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COMMENTARY

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Adaptation and Response in Drylands (ARID): Community Insights for Scoping a NASA Terrestrial Ecology Field Campaign in Drylands

Andrew F. Feldman[1,2], Sasha Reed[3], Cibele Amaral[4,5], Alicja Babst-Kostecka[6], Flurin Babst[7,8], Joel Biederman[9], Charles Devine[7], Zheng Fu[7,10], Julia K. Green[6], Jessica Guo[11], Niall P. Hanan[12], Raymond Kokaly[13], Marcy Litvak[14], Natasha MacBean[15], David Moore[7], Dennis Ojima[16], Benjamin Poulter[1], Russell L. Scott[9], William K. Smith[7], Robert Swap[17], Compton J. Tucker[17], Lixin Wang[18], Jennifer Watts[19], Konrad Wessels[20], Fangyue Zhang[7], and Wen Zhang[7]

[1]Biospheric Sciences Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA, [2]Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD, USA, [3]U.S. Geological Survey, Southwest Biological Science Center, Moab, UT, USA, [4]Earth Lab, Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, Boulder, CO, USA, [5]Environmental Data Science Innovation & Inclusion Lab, Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, Boulder, CO, USA, [6]Department of Environmental Science, University of Arizona, Tucson, AZ, USA, [7]School of Natural Resources and the Environment, University of Arizona, AZTucson, USA, [8]Laboratory of Tree-Ring Research, University of Arizona, Tucson, AZ, USA, [9]Southwest Watershed Research Center, USDA Agricultural Research Service, Tucson, AZ, USA, [10]Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China, [11]CCT Data Science Group, University of Arizona, Tucson, AZ, USA, [12]Jornada Basin LTER, New Mexico State University, Las Cruces, NM, USA, [13]U.S. Geological Survey, Geology, Geochemistry, and Geophysics Science Center, Denver Federal Center, Denver, CO, USA, [14]Department of Biology, University of New Mexico, Albuquerque, NM, USA, [15]Department of Geography and Environment, Department of Biology, Western University, London, ON, Canada, [16]Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, CO, USA, [17]Earth Sciences Division, NASA Goddard Space Flight Center, Greenbelt, MD, USA, [18]Department of Earth and Environmental Sciences, Indiana University Indianapolis, Indianapolis, IN, USA, [19]Woodwell Climate Research Center, Falmouth, MA, USA, [20]Department of Geography and Geoinformation Science, George Mason University, Fairfax, VA, USA

Key Points:

- Adaptation and Response in Drylands (ARID) is a 1-year scoping study for a multi-year NASA Terrestrial Ecology dryland field campaign
- An ARID workshop was held in Tucson, Arizona in October 2023 with more than 30 data end-users and 300 scientists in attendance
- Further input from hundreds of researchers and end-users was obtained through workshops, conference town-halls, and tribal engagement

Correspondence to:

A. F. Feldman,
andrew.feldman@nasa.gov

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Abstract Dryland ecosystems cover 40% of our planet's land surface, support billions of people, and are responding rapidly to climate and land use change. These expansive systems also dominate core aspects of Earth's climate, storing and exchanging vast amounts of water, carbon, and energy with the atmosphere. Despite their indispensable ecosystem services and high vulnerability to change, drylands are one of the least understood ecosystem types, partly due to challenges studying their heterogeneous landscapes and misconceptions that drylands are unproductive "wastelands." Consequently, inadequate understanding of dryland processes has resulted in poor model representation and forecasting capacity, hindering decision making for these at-risk ecosystems. NASA satellite resources are increasingly available at the higher resolutions needed to enhance understanding of drylands' heterogeneous spatiotemporal dynamics. NASA's Terrestrial Ecology Program solicited proposals for scoping a multi-year field campaign, of which Adaptation and Response in Drylands (ARID) was one of two scoping studies selected. A primary goal of the scoping study is to gather input from the scientific and data end-user communities on dryland research gaps and data user needs. Here, we provide an overview of the ARID team's community engagement and how it has guided development of our framework. This includes an ARID kickoff meeting with over 300 participants held in October 2023 at the University of Arizona to gather input from data end-users and scientists. We also summarize insights gained from hundreds of follow-up activities, including from a tribal-engagement focused workshop in New Mexico, conference town halls, intensive roundtables, and international engagements.

Plain Language Summary Drylands are landscapes with limited water availability, which cover 40% of Earth's land surfaces, support billions of humans, and play a substantial role in Earth's weather and climate systems. However, these ecosystems are under threat from droughts and heatwaves. They are also poorly understood because of challenges measuring their highly diverse vegetation types and interspersed vegetation cover and because of incorrect perceptions that they are unimportant "wastelands." These limitations make it challenging to manage their landscapes and quantify how drylands are driving Earth's weather and climate. NASA solicited proposals for a multi-year field campaign, of which Adaptation and Response in Drylands (ARID) was one of two scoping studies selected. The ARID scoping study aims to design a plan for how NASA satellite, aircraft, and field instruments can be used to better understand dryland ecosystems and their response to change. A primary scoping goal is to engage with scientists and data-users, especially those who manage land, to understand research and management priorities in drylands. Here, we discuss details of our meeting with over 300 scientists and data-users in Tucson, AZ in October 2023. We also highlight feedback from our tribal-focused workshop in New Mexico, conference town halls, and international meetings.

