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EDITED BY

Lesley-Ann Dupigny-Giroux,
University of Vermont, United States

REVIEWED BY

Samuel Ikendi,
University of California Agriculture and
Natural Resources, United States
Davin Holen,
University of Alaska Fairbanks, United
States

*CORRESPONDENCE

Ryan J. Longman
✉ rlongman@hawaii.edu

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Improved climate services in Hawai'i: the collaborative development of drought-related decision support tools

Ryan J. Longman^{1*}, Derek Ford¹, Cherrylle Heu¹, Jennifer Geis²,
Abby G. Frazier³, Christian P. Giardina⁴, James T. Potemra⁵,
Sean B. Cleveland² and John J. Marra⁶

¹Sea Grant College, University of Hawai'i at Mānoa, Honolulu, HI, United States, ²Information and Technology Services, University of Hawai'i at Mānoa, Honolulu, HI, United States, ³Graduate School of Geography, Clark University, Worcester, MA, United States, ⁴Institute of Pacific Islands Forestry, Pacific Southwest Research Station, USDA Forest Service, Hilo, HI, United States, ⁵School of Ocean and Earth Science and Technology, University of Hawai'i at Mānoa, Honolulu, HI, United States, ⁶East-West Center, Honolulu, HI, United States

Rising temperatures, prolonged droughts, and increasingly variable rainfall are negatively impacting natural and cultural resources and agricultural production systems in Hawai'i. To effectively manage resources in the face of these changes, stewards and producers now require accurate, timely, and site-specific climate data and information. However, access to such data as well as the ability to interpret available data remain limited for many sectors. In response to various needs, a team of scientists working with the Pacific Drought Knowledge Exchange (PDKE) has developed two open-source decision-support tools (DSTs) through a collaborative, user-informed process aimed at closing longstanding gaps in local climate services. This paper introduces these new tools highlighting how they were co-designed to support resource management and producer needs in Hawai'i. The first DST is the automated Climate Change, Climate Variability, and Drought Portfolio tool which provides customized site-specific, fine-scale climate data and information summaries to end users. The second DST is the Hawai'i Rangeland Information Portal (H-RIP), which is designed to deliver near-real-time and near-future, site-specific drought and forage production information to ranchers in Hawai'i. These tools leverage the latest gridded climate products available on the Hawai'i Climate Data Portal (HCDP) thus providing the highest quality and most up-to-date information available for the state. Both tools were intentionally designed and co-produced with end-users to meet the practical needs of resource managers by providing site-specific information through intuitive, web-based platforms. These DSTs improve climate data accessibility and usability and significantly strengthen the state's overall climate service infrastructure. Collectively, these platforms represent scalable models for enhancing adaptive capacity and resilience through data-driven planning and locally relevant and data informed decision making.

KEYWORDS

climate portfolio, climate services, co-production, decision support, forage production, Hawai'i

1 Introduction

Climate change is causing negative impacts and losses in every region in the world (IPCC, 2023). Extreme weather events, such as storms, heatwaves, droughts, cyclones, and flash floods are becoming more severe, lasting longer, occurring outside of historical seasonal norms, or increasing in frequency across different regions (Seneviratne et al., 2021). Changes are so profound that current assessments suggest that humanity has already exceeded the safe operating space for six of nine key planetary boundaries (Richardson et al., 2023). These global trends are acutely felt across the Pacific Islands region, where average annual air temperatures have risen 2 °F since 1950, drought frequency and severity have increased, sea surface temperatures are rising faster than the global average, and sea level rise poses existential risks to low-lying island communities (Frazier et al., 2023). As regional thresholds and Earth system boundaries approach or surpass tipping points, the prospect of maintaining a climate-resilient environment necessary for societal stability is increasingly at risk (Rockström et al., 2023). Consequently, natural resource managers now identify climate change, climate variability, and drought (CCVD) as critical and growing threats that demand expanded attention and action (Averyt et al., 2018).

In Hawai'i, changes in climate are well documented and include rising temperatures (McKenzie et al., 2019), decreased rainfall (Elison Timm et al., 2015), and more intense and longer-lasting droughts (Frazier et al., 2022), all of which pose significant challenges for resource managers across the state. Moreover, future climate projections indicate that temperatures will continue to rise (Elison Timm, 2017), with profound effects on many of Hawai'i's natural systems (Frazier et al., 2023). To effectively address these evolving environmental conditions, resource managers and producers can proactively plan supported by high-quality, reliable data that can be used to inform plan implementation and decision-making.

