR, eddy covariance, wind speed, and others. They will also include some UAS flights potentially annually. ARID has partnered with this effort and there are opportunities to collaborate by adding additional measurements at these sites based on the leasing arrangements at each site.

***Snowtography***: These sites were designed to monitor a wide variety of ecohydrologic factors including daily snow depth, snow water equivalent, soil moisture, etc. along gradients of forest management including mechanical thinning, commercial harvest, and managed fire. This network is ideally suited for quantitative evaluation of the impacts of management on forest ecohydrologic processes and physical parameters.

**BLM-AIM**: The Bureau of Land Management Assessment Inventory and Monitoring (BLM-AIM) program uses standardized ground-based measurements to assess the natural resource conditions and trends on BLM-managed public lands (Fig. B.14). The AIM Strategy provides quantitative data and tools to guide and justify policy actions, land uses, and adaptive management decisions and offers a wealth of data available to ARID, which could be joined with airborne and spaceborne data. AIM has currently assessed over 20,000 dryland sites that could be leveraged for AIM.

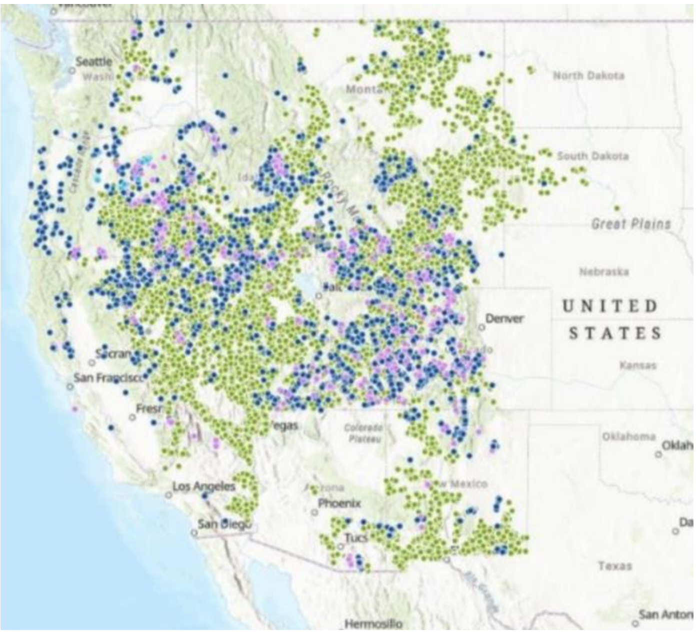


***Figure B.14.*** *Map of BLM AIM sites. There are currently >50,000 BLM AIM sites in the western US.*

**USFS FIA**: Many Forest Inventory and Analysis (FIA) sites are in dryland forests, such as pinyon-juniper woodlands and dry mixed conifer forests, which represent the most extensive forest cover types in the U.S. The FIA annual inventory provides data on the extent, condition, volume, growth, depletion, and health of US forest resources. FIA Plots consist of one field sample site - designed to cover a 1-acre sample area - for every 6,000 acres of forest. Common variables measured regularly across all FIA plots include diameter at breast height (DBH), total height, age, mortality, and crown base height, which can be used for diameter growth increment analysis and biomass assessment through allometric relationships. Additional measurements including tree increment cores, downed woody material (DWM), soil chemistry, and understory plant composition are collected for a subset of plot and can be used to assess ecosystem-level carbon pools and fluxes, forest health and sensitivity to climate, fuels and fire hazard, and trends in forest health, insects and pathogens, and invasive species (Tinkham et al., 2018).

**NPS I&M**: The U.S. National Park Service maintains 32 Inventory and Monitoring networks across the country, many of which are in drylands. NPS I&M uses standardized inventory and monitoring to track natural resources through time - including plant cover, composition, diversity - and these ground-based data represent a strong potential link with remote sensing data, models of ecosystem change, and assessments of the accuracy of satellite sensors in capturing shifts in plant communities and associated resources through time.

**NRCS-NRI**: Natural Resources Conservation Service National Resources Inventory (NRCS NRI). The NRI is a statistical survey of land use and natural resource conditions and trends on U.S. non-Federal lands, offering a powerful inventory complement to BLM-AIM, USFS-FIA, and NPS-I&M, which focus on federal lands. The NRI collects and produces information on the status, condition, and trends of land, soil, water, and related natural resources on the nation’s non-federal lands.

**Landscape Data Commons**: The Landscape Data Commons (LDC) is an inter-agency monitoring data repository and portal, led by the Jornada Experimental Range in collaboration with USDA-ARS and New Mexico State University, that connects standardized monitoring data to analysis tools to support land management and research. The LDC aggregates and harmonizes core methods and data collected across agencies and monitoring programs (e.g., BLM-AIM, NPS I&M, NRCS grazing land on-site program, the National Wind Erosion Research Network, and smaller research and monitoring efforts). There are currently 85,000 locations housed within the LDC. With these aggregated data, the LDC supports natural-resource management, modeling, and research.

**National Wind Erosion Research Network:** The National Wind Erosion Research Network (NWERN) is a multi-partner network established in 2014 that collects standardized measurements of aeolian sediment transport, dust emission fluxes, meteorological conditions, and soil and vegetation. NWERN vegetation inventory and monitoring methods follow those implemented by the BLM AIM and NRCS NRI programs, enabling aeolian sediment transport processes to be linked to dryland ecosystem processes, services and management. NWERN is currently the only network collecting long-term, standardized aeolian process data to support dust model parameterization across ecosystems.

**CrustNet**: In 2023, the National Science Foundation funded a global network focused on biological soil crusts: CrustNet. Biocrust researchers from around the world will assess biocrust and plant community composition and function in drylands and will provide these data to a centralized data repository that can be linked with ARID. Although the collections of spectral data are not planned for CrustNet, ARID and CrustNet could each be benefitted and leveraged by using the same communities and samples to gather remote sensing data that could then be scaled using satellite and modeling approaches.

### *B.2.6 Proposed Field Campaign Implementation Strategy*

#### *B.2.6.1 Field Campaign Strategy Overview and Motivation*

Here, we develop an ARID implementation strategy within the domains defined in Section B.2.4 and leveraging existing networks and campaigns in Section B.2.5 to address dryland science themes and questions in Section B.1. We motivate and outline an overarching strategy in several focal areas within the ARID domains. However, we emphasize that the campaign plan is flexible and expect a variety of approaches will advance the understanding and sensing capabilities of dryland ecosystems. This section focuses on addressing foundational science questions, while B.2.7 expands the approach to applied sciences relevant to NASA Earth Action programs.

The guiding principles of the field campaign strategy include but are not limited to:
(i) The overarching dryland science questions laid out in Section A.2 and expanded science themes in Section B.1
(ii) Multi-temporal airborne acquisitions needed to address the science questions
(iii) Scaling and development needs for remote sensing observations and modeling techniques
(iv) Leveraging existing assets (data and infrastructure) and investments by partners, and particularly supersites (see Section 2.5)
(v) The safety and security of team members and affiliated scientists
(vi) Optimal location of US and international focal areas that bring the most science return and potential for co-development with partners while being feasible and low risk.

*High spatio-temporal sampling with multiple sensors:*
Given the high spatial heterogeneity of drylands and rapidly changing conditions, the ARID field campaign strategy must accommodate sampling across spatial, temporal, and spectral scales. This requires integration of a broad range of sampling strategies that allow for not only capturing of heterogeneity, but also synthesis of approaches and datasets for high interoperability and advances in our understanding of drylands. The optimal field implementation approach will depend on the science themes being addressed. For example, high spatial sampling is necessary for vegetation structure and biodiversity themes. High temporal sampling is necessary for pulse dynamics, drought, and fire themes. A range of spectral measurements are necessary for understanding interactions between themes (water-carbon coupling). High spatial scaling must include use of in-situ, drone, aircraft, and satellite measurements, underscoring the relevance of this effort as a NASA Terrestrial Ecology Field Campaign. Upscaling is especially important for integration with gridded models that predict global climate and contribute to ARID’s central goal of estimating dryland contributions to water, carbon, and energy cycles. Specifically, dryland ecosystems are highly spatially heterogeneous with high vegetation biodiversity, which requires measurements at high resolution (<1m) and linkages with larger scales. In addition to capturing dryland structure at the necessary scale, assessments at these scales can provide insight into satellite remote sensing observation capability and algorithm development. Temporal scaling requires capturing diurnal to interannual timescales to characterize the rapid response of drylands to weather and climate. Drylands are driven by individual moisture pulses, and thus field campaign measurements can blend satellite remote sensing assessments with a focus on these pulse-drydown sequences using complementary ground-based and airborne approaches. Finally, a range of remote sensing modalities and scales are needed, with microwave sensing providing information on water availability and carbon stocks, hyperspectral on ecosystem composition and soils processes, and LiDAR on ecosystem structure. In this way, ARID’s aspiration is to create a new understanding that is multi-scale, multi-sensor, and

hypertemporal, joining new and emerging techniques and process models to assess heterogenous, dynamic drylands.

*ARID Super Sites Strategy:*
Some of the challenges of high spatiotemporal sampling needs of drylands can be overcome with leveraging *Super Sites* (Fig. B.11). Previous NASA field campaigns have demonstrated the need for collocations of field plots, instrumentation (e.g., flux towers and proximal sensing), and UAS surveys across projects so that data may be properly integrated to effectively address complex science questions. Super Sites are high priority field sites, with a rich diversity of historic field data and infrastructure, field experiments that chronicle long-term management practices and treatments, as well as archived and ongoing airborne data (e.g. NEON and LTER sites). They also provide measurements of challenging parameters to estimate with remote sensing, including carbon and water fluxes. In many cases, these Super Sites will form the core locations of ARID airborne flights and effectively create a hotspot of scientific collaboration. Experience from the ABoVE team suggests that such Super Site locations should be very carefully planned (especially those to leverage) at the outset of the field campaign to encourage individual projects to focus field effort to these locations.

*Multi-temporal Airborne Acquisition Strategy:*
ARID identified a community-motivated need for multi-temporal airborne sampling in order to understand the dynamics of drylands, and to address our science themes. Of particular interest are temporal revisits for evaluation of ecosystem responses to disturbance, seasonal changes, and rain pulses and drought. Several multi-temporal sampling strategies can be employed during ARID:

- Pulse chasing: make aircraft measurements immediately after rain event or at the peak of an extreme event such as drought/heatwave over ARID Super Sites
- Seasonal Sampling: remeasure the same location in different phases of growing season (e.g., repeated sampling of NEON sites that are traditionally sampled only at peak greenness)
- Fusion approach: Drones can be used to resample on demand at a specific temporal cadence across Super Sites within the bounds of a single aircraft overpass

To create multi-temporal measurements, ARID will take advantage of existing assets (see Section 2.5) to augment the aforementioned acquisition strategies, especially for building time series and wide spatial extents of measurements. For example, ARID will conduct new aircraft measurements over previously-sampled locations to identify ecosystem changes, coordinate aircraft measurements with ongoing campaigns to capture pulses or seasonal changes (GEMx, NEON, FireSense). As such, a time series can be built by leveraging existing NASA, USGS, and other investments.

*Strategy to Leverage Manipulation Experiments:*
There is a wealth of in-situ climate and land-use experiments in drylands, as well as myriad large scale land management activities that offer exceptional opportunities for addressing

ARID’s science themes and questions. For example, NutNet, DroughtNet, and Dragnet are globally distributed manipulation experiments in grasslands that use standardized methods to alter nutrient inputs and forage consumption, precipitation amount, and land disturbance, respectively (*DRAGNet*, n.d.; *Drought Network*, n.d.; *Nutrient Network*, n.d.). In the US alone there are also dryland warming experiments (Fig. B.15), grazing experiments, and experiments that simultaneously explore the interacting effects of multiple global change drivers. These experiments were designed to simulate global change to assess the mechanisms behind shifts in plant and soil community composition, carbon storage and flux, and factors related to the numerous ecosystem services provided by drylands. They now offer ARID unprecedented opportunity to use remote sensing and ground-based tools to improve the capacity to remotely sense, scale, and model the effects of global change across larger dryland areas. The unique power of an ability to “see” what this change looks like in controlled settings where background soil, climate, and atmospheric conditions can be kept constant. In addition to research experiments that can be leveraged to improve our understanding and remote sensing tools of dryland change, the large observable land management actions taken in drylands offer an opportunity to quantify and predict land treatment success and failure. For example, over the past two years, the Bipartisan Infrastructure Law (BIL) and Inflation Reduction Act (IRA) have provided management agencies billions of dollars, much of this going to drylands of the western US for water, climate resilience, and habitat restoration activities. These recent and planned activities represent the potential for an extremely strong synergy between ARID and US land management agencies, as managers are asking for partners and tools with which to assess the outcomes from this substantial investment in dryland systems, and as these treatments are large-scale experiments that can be learned from and leveraged. ARID research can help learn from the outcome of these treatments in support of future management, and the work these agencies do on the ground offer an unprecedented opportunity to improve our understanding and ability to measure ecosystems and change at the landscape scale. Our manager partners are willing to time and to design these actions in collaboration with ARID PIs to facilitate this co-production of actionable science.

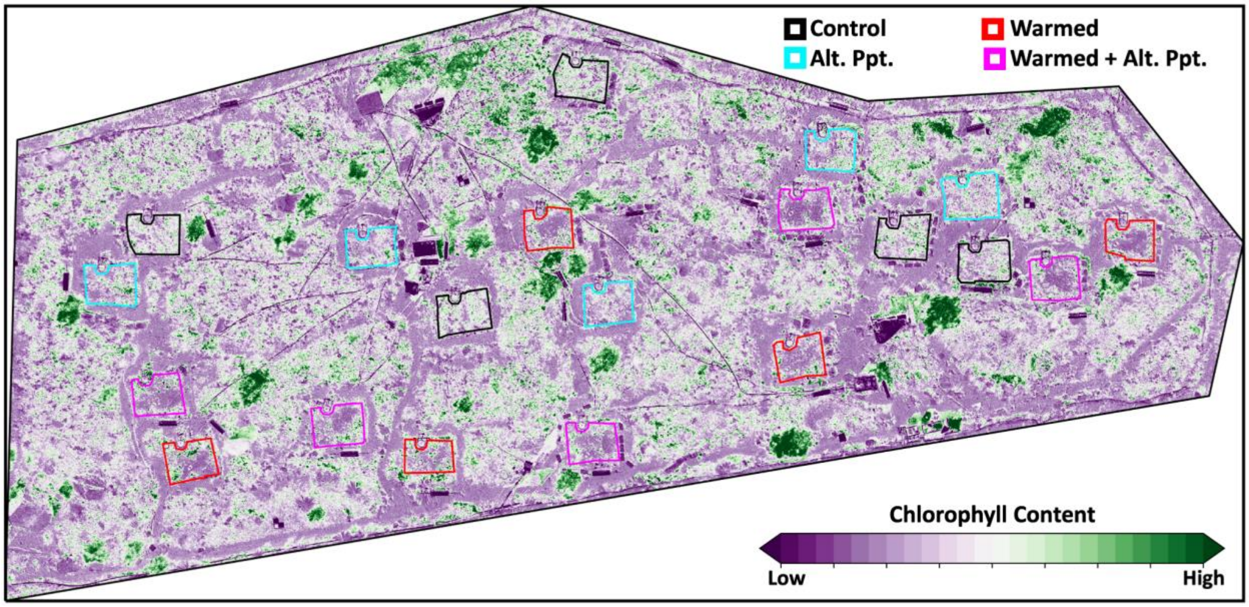


***Figure B.15.*** *An example integration of remote sensing measurements into a long-term climate change experimental manipulation. The base map of chlorophyll content at 10-cm spatial resolution was generated from UAS multispectral data. Experimental plot replicates are shown as colored polygons overlaying the map. Visual inspection reveals that warming greatly reduced chlorophyll content across these biocrust-dominated experimental plots (Phillips et al., 2022).*

*B.2.6.2 Focal Area Selection Criteria*

The selection of focal areas within our domains considers multiple factors, including:

1. Ability to contribute to addressing ARID science themes
2. Representation of diverse dryland environments and environmental gradients, or locations that fill a specific knowledge gap
3. Experiencing the most pronounced climatic events (e.g. extended drought) or change
4. Experiencing a historical disturbance or management regime so as to serve as macro experiments
5. The existence of established field sites with long-term data and instrument infrastructure (e.g. NEON/AmeriFlux sites, LTER/LTAR, BLM-AIM sites)
6. Co-location with on-going airborne campaigns and/or with long-term airborne data (e.g. NEON sites)
7. Containing priority locations identified by end-users and Tribal Authorities

In addition to the above criteria, international focal sites also consider the following criteria:

1. Expanding the global dryland representativeness for data and models
2. Addressing ARID science questions from a global perspective
3. Having an existing track-record of dryland research by local partners (e.g. SAEON, TERN, MexFlux)
4. Containing compatible airborne assets, and capability of international partners and commercial service providers to conduct airborne surveys if needed

5. Availability of logistic support and infrastructure for fieldwork
6. Having high levels of safety for researchers during field work

Within our western US and international domains, we propose several candidate focal areas: Four in the western US and four international areas in Mexico, southern Africa, Australia, and South America. We propose a rotating field sampling strategy, where one domestic and one international focal area is intensively sampled for an approximate two-year period, and rotating to a different site for the next ~two year period and so-on (Table B.4; see Section B.2.9 for information on potential coordination with other field campaigns). However, scientific activities that focus on each of these areas should be continued throughout the duration of the ARID campaign.

***Table B.4.*** *Rotating field campaign strategy with a new domestic and international focal region every approximately two-year period. The ordering of domains is not in order of priority and can be shifted based on feasibility.*

| | Year 1/Year 2 | Year 3/Year 4 | Year 5/Year 6 | Year 7/Year 8 |
|---|---|---|---|---|
| Domestic Domain | Southwest US | Great Plains | Great Basin | Mountain West |
| International Domain | Mexico | Southern Africa | Australia | South America |

We note that this modularity allows for descoping as necessary (see Section B.2.9). At a minimum, a western US-only domain can accomplish many of our goals and science questions. The western US is nearly identical to the global mean of aridity, and we can scale the new collective understanding to other drylands. However, we emphasize the high scientific value our international sites provide in scaling to global domains, including more representation of drier hyperarid and wetter sub-humid biomes, different climate forcing and variability conditions, different vegetation types, and different natural resource management challenges. These international domains also allow deeper insights into several of our science themes by providing a wide range of data points and testing a wider variety of modeling approaches. More details about the value of these domestic and international focal areas follow.

### *B.2.6.3 Domestic Focal Areas*

Here, we motivate our four focal areas and provide example studies to be conducted within the campaign to address ARID's research questions.