1. Global Significance of Drylands

Drylands are water-limited ecosystems where atmospheric demand for moisture greatly exceeds the amount supplied by precipitation. Drylands cover approximately 40% of the Earth's land surfaces (Figure 1) (Wang et al., 2022) and contribute the largest controls over the long-term trend and interannual variability of the terrestrial carbon sink (Ahlström et al., 2015; Fan et al., 2019; Metz et al., 2023; Poulter et al., 2014). Interannual variability in terrestrial carbon uptake, strongly controlled by poorly understood dryland processes, complicates our ability to quantify and forecast impacts of climate change mitigation and policy decisions, such as with natural climate solutions (Novick et al., 2024). Drylands also represent 40% of terrestrial net primary production (Wang et al., 2022), store a third of the planet's soil organic carbon and ~80% of its soil inorganic carbon (Plaza et al., 2018), and have greater carbon storage in woody biomass than previously assumed (Brandt et al., 2020; Tucker et al., 2023). They also host 35% of the global human population (Wang et al., 2022) with the highest population growth rate of any ecological zone (Gaur & Squires, 2018). Livelihoods of people in drylands are tightly coupled to local ecosystem services via pastoralism and agriculture, and drylands provide extensive services including providing 60% of the world's food, a variety of critical mineral resources, and unique cultural and biological diversity (Alikhanova & Bull, 2023; Cartereau et al., 2023).

Under rapid anthropogenic change, many dryland ecosystem services are threatened and coordinated dryland measurement campaigns are thus urgent. Specifically, drylands are experiencing more extreme heatwaves and droughts, for example, in the western United States, where the most severe decadal-scale drought in more than 1,200 years is currently taking place (Dannenberg et al., 2022; Williams et al., 2022). Record-high temperatures are putting pressure on the region's inhabitants, carbon stores, water resources, and ecosystem services. These changes in climate are resulting in vegetation transitions including substantial mass mortality of dryland forests in the face of "hot drought" (Allen et al., 2010; Anderegg et al., 2013). Drylands maintain photosynthetic soils, which uptake carbon, add nutrients, and stabilize soils, and these biological soil crusts are also under threat from anthropogenic change (Reed et al., 2016). Additionally, about 90% of the world's dryland human population is in developing countries, which are facing developmental pressures of increasing food production under water limited conditions (Wang et al., 2012). Furthermore, because these ecosystems sustain high biodiversity, comprising myriad endemic species, there is a high risk of species loss and trophic cascades under anthropogenic change (Cartereau et al., 2023). The extent of drylands is also projected to increase 11%–23% by the end of the century with aridification (Hanan et al., 2021; Huang, Ji, et al., 2016, Huang, Yu, et al., 2016). The mechanisms regulating drylands (such as pronounced wetting-drying cycles and hydraulic redistribution) are expected to have expanded importance in a warmer, drier world, even across wetter ecosystem types (Grünzweig et al., 2022).

Most drylands are well-vegetated and green, for some to all months of the year (Figure 1). They often contain forests–about 30% of North American drylands sustain forest and an additional 23% support lower woody vegetation (FAO, 2019). Even some of the driest locations are carbon sinks (Biederman et al., 2017) and contain distributed shrubs and trees (Tucker et al., 2023). In addition to plants, they often include biological soil crusts that photosynthesize (Figure 1c) (Phillips et al., 2022). Global attention on drylands is now increasing, with the United Nations recently developing assessments for dryland land management and biodiversity conservation (Montanarella et al., 2018). Science community interest is also increasing, partly spurred by findings of the large dryland role in the carbon cycle (Ahlström et al., 2015; Poulter et al., 2014). The *Nature* journal portfolio began a "Dryland Biodiversity" collection, which motivates further dryland studies and captures increasing high-impact publications focused on drylands in the past few years (e.g., Tucker et al., 2023). Despite their importance, rapid change, and increasing community attention, the world's drylands are yet understudied and continue to be undervalued in being viewed as "wastelands" (Hoover et al., 2020).

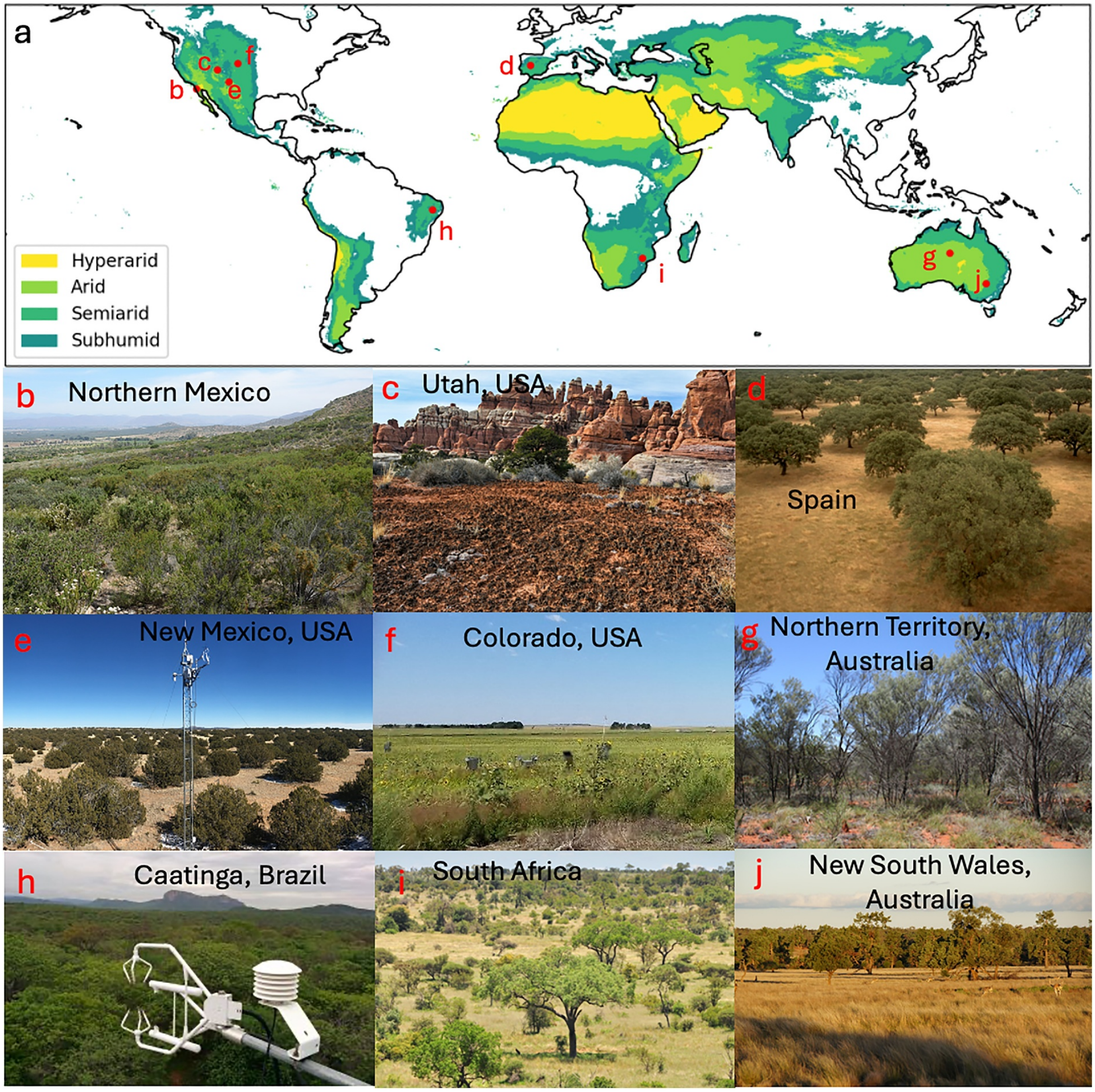

Figure 1. (a) Global dryland distribution based on aridity index computed from TerraClimate precipitation and radiation data (Abatzoglou et al., 2018). Aridity index (AI) is defined as in Wang et al. (2022) as precipitation/potential evapotranspiration with hyperarid as AI < 0.05, arid as AI = 0.05–0.2, 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).

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2. A Proposed NASA Dryland Field Campaign

The NASA Terrestrial Ecology program field campaigns present a unique opportunity to study drylands in a coordinated way with the newest field and airborne measurement technologies. This NASA program has a legacy of supporting field campaigns with goals including addressing critical science questions in ecosystems with outstanding knowledge gaps, providing finer-resolution measurements with pioneering techniques to support NASA's existing satellite retrievals, supporting development of emerging satellite technology, and training the next generation of scientists. Previous NASA Terrestrial Ecology field campaigns include the First International Satellite Land Surface Climatology Project Field Experiment (FIFE) between 1987 and 1989, Boreal Ecosystem-Atmosphere Study (BOREAS) between 1992 and 1999, Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) between 1998 and 2011, and Arctic-Boreal Vulnerability Experiment (ABoVE) from 2015 to approximately 2025. Together, these field campaigns have extensively assessed boreal, temperate, and tropical ecosystems.

In 2022, the NASA Terrestrial Ecology program solicited scoping studies for the next multi-year field campaign. Adaptation and Response in Drylands (ARID) was one of two scoping studies selected. ARID includes a core team of scientists and an extensive group of end-users applying remote sensing data for decision-making and land management. Together, we are scoping an ARID field campaign that will address pressing issues and knowledge gaps in drylands by upscaling drylands' spatiotemporally heterogeneous processes and uncertainties from point to pixel to planet.