***Southwest*:** The Southwest focal area includes Arizona, New Mexico, and southwestern Colorado (Fig. B.16). A key feature of this region is extensive field sampling and strong in-place knowledge by university, tribal, and government-based partners. The region includes existing in-situ networks with dense coverage between AmeriFlux, LTER/LTAR, NEON, and Snowtography sites. Additionally, existing aircraft measurements include GEMx aircraft coverage in 2023 and 2024 (scheduled to continue into 2026) and several G-LiHT flights between 2011 and present. Therefore, there is high potential to scale understanding of dryland processes between in-situ, aircraft, and satellite scales. The region also offers a southwest-to-northeast gradient of hot to cold conditions (with elevation gain) and transition from summer-dominated to winter-dominated seasonal precipitation (Fig. B.17).

Example studies:

1) *Vegetation Structure Heterogeneity Tests*: The region's highly heterogeneous landscape with mixture of grassland, shrubland, woodland, and forest offers a testbed for evaluating remote sensing indices' ability to quantify vegetation structure at finer spatial scales and scale up to that of satellite observation resolutions. Single aircraft overpasses over instrumented supersites (NEON, AmeriFlux, LTER sites) are particularly useful for meeting this goal.
2) *Tribal Land Management*: Given strong tribal interest in water availability at site scales, UAVSAR and NISAR measurements can be used to both monitor soil water availability but also map spatial distributions of soil moisture at high resolution (<200m) across managed tribal lands.
3) *Water Availability*: High resolution soil moisture sampling from in-situ networks and microwave aircraft measurements (UAVSAR, SLAP) can provide insight into the spatial distribution of soil moisture, particularly with regard to proximity to higher vegetation density and riparian zones. It also can provide insight into the effect this soil moisture heterogeneity has at NISAR's 200m scale and SMAP's ~30km scale.
4) *Drought and Fire Disturbance*: With high potential for drought and fire disturbance in the region, ARID can include AVIRIS flights after such a disturbance, while using GEMx AVIRIS 2023-2024 measurements as a baseline for change detection.
5) *Pulse Chasing*: With strong summer monsoonal effects in the Southwest US, pulse chasing is particularly useful for capturing vegetation and soil pulse responses to large rainfall events. Both in-situ field sampling teams and airborne teams can begin sampling after a large rainfall event to monitor both vegetation (pulse-reserve) and soil (birch effect) responses. Such responses are particularly important for model integration.

***<u>Great Plains</u>*****:** This focal area extends from northern Texas to the northern Great Plains in South Dakota, as well as between eastern Colorado to western Nebraska and Kansas. The goal for this region is to address rangeland and cropland management questions, given a gradient between rangelands of eastern Colorado and croplands throughout the midwestern states in the domain. Airborne assets to leverage include the upcoming FarmFlux campaign (post 2027) with carbon and nitrogen flux measurements, NEON flights at Colorado and Oklahoma sites, and upcoming WHyMSIE planetary boundary layer flights. In-situ assets include Mesonet soil moisture sites, especially throughout Oklahoma and Nebraska.

Example studies:

1) *Rangeland and Cropland Management*: AVIRIS flights are particularly useful for fractional cover of plant functional types (PFTs) and biomass, which are variables that are useful for BLM's decision-making tools.
2) *Cropland Carbon Uptake Contribution*: Given potential for CARAFE flights in this region and as a part of ARID, there is an opportunity for quantification of carbon fluxes for specific vegetation types throughout croplands and rangelands. Such flights can be coupled to flux tower measurements such as from NEON for scaling of the site and aircraft data to drive remote sensing-based carbon flux estimates.
3) *Land-atmosphere Interactions*: The dry to wet gradient from west to east in this region is an opportunity to test the contribution of soil moisture to dryland ET and consequent convection development in this region. Possibly, there is less potential for convection initiation further west where the ET magnitude is lower. AmeriFlux and NEON towers, as well as potential lower atmosphere aircraft measurements from WHyMSIE, allow testing of these hypotheses from drier to wetter sites.

***<u>Great Basin/Mojave:</u>*** This focal area is recommended mainly from southern Idaho through Nevada and extending into hyper-arid regions of central California and the Imperial Valley. The

Great Basin is a notoriously undersampled area and a goal for ARID is to provide more field and airborne sampling in this region. Under climate change, the Great Basin and the Mojave deserts are experiencing exceptional increases in fire frequency, invasive grasses, and woody plant encroachment, with severe implications for carbon storage, endangered species, dust production, and grazing (J. T. Smith, Allred, Boyd, Davies, Jones, et al., 2023; J. T. Smith et al., 2022). Therefore, understanding fire regimes is a focal point in this region. GEMx airborne measurements have been made in 2023 with plans for GEMx measurements in 2025 in this region and potential FireSense measurements through 2028. These serve as a baseline for change detection if VSWIR imaging or thermal measurements are made in future cases post 2028. There is also potential for the NASA Catalyst biodiversity effort to take place in this region. We acknowledge that southern Nevada may be infeasible to sample because of military airspace restrictions, but ARID has built strong partnerships with the Department of Defense and there is a likelihood of permission, at least with ground-based sampling.

Example studies:

1) *Invasive Species and Fire Management*: AVIRIS flights are particularly useful for vegetation type identification and fraction of vegetation cover, which are variables that are exceptionally useful for land manager decision making tools (e.g., BLM). Multiple aircraft measurements in the same location provide an opportunity to evaluate post-fire impacts and/or change in species composition (native versus invasive vegetation), as well as the ability to assess the efficacy of post-fire management actions. Such measurements coupled with ground information (such as surveys from BLM and USFS) will allow testing of high-resolution satellite remote sensing (from Landsat, EMIT, and SBG) to characterize vegetation coverage and species types.
2) *Soil and Geology*: VSWIR imaging spectroscopy from AVIRIS flights (GEMx) and EMIT measurements allow characterization of soil types, minerals, and biocrust across these lower vegetation cover deserts. This can be linked with ground-based data collections, such as through ARID's partnerships with NRCS, ARS, and NSF's CrustNet.

***Mountain West:*** This focal area consists of higher elevation, cold drylands across Idaho, Wyoming, and Utah (Figure B.17) with a gradient of hot to cold semi-arid environments from west to east. It includes Snowtography and AmeriFlux sites, as well as G-LiHT flights, though this region is generally more sparsely sampled. This region will provide insights into the effects of lower temperatures on dryland vegetation function, differences of dryland vegetation structure at higher elevations, and effects of water sources (soil water versus snowmelt) on ecosystem function.

Example studies:

1) *Vegetation Structure and Composition*: VSWIR imaging spectrometer and LiDAR measurements allow characterization of how the vegetation structure and composition changes between lower to higher elevation regions.
2) *Rangeland Management/Water Availability*: Evaluating soil moisture dynamics of this region and its rangelands is pivotal for understanding rangeland response to water-limitation. Particularly, this can involve evaluating seasonal moisture availability and partitioning sources of moisture between from rain versus snowmelt, which likely have varying seasonal inputs. These measurements can be directly linked with models of western US soil moisture (e.g., SOILWAT), which can blend the remotely sensed and ground-based data into contemporary and future projects of soil moisture and edaphic drought (Lauenroth & Bradford, 2012).

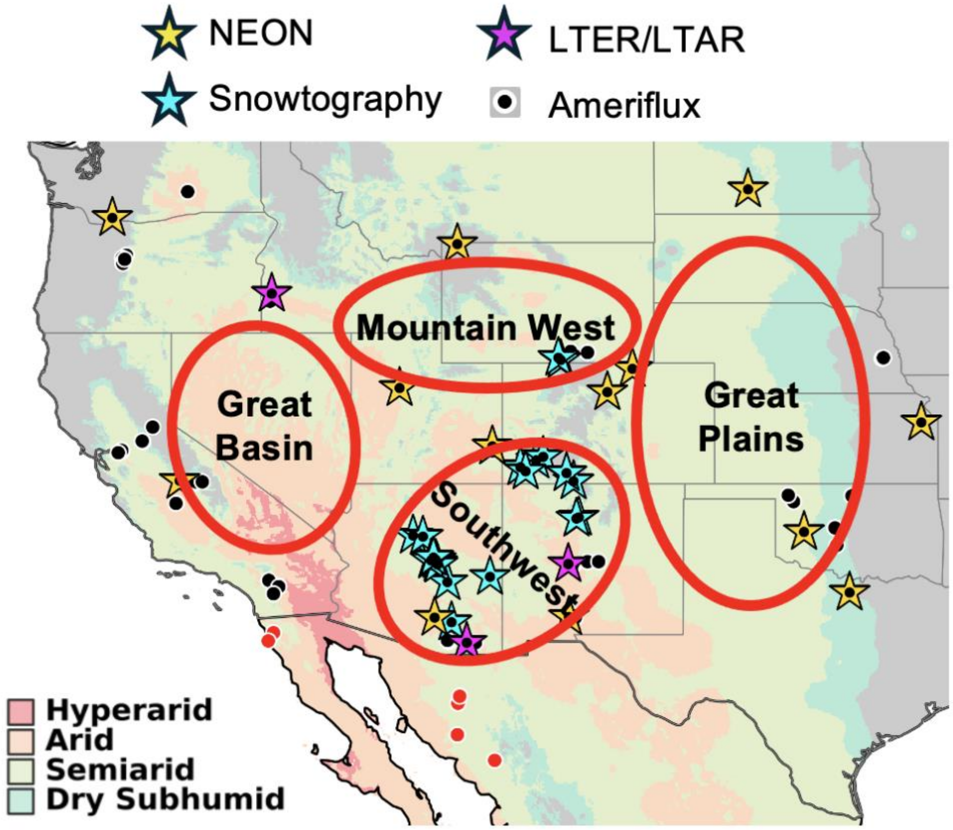


*__Figure B.16.__ Proposed focal areas within ARID’s western US domain. Red borders roughly outline focal regions.*

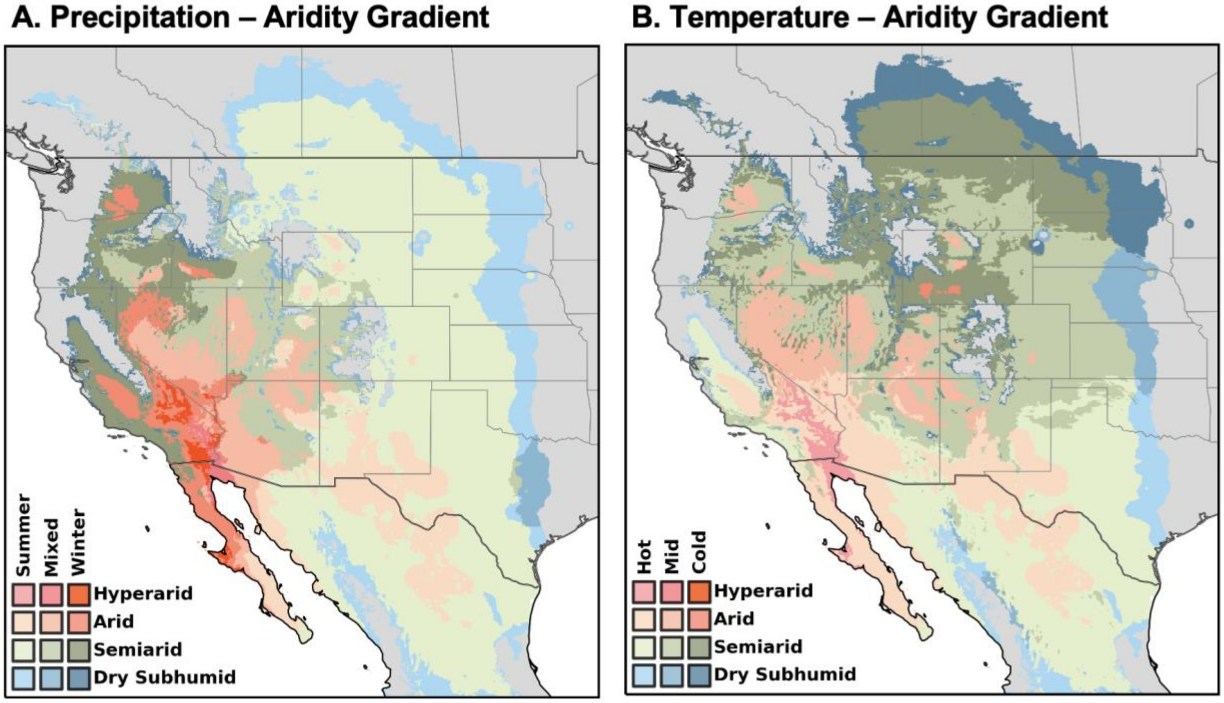


***Figure B.17.*** *The ARID focal areas take advantage of varying temperature and rainfall seasons across the western US.*

### *B.2.6.4 International Focal Areas*

Here, we provide motivation for our international focal areas. However, we note that our international implementation strategy differs from our domestic strategy by aligning activities with existing, in-place international research efforts in these focal areas that will address ARID's science themes (Fig. B.18). By aligning and co-developing with international research partners, we ensure continuity of the campaign activities (with the assets and measurements being leveraged beyond the bounds of the ARID campaign), allow for leadership of in-place researchers to champion the ARID campaign activities, and ultimately mitigate against ill-informed “parachute” science strategies.

International focal area suggestions were selected based on:
(i) Community interest in the region
(ii) Contribution of region to addressing ARID science questions at global scale
(iii) Scientific partners and their assets (data, and infrastructure)
(iv) Feasibility and operational risk

Based on these criteria, the suggested international domains are: Australia, northern Mexico, southern Africa, and the dry diagonal in South America.  We do not provide extensive details on study type examples, but offer an overall vision for the types of research and engagement in international domains.

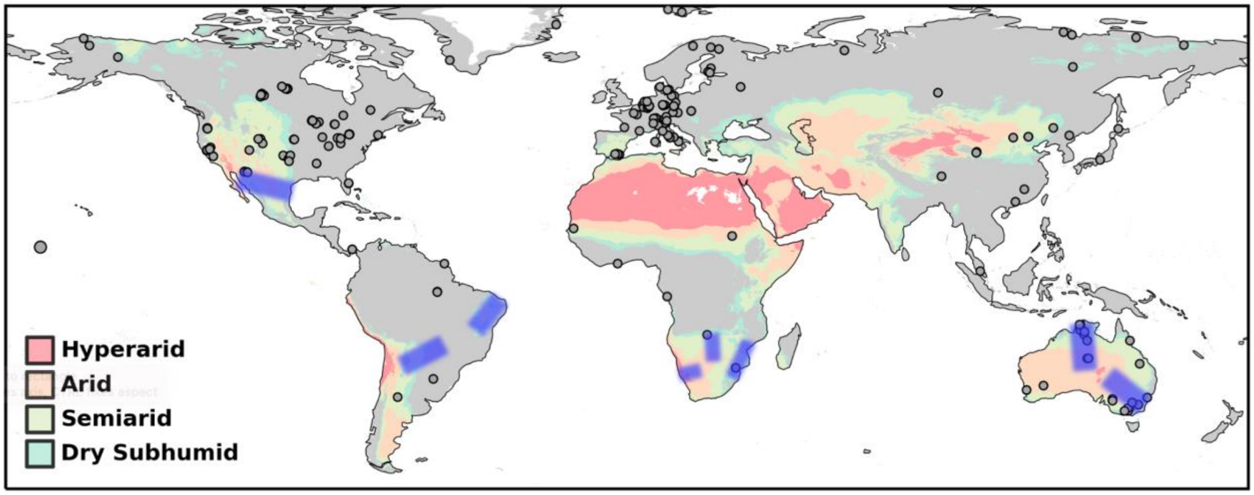


***Figure B.18.*** *Potential focal areas within ARID's distributed international domains. Existing FluxNet sites are shown as gray circles with black outlines. Blue shading roughly outlines potential focal regions, though these will likely change with input from partners and mission feasibility.*

_Australia:_ The ARID team has partnered with CSIRO (Commonwealth Science and Industrial Research Organization, Earth Observation Center), TERN, and OzFlux community, as well as a multi-university effort that is initiating a Centre of Excellence focused on heatwave impacts on ecosystem function. Australia has been identified as a potential strong source of carbon cycle interannual variability. Therefore, scaling between OzFlux sites, ground sampling, and potential hyperspectral aircraft measurements will be critical to understand relationships between vegetation spectra and vegetation carbon flux magnitudes. Sampling should also occur in El-

Nino (dry) and La-Nina (wet) years to understand the impacts of strong ENSO forcing in this region which heavily impacts the global C budget. Such scaling will inform vegetation remote sensing product development, especially for quantifying carbon fluxes. Additionally, with some of the most extreme global temperature occurrences, especially temperatures beyond which plants have experienced, Australia serves as a location to understand ecosystem process and response to high temperatures. Beyond distance constraints to the United States, there is a high feasibility of co-conducting research with a strong Australian research community. There is also potential for NASA instruments to be mounted on Australian aircraft to reduce US aircraft transportation costs or we can utilize their government-managed or commercial airborne sensors. Potential focal regions include dry-wet transects in New South Wales and Northern Territories that include OzFlux measurements (Fig. B.19). **More than 95% of Australia is drylands**.

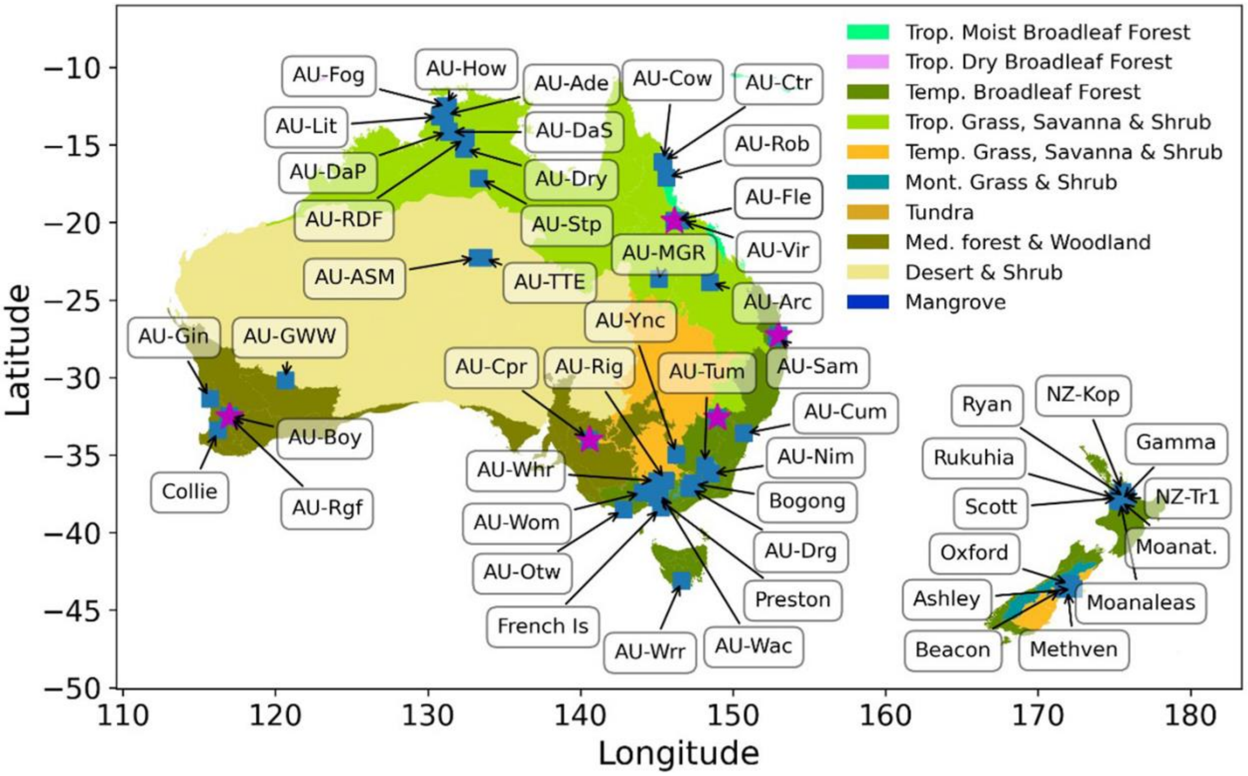


***Figure B.19.*** *OzFlux site locations across Australia (Beringer et al., 2022).*

*Mexico:* MexFlux and several university researchers have partnered with the ARID team, offering the ability to co-conduct research and extend the ARID domain south of the US border. This will extend representativeness into the Chihuahuan desert, the largest desert in North America to address questions related to the impacts of droughts, heatwaves, and rainfall pulses. Furthermore, as the Sonoran Desert extends further into northeastern Mexico, summertime rainfall becomes more dominant and plentiful, with a transition from semiarid to sub-humid conditions. With MexFlux and NEON sites, Mexico offers high potential for scaling understanding of hot deserts to global scale, especially with the addition of drone and aircraft measurements. With MexFlux, Mexico also has the potential to be a partner Super Site, and flights that include data collection of the US and Mexico are logistically straightforward. There are also strong capacity building opportunities for ARID between the US and Mexico, and students from both countries could benefit greatly from shared training and educational opportunities. ARID also has strong ability to address end-user needs in Mexico, especially related to cropland management and related water management. Such needs are motivated by food supply demands in northern Mexico amongst indigenous communities and dry conditions that limit food production, which partnerships with SAGHARPA can be leveraged to address these end-user gaps. **More than 50% of Mexico is drylands**.