The advancement of satellite sensor technology, and particularly higher spatial resolution especially with NASA sensors, now enables precise monitoring of drylands, offering an unprecedented opportunity to enhance the global Earth observing system. Drylands present key uncertainties in estimates of ecosystem function and change that can only be quantified and disentangled through coordinated field, airborne, satellite-based, and modeling analysis. Because they have mainly been developed for homogeneous landscapes with predictable seasonality, remote sensing tools and models are challenged by drylands' relatively lower vegetation signals, high spatial variability (often meter scale soil-plant variability), and high temporal variability (hourly to daily ecosystem responses to rain pulses), which make it challenging to track short and long-term changes of key variables and attribute these to specific drivers (Fawcett et al., 2022; MacBean et al., 2021; Smith et al., 2019; Teckentrup et al., 2021). For example, high spatial heterogeneity of herbaceous and woody plants interspersed over short distances amongst bare soil and biological soil crusts, suggest the need for high-resolution data collection to support plot to regional scale analyses (Figure 1) (Pervin et al., 2022; Smith et al., 2019). Such large and complex spatial heterogeneity in drylands causes errors within dryland models, especially due to plant functional type uncertainties (Hartley et al., 2017). Also, dryland productivity and biogeochemical processes are driven by periodic precipitation pulses interspersed with extended dry periods (Collins et al., 2014; Feldman et al., 2024; Wang et al., 2015; Zhang, Biederman, Pierce, et al., 2021) and experience irregular growing seasons (Nicholson, 2013). These ecosystem responses to pulses at different times of a season are challenging to model (Ogle & Reynolds, 2004). There is thus a need for continuous or higher temporal frequency measurements to capture and understand ecological responses (Smith et al., 2019). Our understanding and capacity for science-informed decisions for drylands would be dramatically improved through coordinated monitoring of these critical ecosystems.

Given a scoping goal of capturing community needs and challenges with understanding dryland processes, this commentary aims to describe ARID's engagement efforts to date with the science, data end-user, and rights holder communities, with an emphasis on our kickoff meeting, and to discuss how community input is being used to build on the ARID field campaign framework. We provide a brief overview of ARID here, but we emphasize that the information presented is updated continually with community input through December 2024, when the final ARID scoping study report will be submitted to NASA Headquarters. This commentary therefore provides examples of how community feedback is shaping the proposed ARID field campaign, while also providing a timely update to solicit more community input. Ultimately, if ARID is selected by the NASA Terrestrial Ecology program, the funding will be distributed in various ways to the research community, not to the ARID scoping team. Therefore, community input is paramount such that the ARID framework reflects the community's interests, expertise, and needs.

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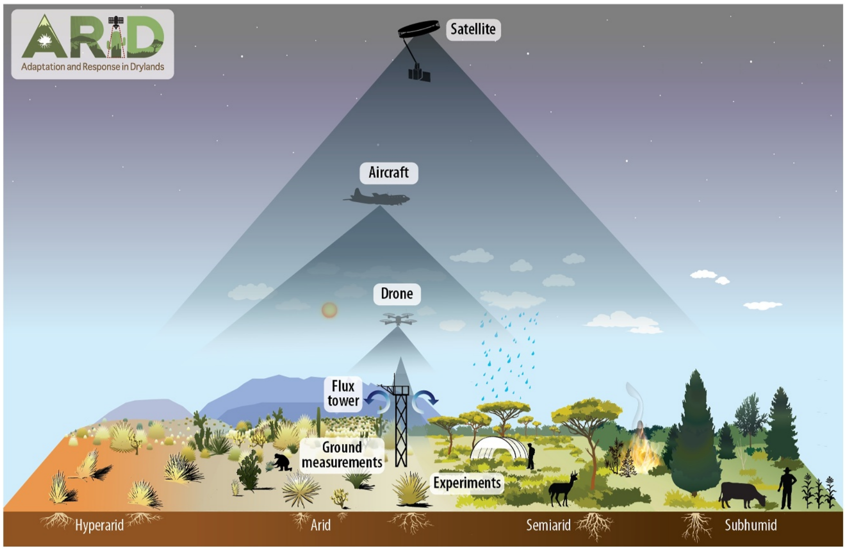

Figure 2. The NASA ARID concept to scale dryland understanding from field to planet scales. Dryland modeling efforts will be used to inform strategic deployment of multiple-scale measurement campaigns (depicted in this schematic), which will in turn be used to improve dryland modeling through model-data fusion techniques.

3. ARID Overview

ARID proposes to scale dryland understanding from ground measurements to drone, aircraft, and satellite retrievals, across hyperarid, arid, semiarid, and subhumid drylands, in both natural and managed landscapes (Figure 2). Historically, NASA satellite resources have been relatively less suited to study the specific spatial, spectral, and temporal dynamics of drylands. However, a variety of modern higher spatial and spectral resolution NASA sensors (such as Global Ecosystem Dynamics Investigation (GEDI), ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS), Earth Surface Mineral Dust Source Investigation (EMIT), NASA-ISRO Synthetic Aperture Radar (NISAR), Surface Biology and Geology (SBG), Landsat-Next) allow tracking these phenomena, with support of higher resolution field and airborne measurements. NASA also now has data computing resources to process, manage, and analyze these larger satellite data sets. The field measurements will be further used to constrain process models and remote sensing algorithms, which have struggled to capture dryland functioning (Biederman et al., 2017; MacBean et al., 2021) enabling more accurate future projections of dryland function under various climate and land use change scenarios (Haverd et al., 2013; Mahmud et al., 2021). ARID is proposed to have an intensive domain in the western United States and in several international sites to understand global drylands potentially within dryland areas of Mexico, Africa, Australia, South America, Asia, and Europe.

Such a field campaign is expected to have far-reaching consequences for both the science, end-user, and rights holder communities (government agencies, tribal nations, private land managers, etc.). Specifically, ARID's main pillars include fundamental science goals to understand the drivers of dryland changes and the responses of dryland ecosystems to these changes. ARID also incorporates understanding human and ecosystem services and supporting science-informed dryland ecosystem management through adaptation. Given that more intense and frequent climate extremes and other changes are already affecting many drylands (Williams et al., 2022; Zhang, Biederman, Dannenberg, et al., 2021), developing adaptive responses to these changes is paramount.

Through these goals, ARID overall aims to substantially improve (a) process understanding and modeling of dryland ecosystem function, (b) estimates of dryland contribution to global terrestrial carbon fluxes and stores, (c) understanding of livelihoods and management in drylands under water-limitation and change, and (d) interpretation of NASA remote sensing observations in these spatiotemporally heterogeneous ecosystems. Among many other outcomes, ARID also aims to (e) develop the next generation of transdisciplinary researchers across remote sensing, modeling, and field approaches.

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Figure 3. (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.

By bringing together scientists and end-users to scope a multi-year NASA dryland field campaign, ARID strongly aligns with the 2024 launch of the NASA Earth Science to Action strategy (ES2A) (St. Germain et al., 2024). A response in part to the Decadal Survey (NASEM, 2018), ES2A is a new 10-year strategy to build support for projects that use Earth observations for applications in partnership with end-users. ARID is intentionally designed as a means to implement this ES2A strategy, with half of its main pillars devoted to applied sciences and human elements. ARID thus aims to bridge the connection between a wide array of dryland end-user needs and NASA-based findings and tools.

4. ARID Kickoff Meeting

4.1. Meeting Overview

Our ARID leadership team held a kickoff meeting on October 23rd-26th, 2023, at the University of Arizona in Tucson, Arizona (Figures 3a and 3b). The meeting's purpose was to gather not only input, ideas, and buy-in from end-users and the science community about what they see as most important for an ARID field campaign, but also to create an inclusive community that can sustain and create impact for a large research endeavor.

Given that applying research for action requires starting with understanding end-user needs, we began the first day of the first ARID event by listening to the perspectives, expertise, and input of the data user community. Over 30 end-users attended in person with more attending virtually. 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, international data end-users, several non-profit and private companies, and private landowners, including cattle ranchers.

Dr. Sasha Reed, ARID's Principal Investigator who is based at the U.S. Geological Survey Southwest Biological Science Center, briefly introduced our proposed field campaign, highlighting our science goals to understand dryland ecosystem drivers and responses and to improve our management options for adapting under global change.

4.2. Data End-User Insights

Our invited keynote speaker, Karen Prentice, who is the National Science Advisor for the U.S. Bureau of Land Management (BLM), discussed the importance of landscape-level, multi-scale management across administrative and political boundaries and the need for managers and information providers to have a shared understanding of the science and information that will be used to address management questions. She highlighted the need for cross-scale information, such as the measurements and tools that ARID would provide. Key takeaways we took from her talk were that (a) incorporating research and data products into the decision-making process at the BLM requires time and that (b) 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. Lands managed by the BLM make up nearly 10% of the U.S. land area, many of which are in drylands across the western United States. The BLM's National Science Advisor noted the increasing challenges for land management agencies in the face of change, and she discussed the utility of the science-management co-production process for data products to effectively inform land management decisions.

We next heard from invited speaker Jon Norred, Branch Chief of Resource Data Services at the BLM. He emphasized the importance of satellite and Uncrewed Aerial System remote sensing, and other cross-scale technologies, to inform land management decisions. However, BLM faces challenges with such an effort including storage and retrieval capacity for very large remote sensing data sets 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. This again echoed key objectives of NASA's ES2A that ARID aims to address.