*Southern Africa:* Southern Africa hosts a wide variety of dryland ecosystems, including arid shrublands, savannas, and woodlands, which supply the vast majority of the rural population's energy needs (e.g. fuelwood and charcoal) and where livelihoods are tightly linked to dryland ecosystem services. This region is also a hub of scientific activity which can help address dryland science questions in a continent that otherwise has a dearth of data and capacity. Community inputs motivated the ARID team to focus on this region. NASA also successfully carried the BioScape airborne campaign in South Africa, with demonstrated logistic support, safety, and scientific collaboration. We have consulted with NGOs (Conservation International) in Botswana, NASA SERVIR, USAID, and universities in Mozambique and Namibia, as well as research institutes in Namibia (Gobabeb-Namib Research Institute) and Botswana (Okavango Research Institute) (see letters of support). The South African Environmental Observation Network (SAEON) (similar to NEON) conducts research and provides facilities, instruments (flux towers), infrastructure (airborne sensors), datasets, models and staff across a diversity of ecosystems, including two nodes in drylands (see letter of support). SAEON can provide significant support and research partnership, as demonstrated during BioScape in South Africa.

Southern Africa, including at these partners' locations, offers a high potential to address key ARID research questions from a different perspective with in-place knowledge. Savannas have the potential to be a major carbon sink, but fire regimes, fuel wood removal, overgrazing and elephant impacts can lead to a net loss of carbon, resulting in controversial scientific and management debates. For example, both Conservation International and USAID are assisting end-users with sustainable rangeland management to prevent overgrazing and invasive species establishment. Partners at Eduardo Mondlane University in Mozambique are evaluating the fire regimes of sub-humid miombo woodlands and attempting to create tools for locals to conduct sustainable management practices. Okavango Research Institute in northern Botswana have collaborated with US Army Corps of Engineers studying the dry to wet transitions between dry savanna and dry tropical forest and particularly how carbon fluxes change across this gradient. Namibia's Gobabeb Research Institute studies the hyperarid desert ecosystems which are relatively sparse in the US, and which are excellent examples of ecosystems that receive inputs from non-rainfall dew and fog as a dominant water source. ARID also has the opportunity to strongly build upon BioSCape campaign, which, although focused on biodiversity in the Cape Floristic Region (Fynbos), also included additional dryland sites in South Africa. ARID would also benefit from the heritage of SAFARI2000 and the Kalahari transect. All partners offered to guide NASA and ARID for their respective country's governmental processes to fly aircraft for research purposes, and they noted experience and confidence for success with permissions processes.

*South America:* South America has a range of dryland ecosystems and infrastructure that can be leveraged and contributed to by ARID. For example, Brazil's national natural disaster monitoring and alert center (Cemaden/MCTI) uses a remote-sensing based dryland drought monitoring to provide monthly updates of an integrated drought index based on soil moisture and vegetation data. There are strong opportunities for ARID to partner with this organization. Brazil also maintains a semi-arid ecosystem rainfall and soil moisture network with 495 sites that offer strong opportunities to collect complementary data and to ground truth remote sensing. Multiple eddy covariance towers in semi-arid South American ecosystems maintain a focus on dryland responses to flash drought and could represent candidate international Super Sites. South America maintains an exciting phenological network (e-phenology) that crosses the continent and is focused on seasonally dry forests and woodlands. This network assesses productivity and functional traits, links with water cycles, woody vegetation and grassland dynamics, carbon sinks and sources, and provides a powerful opportunity to scale with drones, satellites, and models. This and other networks (e.g., DRYFLOR and SECO) focuses on biodiversity and other ecosystem services and could be used as test beds for exploring remote sensing capabilities for biodiversity in tropical drylands. The Deforestation Dryland Alert System (DDAS) is an innovative system designed to monitor and quantify deforestation in dryland regions, with a focus on the Caatinga. The DDAS uses advanced geospatial technology, satellite imagery, and cloud computing to detect and analyze changes in vegetation cover and can provide near real-time alerts on deforestation activities, enabling timely enforcement actions. Areas of potential focus include the Caatinga, which spans 884,453 km2 and is the largest tropical dry forest in South America, and the Cerrado, a vast ecoregion of tropical savanna in eastern Brazil and second largest of Brazil's major habitat types (after the Amazonian rainforest), accounting for 21% of the country's land area. Not all of the Cerrado are drylands but many parts are and the region represents an area of transition where more of the Cerrado could be drylands in the future. Extensive research, expertise, and infrastructure in the region offer substantial scientific opportunities. Finally, the Gran Chaco semi-arid lowland area than brings together more than 50 different ecosystems united by the same pattern of vegetation and climate and one of the highest deforestation rates on the planet (every month >340 km2 is lost). There is a particularly strong emergent need to understand and forecast the impact of fires in the South American Dry Diagonal to socio-ecological systems and global carbon budgets. The region is facing dramatic heat, drought, and wildfire combinations, which are consuming large areas of dry forests from the Chiquita no (Bolivia) to Caatinga (Brazil). ARID has built partnerships with the scientists of South America, with great mutual interest in collaborating on a NASA field campaign focused on drylands. **More than 30% of South America is drylands**.

### *B.2.7 Earth Science to Action Strategy and Application*

ARID is fully aligned with NASA’s ES2A goal to “advance and integrate Earth science knowledge to empower humanity to create a more resilient world.” ARID envisions three types of application strategies. (1) As with former Terrestrial Ecology field campaigns, ARID will generate datasets that drive foundational knowledge development that can indirectly inform societal applications with further development of the data and knowledge into the decision framework, or information development lower on the ES2A pyramid (Fig. A.6). Such a strategy is more indirect. However, with the rollout of ES2A, ARID is committed to conducting projects that will directly involve end-users. In fact, much of the ARID engagement activities during scoping were focused on understanding end-user needs before we started developing the science themes or field implementation strategy. This produced two other strategies which involve directly working with and co-developing with end-users, including (2) broader NASA-directed efforts between a group of scientists and an end-user agency (like BLM, see below) and (3) through individual efforts that can be conducted as a part of competed projects. We describe our strategy for these latter two more direct efforts and then highlight several specific use-cases we envision, developed with extensive conversations with our partners, where ARID will advance decision making and products used inside existing and future applications.

### *End-User Co-Development Strategy*

The ARID field campaign will directly engage operational agencies (e.g. BLM, USFS, USDA), rural and tribal communities, united around fundamental dryland science questions to address science-based decision making. These partnerships began during scoping with their needs discussed and used to develop our science themes and implementation strategy. The ARID field campaign aims to improve the algorithm development and uncertainty estimation of fundamental remote sensing products that feed directly into existing workflows of agencies with established user-basis and decision-making frameworks. These applications will facilitate adaptation and mitigation to changes in drylands, demonstrating the societal value of NASA's science to a large population of diverse users and fostering inter-agency support for ES2A.

Our suggested strategy to improve and facilitate end-user decision making includes first understanding the end-user needs and constraints. We have gained many insights about end-user needs (see Section C), but the scientist(s) will need to converse with the end-users in each specific case. Boundary organizations like the NASA Satellite Needs Working Group can help guide this process. The next step is to develop the data product and/or monitoring tool and then iterate again by discussing with the developments with the end-user. In the final phase of implementing the new information into the decision-making framework, the ARID-funded scientist needs to continue facilitating and revising the data product as necessary and respond to any shortcomings identified by the end-user. Such early, iterative, and continuous engagement with end-users is critical to build the new knowledge and data products into the specific decision-making frameworks.

The impact of these end-user engagements can be measured by consulting the **"***Defining and Measuring Impact in NASA Ecological Conservation Projects*" handout. After an applied science project is carried out, such a framework can be consulted to quantify the impact the work had on the end-user in terms of knowledge gain, extent of use, change in behavior, benefit, awareness and perception, and sustainability.

### *BLM Rangeland Monitoring*

BLM has co-developed remote sensing-based rangeland monitoring applications and NASA's Ecological Conservation program funded the development of one of these approaches (BLM, LandCart). These applications have a very large and diverse user base (e.g., Rangeland Analysis Platform has > 22,000 sites visits per year, referenced > 155 publications) and they have developed through multiple versions and stages of maturity. The approach uses basic algorithms to estimate PFT fractional cover and biomass from Landsat data to track rangeland condition (M. O. Jones et al., 2021; Kleinhesselink et al., 2023; Robinson et al., 2019). Similarly, the USGS has developed the Rangeland Condition, Monitoring, Assessment, and Projection (RCMAP) products  of fractional cover components (shrub, grass, annual / perennial grass, sage-brush) across the western US, trained with field estimates of fractional cover types and limited high resolution commercial satellite imagery  (1985–2020) (Rigge et al., 2019; Shi et al., 2022). *The ARID field campaign can significantly improve the estimation of fine-scale fractional cover and biomass of PFT through improved calibration and validation of algorithms trained with* *fraction PFT data from multi-temporal hyperspectral airborne and UAS data, but applied to Landsat imagery (and SBG in future) to ensure wide area coverage (see section B.2.1.2 for details). These improved fundamental input products will feed into the established workflows to inform BLM and other decision makers.* These applications have evolved in their operational capabilities and BLM has recently entered into multi-year contracts to support these applications (Climate Engine).

BLM furthermore need species-specific products on the extent of Sagebrush (primarily for conservation of endangered Greater sage-grouse, *Centrocercus urophasianus*) and pinyon juniper cover, as well as invasive annual grass cover specifically. BLM furthermore uses the fundamental and derived data products for decisions related to habitat conservation, restoration and reclamation effectiveness. *The BLM rangeland application will allow ES2A to demonstrate societal impact of ARID campaign and science.* The ARID-derived fundamental PFT data products can feed into multiple applications (e.g. fuel properties for wildfire risk predictions) for multiple agencies, including USFS and National Park Service. The BLM rangeland application will allow ES2A to demonstrate societal impact of ARID campaign and science. Such an effort is more aligned with the second strategy noted above and will require a team of scientists to consistently work with BLM, and should be encouraged to be a directed effort or competed effort with more continuous funding beyond three years.

*Tribal Rangeland Monitoring*

Three specific tribal land management needs that arose during the scoping study were: (1) water availability, specific mainly to tribes in Arizona and New Mexico; (2) rangeland productivity, specific to tribes in the Great Plains, Arizona, and New Mexico; and (3) buffalo restoration, specific to tribes in the Great Plains. Such work can be funded as a part of the third strategy noted above with more individual-based collaborations between scientists and the tribes. In this case, it is encouraged that tribal members are leaders of the funded effort or co-funded between NASA funded scientists and tribal scientists or managers.

For water availability, Natural Resources Departments, for example at the Pueblo of Santa Ana or Pueblo of Jemez, need to be consulted first with their elders first providing permissions and recommendations on any measurements or research going forward. Soil moisture sensors can be deployed, and a higher resolution microwave measurement like from active satellite radar (NISAR) or aircraft (SLAP or UAVSAR) can be used to monitor spatial distributions of soil moisture at 100s of meter scales. Additionally, OpenET can be used which is a proxy for moisture availability via Landsat at 30m resolutions. Such datasets can be developed into a simplified framework for the tribe to use continuously. Finally, NASA co-developed the Navajo Drought Severity Evaluation Tool with the Navajo Nation. Measurements generated from ARID can further constrain that tool’s outputs.

For rangeland productivity, it was recognized that increasing precipitation variability and extremes driven by climate change are already having significant impacts on rangelands of the western US, with critical consequences for livestock grazing and wildlife. There is an urgent need for monitoring and forecasting the seasonal productivity of these vulnerable agroecosystems in order to support effective resource management and conservation efforts. The United States Department of Agriculture (USDA) Grass-Cast rangeland productivity forecast tool is available for the Great Plains and was recently expanded to the Southwest U.S. and provides short-term seasonal forecasts of rangeland productivity with the major objective of providing early decision support for rangeland managers. For Grass-Cast Southwest, Navajo Nations shared a wealth of field-based estimates of grassland aboveground net primary productivity that was key for parameterizing this model. There are opportunities to expand Grass-Cast to other tribal lands and western US ecoclimate zones that we hope to initiate with ARID.

For buffalo restoration, climate adaptation centers, such as the Rosebud Sioux Tribe, are focused on broader buffalo restoration efforts across the Great Plains. There are potential applications for Landsat and ECOSTRESS to generate maps of grazable land and vegetation biomass in conjunction with buffalo population distribution data via machine learning or other statistical approaches. Focus can be placed on sustainably managing these lands to enable growth of buffalo populations.

### *B.2.8 Technical and Logistical Feasibility*

***The ARID field campaign is a low-risk, high-reward endeavor*** designed to significantly advance our understanding of Earth's dryland regions and their dynamic responses to environmental changes. ARID is low-risk in that it leverages existing networks, sites, infrastructure, and local knowledge and proposes new measurements across easily accessible dryland systems. This method reduces costs, increases field safety, and provides high value to additional field and aircraft measurements in their ability to advance dryland science. ARID is also high-reward in applying state-of-the-art yet readily available satellite remote sensing technologies along with field deployments to understand a poorly understood and generally understudied ecosystem: drylands. With research findings increasingly emphasizing drylands’ large role in the Earth system (see Section A.1), ARID presents an opportunity to bring the science community together to gain substantial new understanding of the global relevance of these ecosystems, which encompass 41% of the global land surface. These findings are essential for informing sustainable land management and mitigating the impacts of rapidly evolving climate change in drylands.

Most ARID field activities can be conducted within the extensive range of dryland ecosystems in the U.S., or in collaboration with local international partners where successful field operations with NASA have already been carried out. The U.S. provides a highly tractable environment with established infrastructure and logistical advantages that ensure the campaign's success while maximizing its potential for groundbreaking scientific discoveries. Conducting operations domestically allows NASA to allocate funds efficiently, supporting U.S.-based personnel, technology, and research. The familiarity and extensive training of U.S. personnel with NASA assets enable a rapid start to the campaign and the production of high-impact results. Logistically, planning for aircraft operations is more feasible due to fewer regulatory constraints, allowing flexible scheduling of flights across the western United States. The dense distribution of airports further enhances flight safety, enabling "pulse-chasing" experiments that capitalize on the rapid, day-to-day evolution of dryland environments following rain events.

By focusing on these elements, the campaign aims to maximize the feasibility and success of its flights and fieldwork while ensuring the safety of all field and flight crews. This approach is crucial for achieving the campaign's objectives, allowing for efficient resource use and minimizing uncertainties associated with large-scale field operations.

Internationally, the ARID campaign stands to benefit from established collaborations with highly capable scientific teams in regions like South Africa and Australia. These partnerships, strengthened by previous NASA field campaigns, enhance the likelihood of obtaining necessary permissions and flight permits, making international operations more feasible. For instance, South Africa's experience with NASA's BioSCape and Australia's airborne and in-situ assets can provide valuable support to the ARID initiative. Additionally, using local aircraft and UAS technology in these regions reduces the need for long-distance transport of NASA equipment, lowering costs and simplifying logistical planning. In situations where NASA aircraft operations are not feasible due to logistical constraints, local partners or private companies could provide equivalent airborne data, such as the HyMap HSI in Australia, ensuring the continuity and success of the ARID campaign.

Technically, the ARID field campaign is positioned to succeed with minimal risk, employing mature remote sensing technologies that ensure robust and reliable data collection. While the campaign may include some new or experimental sensor technologies, such as multi-temporal, multi-spectral drone data collection, the risks are manageable and represent opportunities for significant innovation in sensor technology. For example, cross-calibration with NASA assets could fall within the scope of a proposed PI-led research project. Moreover, proximal sensing from towers, involving innovative yet low-risk sensors, could further enhance the campaign's capabilities.

The ARID initiative is well-prepared to deliver high-impact results by building on a foundation of strong existing expertise and collaborations. With ongoing partnerships with agencies like the Bureau of Land Management (BLM) and tribal nations, the campaign is positioned to secure necessary permits and permissions, ensuring high accessibility to field sites. By leveraging partners such as NEON and USGS for UAS data acquisitions, and employing a mix of U.S.-produced and international UAS technologies, ARID minimizes risks and ensures the collection of scientific-grade data. *This strategic approach to logistics, technical readiness, and international collaboration underscores ARID's potential for groundbreaking discoveries, all while maintaining a low-risk profile.*

### *B.2.9 Modularity and Sequence*

The ARID study domain and research framework allow for a modular approach to the collection, analysis, harmonization, and communication of data. For example, the sequence and priority of study domains would be straightforward to plan and modify due to the lack of many of the logistical challenges that hinder operations in locations where research regulations, permissions, and safety are more challenging and uncertain. New data collection in the ARID's US domain could begin quickly due to the high feasibility and access to US sites for ground-based and airborne data collection, as well as the ability to access substantial existing infrastructure and partnerships. In addition to the US, there are many strong existing collaborators and networks in Mexico and Australia on which ARID could build, and there is a history of NASA field work in our focal regions in southern Africa. These allow for more rapid spin-up of field work. There is also the possibility for measurements in Mexico where takeoff and landing occur in the US, and the feasibility of such an approach can be investigated. Moreover, there is a range of data that already exists for drylands of the US, which could be leveraged, added to, and synthesized in new ways. Although many of these datasets were collected to inform sensor and mission development and not to address ecological questions, ARID can draw on many datasets already collected by NASA (section B2.5), providing even more return on investment. There are aspects of the ARID campaign that would be more challenging to separate in space or time. For example, transect and Super Site data collections require the concurrent assessment of ecosystems with coordinated ground based and remote sensing tools, thus it would be preferred to collect the necessary data at focal sites in series (i.e., not all the sites at the same time) over not collecting the full suite of complementary data needed to answer core questions.