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. From these breakout discussions responses, the interest and perceived utility of ARID was consistently apparent and the resource managers and decision makers provided critical expertise and ideas for the research framework. A common theme was that they all had extensive field sampling capacity and, often, strong science backgrounds in understanding the 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. They also discussed the need for high spatial resolution information relevant to their site conditions for monitoring vegetation types, soil moisture, 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. Technical training to perform these measurement, remote sensing, and computational tasks could also be provided in various ways throughout the campaign. Therefore, NASA-based and university scientists working with other U.S. agencies, landowners, and tribal communities would have a high potential to produce transdisciplinary, quality science with applications that align with NASA's ES2A strategy. This demonstrates the high-value NASA would bring in partnering with these agencies that have strong field sampling capacity and clear land management needs that NASA data can support.

4.3. Research Community Insights

The second half of our kickoff meeting included a dryland science discussion covering the past, present, and future of remote sensing of drylands. Dr. Sasha Reed discussed research gaps in drylands and ARID's science themes. Dr. Ben Poulter, an ARID Co-I based at NASA Goddard Space Flight Center, gave context about how a dryland field campaign would support NASA's many satellite missions, including those producing high spatio-temporal and spectral resolution retrievals like GEDI and ECOSTRESS and upcoming SBG and NISAR. There were more than 300 scientists in attendance in person and online, highlighting wide interest in a drylands-focused Terrestrial Ecology Field Campaign. Following the introduction, two invited speakers gave seminars:

Dr. Steve Running's (University of Montana) talk was retrospective. He discussed the history of how field eddy covariance networks coevolved with the development of NASA remote sensing products aimed at estimating vegetation status and land-atmosphere fluxes, such as products like vegetation indices and gross primary

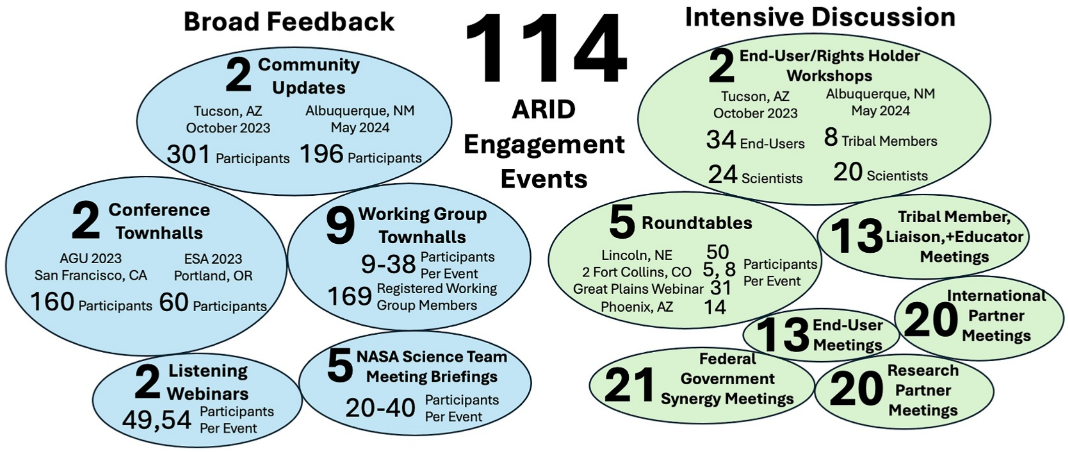

Figure 4. Summary of ARID engagement events, including both broad feedback (from listening sessions) to intensive discussions, primarily occurring between October 2023 and July 2024. Total participants are based on event documentation from ARID team members. Most engagements consisted of approximately 1–1.5-hr meetings. However, the workshops included 1–2-day discussions with end-users and rights-holders across several topics and 2-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.

production using the Moderate Resolution Imaging Spectroradiometer (MODIS) satellites. Much of the validation of these NASA products was conducted throughout drylands of the western United States partly because of their low cloud cover (Huete et al., 2002; Running et al., 2004). This shows the value that dryland ecosystems have for upscaling field measurements and for calibrating and validating spaceborne missions, especially for the next generation of satellites which are mostly proposed to be at higher resolution (<100 m).

Dr. Compton Tucker's (NASA Goddard Space Flight Center) talk was forward-looking in presenting his and his colleagues' new research mapping individual trees across drylands and scaling up estimates of biomass and carbon stocks using in-situ measurements (Brandt et al., 2020; Tucker et al., 2023). This recent work has revealed even more trees and greater carbon stocks in the drylands of Africa than previously thought, and their continued research is showing the same results in other global drylands. The talk emphasized that drylands are challenging ecosystems to monitor because they are spatially heterogeneous, with land cover often changing at meter-scales among several vegetation types and soil. However, this method highlights a new "hyperspatial" technique useful for spatially heterogeneous dryland landscapes that uses combinations of very high-resolution measurements (<1 cm scales), field allometry, and machine learning. Such a method can be developed more generally with field and/or satellite measurements to map other carbon cycle or end-user-relevant variables beyond tree cover and carbon stocks that can be used, for example, for grazing and invasive species monitoring.

With over 300 people in attendance virtually and in person, we started receiving feedback and new ideas from the community about their expectations for our proposed dryland field campaign. Given the large amount of interested personnel, our question-and-answer session needed to be extended beyond the kick-off meeting. We thus conducted listening sessions in other settings including Town Halls in 2023 at the Ecological Society of America (ESA) Annual Meeting and American Geophysical Union (AGU) Fall Meeting, which included over 60 and over 160 in-person participants, respectively (Figures 3 and 4). We also held two virtual webinars in November 2023 with over 100 total participants for additional opportunities for feedback from those that could not attend the conference sessions. Attendees provided extensive and detailed input about our study domain, instruments to be consulted, key data end-users, research networks, and many other topics. All input has guided ARID's research plan and further engagement.

5. Continued Community Engagement

5.1. Feedback Guiding ARID's Framework and Continued Engagement

The Fall 2023 engagement events included many recommendations to meet and talk with others in the community. Therefore, the ARID scoping activities expanded, and by July 2024, we have received feedback from 114

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meetings with the goal of capturing as much of the community's voice as possible (Figure 4). Input was provided by hundreds of scientist, end-user, and rights holder community members across ARID workshops, townhalls, webinars, roundtables, working groups, and individual community inputs. Through these broad listening sessions and more intensive discussions on specific topics, ARID's framework has been continuously updated. This includes enhancements to ARID's proposed goals, science themes, and domain, and types of measurements and products ARID should focus on. From the feedback we received, the research community clearly agrees that drylands are highly important and understudied, and that there is an urgent need to understand drylands and their response to global change using a coordinated satellite and ground-based approach.

As examples, we discuss the consistent input we received on the science themes and domain suggestions across engagement events (Figure 4). The community drove us to broaden our scope and revise several of our originally proposed science themes. For example, biodiversity and wildfire were only sub-components of our original framework and cropland and rangeland management were even less considered. However, extensive community recommendations and excitement about these topics warranted them being explicitly focused on as central themes. Taken together, there is strong community interest in understanding dryland water availability, pulse and drought dynamics, fire, land-atmosphere feedbacks, carbon stocks and fluxes, geologic and soil processes, vegetation structure, biodiversity, and social-ecological systems (including cropland and rangeland management).

There is strong interest in ARID having both domestic and international domains. A global distribution makes sense given that drylands can vary globally in composition, forcing, response, land use intensity, and other factors. In turn, a U.S. focus on drylands is also a major strength of ARID and, when coupled with the research infrastructure and data sets that already exist, create a "low risk, high reward" component of the research. While there is strong interest in sites in the southwestern United States, we also increasingly received input to continue to include the full dryland western United States as the domestic ARID domain including the Great Basin and western Great Plains.

Furthermore, while we received 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 strong interest in Africa and particularly southern African countries. Input also included disproportionately high interest in Mexico because ARID's proposed western U.S. domain already includes portions of the Chihuahuan and Sonoran deserts that are shared by the U.S. and northern Mexico.

5.2. Follow-On Science-Focused Engagement

Highlighting the iterative process of our scoping, these community insights about the domain and science themes were provided early (and reiterated throughout the remainder of meetings) and helped focus continued outreach and engagement. For international engagement, interest in southern Africa and Mexico 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.

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 (Figure 4). 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 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).

In April 2024, to further engage with Mexican colleagues and others, we hosted an ARID presentation and discussion at the 5th International Conference on Biological Soil Crusts, in Chihuahua City, Mexico with over 60 participants from Mexico, and other international locations.

The ARID 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

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Change program, NASA SBG team, NASA Soil Moisture Active Passive 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, established university dryland centers and institutes, and others such that ARID can leverage resources and personnel across many partnerships.

5.3. Indigenous Insights

We were motivated to host an ARID meeting in Albuquerque, New Mexico in May 2024 because of our own interest in and the community feedback on the importance of taking into account tribal data needs, expertise, and collaborative opportunities. Our New Mexico meeting was focused on tribal engagement. From initial discussions with tribal liaisons and our expanding network, it was clear that we needed to visit tribal members where they live and to better listen to and understand tribal challenges and collaboration opportunities.

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.

Some primary outcomes included recommendations to incorporate tribal members on the ARID team throughout the duration of the campaign, forge long-term relationships between NASA and tribal members that extend beyond the duration of a scoping study or field campaign, build traditional and indigenous knowledge explicitly into the ARID campaign, include tribal scientists on ARID proposals and publications with a goal to co-develop understanding, and provide early career tribal scientists exposure to NASA science and ARID through various options including school visits, training opportunities, and internships during the field campaign. Our ARID scoping report is being written to include these outcomes and others, including ARID's data policies aligning with tribal data sovereignty.