This modularity and ability to perform data collections in sequence could be valuable for a number of reasons (e.g., unexpected changes in funding, an opportunity to leverage a large-scale US land management treatment), but there are also options unique to a framework in which both ARID and PANGEA were selected to advance as field campaigns. First, the ability for ARID to start quickly could allow for a system in which ARID began data collections first, while PANGEA coordinated their collections with international partners. ARID could then spend time analyzing collected data, parameterizing, and evaluating model developments, while PANGEA performed a period of new data collection. ARID could then return to a local or international data collection phase while PANGEA transitioned to its data analysis phase and then subsequently returned to data collection. This “ebb and flow” approach could continue for the lifetime of the campaign. There is a great deal of interest from other federal partners that could result in additional funding for ARID or for large scale coordinated treatments co-designed for science and management and conducted by agency partners, and this framework could allow for more time to plan and coordinate. Second, in addition to coordinating data collection and processing for ARID and PANGEA, there are geographically tractable and climatically strong gradients that exist spanning from drylands to the wet tropics that could be used to integrate questions and expand inference. For example, in South America, Africa, and Australia (see Sections B.2.4, B.2.6). This offers a chance to study key aspects of ecosystem structure and function (e.g., biodiversity, carbon cycling) along environmental gradients that could address both ARID and PANGEA goals, offer information on what drives the transition between drylands and tropical forests, and could lend a deeper insight into larger terrestrial function and how ecosystems may transition in a drier, hotter future.

# C. Community Engagement and Co-Development

## C.1 ARID Community Engagement Vision

ARID has engaged and partnered with numerous communities that provided input throughout the scoping study and helped develop the perspectives, questions, and framework outlined here. If the ARID campaign is selected, this community is extremely enthusiastic to be involved in writing proposals, conducting research, and providing new knowledge and capability to understand and make decisions for drylands. In particular, we have worked to cultivate relationships with three major types of communities - researchers, data end-users, and indigenous stewards - to contribute to improving the design, implementation, and usage of the knowledge generated by ARID. These communities are not mutually exclusive of each other, and some groups contribute to multiple aspects of research and end-user project design, such as tribal nations and natural resource managers.

ARID's networks were developed based on both broad feedback during wide-scoped knowledge gathering sessions, as well as intensive discussions in smaller groups on more focused topics (Fig. C.1). Overall, the ARID team conducted 140 engagement events, including roundtables with end-users and conference town halls (Fig. C.1, C.2). This is in addition to ARID's many working group and leadership team meetings. A full list of events and communities consulted are listed in Appendix F.6, F.7.

Consequently, the ARID team has established an advisory network of partners who would directly contribute to knowledge development, guide or advise the campaign, benefit from the campaign, and/or, in some cases, co-fund the campaign (Fig. C.3). If funded, this structure can persist, with end users helping to inform and/or be a part of ARID designated and competed science teams (see Section D.1 for more description of ARID's management structure). The interactions are anticipated to be primarily mutualistic. For example, ARID's data gathering would inform end-user issues and decisions and could be used to design or inform decision making tools. End-user data use will guide more optical data collection. Boundary organizations like NASA's Satellite Needs Working Group (SNWG) and Western Water Applications Office (WWAO) can help guide this communication with end-users. While making use of NASA satellite products throughout the campaign to advance dryland science, ARID can also inform the development of current and future NASA missions (SBG, NISAR).

In this section, we discuss our domestic and international research partners, end-user partners, and tribal partners, including discussing who our partners are, how they would co-develop the ARID campaign, and our philosophy for a continued engagement strategy. We also discuss capacity building of the next generation of scientists, including options for "place based" researchers and end-users. Finally, we discuss our overall vision for diversity, equity, and inclusion. Note that a summary of our ARID engagement and strategies appears in our *Earth's Future* publication (Feldman, Reed, et al., 2024).

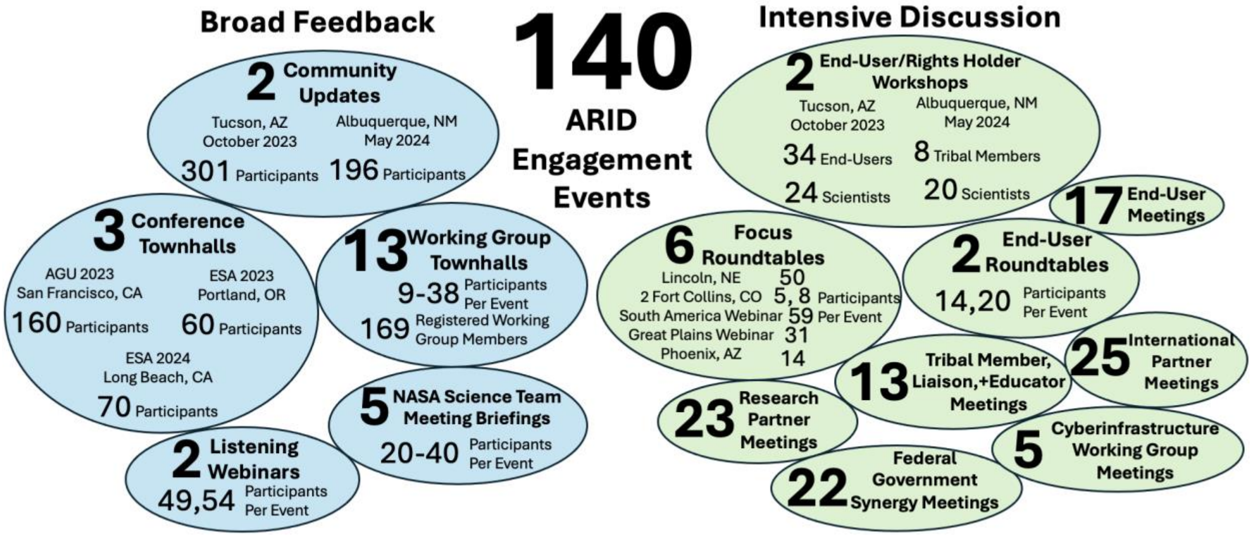


***Figure C.1.*** *Summary of ARID engagement events, including both broad feedback (from listening sessions) to intensive discussions, primarily occurring between October 2023 and September 2024. Total participants are based on event documentation from ARID team members. Most engagements consisted of approximately 1-1.5-hour meetings. However, the workshops included 1–2-day discussions with end-users and rights-holders across several topics and two-day science-focused workshops. Note that "end-user meetings" included with end-users and those who liaise between researchers and end-users. Numbers do not include internal meetings between ARID team members.*

***Figure C.2.*** *(a) Data end-user meeting and (b) science meeting at the ARID Kickoff meeting at University of Arizona in October 2023. ARID town halls at the (c) 2023 Ecological Society of America (ESA) and (d) 2023 American Geophysical Union (AGU) conferences. The photos are owned by the authors.*

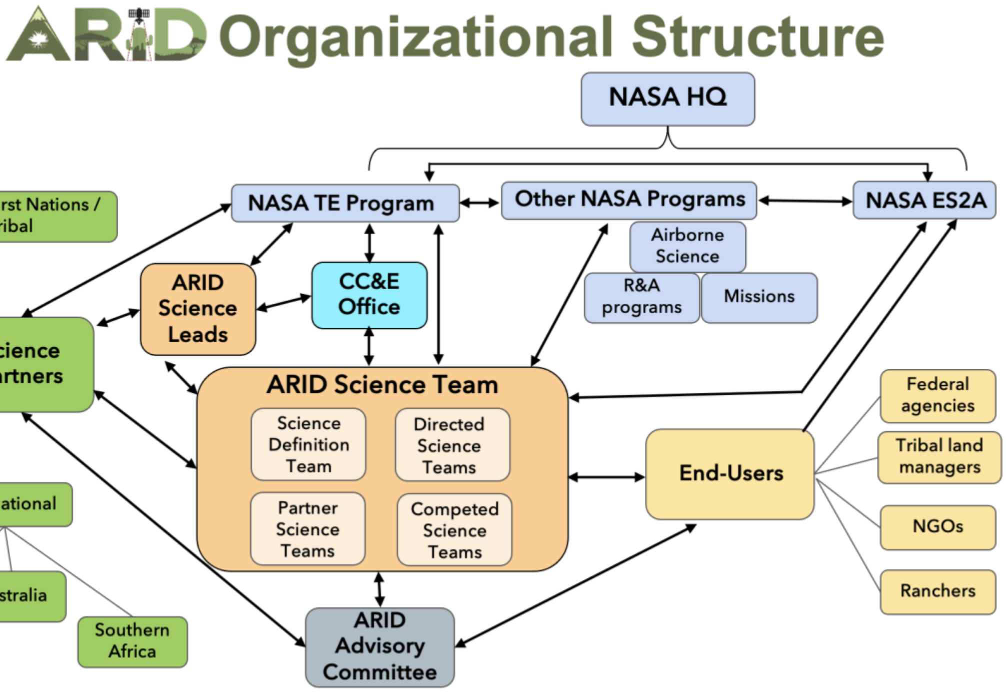


***Figure C.3.*** *An overarching ARID network describing how the ARID Science Team and Leads would be informed by and inform domestic and international partners, end-users, and NASA-based groups.*

## C.2 ARID Research and Technology Partners and Collaborators

### *C.2.1 Domestic Research Partners and Collaborators*

The ARID Field Campaign is envisioned to be multi-national in scope, but also to rely heavily on a US focused implementation plan, building on domestic collaboration across multiple institutions, tribal nations, and agencies in the western US. The domestic efforts will incorporate partners at various levels of the field campaign, ranging from site level operators conducting on-the-ground observations and experiments to flux tower operators, aircraft and drone operators, modeling groups, and remote sensing specialists. These technical groups will work with resource managers in both a research capacity, as well as in the translation of new knowledge to be used in management decisions.

Our domestic partners are summarized in a list below, consisting of (1) ground networks that have existing infrastructure that ARID can use in collaboration with the leadership of the networks; (2) domestic institutions interested in co-funding research and/or campaigns and that have networks of personnel interested in collaborating and leading projects of their own. Others include (3) private institutions and companies that have an interest in ARID data for their applications; (4) Federal agencies that ARID researchers can work with to meet their decision and management needs, as well as provide support in conducting the campaign on public land (e.g., BLM, DOD); and (5) Tribal Nations interested in co-developing research and land management with ARID.

Of note, the ARID scoping study team established strong partnerships with a number of US federal agencies, and especially BLM and USFS, which would serve as direct end users of ARID data with clear use cases. For example, BLM National Science Advisor, Karen Prentice, and other BLM staff, such as BLM's new Climate Science Program Manager (Dr. Julian Reyes) emphasized the critical importance of the data ARID would provide for the lands that BLM manages in the western US. They described themselves as data 'super users' and made clear their excitement and willingness to engage in ARID. Dr. Julian Reyes accompanied the ARID team to several NASA HQ meetings to emphasize these points (Appendix F.6).

This adds to a strong partnership with the USGS, which is highly motivated to facilitate and collaborate on ARID as an opportunity for additional successful collaboration between USGS and NASA (e.g., building on GEMx). There are also numerous potential opportunities to co-fund ARID, which can be considered during the science definition team phase. For example, the DoD program manager mentioned a strong interest in DoD understanding dryland ecosystem disturbance, habitability, and response because of the large US military installations across the western US drylands (e.g., 5% of New Mexico and Nevada are DoD lands, an extremely large amounts of federal drylands) and because of global instability within many drylands. If budgets remained at their current states, there could be strong opportunity for DoD and the U.S. Navy to support aspects of ARID through the funding of PIs, thus leveraging the funding provided by NASA. The NSF program managers further supported ARID's plans to work directly with the NEON site PI's to co-conduct work. The DOE talked about the needs of improved dryland understanding for informing their Earth System Models. Finally, NASA terrestrial hydrology program managers mentioned the possibility their program could consider co-funding components that relate to GEWEX activities and water and energy cycle topics, and there are strong linkages to the LCLUC, Fire, and ES2A programs.

Here, we list several of our main domestic U.S. partnerships. This list is non-exclusive (see letters of support for more details):

- *U.S. Federal Agencies*: BLM, USFS, DoD, Navy, USDA ARS (Jornada, Fort Collins, Southwest Watershed Research Center, Beltsville, Biose) USGEO, BoR, NPS, NOAA
- *Research Networks*: NEON, AmeriFlux/FLUXNET, LTAR, LTER, Mesonet, BLM AIM, PSINet, NOAA Fire Sites
- *Domestic Efforts*: GEWEX, RUBISCO
- *University Partners*: ASU Global Drylands Center, UNM Arid Institute, UA Arizona Experiment Station, NMSU Agricultural Experiment Stations, CSU Natural Resource Ecology Laboratory

- *Tribal Nations Partners, Liaisons, and Collaborators*: SIPI, Greyhills Academy High School, Pueblo of Jemez, Pueblo of Santa Ana, Ute Mountain Ute, Rosebud Sioux, NASA IPI, USGS CASC North Central, USGS CASC Southwest, NASA MUREP MAIANSE
- *Private Industry*: BHP Copper, Rio Tinto, Ball Aerospace

### *C.2.2 International Research Partners and Collaborators*

The science that ARID would produce will also provide new information that will be useful to the international research community, and international partners will play various roles in ARID's implementation phase. International partners and collaborators will enable a more robust test of process understanding of ecosystem changes in relation to different stresses and under control of different biodiversity controls. These partners can conduct simultaneous field campaigns to coincide with those conducted in the western US and in line with shared remote sensing tools and techniques. In addition, these collaborators will expand our observations of ecosystem processes determining the extent ecosystem services would be impacted under different climate and land use changes. Harmonizing flux emissions and other ecosystem variables for dryland systems will be feasible with the coordinated efforts among domestic and international partners.

ARID's international partners are summarized in lists below. Candidate international countries and partners were identified according to following criteria: (1) significance of drylands in that region/country (uniqueness of climate, vegetation, specific management techniques, etc.); (2) existing research networks and connections (university, institutes, government agencies); (3) community input (See Appendix F.9) (4) existing measurement infrastructure; (4) previous efforts in these regions (especially related to NASA); (5) feasibility and security; and (6) maturity of scientific relations with US.

There are various international efforts that strongly align with ARID research approach and goals. Countries, such as Australia and South Africa, have comparable research assets to conduct similar observational and research efforts coincident with ARID campaign timeframe. Other countries can provide ground-based observations to assist in verification studies and information to inform observational and modeling efforts to incorporate in the research analysis of ARID across various ecosystem structural types and processes. International partnerships also provide a broader context for dryland land use and stewardship approaches across a range of social-ecological systems.

While global drylands and associated livelihoods face similar challenges due to climate change, they vary greatly in their environmental conditions, drivers of change and management objectives. International expansion of the ARID approach allows for a broader range of environmental gradients and environmental responses as well as greater range of results and applicability of models. ARID created an international network of partners that will collectively address science questions by leveraging existing field data, instrument, and remote sensing data sets. International partners will contribute local knowledge and data. They can also benefit greatly from NASA airborne acquisitions where feasible. Several alternative scenarios are available for airborne data acquisition: (i) NASA aircraft and NASA sensors, (ii) local aircraft and

NASA sensors, and (iii) local aircraft and local sensors. There are also impactful opportunities for the training and education of early career scientists from other nations during the international campaign.

As an example, the South African Environmental Observation Network (SAEON) is a government-funded long-term environmental observation and research facility, similar to NEON and also part of Global Ecosystem Research Infrastructure (GERI). SAEON conducts research and provides facilities, instruments (flux towers), infrastructure (airborne sensors), datasets, models and staff across a diversity of ecosystems, including two Expanded Freshwater and Terrestrial Environmental Observation Network (EFTEON) in drylands. SAEON was a major partner in NASA's successful BioScape airborne campaign in the western Cape which demonstrated logistic support, safety and scientific collaboration of this focal area. SAEON has expressed their willingness to be a leading participant in ARID and their existing relations with TERN (Australia) and NEON will be of great benefit (see letter of support).

Here, we list several of our main international partnerships. This list is non-exclusive (see letters of support for more details):

- *Southern Africa*: South African Environmental Observation Network SAEON, BioSCape (South Africa), University of Cape Town (South Africa), Okavango Research Institute (Botswana), University of Namibia, Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL)
- *Australia*: ARC Centre of Excellence (which includes partners at University of Melbourne, Australian National University, Western Sydney University), OzFlux, CSIRO, and TERN
- *Mexico*: National Autonomous University of Mexico (UNAM), MexFlux, SAGARHPA
- *South America*: SECO, DryFlor, e-phenology/UNESP, CEMADEN/MCTI, SOS sertão (NGO), Biospheric and Climate Laboratory IAG/USP
- *Central Asia and Mongolia*: National University of Mongolia, Mongolian Ministry of Environment and Tourism, Samarkand State University, Uzbekistan
- *International Agency Efforts*: NASA SERVIR, USAID, FEWSNET
- *NGOs*: Conservation International, Organization of American States

### *C.2.3. Research and Data User Engagement*

The science community was engaged in several ways throughout the scoping study, and we received valuable feedback on the ARID framework from a large number of diverse research communities and range of career stages throughout scoping effort.

Conference town halls and science webinars provided broad feedback from across the research community. These events served as an efficient means to describe the plans for the ARID campaign while allowing time for question-and-answer and general feedback. These events were well attended, with 200 and 300 virtual attendees at our two ARID science meeting briefings and over 60, 70, and 160 in-person attendees at our three conference town halls: the ESA Annual Meeting 2023, ESA Annual Meeting 2024, and AGU Fall Meeting 2023, respectively. These events were most useful early in the ARID scoping effort, mainly between August 2023 to December 2023, for ARID to receive broad input and to look for commonalities in the feedback. The ARID leadership team members carefully evaluated the feedback to identify common threads of input, which guided discussions about the main science themes, research questions, and measurement techniques to be used throughout the ARID campaign.

More specific topics and thoughts were discussed during working group meetings and with write-in responses. ARID formed several types of working groups including science theme working groups and technological working groups. The science theme working groups primarily consisted of the main contributors of this ARID white paper and were organized around the ARID sub-themes discussed in Section B.1. They were tasked with outlining and drafting the ARID science sub-themes, and initiated their activities during the October 2023 Tucson, AZ kickoff workshop (Appendix F.2). The ARID technological working groups were organized into four groups including ground network and in-situ measurements, remote sensing measurements, model development, and cyberinfrastructure (Appendix F.5). These groups were tasked with having more focused group discussions about the respective approach. Across the three working group topics of ground network measurements, remote sensing measurements, and model development, there were 169 registered members of the ARID working groups and 9-38 attendees in any of these 13 total townhalls. Subject experts from the community were invited to give seminars about their approaches and how they can be used in or inform the ARID campaign. These inputs were most useful mid-way to later in the scoping effort, conducted mainly between April to August 2024. These engagement activities specifically allowed querying about our more updated framework. The cyberinfrastructure working group conducted more specific discussions across 5 meetings. Beside the working group activities, throughout the duration of ARID, we received over 350 written inputs. The ARID scoping steering committee (authors of this white paper) met weekly and sometimes twice-weekly (ARID writing committee) to plan these activities, discuss the received feedback, and revise the ARID framework.

As an example of how input was used to develop ARID’s framework, the community drove the ARID scoping team to broaden our scope and revise some of our originally proposed science themes (Appendix F.9). For example, biodiversity and wildfire were only sub-components of our original framework, and cropland and rangeland management were not prominently considered. However, extensive community recommendations and excitement about these topics warranted them being explicitly elevated as central themes. The community also confirmed that dryland water availability and carbon stocks and fluxes were priority interest topics. In another example, there is strong interest in ARID having both domestic and international domains, which encouraged the domain to be both domestic, taking advantage of reliable logistics and exciting opportunities to meet US information needs - and international - allowing us to broaden the range of insight and build a transdisciplinary international dryland research community.

While there is strong interest in sites in the southwestern US, we received overwhelming input to include the full dryland western US in the domestic ARID domain, including the Great Basin and western Great Plains (Appendix F.9). Community interest in the Great Plains encouraged us to conduct roundtable discussions with researchers and end-users in rangeland and cropland landscapes across Colorado, Nebraska, and Texas. This included a meeting at University of Nebraska in February 2024 as a part of the “Harnessing the Heartland” effort, as well as roundtables in Fort Collins, CO with Colorado State University and USDA Agricultural Research Service (ARS) throughout Spring 2024. Furthermore, a virtual Great Plains roundtable was held with over 30 scientists and end-users (across universities and agencies in Texas, Oklahoma, Colorado, Wyoming, Kansas, and Nebraska) in June 2024 with the goal of understanding rangeland and cropland research and land management gaps, as well as understanding how to leverage monitoring sites like National Ecological Observatory Network (NEON) and Mesoscale Network (Mesonet).

Furthermore, while we received strong input to include many global dryland locations across Australia, South America (such as the Cerrado and Caatinga), and Asia (such as Mongolian grasslands), the community showed substantial interest in Africa and, particularly, southern African countries. Community input also included disproportionately high interest in Mexico, both because of the relevant research that could be linked, and also because ARID’s proposed western US domain already included portions of the Chihuahuan and Sonoran deserts, which are shared by the U.S. and northern Mexico. There are also significant knowledge gaps for Mexico, and science in the region could help address requests by indigenous and rural communities in Mexico for improved understanding of their lands and the ways they are changing. Additionally, this feedback motivated engagement with, for example, the Okavango Research Institute (Botswana), the Gobabeb-Namib Research Institute (Namibia), and investigators of the MexFlux sites located in northern Mexico. We also held an ARID South America Workshop which included 59 researchers, many of which were from research institutions across South America and particularly Brazil.

The ARID scoping study team also met with NASA science teams to determine their field and airborne data needs and to find synergies with their planned activities. This included meetings with the NASA Land-Cover and Land-Use Change (LCLUC) program, NASA SBG team, NASA Soil Moisture Active Passive (SMAP) team, NASA ECOSTRESS team, NASA Orbiting Carbon Observatory-2/3 (OCO-2/3) team, and NASA GEDI team. Our ARID team members are also finding synergies with a diverse array of efforts, including with ongoing domestic field network efforts (e.g., NEON, LTER, AmeriFlux), international institutes and initiatives, non-government organizations (NGOs), established university dryland centers and institutes, and others such that ARID can leverage resources and personnel across many partnerships.

## C.3 End-user Engagement and Decision Support

### *C.3.1. ARID’s End-User Engagement Vision*

ARID envisions an active engagement effort throughout the duration of the field campaign, with end-users and practitioners dealing with environmental changes affecting the ecosystem services communities rely upon for sustaining livelihoods. Our end-users include managers and decision makers from a diverse set of groups, such as natural resource managers, tribal communities, rangeland managers, agronomists, and conservationists. The engagement is envisioned to operate in a co-production paradigm, with close collaboration between ARID research community and the end-user groups. Particularly, it is key to start discussion with end-users to determine the data or process that best fits their needs. For achieving the highest application readiness levels, it is also critical to establish the datasets, knowledge, and/or tools needed that are directly useful and feasible for these end-user needs. However, not all proposed ARID field campaign measurements are well-positioned to address end-user needs and thus ARID science definition team and individual proposing PIs would need to champion applications in collaboration with end-users (see Section B.2.7).

This vision was developed from our end-user engagement during scoping. In speaking with these different groups of end-users, we've identified groups and individuals extremely interested in working with ARID-funded scientists, and these established relationships can continue to be developed throughout the ARID campaign. We also identified a range of end-user needs specific to drylands and the drylands in which end-users live and work.

### *C.3.2. ARID's End-User Engagement Strategy*

To facilitate engagement activities during the implementation of ARID, engagement with diverse end-user and practitioner groups was undertaken to develop a better sense of the scope of information needs and data products that might be useful to these end-user groups. The strategies outlined here can be further developed throughout the ARID campaign. In order to reach the larger goal of actionable science, it is essential to continue fostering relationships with ARID's end-users.

*Our engagement strategy included in-person meetings in small group settings to speak with end-users, rights-holders (tribal), and scientists who work with end-users communities. Because of the specific needs of each end-user, smaller group discussions and one-on-one meetings with end-users were prioritized.* We also allowed the end-user(s) to guide the conversations given the unique (and often less predictable) topics for each discussion and the fact that they were almost always more well-equipped to address their needs than ARID personnel. This is in contrast to meetings with the scientific research community, which tended to include more generalizable discussion topics.

We identified organizations, agencies, and individual personnel we felt would potentially co-develop the campaign and also directly benefit from using ARID field campaign measurements and developed knowledge. We invited these end-users to our in-person meetings and, in some cases, for one-on-one virtual discussions.

For relationship and capacity building, we felt it was important to travel to where the end-users live as much and as early as possible in the scoping to conduct these discussions. This included in-person meetings in Arizona, New Mexico, Utah, Nevada, Colorado, and on tribal lands. ARID could be conducted in these locations and co-developed and led by in-place partners. For example, our ARID leadership team held a kickoff meeting on October 23rd-26th, 2023, at the University of Arizona in Tucson, Arizona (Fig. C.2). Given that applying research for action requires starting with understanding end-user needs, we wanted the first day of the first ARID event to begin with listening to the perspectives, expertise, and input of the data user community. The event began with keynote speakers from the U.S. Bureau of Land Management

(BLM). We then divided into four smaller groups to allow our visiting data end-users to offer their thoughts on the value of a NASA field campaign focused on drylands, and the utility of a ground-to-satellite approach to better characterize and understand the drylands they manage.

We believe it is critical for ARID to leverage boundary personnel and organizations, or those that support end-user engagement of existing efforts to co-develop usable products from various NASA activities. These groups include personnel that are experts at gathering input from end-users and communicating with scientists about information needs. By streamlining the process of connecting with end-users in having formed relationships, they also mitigate end-user “burnout” from end-users being contacted to excess by scientists with similar questions. The ARID team identified and engaged with several of these groups during scoping. These groups agreed that they can, to varying degrees, informally advise the ARID science team with overall co-development with end-users. They include NASA SERVIR and USAID partners conducting work in southern Africa (primarily in Mozambique), NASA Western Water Applications Office (WWAO), NASA Carbon Monitoring System (CMS) team members who work with end-users to varying degrees especially in the western US, NASA’s Harvest, NASA’s Indigenous People’s Initiative (IPI), and the NASA Satellite Needs Working Group (SNWG) and USGS National Land Imaging Program that both extensively gather end-user needs to inform satellite mission development.

### ***C.3.3. End-User Engagement Summary***

ARID’s end-user engagement included workshops, roundtable discussions, written input, and individual meetings with boundary personnel and other US agencies. The ARID scoping team held end-user focused workshops and roundtables in Arizona, New Mexico, and Colorado, engaging a vast array of end-user knowledge in the western US. They also held several individual meetings with personnel from several US agencies that would likely serve as end-users. A more detailed list of meetings and dates can be found in Appendix F.6.

*Tucson Workshop*: An ARID end-user focused workshop was held at University of Arizona in Tucson, AZ, USA on October 23, 2023. Over 30 end-users attended in person with more attending virtually. It consisted of two keynote speakers from BLM - Karen Prentice, National Science Advisor for the BLM and Jon Norred, BLM Branch Chief of Resource Data Services - and breakout group discussions. The majority of these data end-users are land and resource managers in Arizona, New Mexico, and Utah with affiliations in the Bureau of Land Management, the National Park Service, the U.S. Department of Agriculture, the University of Arizona, U.S. Army Corp of Engineers, The Salt River Project, The Nature Conservancy, several non-profit and private companies, and private landowners, including cattle ranchers. Several end-users could not attend the meeting but provided written input.

*Albuquerque Workshop*: An ARID sovereign nation-focused workshop was held at University of New Mexico in Albuquerque, NM, USA on May 7, 2024. This meeting included discussions with tribal scientists, natural resources departments, educators, and liaisons about tribal land management needs, education needs, and data sovereignty. Eight tribal members were in attendance, and we acknowledge their affiliations across Rosebud Sioux Tribe, Navajo Nation, Hopi Tribe of Arizona, Cherokee Nation, Pueblo of Isleta, and Pueblo of Santa Ana. Our meeting also included a visit to a high school in Tuba City, Arizona on the Navajo Nation to demonstrate to over 100 students the use of field instruments and discuss how ARID can provide wider use of such instruments. Follow-up meetings were conducted with USGS-based and NASA-based tribal liaisons based in New Mexico as well as natural resources departments of several Pueblos in New Mexico.

*Roundtables*: ARID team leadership held in-person roundtables with several USDA ARS land managers in Fort Collins, CO in February and May 2024 and discussed cropland and rangeland management in the Great Plains. In September 2024, they also spoke at and held listening sessions at virtual webinars at the Applied Earth Observations Innovation Partnership (AEOIP) webinar which included approximately 20 end-users from the US Forest Service, and held a round table with approximately 15 USFS Rocky Mountain Research Station scientists and managers.

*Washington DC End-User Focused Roundtables*: Several ARID team leadership members held meetings in Washington DC on July 17-19, 2024, with several federal agencies to define synergies and partnerships that the ARID campaign could both leverage and use to extend the work's impact. In particular, end-user governmental personnel at DOI and BLM, USDA Office of Energy and Environmental Policy, and USGCRP are directly considered end-users, while others can connect the ARID field campaign data to end users.

*Boundary Organization Meetings*: ARID team members held individual meetings with personnel at boundary organizations including NASA SERVIR, USAID, NASA WWAO, NASA CMS, NASA IPI, NASA's SNWG, and USGS National Land Imaging Program.

*Other End-User Meetings*: ARID team members also conducted individual meetings with USFS, BLM, USDA ARS, NRCS, DoD, Navy, BoR, NPS, USFWS, and mining companies.

### ***C.3.4. Summary of End-user Needs***

To meet end-user needs, it would be necessary to maintain continued engagement with the end-user communities and practitioners, including tribal communities. These engagement efforts would facilitate co-production of products useful in decision making for managing ecosystem services and utilizing research products from ARID research. We envision ARID working to sustain connections with end-user communities throughout the course of the campaign. The early portion of the campaign could support a working group of end users to initiate development of new usable products derived from currently available remote sensing products. This initial effort could establish a framework to launch new co-production efforts from ARID's measurements and research findings.

While we received a diverse array of feedback from end-users throughout the engagement activities highlighted in C.2.3, several themes arose. We provide a few examples here.

*Data Access and Use Challenges*: A common theme was that most end-users have extensive field sampling capacity and, often, strong science backgrounds in understanding dryland ecosystem processes. However, despite NASA's and other space agencies' freely available data products that could support data end-users, land managers find it challenging to access products and tools directly applicable for their needs. For example, during our ARID kick-off meeting, we learned that BLM faces technical challenges including storage and retrieval capacity for very large remote sensing datasets and limited in-house knowledge for how to process and use the data and technologies. There is substantial value in external scientific support to help build technical frameworks to process data into products, tools, and services useful for land managers and agencies such as the BLM in their decision-making process.

*High Resolution Data Needs:* End-users and boundary personnel consistently discussed the need for plot level data, or high spatial resolution information relevant to their site conditions for monitoring vegetation types, soil moisture, evapotranspiration, animals, fire, streamflow, and mineral mining. They often mentioned needing data-informed decision tools, such as dryland plant productivity and vegetation type maps, so that they can more closely monitor, for example, vegetation growth and/or invasive species. A NASA Terrestrial Ecology field campaign would provide more in-situ and airborne measurements as well as efforts to scale field data to satellite observations and generate end-user relevant variables in the service of decision-support tools.

*Fostering the Application Process*: Incorporating research and data products into the decision-making process with end-users, especially at BLM, requires time. The data product is not the end of the application process; there is a need for scientists to directly work with decision makers early and iteratively throughout the process. With the longer multi-year-to-decadal timeline often permitted in a NASA Terrestrial Ecology field campaign, these relationships could truly be solidified with significant benefit for science being useful and used.

*Early engagement*: It is critical to engage with end-users early. End-users requested that ARID scientists develop data products by starting from end-user needs and working backwards. If this step is avoided, there is often a large gap between the data need and the data product and, consequently, applications and implementation into end-user decision frameworks does not occur.

## C.4 Tribal Engagement

Tribal Nations (First Nations) are sovereign nations, and are located throughout ARID's proposed domestic western US domain. These personnel have extensive experience and have passed knowledge along for generations (at times for millennia) about their land, and they are thus pivotal for enhancing the ARID campaign and its outcomes. ARID recognizes the value of traditional knowledge as a systematic way of knowing that informs and increases our understanding of drylands, creates a more comprehensive knowledge base, and provides innovative solutions to help mitigate and adapt to dryland transformation in the face of change. Tribal members often have first-hand experience and a keen interest in how climate change is impacting their environment. ARID can work to include this expertise in the assessment of drylands ecosystems, their change, and opportunities for adaptation, and outreach activities specifically designed to inform Tribal communities of the results of ARID will be developed. Tribes have their own unique goals, needs, and resources that do not necessarily align with all aspects of end-users of NASA data and tools as discussed in Section C.2. Rather, engaging with Tribal Nations should be focused on co-developing work such that both parties (Tribal Nations and non-tribal NASA funded researchers) mutually benefit from any interactions.

The ARID team received feedback early during the scoping to prominently include Tribal Nations within the ARID scoping effort and within the field campaign. Acknowledging deeply impaired relations between tribes and the US government, engaging with tribes requires time and care through trust building. As such, early engagement with tribes is critical for allowing the time to build relationships and define shared values. We, therefore, share our goals, engagement techniques, engagement summaries, understanding of tribal needs, and proposed co-development strategy. While we feel we have made substantial progress engaging with tribes during the ARID scoping study, we acknowledge that our tribal engagement effort could be greatly improved and, therefore, we provide these details here in such that the ARID campaign and any future efforts that co-develop with indigenous peoples can build on and refine our framework and strategies.

### *C.4.1. ARID Tribal Engagement Scoping Goals*

During scoping, we aimed to accomplish the following with regard to engagement with Tribal Nations:

1) Engage with Tribal personnel to a degree that the following goals can be sufficiently met while avoiding overburdening their time commitments.
2) Provide a general awareness of a potential ARID campaign and define opportunities to directly be involved
3) Define potential NASA ARID resources and Tribal Nations resources that, together, can co-develop new knowledge about drylands and/or new land management strategies
4) Gain an initial understanding of common goals and needs of different Tribal Nations, particularly related to land and resource management
5) Understand methods to co-develop new knowledge while applying and protecting traditional ecological knowledge
6) Define boundaries and required permissions that tribes have with regard to ability to conduct the ARID campaign within Tribal Nations
7) Include Tribal personnel directly within ARID leadership and especially discussions related to Tribal co-development
8) Ensure open discussions of data sovereignty and the way data can and cannot be used and shared
9) Build a Tribal engagement strategy to be used and refined by NASA and other agencies for years to come.

### *C.4.2 Tribal Engagement Techniques*

<u>*Gaining an understanding of tribal needs*</u>: we learned that Tribal needs are unique and diverse across different communities and across individuals. It is not possible to view one tribal member as a spokesperson for all Tribal Nations, and in some cases for their own Tribal affiliation. We therefore held multiple discussions within tribes with liaisons, educators, students, and land managers to broaden our understanding of goals and needs. We also held discussions with members with affiliations across over 10 tribes across the western US.

<u>*Building long-term relationships and trust*</u>: A general strategy was to reach out to tribal members early during scoping and make clear that their input would guide our campaign. Early engagement is critical for building trust with typically a more positive reception and allowing more time to build relationships. However, response rates of Tribal Nations to “cold contacting” tended to be low, especially when there was not an existing relationship. A successful strategy was to first leverage existing relationships that ARID team members and NASA colleagues had. From these initial conversations stemming from established relationships, Tribal personnel would commonly recommend and facilitate building new relationships with other Tribal personnel that would provide value to the scoping. Tribal liaisons are also key figures for facilitating this process because they often have tribal affiliation(s) themselves and have built relationships. They are also aware of common needs and goals across many tribes. Finally, it is critical that the relationships are long term and thus collaborations should be set up to start early and last beyond the bounds of the field campaign.

<u>*Prioritizing in-person interactions*</u>: To convey our sincerity for meaningful and continued engagement, most of our interactions with tribal members included ARID team members traveling to meet them where they live.

<u>*Inviting Tribal members to guide conversations:*</u> It is common for tribal members in the western US to spend time listening, pausing to think, and waiting to be invited to contribute to a conversation. This often results in non-tribal members from western cultures dominating the conversation. Therefore, within our interactions, we prioritized asking questions, allowing pauses and silence, and invited tribal members to provide their thoughts.

### ***C.4.3 Tribal Engagement Examples***

We provide several examples of ARID’s engagement with Tribal Nations, which provided awareness of the ARID campaign in the form of both deeper-dive conversations and broad feedback.

*Tribal Engagement Workshop*: The ARID team held a Tribal focused workshop at University of New Mexico in Albuquerque, NM on May 7th, 2024, with 8 tribal members in attendance that are liaisons from NASA and USGS, educators (high school and university), and land managers. They included affiliations across the Rosebud Sioux Tribe, Navajo Nation, Hopi Tribe of Arizona, Apache tribe, Cherokee Nation, Pueblo of Isleta, and Pueblo of Santa Ana. Tribal members discussed development of a tribal engagement framework, college-level educational needs, research experiences and pitfalls, and opportunities for liaison support. ARID Team leadership also traveled to Sante Fe, NM to meet with a NASA IPI liaison.