5.4. U.S. Federal Government Synergies

In July 2024, several members of the ARID leadership team traveled to Washington D.C. to meet with mainly federal government personnel to discuss synergies and partnerships between a potential NASA ARID field campaign and their climate and environment focused activities. Insights were gained in discussion with the U.S. Department of the Interior, U.S. Bureau of Land Management, National Science Foundation, Ecological Society of America, U.S. Department of Agriculture Office of Energy and Environmental Policy, U.S. Department of Energy Environmental System Science Program, U.S. Global Change Research Program, and U.S. Department of Defense Strategic Environmental Research and Development Program. A common theme amongst the discussions was a recognition at these agencies that the western US drylands are under threat from rapid climate change and extreme weather. They also shared excitement about a potential NASA dryland field campaign and offered ideas about how to co-conduct research with their existing efforts, for example, with NSF-funded NEON sites and LTAR sites in the western US.

Given ARID's focus on tribal engagement during the scoping phase of the project, James Rattling Leaf, Sr, representing the Rosebud Sioux Tribe's new Climate Center, accompanied the ARID team during these meetings and discussed the importance of government-wide investment in understanding the western US lands, including those owned by tribal nations. Given many tribes' desires to use data (such as from satellites) to inform their decision making, James emphasized the importance of co-developing such scientific efforts with tribes through early engagement during scoping and empowering them throughout the effort. With many tribes and a wide range of needs, tribal liaisons, like James, can guide campaign efforts to focus on common tribal themes like buffalo restoration and water management. These discussions are guiding ARID to develop a broader framework for tribal engagement that can be built upon by future NASA efforts and other federal government efforts.

6. Focusing Engagement and Future Work

With vast and generous input from members of the community, the ARID team has expanded to include diverse experts that provide new perspectives to refine the framework and tentative field campaign plan. The ARID team has also expanded to include technology working groups that are conducting townhalls and roundtables to discuss remote sensing, modeling, and field measurements in drylands and how these approaches can be coordinated across scales in a nested manner (Figure 2). The technology working groups aim to identify research questions within the dryland science themes and the broader ARID framework that can be addressed with existing field and satellite measurement infrastructure coupled with potentially ARID-funded field, drone, and airborne measurements. Over 169 community members signed up to join the technology working groups (for more information: https://aridscoping.arizona.edu/get-involved). Like many of the ARID engagement events, these working groups consist of a distribution of researchers from those that conduct nearly all work in drylands to those that do not typically conduct work in drylands, indicating ARID is likely to increase participation in dryland research. Importantly, approximately half of the working group members are early career researchers, highlighting interest from the next generation of scientists that ARID would support.

In addition to continuing overall community engagement, our leadership team is continuing dialogs with international collaborators on the feasibility of co-conducting field experiments in tandem. The goal is to empower these nations' researchers to lead the research, benefit from the shared data, co-produce new knowledge and products, and train the next generations of scientists and practitioners who will continue the multi-disciplinary work through time. Specifically, we are developing relationships with and partnering with southern African, Mexican, Australian, Asian, and South American researchers and learning about their existing initiatives and existing field networks.

Our ARID leadership is continuing valuable dialogs with tribal scientists, tribal liaison offices, and tribal land managers in the U.S. A central goal for ARID is building trust, long-term relationships, and collaborative networks with tribal partners. This also includes exploring education and funding opportunities, especially for early career tribal scientists. Finally, we acknowledge valuable discussions with James Rattling Leaf, Sr. of the Rosebud Sioux Tribe to develop a framework within ARID about early tribal engagement during scoping that should be used across government agencies.

Following ES2A, we are continuing to build relationships with end-user communities such as in government agencies, tribal nations, and private companies who share their knowledge, vision, concerns, and priorities to collaboratively develop ARID. This includes continuing to solicit input through one-on-one conversations and, when appropriate, responses to our end-user questionnaire. Such relationships serve as a bridge between NASA Earth Science data, tools, models, and knowledge, and the information needed to make science-informed policy decisions and adaptive land management plans. As such, ARID is closely aligned with the ES2A "virtuous cycle" in being end-user-driven at the outset by aligning planned foundational measurements and knowledge development during the ARID field campaign with the needs and interests of public and private land managers.

With new and upcoming missions with the capacity to provide a variety of observations with high spatiotemporal and spectral resolution, evolving ground-based proximal remote sensing and drone technologies, increasing extremes already impacting drylands, and a large, diverse community of highly motivated scientists and data end-users interested in dryland science, now is the time for an unprecedented NASA dryland field campaign.

Data Availability Statement

Several photos used in Figure 1 are used with permission from AmeriFlux, PhenoCam, and OzFlux site principal investigators. They are available at https://ameriflux.lbl.gov/sites/siteinfo/US-xSL, https://ameriflux.lbl.gov/sites/siteinfo/MX-EMg#image-gallery, https://phenocam.nau.edu/webcam/sites/eslm1/, https://ameriflux.lbl.gov/sites/siteinfo/BR-CST, https://www.ozflux.org.au/monitoringsites/alicesprings/alicesprings_pictures.html. The remainder of the photos are owned by the authors. The global aridity index was computed from TerraClimate data https://www.climatologylab.org/terraclimate.html. This aridity index map and script to plot Figure 1a panel is available in Feldman and Smith (2024) in a Zenodo repository.

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