***Figure C.4. (Left)** ARID team discussing tribal engagement strategies at University of New Mexico. **(Right)** Faculty at SIPI, a tribal college, giving a talk about SIPI's tribal program and collaboration opportunities with NASA and ARID*

*Navajo Nation High School Student Engagement*: ARID Team leadership traveled to Tuba City, AZ to meet with Navajo Nation and Hopi Nation high school students. The ARID team taught two classes with 50 students in each about how to analyze multi-spectral remote sensing data using NASA STELLA instruments as well as discussed, the ARID campaign and how it would present research and educational opportunities. ARID team leadership also conducted a broadcast to KGR 91.3 FM about the potential impact of ARID on Navajo Nation and its next generations and NASA's engagement with the high school. This broadcast was released on September 2024 and has been running on a 30 minute segment every few hours on the KGR 91.3 FM, which services much of the northwest Navajo Nation in northeastern Arizona.

*Washington D.C. Tribal Focused Meetings*: James Rattling Leaf Sr. joined ARID team leadership in D.C. as a representative of the Rosebud Sioux Tribe and their new Climate Center. In all meetings, he described the importance of early engagement with Tribes, not only within NASA campaigns but also across agencies. He highlighted how the Rosebud Sioux Tribe's Climate Center is developing climate adaptation plans and determining how data can be combined with traditional ecological knowledge for Tribal Nations. James discussed excitement about ARID and its framework for engaging Tribes early and often and for considering how to incorporate Tribal data needs, expertise, and actionable science opportunities. He noted the importance of campaigns like ARID including Tribal leadership directly on NASA science teams. Such principles were encouraged to be used not only for ARID but across any future campaign.

*Tribal Land Management Focused Discussions*: ARID Team leadership met with tribal land managers across three tribes in February, April, and May 2024 to discuss their land management challenges, discuss their climate adaptation plans, and/or find synergies with how they can co-develop new knowledge and methods with ARID. This included Ute Mountain Ute Tribal Council, Pueblo of Jemez, and Pueblo of Santa Ana.

*Lakota meeting*: TBD October 2024

### *C.4.4 Tribal Resources, Goals, and Needs*

In having conversations with tribal members during our visits, we summarize several goals, resources, and needs here:

*Land Management*: While land management goals range widely across tribes, common themes arose. These include buffalo restoration throughout the Great Plains, including tracking and protecting their movements. Most of their needs in the southwestern US are related to mitigating issues of low water availability for crops and grazers. They also mentioned issues with invasive species and monitoring needs. High resolution satellite and drone measurements can be useful for helping to identify these species instead of counting and surveying individual plants manually.

*Remote sensing assistance*: Typically, Tribal Nations have natural resources departments and different instruments, such as in-situ monitoring devices and drones. These departments range widely in availability of resources and personnel on staff. However, like our US agency end-user partners, not all were well-versed in processing and applying remote sensing data, but agreed the data would be valuable for their decision-making processes. Therefore, ARID personnel can directly be involved through providing satellite measurement experience and expertise and guiding the downloading, storage, and use of the datasets.

*Climate Adaptation Plans*: Tribal Nations often have climate adaptation plans they are creating or revising for their specific land and needs, and how they plan to address these needs under varying and changing climate conditions. Measurements and findings made during ARID can inform and supplement these plans.

*Educational*: Tribal students are interested in learning science and remote sensing, and often specifically for how it would address their Tribe's needs. Therefore, ARID can provide a range of opportunities to train Tribal students. However, ARID leadership learned that it is a sensitive topic of what Tribal students want to do after completing their education, with often a preference to live near family and/or on their tribal land. Therefore, it is highly important for ARID to provide a range of opportunities for Tribal students for them to choose.

### *C.4.5. Tribal Co-Development Strategy*

We provide several strategies and identify resources ARID would bring that can facilitate co-development with Tribal Nations. For a successful completion of ARID in co-development with tribes, these strategies will need to be advanced and updated.

*ARID Team to include Tribal personnel*: Including Tribal personnel on the ARID leadership team is critical for facilitating the co-development of the ARID campaign with tribes, identifying resources in both parties, and utilizing and protecting traditional ecological knowledge. In these cases, tribes may need to appoint a leader based on decisions of tribal elders. Therefore, it is critical to begin the process early of requesting tribal personnel to join the ARID team.

*Tribal PI’s and Co-I’s*: It is encouraged for tribal members to lead ARID projects as PIs and for non-tribal PI’s to include tribal Co-I’s. Such collaborations can facilitate co-development practices directly.

*Mentorship and Educational Opportunities*: ARID can facilitate a range of opportunities for Tribal early career involvement. NASA’s MUREP MAIANSE provides NASA funding for tribal early career scientists to conduct research alongside NASA researchers virtually or onsite. MAIANSE coordinators are aware of ARID and are excited to facilitate opportunities for Tribal students to be involved in the ARID campaign. Similarly, on-site NASA center fellowships, like the NASA Postdoctoral Program, is another avenue for more intensive exposure and training with remote sensing data and the ARID campaign. Other options include exposing tribal students to NASA field work and instruments in partnership with professors at Tribal colleges. ARID team members have various means to contact Tribal students about opportunities including via tribal college professors who have connected with ARID during the scoping study phase, and tribal conferences like AISES.

*Training and Informational Communication*: Given new datasets and new products that would be developed during ARID, it will be critical to collate and share these developments with tribes. A task of the ARID science definition team can be to develop a method to assist tribal members with accessing, downloading, and/or processing publicly available NASA data. Available online NASA ARSET trainings can be leveraged in this regard.

*Continued Engagement*: It will be critical for the ARID scoping team to continue to meet with existing tribal partners and form new tribal partnerships to facilitate the building of those relationships with, if funded, the ARID field campaign leadership team. Relationships should be developed into long-lasting collaborations that should continue long after a field campaign. If ARID is funded, outreach should be more widespread given the ability to more clearly communicate funding opportunities and available resources than during scoping.

### ***C.4.6. ARID Proposed Data Sovereignty and Data Policies***

A more comprehensive data management plan is discussed in Section D, but here we state our commitment to good stewardship of data sovereignty. Data collected by Tribal Nations will only be used if permission is granted. Traditional ecological knowledge (TEK) should only be used in a project and published if permission is granted by Tribal members and leaders. If measurements on Tribal lands are desired, we will directly seek permissions for any airborne or ground-based measurements campaigns and assure that data will not be collected on tribal lands without tribal approval.

## C.5 Preparing the Next Generation of Earth Scientists and Practitioners

*Early Career Scientist Engagement during Scoping*

The ARID team involved early career scientists throughout scoping through several means. (1) Over 50% of the 169 ARID working group participants were early career scientists, demonstrating that the proposed ARID campaign was co-designed with their direct technical input. This number appears representative of similar proportions of early career scientists who participated in conference townhalls, roundtables, workshops, and other engagement events. (2) Over 50% of over 350 written inputs sent to the ARID team also came from early career scientists, demonstrating both their interest levels in the ARID campaign and their contributions that contributed to building the ARID framework (see Appendix F.9). (3) The ARID team leadership included early career scientists. A. Feldman was co-I and co-lead of the ARID scoping study and seven other early career scientists were members of the ARID scoping team, showing that ARID's vision was directly developed by the scientists that would participate in the duration of the ARID campaign. Including early career researchers on the leadership team also ensured more early career involvement throughout the engagement process.

There were many notable engagement events that directly engaged or focused on early career researchers during ARID scoping. Examples include: (1) ARID team leadership met with approximately 100 high school students at a high school in Navajo Nation (Fig. C.5; see Appendix F.7) and provided a general overview and proximal remote sensing instrument demonstration about how multi-spectral instruments can observe relevant features of the land surface. (2) The ARID team discussed educational needs with a SIPI professor (see Appendix F.2) about how to involve tribal early career researchers and provide training opportunities. (3) ARID team leadership attended the 6th Federal UxS Workshop at SIPI (see Appendix F.7) and had direct interactions with students about dryland science and remote sensing. (4) ARID team leadership mentored DEVELOP summer interns regarding a dryland project and noted how such internship opportunities provide training and career pathways into NASA and ARID-related research.

***Figure C.5.*** *ARID team leadership discussing remote sensing and field campaigns like ARID with students at Greyhills Academy High School in Navajo Nation.*

*Vision for Early Career Scientist Involvement in ARID*

ARID is committed to fostering the development of early career researchers throughout the ARID campaign, and propose several diverse approaches: (1) Inclusion of early career scientists on ARID science definition team throughout the campaign. (2) Encouragement and commitment to recruit underrepresented early career scientists to be participants on ARID-funded grants, such as through ESA SEEDS and from tribal conferences like AISES. (3) Encouragement for ARID-funded scientists to fund and mentor early career researchers on ARID grants as well as through internships like NASA's summer internship program, NASA's MUREP MAIANSE (tribal internship opportunities through NASA), and fellowships like the NASA Postdoctoral Program. (4) Encourage ARID scientists, end-users, and partners to participate in NASA's ARSET virtual and in-person training, as well as establishing more specific in-person remote sensing training such as HYR-SENSE, as conducted by NASA SBG.

Expanding more on the third point in the previous paragraph about early career funding, research projects supported by NASA typically fund graduate and undergraduate students, as well as post-docs, and we expect this to continue throughout ARID. With one of ARID's focal regions being the western U.S., we have also worked with other U.S. agencies to outline educational support that could be independent of PI-funded projects in ARID, for example, the USGS Mendenhall Program and the Presidential Management Program. Our partnership with the Nature Conservancy also highlights the NatureNet Science Fellows, which is specifically designed to "embrace existing and emerging technologies". There are also opportunities for graduate students to develop their own independent research, independent from their advisor's projects, through NASA's Earth and Space Science Fellowship program. ARID can facilitate further involvement of undergraduate students via collaborations with the numerous projects funded by NSF, such as, NSF's Research Experience for Undergraduates (REU) program, as well as through NASA's GLOBE program, and the collaborations between NSF and GLOBE.

## C.6 Diversity, Equity, Inclusion, and Accessibility

ARID is committed to building a diverse and inclusive community with equitable and accessible opportunities and interactions throughout the scoping study. ARID adhered to these values throughout the scoping study and will continue to value these efforts throughout the ARID campaign. We describe our vision here, but refer the reader to our tribal and early career scientist engagement efforts (throughout Section C) for efforts that demonstrate the scoping team's vision for diversity, equity, inclusion, and accessibility.

As a part of commitment to diversity and inclusion, we made and will continue to make strong efforts to include tribal voices directly within ARID. ARID team leadership worked hard to build relationships with tribal members. Such partnerships and co-development bring invaluable ideas, perspectives, and in-place knowledge to ARID. This includes membership directly on the ARID leadership team, including Raymond Kokaly and James Rattling Leaf Sr. and extensive tribal engagement throughout scoping (see Section C.3). We will maintain commitment to gender diversity, with scoping including a PI and several members of ARID leadership who are women. Ultimately, we span a wide range of backgrounds, institutions, and career stages. Such commitment to diversity needs to remain active throughout the ARID campaign. It is especially critical to recruit underrepresented researchers to be funded participants of ARID, including at early career stages to build a diverse NASA and Earth science community. This includes recruiting from networks that support inclusion of underrepresented scientists (i.e., Black, Latinx, Tribal, etc.) including at AISES and ESA SEEDS.

To maintain equitable and accessible interactions between scientists, we developed a Code of Conduct (Section D.3) to set expectations for safe and meaningful interactions and to ultimately retain underrepresented ARID participants. These ideals were upheld and enforced throughout the scoping study. For all ARID participants, ARID should require field safety and bystander intervention trainings, such that all are aware of the Code of Conduct, understand consequences, and know how to intervene. Such trainings are often virtually available at NASA centers, which can be leveraged during the campaign. Finally, the ARID leadership team will develop a reporting system that has anonymous options and is independent of any human resources department such that victims feel comfortable discussing and reporting offenses. This will include several designated reporting officers which serve as points of contacts and will be of varying demographic backgrounds (career stage, gender, race, etc.).

## C.7 Capacity Building: Education and Training

ARID's capacity building plan will develop and strengthen the skills, capabilities, available resources, and structures to meet NASA and community goals to educate, train, and uplift dryland communities. This will encompass a wide range of activities, including training, mentoring, and resource allocation, aimed at enhancing capabilities in areas including research, data accessibility, and technical proficiency. We seek to empower people and organizations to be well-trained and self-sufficient, supporting the dryland community in addressing challenges and seizing opportunities over the long term. ARID's process is not only targeted at providing technical knowledge and tools; it also emphasizes the creation of enabling environments, such as inclusive policies (see C6. Diversity, Equity, Inclusion, and Equitability), access to information (see D.3 Data Management and D.4 Computing Resources), and collaborative networks (see C.1 and D.2 Code of Conduct). Ultimately, ARID's capacity building aims to create long-lasting improvements that allow organizations or communities to grow, thrive, and be resilient in the face of change.

ARID was built strongly on NASA's long-standing commitment and resources in support of capacity building, as well as on the opportunities and knowledge provided by agencies such as USAID. NASA SERVIR, ARSET, DEVELOP, GLOBE, and the Indigenous Peoples Initiative have been integral in designing opportunities for ARID to build capacity, and, during the scoping study, as described in the other sections of Section C, we performed consultations and needs assessments, end-user/practitioner mapping, service design, as well as monitoring, evaluation, and learning and used SERVIR's capacity building model as framework for international capacity building.

ARID has specific focus on building capacity and providing educational opportunities for tribal communities. Strong opportunities exist to directly collaborate with these communities to build capacity in several ways. Tribal communities have powerful knowledge and understanding of dryland ecosystems and are actively involved in documenting and adapting to change. As we learned through our tribal partners during scoping, some of the training and skill building opportunities that work well for other scientists may not be appropriate for some tribal members who are otherwise ready to make great strides in advancing science. Additional options for tribal capacity building are needed to provide opportunities for tribal students and scientists to be exposed to NASA ARID, with both field measurements and satellite data. From NASA's foundational work and from our scoping, we know this can include seminars and training for non-tribal scientists who are engaging with tribal scientists and students, on-site trainings for tribal and other rural communities where the scientist comes to them, exposure to instruments that does not require travel, and support in working with data and analysis remotely. ARID could fund installment of instruments at tribal colleges and universities (TCUs), as well as scientist visits to TCUs to provide educational and training opportunities on field instruments. Professor Dennis Dye at SIPI Tribal College suggested a powerful approach in ARID, for example, supporting trainings such as Hyr-Sense through ESIIL (ARID team member Cibele Amaral is a staff scientist at ESIIL and has extensive experience in working with tribal partners.) Also possible are NASA Internships and fellowships, such as MAIANSE, Summer Intern Program, FINESST, and NASA Postdoctoral Program.

# D. Management and Plan of Work

## D.1 Management Structure and Personnel Responsibilities

We describe our vision for the ARID science team structure, with the overall network illustrated in Fig. C.3. We envision a core "ARID Science Team" that consists of the science definition team, any directed science teams, and the competed science team funded through ROSES, as well as the potential for partner science teams. We recommend that the NASA CC&E office supports and advises ARID. It is critical that the ARID Science Team includes representation across the science community from early to late career, domestic and international researchers, and with Tribal Nation representation. Officers should be defined within the ARID team that will focus on continued community engagement, field campaign safety (handling enforcement of ARID's code of conduct in Section D.2), and coherence of ARID's efforts across satellite, airborne, ground, and modeling strategies.

The ARID team will also have an independent advisory committee which includes science community, agency (BLM, USFS), Tribal, international, and end-user/practitioner representation. This independent advisory committee can consist of a wide range of communities that can assist with end-user engagement (boundary organizations and personnel experienced in working with end-users and practitioners) such as the NASA SNWG and NASA CMS team. NASA IPI can advise tribal engagement. NASA SERVIR can advise international engagement and field deployment. The committee can also provide independent annual reviews of ARID's activities in scientific merit of findings, campaign planning strategies, field safety, and inclusiveness of campaign efforts and engagement.

Throughout the ARID implementation in Section B.2, there are two main recommended directed efforts to include within the ARID Science Team. First, ARID's modeling efforts should partially be directed, with two different modeling teams focusing on Earth system modeling and dynamic vegetation modeling (see Section B.2.2). Second, we recommend a larger, directed end-user engagement effort with BLM and USFS to support their modeling and decision-making frameworks (see Section B.2.7). Both of these efforts across modeling and applied sciences efforts are recommended to be directed given the continuity involved beyond a typical three-year ROSES effort.

We additionally recommend different management and campaign planning strategies for domestic and international efforts. For domestic efforts, the science themes of ARID outlined in B.1 and the implementation strategy in B.2.6 should be prioritized. By contrast, international activities should strongly rely on in-place champions that ARID has already partnered with. While the ARID team can define research goals and field site locations, they should emphasize coherence with the in-place research activities. For each international location, a committee of international researchers should be defined that will be assisting or directly a part of the ARID campaign.

## D.2 Code of Conduct

We envision ARID as a community founded upon our shared interest in dryland science, and we are open to everyone from anywhere in the world. ARID is fully committed to providing a safe and inclusive experience for all those involved. Together, we can make an ARID community of which we are all proud to be a part. The following Code of Conduct was developed during scoping and posted to our ARID scoping website upon its establishment early in scoping on November 2023 (https://aridscoping.arizona.edu). It will need to be adapted in real time as the ARID field research and collaborations develop.

Participants in our programs, field work, research, and events agree to the below Code Of Conduct:

- Follow the rules. Please respect the rules and policies of meeting venues, hotels, online platforms, or any other venue. During online events, we will create structure to ensure respect for our facilitators, presenters, and attendees. For example, you may be asked to hold questions until the end or keep your microphones and phones on silent.
- Be respectful. Use good practices for intercultural collaborations. Disagree with ideas openly but respectfully, without demeaning or embarrassing others or calling individuals out (i.e., criticize ideas, not people). Be open to challenges to your own ideas, and don't dismiss the ideas of others. Acknowledge other's identities by using their correct pronouns.
- Be kind. Assume everyone is bringing their best self and treat everyone with dignity. Be cautious of using humor or sarcasm, especially in online communication. Avoid jokes that demean others or make fun of people, even if indirectly.

- Be an ally. Speak up if you see or hear something that might be inconsistent with the ARID Code of Conduct. You are empowered to make others aware of their actions if you feel they are in conflict with expected, collaborative, respectful behavior.
- Be accountable. When we as organizers or participants fail to meet these guidelines, we will work together to identify problems and adjust policy and practice together.

We do not tolerate harassment of program or event participants in any form, including:

- Physical, verbal, written, or other forms of abuse of any attendee, speaker, volunteer, exhibitor, staff member, service provider, or other guest.
- Examples of abuse include, but are not limited to, verbal comments related to gender, sexual orientation, disability, physical appearance, body size, race, religion, national origin, or socioeconomic class; inappropriate use of nudity and/or sexual images in public spaces or in presentations.
- Sustained disruption of talks or other events. This includes interrupting speakers or other guests, dismissing others' ideas, or dominating the time in a manner that overpowers other voices.
- Personal attacks, intimidation, stalking, or unwelcome following, whether in person or online.

We understand that some of these behaviors might be done unintentionally, so we ask that if you are made aware that your words or actions are offensive, stop immediately. If you do not stop, you will need to leave and could be removed from future participation.

Note, ARID adapted this Code of Conduct from the existing American Geophysical Union (AGU) and Ecological Society of America (ESA) Codes of Conduct. We will fall back to these more thorough documents for any issues or situations that are not explicitly covered here.

If you experience or witness any behavior that violates these guidelines or any other behavior that makes you or someone else uncomfortable, please reach out to the ARID leadership team or NASA Carbon Cycle & Ecosystems Office.

## D.3 Data, Software, and Information Management

ARID holds at its core the best practices of Open Science to accelerate data, software, and knowledge sharing responsibly and ethically. This includes adherence to NASA’s SPD-41a scientific information policy, NASA Earth science data & information policy, and community guiding principles and best practices. ARID will follow the science community-defined FAIR principles (Wilkinson et al., 2006) for data and metadata curation and management to improve the findability, accessibility, interoperability, and reusability of ARID products and CARE principles (Carroll et al., 2020) for data sovereignty to ensure that ARID products involving Indigenous Peoples are managed in a way that respects their rights, interests, and values. Below, we provide several guiding strategies and critical considerations that suggest the best practices and policies ARID data, software, and information should be built upon and adhered to during the ARID campaign.

- ARID Products: “ARID products” represent any dataset, software, or information generated to meet ARID goals, such as primary observations, monitoring data, site characterization information, algorithms, codes, and output, remotely sensed products, documentation, and ancillary information, supported explicitly by NASA and its partner institutions. Domestic and international partners will define, share, and agree upon general policies for data standardization, uncertainty assessment, metadata, code documentation, data governance, and stewardship.

- Data and Software Sharing: ARID data and software will be publicly available as soon as possible after validation and quality control. For NASA airborne acquisitions, project teams will have no period of exclusive use. However, PI-led projects may request an embargo from the public release of collected data for an extended period to ensure master students and doctoral candidates can publish their papers and theses before data is publicly available. All ARID datasets will be archived through the assigned DAAC(s) or other public repositories (non-NASA data) and openly accessible through NASA Earthdata, other NASA-relevant data portals, and the ARID website. Data will be accessible through standard services and Application Program Interfaces (APIs) as applicable. In addition to working with the assigned DAAC(s) to make data publicly available, ARID cyberinfrastructure will support the integration of relevant NASA and non-NASA datasets. It will facilitate ARID multi-source data sharing and processing for project affiliates (see section D5). ARID will request that PIs share their codes, Jupyter Notebooks with “vignettes” and examples of using relevant APIs, and Docker containers on ARID’s GitHub and DockerHub to foster collaborations within the ARID network and ensure the reproducibility of workflows for the wider community. The ARID website will centralize the links to relevant data and infrastructure facilitating access to all ARID products.

- Data and Software Credit: Each published ARID dataset, and software will be assigned a Digital Object Identifier (DOI) and a formal citation. Following NASA Earth Science Data and Information System (ESDIS) Project Data Use Policy and community practices, ARID will ensure that data and software are credited appropriately, either by co-authorship, citation, or acknowledgment, depending on the participants' involvement in data collection and software creation in the publication.

- Protecting Students’ Data: ARID recommends that PI-led projects may request an embargo from the public release of collected data for a defined period to ensure master students and doctoral candidates can publish their scientific papers and theses before data is publicly available. Such an embargo is at odds with SPD-41a, and the ability to allow an embargo and define its length will be done in consultation with NASA program managers.

- Indigenous Data Sovereignty: ARID recommends the CARE principles and relevant policies to ensure data collected over tribal lands and Indigenous datasets are appropriately managed, shared, and used. ARID will include tribal representative collaboration to define data collection and governance. Provenance information, contextual metadata, protocols, access permissions, and data use and circulation will be added for these specific datasets. ARID PIs shall work with tribal partners to clearly define the expected benefits for the communities directly involved or affected by any ARID products related to tribal lands.

- ARID Products Format and Archive Recommendations: ARID will collaborate with the NASA ESDS program to streamline the DAAC assignment process and ensure that researchers understand the need to archive their NASA data with the assigned DAAC(s). ARID will advise that non-NASA data be archived in the PIs institutional repositories. As early as possible, All ARID project PIs will receive training on optimal data formatting and archiving practices to ensure the accessibility, reproducibility, and interoperability of ARID products, regardless of the public repository in which they are archived.

- Standardization and Training: As a critical step, ARID will work closely with the assigned DAACs and other data experts to apply standard formats and data curation/management best practices to improve the interoperability and usability of ARID data to better support meta-analysis and model integration. These standard formats and best practices will apply to all directed field and airborne datasets, as well as PI-led project-generated datasets, to improve data formatting and organization, reporting of uncertainties, provision of metadata, etc. Lessons learned from past campaigns suggest such efforts must be planned early instead of at the conclusion of the funded projects. Sufficient and timely training, in close collaboration with assigned DAACs and NASA Open Science programs, needs to be provided to the ARID-funded PIs and participants to ensure the established standards and practices are appropriately followed. As of scoping, we envision ARID datasets will be stored in formats such as Climate & Forecast (CF) compliant NetCDF and Cloud-optimized GeoTIFF (CoG). Archival at the assigned DAAC(s) will also enable public search of ARID data through multiple interfaces, including a SpatioTemporal Asset Catalog (STAC) API, the Earthdata Search, and the Common Metadata Repository (CMR) API. This will enable the use of ARID data across a wide range of programming applications and allow it to be processed in a range of environments from personal computers (within the limits of data volume) to cloud services. ARID will conform to SPD-41a and follow community practices to ensure research software developed by ARID is publicly available with a permissive software license (such as MIT or BSD 3-Clause License) and is citable no later than the research publication.

- Near and Long-term ARID Resources Preservation: ARID will follow NASA’s Earth Science Data Preservation Content Specification (PCS) and the Preservation Content Implementation Guidance, which complement the above-described policies and practices, to preserve valuable ARID data, software, and information beyond the life of the ARID-related project. It will enable concurrent and future projects and users to understand and utilize ARID products and derive information, knowledge, and policy recommendations. These ARID resources may include instrument and platform description, site characteristics, calibration data and methods, science data product validation method and results, product quality, processing and algorithm version history, science data access, and analysis tools.

## D.4 Computing Resources

The ARID Cyberinfrastructure (ARID CI) is committed to leveraging existing NASA cyberinfrastructure, nurturing its open science mission, and fostering collaboration among scientists and end-users working on dryland adaptation and response studies. It will seamlessly integrate NASA and non-NASA data repositories and cloud computing sources, provide a user-friendly interface, and establish open data governance, licensing, and indexing standards. ARID CI aims to make ARID data, softwares, and CI resources accessible to everyone, supporting crucial local and global dryland research. Its cloud environment is a vital component of ARID's mission. It enables collaborative knowledge production by offering a centralized platform for NASA and non-NASA data sharing and cloud computing resources for collaboration among diverse teams of scientists and end-users (Fig. D.1).

The ARID cloud environment interface such as the Science Managed Cloud Environment (SMCE) will empower scientists from a range of career levels, disciplines, and locations to efficiently store data and deploy virtual machines for running Jupyter notebooks and Docker images, thereby enabling the processing and integration of substantial multi-modal datasets. As for scoping, we envision one environment where participants can run Jupyter notebooks from ARID collection, which includes Earthdata cloud-based services, such as Harmony, OPeNDAP, and EGIS, that will facilitate large dataset transformation and harmonization directly from NASA Earthdata Cloud. PIs-led Jupyter Notebooks and Docker containers will also foster collaborations within the ARID network and ensure the reproducibility of ARID workflows for the wider community. This will facilitate scientists and end-users in processing their data within the ARID cloud environment and leverage other NASA and non-NASA CI tools such as VEDA, MAAP, Cyverse, and PIs institutional HPCs and local computers.

To grant a diverse end-user community access to datasets, existing NASA tools, including CMR STAC APIs and the APPEEARS tool for simplified data access, management, and download, as well as dashboard applications such as NASA EIS, VEDA, and MAAP, will be accessible to users on the ARID website. These applications will enable users without expertise in cloud computing to access, process, and visualize multiple datasets and information resulting from ARID research. Committed to the CARE principles and respecting data and knowledge sovereignty, the utilization of ARID CI resources is optional. End-users have the freedom to download their datasets of interest and process them on local machines, applying their knowledge without constraints and with individualized security.

We further propose ARID invest in capacity building to promote open science and scalable computing best practices within the ARID community and beyond. We expect that ARID PIs understand and are committed to nurturing NASA Open Science and DEI vision by following NASA SPD41a, as well as the community-driven FAIR and CARE principles. ARID may also encourage training on the best use of ARID datasets and cyberinfrastructure through partnerships with programs such as NASA TOPS and OpenScapes. The ARID webpage will provide easy access to data, existing NASA resources, and the ARID cloud environment, offering links to all ARID-related resources. Recorded trainings on best practices for open data and code management and publication will be accessible to the ARID and broader community. Furthermore, ARID CI will be established to streamline data synthesis among ARID-funded scientists and end-users and ensure a lasting ARID products legacy for the future generation of dryland scientists, managers, and local communities.

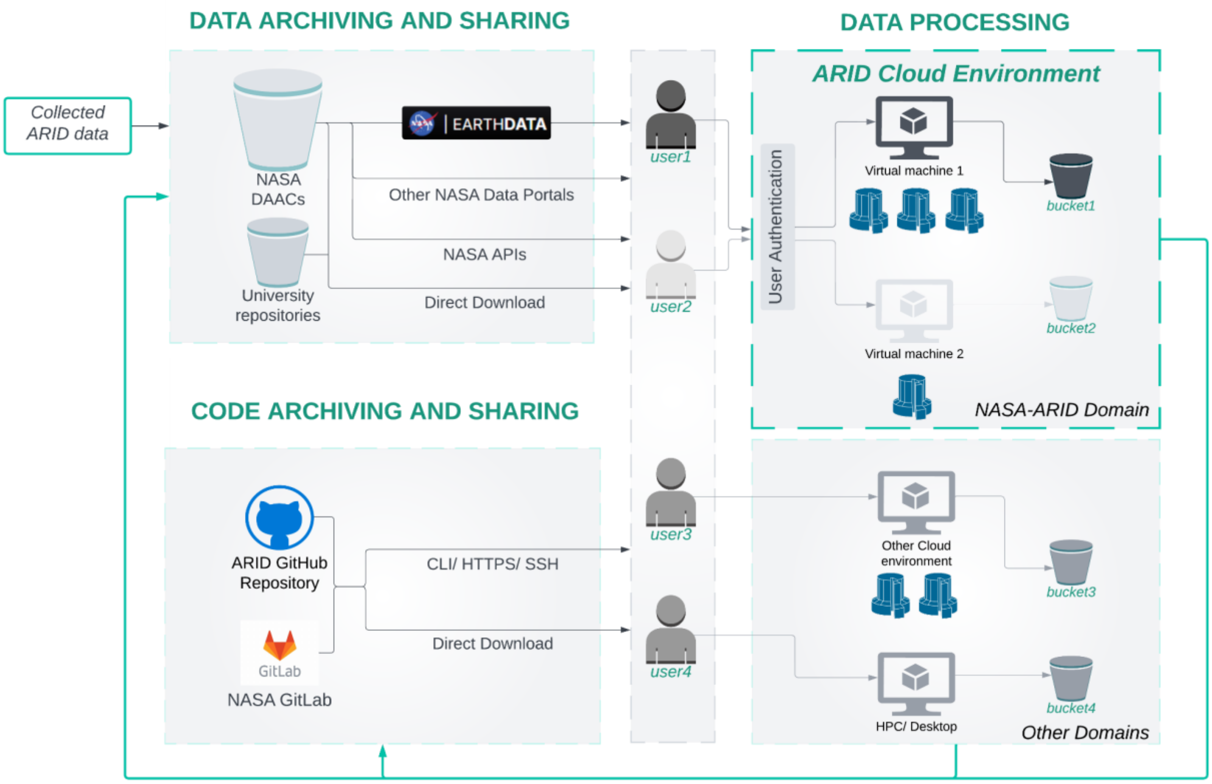


***Figure D.1.*** *Diagram delineating the ARID cyberinfrastructure data and code storage, sharing, processing, and archiving procedures. The ARID cloud environment will be developed to facilitate data synthesis for recipients of NASA's ARID awards. The workflow adheres to the FAIR principles, ensuring the findability, accessibility, interoperability, and reproducibility of ARID data and codes. At the same, it gives freedom to end-users to download and apply their knowledge to ARID datasets on local machines. ARID awardees and the wider community will be granted access to training sessions covering best practices for open data and code management and publication. The ARID webpage will provide easy access to data, existing NASA resources, and the ARID cloud environment, offering links to all ARID-related CI resources.*

# 1 Acronym List

| Acronym | Definition |
|---|---|
| ABoVE | NASA Arctic-Boreal Vulnerability Experiment |
| ACT-America | Atmospheric Carbon and Transport - America |
| AEOIP | Applied Earth Observations Innovation Partnership |
| AGB | Aboveground Biomass |
| AGU | American Geophysical Union |
| AI | Artificial intelligence |
| AIM | Bureau of Land Management Assessment, Inventory and Monitoring |
| AIRS | Atmospheric Infrared Sounder |
| AISES | American Indian Science and Engineering Society |
| API | Application Programming Interface |
| APPEEARS | NASA Application for Extracting and Exploring Analysis Ready Samples |
| ARC | Australian Research Council |
| ARID | Adaptation and Response in Drylands (scoping study for NASA) |
| ARID CI | ARID Cyberinfrastructure |
| ARM | Atmospheric Radiation Measurement |
| ARSET | Applied Remote Sensing Training Program |
| ASD | Analytical Spectral Device |
| ASU | Arizona State University |
| AVIRIS | Airborne Visible/Infrared Imaging Spectrometer |
| AWS | NASA Amazon Web Service |
| AZ | Arizona |
| BHP | BHP Copper Co |
| BIL | Bipartisan Infrastructure Law |
| BLM | Bureau of Land Management |
| BOREAS | Boreal Ecosystem-Atmosphere Study (NASA-terrestrial field campaign) |
| CA | California |
| CAM | Crassulacean Acid Metabolism |
| CARAFE | Carbon Airborne Flux Experiment |
| CARE | Collective Benefit, Authority to Control, Responsibility, Ethics |
| CARVE | NASA Carbon in Arctic Reservoirs Vulnerability Experiment |
| CASC | USGS Climate Adaptation Science Centers |
| CCE | NASA Carbon Cycle and Ecosystems |
| CF | Climate and Forecast |
| CFIS | Chlorophyll Fluorescence Imaging Spectrometer |
| CHIME | Copernicus Hyperspectral Imaging Mission for the Environment |
| CMR | NASA EarthData common metadata repository |
| CMS | NASA Carbon Monitoring System |
| CO | Colorado |
| COG | Cloud Optimized GeoTIFF |

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|---|---|
| ONAHCYT | Mexican National Council of Humanities, Science and Technology |
| CREW | Climate Response Early Warning |
| CSIRO | Commonwealth Science and Industrial Research Organization, Earth Observation Center |
| CSU | Colorado State University |
| DC | District of Columbia |
| DGVM | Dynamic Global Vegetation Model |
| DOD | Department of Defense |
| DOE | Department of Energy |
| DOI | Department of Interior |
| DryFlor | Latin American Seasonally Dry Tropical Forest Floristic Network |
| ECOSTRESS | ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station |
| EDGE | Earth Dynamics Geodetic Explorer |
| EFTEON | Expanded Freshwater and Terrestrial Environmental Observation Network |
| EIS | Earth Information System |
| EMIT | Earth Surface Mineral Dust Investigation |
| ENSO | El Niño-Southern Oscillation |
| EO | Earth Observation technologies |
| EOS | Earth Observing System |
| ESA | European Space Agency and Ecological Society of America |
| ESD | NASA's Earth Science Division |
| ESIIL | Environmental Data Science Innovation & Inclusion Lab |
| ESM | Earth System Models |
| ESTO | NASA Earth Science Technology Office |
| ET | Evapotranspiration |
| FAIR | Findability, Accessibility, Interoperability, and Reusability |
| FAPAR | Fraction of photosynthetically active radiation absorbed |
| FEWSNET | USGS Famine Early Warning Systems Network |
| FIFE | First International Satellite Land Surface Climatology Project Field Experiment (NASA- terrestrial field campaign) |
| FIREFLY | Fluorescence Imaging of Red and Far-Red Light Yield |
| FLAME VNIR | Flame (Near-Infrared) spectrometer from Ocean Optics |
| FLEX | NASA Flame Extinguishment Experiment |
| GEDI | Global Ecosystem Dynamics Investigation |
| GEMX | NASA-USGS Geological Earth Mapping Experiment |
| GERI | Global Ecosystem Research Infrastructure |
| GEWEX | NASA's Global Energy and Water Cycle Experiment |
| GIS | Geographic Information System |
| GLACE-CMIP5 | Global Land-Atmosphere Coupling Experiment–Coupled Model Intercomparison Project phase 5 |
| GLIHT | NASA Goddard's LiDAR, Hyperspectral & Thermal Imager |
| GLOBE | NSF Global Learning and Observations to Benefit the Environment |
| GNSS | Global Navigation Satellite System |

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|---|---|
| GOES | Geostationary Operational Environmental Satellites |
| GOSAT | Greenhouse gases observing satellite |
| GPM | Global Precipitation Measurement |
| GPP | Gross Primary Production |
| GPR | Ground Penetrating Radar |
| GRACE | NASA Gravity Recovery and Climate Experiment |
| GRACE-FO | Gravity Recovery and Climate Experiment Follow-On mission |
| GSD | Global Spectral Deconvolution |
| GSFC | NASA Goddard Space Flight Center |
| HIS | Hyperspectral Image Spectroscopy |
| HISUI | Hyperspectral Imager Suite |
| HLS | Harmonized Landsat and Sentinel-2 |
| HQ | Head Quarters |
| HSI | Hyperspectral Imaging |
| HYR-SENSE | Hyperspectral and Thermal Remote Sensing for Environmental Justice |
| HYSPIRI | Hyperspectral Infrared Imager |
| HYTES | Hyperspectral Thermal Emission Spectrometer |
| IAV | Interannual Variability |
| ICOS | Integrated Carbon Observation System |
| IN | Indiana |
| INIFAP | Institute for Forestry, Agriculture and Livestock Research |
| IPBES | Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services |
| IPCC | Intergovernmental Panel on Climate Change |
| IPI | NASA's Indigenous Peoples Initiative |
| IRA | Inflation Reduction Act |
| IRT | Infrared Thermometer |
| ISS | International Space Station |
| ITSON | Instituto Technologica de Sonora |
| JAXA | Japan Aerospace Exploration Agency |
| JPL | Jet Propulsion Laboratory |
| LAI | Leaf Area Index |
| LandSat | Land Satellite |
| LASI | Latin America Sustainability Institute |
| LBA | Large-Scale Biosphere-Atmosphere (NSAS-terrestrial field campaign) |
| LCLUC | NASA Land-Cover and Land-Use Change |
| LDC | Landscape Data Commons |
| LIDAR | Light Detection and Ranging |
| LPDAAC | NASA Land Processes Distributed Active Archive Center |
| LST | Land Surface Temperature |
| LSTM | NASA Land Surface Temperature Monitoring |
| LTAR | Long-Term Agroecosystem Research |
| LTER | Long Term Ecological Research |

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|---|---|
| LVIS | Land, Vegetation, and Ice Sensor |
| MA | Massachusetts |
| MAAP | NASA Multi-Mission Algorithm and Analysis Platform |
| MAIANSE | NASA MUREP for American Indian and Alaskan Native STEM Engagement |
| MASTER | Spaceborne Thermal Emission and Reflection Radiometer (ASTER) |
| MC | NASA Mission Concepts |
| MD | Maryland |
| MERLIN | NASA The MISR Enhanced Research and Lookup Interface |
| MODIS | Moderate Resolution Imaging Spectroradiometer |
| MRI | USGS Earth Mapping Resources Initiative |
| MSG | Microgravity Science Glovebox |
| MUREP | NASA Minority University Research & Education Project |
| NASA | National Aeronautics and Space Administration |
| NASEM | National Academies of Sciences, Engineering, and Medicine |
| NC CASC | North Central Climate Adaptation Science Center |
| NCA5 | United States National Climate Assessment |
| NDVI | Normalized Difference Vegetation Index |
| NEE | Net Ecosystem Exchange |
| NEESPI | Northern Eurasia Earth Science Partnership Initiative (NASA research program) |
| NEON | National Ecological Observatory Network |
| NEON-AOP | NEON Airborne Observation Platform |
| NG | Airborne Visible InfraRed Imaging Spectrometer - Next Generation |
| NGEE | Next-Generation Ecosystem Experiments |
| NIR | Near-Infrared |
| NISAR | NASA-ISRO Synthetic Aperture Radar |
| NM | New Mexico |
| NMSU | New Mexico State University |
| NOAA | National Oceanic and Atmospheric Administration |
| NOHRSC | National Operational Hydrologic Remote Sensing Center |
| NPP | Net Primary Production |
| NPS- I&M | National Park Service Inventory and Monitoring |
| NRCS | Natural Resources Conservation Service |
| NRCS-NR | Natural Resources Conservation Service National Resources Inventory |
| NSF | National Science Foundation |
| OCO | NASA Orbiting Carbon Observatory |
| OCO-2 v10 MIP | Orbiting Carbon Observatory-2 (OCO-2) Model Intercomparison Project (MIP) |
| ORNL DAAC | Oak Ridge National Laboratory Distributed Active Archive Center |
| OSSE | Observing System Simulation Experiments |
| PACE | Plankton, Aerosol, Cloud, ocean Ecosystem |
| PALS | Passive Active L-band System |
| PBL | Planetary Boundary Layer |

| | |
|---|---|
| PERSIANN-CDR | Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks–Climate Data Record |
| PFT | Plant Functional Types |
| PI | Principal Investigator |
| PICARD | Pushbroom Imager for Cloud and Aerosol Research and Development |
| PRI | Photochemical Reflectance Index |
| RCMAP | Rangeland Condition Monitoring Assessment and Projection, |
| REU | Research Experiences for Undergraduates |
| RFP | NASA Requests for Proposals |
| RGB | Red Green Blue |
| RIZA | International Network for Drylands Sustainability |
| RS | Remote Sensing |
| RUBISCO | Ribulose-1,5-bisphosphate carboxylase/oxygenase |
| RZSM | Root Zone Soil Moisture |
| SAEON | South African Environmental Observation Network |
| SAFARI | Southern African Regional Science Initiative |
| SASSCAL | Southern African Science Service Centre for Climate Change and Adaptive Land Management |
| SBG | Surface Biology and Geology |
| SDC | NASA Surface Deformation and Change |
| SDG | Sustainable Development Goals |
| SECO | Bosque Seco Biosphere Reserve |
| SEEDS | Strategies for Ecology Education, Diversity and Sustainability |
| SEPO | Social-Ecological Participatory Observatories |
| SERDP | Strategic Environmental Research and Development Program |
| SERVIR | Regional Visualization and Monitoring System (SERVIR's name is derived from the Spanish word meaning “to serve”) |
| SES | Social Ecology Systems |
| SEVIRI | Spinning Enhanced Visible and Infrared Imager |
| SFM | Structure From Motion |
| SHIFT | High-Frequency Time Series (NASA research Program) |
| SIC | Soil Inorganic Carbon |
| SIF | Solar-Induced Fluorescence |
| SIPI | Southwestern Indian Polytechnic Institute |
| SLAP | Scanning L-band Active/Passive |
| SM | Soil Moisture |
| SMAP | Soil Moisture Active Passive |
| SMAPVEX15 | Soil Moisture Active Passive Validation Experiment 15 |
| SMCE | Science Managed Cloud Environment |
| SMOS | Soil Moisture and Ocean Salinity |
| SNOTEL | Natural Resources Conservation Service "Snow Telemetry" |
| SNWG | NASA’s Satellite Needs Working Group |
| SOILWAT | water balance simulation model |

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|---|---|
| SPAC | Soil Plant Atmosphere Water Continuum |
| SPD-41a | Scientific Information Policy for the Science Mission Directorate |
| SPECNET | Spectral Network |
| SSAI | Science Systems and Applications, Inc |
| STAC | SpatioTemporal Asset Catalog |
| STELLA | NASA Science and Technology Education for Land/Life Assessment |
| STV | Surface Topography and Vegetation |
| SWE | Snow Water Equivalent |
| TEK | Traditional Ecological Knowledge |
| TEMPO | Tropospheric Emissions: Monitoring of Pollution |
| TERN | Terrestrial Ecosystem Research Network |
| TIR | Thermal Infrared Emittance |
| TLS | Terrestrial Laser Scanning |
| TOPS | Transform to Open Science |
| TRISHNA | Thermal Infra-Red Imaging Satellite for High-resolution Natural Resource Assessment |
| TRUST | Transparency, Responsibility, User focus, Sustainability, and Technology |
| TWS | Terrestrial Water Storage |
| UA | University of Arizona |
| UAS | Unmanned Aircraft System |
| UAS-LS | Uncrewed Airborne System - Laser Scanner |
| UAV | Unmanned Aerial Vehicle |
| UAVSAR | Uninhabited Aerial Vehicle Synthetic Aperture Radar |
| UDSA | United States Department of Agriculture |
| UK | United Kingdom |
| ULS | Unmanned Laser Scanning |
| UN | United Nations |
| UNAM | Universidad Nacional Autonoma de Mexico |
| UNCCD | United Nations Convention to Combat Desertification |
| UNM | University of New Mexico |
| US | United States |
| USA | United States of America |
| USAID | United States Agency for International Development |
| USDA | United States Department of Agriculture |
| USDA/ARS | USDA Agricultural Research Service |
| USFS | United States Forest Service |
| USFS FIA | Forest Inventory and Analysis |
| USFWS | United States Fish and Wildlife Service |
| USGCRP | United States Global Change Strategic Plan |
| USGEO | United States Group on Earth Observations |
| USGS | United States Geological Survey |
| VA | Virginia |
| VEDA | NASA Visualization, Exploration, and Data Analysis |

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|---|---|
| VHR | Very High Resolution Satellite Imagery |
| VIIRS | Visible Infrared Imaging Radiometer Suite |
| VOD | Vegetation Optical Depth |
| VPD | Vapor Pressure-Deficit |
| VSWIR | HyspIRI Visible to Short Wavelength InfraRed |
| VWC | Vegetation Water Content |
| WDTS | Western Diversity Time Series |
| WGEW | Walnut Gulch Experimental Watershed |
| WPE | Woody Plant Encroachment |
| WTDS | Wisconsin TeraGrid Data System |
| WUE | Water Use Efficiency |
| WWAO | Western Water Applications Office |

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# F. Appendix

We have redacted most Appendix sections given personally identifying information. This information is not publicly available and will only be available for internal review.

## F.1 Science and Application Traceability Matrix

***Table F.1.*** *Modified Science and Application Traceability Matrix (SATM, Appendix F.1) Physical parameters required to address science sub-themes (numbered in footnotes) and the various remote sensing sensors available on proximal (e.g. towers), UAS, airborne and spaceborne platforms. Names of sensors are given in the footnotes of this table. The table lists the current and future sensors that can make the most significant advances and do not attempt to list all available options. Science Sub-themes: 1.1 Water availability, 1.2 Dryland climate variability: Pulses and Drought, 1.3 Fire, 1.4 Land-Atmosphere interaction, 2.1 Vegetation Structure, 2.2 Dryland Biodiversity, 2.3 Ecosystem Function, 2.4 Dryland Geology and Soil Processes, 3.1 Carbon stocks and fluxes, 4.1 Land Management, 4.2 Adaptation and Mitigation.*

| **Physical Parameter or process / Observable** | **Science theme number** | **Comment: need and current status** | **Near surface and Proximal** | **UAS** | **Airborne** | **Spaceborne/ Satellite** |
|---|---|---|---|---|---|---|
| Precipitation (P) | 1.1, 1.2 | | | | | GPM |
| Soil Moisture (SM) | 1.1, 1.2, 2.1, 2.2 | Poorly estimated for the subsurface/root zone; identified need for higher resolution (10 m to <1 km) estimates<br>Driver for local models<br>Validation/diagnostic for water cycle in LSMs/ESMs | Soil moisture network, GNSS receiver above and below canopy | Thermal | UAVSAR / AirMoss, SMAPEx; NOAA airborne gamma NOHRSC, AirSWOT, | SMAP, ECOSTRESS, Hydrosat, SMOS, NISAR, Sentinel1, |
| Evapotranspiration (ET) Level 4 model output | 1.1, 1.2, 1.3, 2.1 | Calibration/Validation for model estimates of ET, E and T. Open ET models can use multiple RS inputs | Infrared Thermometer (IRT): Apogee SI-111-SS<br>Thermal Camera: FLIR A700f; ICI P-Series | Thermal | HYTES, MASTER | ECOSTRESS, Landsat, |
| Surface temperature (ST) of soil vs. plants | 1.4 | Input to ET, GPP, NEE, plant stress | Infrared Thermometer (IRT): Apogee SI-111-SS<br>Thermal Camera: FLIR A700f; ICI P-Series | Thermal | HYTES, MASTER | ECOSTRESS, Landsat, |
| Vegetation fractional cover of Plant | 1.3, 2.1, | PFT: Trees, shrubs, grasses, forbs, | PhenoCam; Terrestrial Laser | Multi-spectral Lidar | AVIRIS-NG, NEON-AOP, G- | Landsat, SBG, EMIT |

| | | | | | | |
|---|---|---|---|---|---|---|
| functional types (PFT) | 3.1 | biocrust. Grass biomass poorly estimated.<br>Local calibration/ initialization for models<br>DGVM constraint<br>Trait information | Scanning (TLS) | | LiHT, LVIS | |
| Vegetation height: Grass, shrubs, trees | 1.3, 2.1, 3.1 | Shrub (<3m) biomass poorly estimated with optical and space-based LiDAR algorithms. Individual tree heights can be extracted using SFM from airborne imagery.<br>Potential constraint for data assimilation | TLS | RGB SfM<br>LiDAR | Discrete Lidar, G-LiHT<br>LVIS, UAVSAR, AVIRIS-NG, NEON-AOP | NISAR, S1, GEDI, IceSat2, WorldView, |
| Above ground biomass: grass | 1.3, 2.1, 3.1 | Grass biomass poorly estimated with optical | TLS | Multi-spectral Lidar | AVIRIS-NG, G-LiHT, NEON-AOP | EMIT, LandSat NEXT, HLS, SBG, |
| Above ground biomass: shrubs | 1.3, 2.1, 3.1 | Shrub biomass is poorly estimated with optical and space-based LiDAR algorithms.<br>Calibration/Validation for model estimates of NPP<br>Potential constraint for data assimilation | TLS | LiDAR | Discrete Lidar, G-LiHT<br>LVIS, UAVSAR, AVIRIS-NG, NEON-AOP | NISAR, S1, GEDI, IceSat2, EDGE, STV |
| Above ground biomass: trees | 1.3, 2.1, 3.1 | Lidar is most accurate. SAR-based estimates of AGB with models trained with airborne Lidar data. Individual tree biomass can be estimated with VHR commercial imagery and AI.<br>Calibration/Validation for model estimates of NPP.<br>Potential constraint for data assimilation | TLS | RGB SfM<br>LiDAR | Discrete Lidar, G-LiHT<br>LVIS, UAVSAR, AVIRIS-NG, NEON-AOP | NISAR, S1, GEDI, IceSat2, EDGE, STV, WorldView, |
| Below ground biomass | 3.1 | Very poorly estimated, require ground penetrating radar (GPR) | Ground Penetrating Radar (GPR) | | | |
| Photosynthetically active vegetation fractions of PFT’s | 1.3, 3.1 | Essential to make a distinction between active and non-active components | Phenocams, spectrometer (e.g., Ocean Insight FLAME VNIR spectroradiometer) | Hyperspectral, Multi-spectral | AVIRIS-NG, LVIS | EnMap, SBG, Landsat |
| Coarse and fine fuel loads | 1.3 | Derived in similar way to PFT biomass | TLS; GNSS receiver | Hyperspectral, Multi-spectral, | AVIRIS-NG, LVIS | EnMap, SBG, |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | LiDAR | | |
| Sub-canopy fuel loads | 1.3 | Currently poorly estimated. Requires LiDAR for 3D structure estimates | TLS; GNSS receiver | LiDAR | Discrete Lidar, G-LiHT<br>LVIS, AVIRIS-NG, NEON-AOP | GEDI, IceSat2, EDGE |
| Vegetation moisture content | 1.3 | | TLS; dual GNSS receivers installed above and below the canopy | Hyperspectral, Multi-spectral, SAR | AVIRIS-NG, UAVSAR | S1, NISAR, EnMap, SBG, Landsat 8,9,10, NEXT, HLS, PACE |
| Vegetation greenness / curing | 1.3 | Requires long time series of greenness | Phenocams; spectrometer (e.g., Ocean Insight FLAME VNIR spectroradiometer) | Hyperspectral, Multi-spectral | AVIRIS-NG, LVIS | EnMap, SBG, Landsat 8,9,10, NEXT, HLS |
| Vegetation Chlorophyl content | 2.1 | | Phenocams; spectrometer (e.g., Ocean Insight FLAME VNIR spectroradiometer) | Hyperspectral, Multi-spectral | AVIRIS-NG | EnMap, SBG, Landsat 8,9,10, NEXT, HLS |
| Vegetation Nitrogen content | 2.1 | Poorly estimated in discontinuous canopies | Hyperspectral: ASD FieldSpec; Spectra Evolution RS-3500, 8800, PSR+ | Hyperspectral | AVIRIS-NG, SHIFT | EnMap, SBG |
| Invasive species: tree, grass, shrub, forbs | 2.1 | Individual Invasive plants species could be spectrally distinguished | Hyperspectral: ASD FieldSpec; Spectra Evolution RS-3500, 8800, PSR+ | Hyperspectral | AVIRIS-NG | EnMap, SBG, |
| Solar-induced Fluorescence (SIF) | 1.2, 3.1 | | Ultra-hyperspectral VNIR: PhotoSpec; FluoroSpec; FloX Box | Ultra-hyperspectral VNIR | FIREFLY, CFIS | OCO-2,3, TEMPO |
| Fraction of photosynthetically active radiation absorbed (FAPAR) per PFT | 3.1 | Input to carbon-flux models | Hyperspectral, Multi-spectral | Hyperspectral, Multi-spectral | AVIRIS-NG | EnMap, SBG, GOES-R |
| Gross Primary Production: Trees, grass, shrubs. Level 4 model output | 1.2, 1.4, 3.1 | Modeled variable, require FAPAR of PFT and meteorological variables as input | Hyperspectral; Thermal; SIF | FAPAR of PFTs derived above | FAPAR of PFTs derived above | FAPAR of PFTs derived above, GOES-R |
| Net Primary Production (NPP). Level 4 model output | 3.1 | Modeled variable, require FAPAR, GPP and estimated of respiration | Hyperspectral; Thermal; SIF | | | |
| Plant Stress<br>Level 4 model output | | Requires inputs: ST, Leaf moisture content | Hyperspectral; Thermal; SIF | | | |
| Snow Water | | | TLS; GNSS receiver | | NOAA airborne | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Equivalent (SWE) | | | | | gamma<br>NOHRSC | |
| Soil Carbon Organic, Inorganic??) | 2.1, 2.2, 3.1 | | Hyperspectral | | | |
| Biocrust fractional cover | 2.2 | Validation for C stocks in ESM model spin-up | Hyperspectral | Hyperspectral, Multi-spectral | AVIRIS-NG | EnMap, SBG, |
| Biocrust community composition | 2.2 | | Hyperspectral | Hyperspectral, Multi-spectral | AVIRIS-NG | EnMap, SBG, |
| Atmospheric Carbon concentrations and flux (Level 4 model output) | | Calibration/Validation for model estimates of GPP<br>Potential constraint for data assimilation | Flux tower | | CARVE, ATom, ACT-America | OCO-2/-3 |
| Geology/ geochemistry | | Geologic constraints on nutrient and water availability; geologic materials affecting environment and human health; acid rock drainage; dust source mineral composition and quantification | Hyperspectral | VSWIR hyperspectral; Infrared multispectral and hyperspectral (MWIR 3-5 microns and TIR 8-12 microns) | AVIRIS-NG, -3, -5; MASTER; HYTES, HYTES-2 | Present: EMIT, ECOSTRESS, other national space agency imaging spectrometers<br>Planned: SBG VSWIR and TIR; Landsat NEXT; |

Abbreviations: SfM - RGB: Structure from motion, S1: Senitinel1, SBG: Surface Biology Geology, AirMOSS: Airborne Microwave Observatory of Subcanopy and Subsurface, UAS-LS: Uncrewed AirborneSystem - Laser Scanner, FIREFLY: fluorescence imaging of red and far-red light yield

## F.2 ARID Workshop 1: Tucson, AZ

[Redacted]

## F.3 ARID Workshop 2: Albuquerque, NM

[Redacted]

## F.4 ARID Science Theme Working Groups Participants

[Redacted]

## F.5 ARID Technical Working Group Participants

[Redacted]

## F.6 ARID Engagement Archive

[Redacted]

## F.7 Tribal Engagement Archive

[Redacted]

## F.8 Acknowledgement of ARID Scoping Participants

[Initially Redacted, May Appear in Final Version]

## F.9 Community Feedback: Response to Forms

[Redacted]

## F.10 Airborne Remote Sensing Feedback

[Redacted]

## F.11 End-User Input

[Redacted]

## F.12 Archive of Dryland Efforts that ARID can Leverage

[Initially Redacted, May Appear in Final Version]