Over the past decade, access to and analyses of environmental data have increased exponentially, significantly transforming the capacity of climate scientists to deliver climate services, including improved climate-sensitive decision making across sectors and scales. Climate services are generally defined as the provision of climate information, products, or advisory tools designed to assist decision-making by individuals, institutions, and governments (WMO, 2014; Brasseur and Gallardo, 2016). An overarching goal is to make climate information “useful, usable, and used” (Findlater et al., 2021) by addressing a long-standing disconnect between climate science and the practical needs of users including managers and decision-makers (Hewitt et al., 2012; Kruk et al., 2017). From managing immediate climate hazards such as floods or droughts to informing long-term strategic planning and adaptation, climate services enable better-informed, life-saving decisions in sectors such as agriculture, disaster risk reduction, public health, and energy (Faniriantsoa and Dinku, 2022).

Achieving the goal of making climate information “useful, usable, and used” increasingly depends on intentional co-production processes between climate service providers and their users. Co-development of climate services can enhance their usefulness, usability, and usage by ensuring iterative engagement, the development of timely and reliable products, and delivery in a truly accessible manner (Jacob et al., 2025). These processes go beyond simple consultation as they are sustained, iterative engagements involving relationship building, capacity development, and the creation of shared

understanding and joint outputs (Ostrom, 1996; NRCS (Natural Resources Conservation Service), 2018; Carter et al., 2019; Bojovic et al., 2021; Jasanoff, 2021). Co-production efforts most often span researchers, practitioners, and stakeholder groups operating under different criteria and decision-making arrangements, requiring transdisciplinary competence across public, private, and civil society sectors (Pulwarty and Sivakumar, 2014; Jacob et al., 2025). Engaging partners in the design and implementation of climate science can also lead to more actionable outcomes with broader societal benefit (Lemos et al., 2018; McClure et al., 2024). Despite being recognized as standard recommended practice, co-production remains less widely implemented than needed (Jacob et al., 2025).

The importance of demand-driven, context-specific services is widely recognized (Lemos et al., 2018; Prokopy et al., 2008; Wall et al., 2017), particularly because traditional, supply-driven scientific outputs often lack the accessibility, relevance, or predictive skill required to support real-world decision making (Dilling and Lemos, 2011; Bruno Soares et al., 2018). As Hewitt et al. (2020) and Doblas-Reyes et al. (2021) emphasize, climate services encompass a complex system of data, delivery mechanisms, knowledge sources, and institutional arrangements to ensure climate information is scientifically robust and tailored to user needs. Services typically include insights into past, current, and projected climate conditions, including extreme weather events (WMO, 2014; Hewitt et al., 2012; Tola et al., 2025). Access to such credible, timely, and actionable information is essential to help communities, particularly those most vulnerable, adapt to climate extremes and long-term changes [United Nations Development Programme (UNDP), 2024; Jacob et al., 2025]. Ultimately, climate services play a critical role in advancing climate-resilient development and enabling anticipatory action in a rapidly changing climate (Faniriantsoa and Dinku, 2022; Findlater et al., 2021).

In response to increasing concerns over the impacts of climate change-induced drought in forest and rangeland ecosystems, the U.S. Department of Agriculture Forest Service (USDA FS) published a comprehensive synthesis report in 2016 that detailed the effects of drought across the United States (Vose et al., 2016). This report highlighted projections of more frequent and prolonged drought events due to rising surface air temperatures. A companion report published in 2019 provided region-specific management strategies to build drought resilience, with Chapter 5 focusing explicitly on the Hawaiian Islands and the U. S.-Affiliated Pacific Islands (USAPI) (Frazier et al., 2019). These publications emphasized the vital role of climate data in supporting research, management, and climate services across key sectors such as agriculture, water resources, disaster risk reduction, and energy. However, the efficacy of these services is fundamentally dependent on the quality, availability, and timely access to the underlying climate data.

Building on the data synthesis and engagement efforts described in Frazier et al. (2019) and related initiatives (Giardina et al., 2019), resource managers in Hawai'i expressed the need for enhanced mechanisms for the transfer and co-production of drought-related information. This included improved access to site-specific data, formalized opportunities for knowledge exchange, and more collaborative formats for engaging with climate information. Prior outreach efforts in Hawai'i were often limited to workshops, lectures, or small-group meetings, offering only sporadic opportunities for meaningful dialogue between scientists and managers (e.g., Longman et al., 2022). To our knowledge, little effort

had been made to specifically engage agricultural producers and ranchers in these types of outreach efforts prior to the work described here.

Federal assessments have long recognized the challenge of translating technical climate research into readily understandable information for farmers and ranchers, and the need for tools that communicate economic costs and returns of climate adaptation actions in accessible formats (USGAO, 2014). To address these limitations, the Pacific Drought Knowledge Exchange (PDKE) was launched in November 2019 as a structured knowledge-exchange initiative designed to foster sustained, collaborative engagement between researchers and resource managers (Longman et al., 2022). The PDKE aims to increase the usability and accessibility of drought and climate information through a co-production model and addresses four primary objectives: (1) improving access to sector- and geography-specific information; (2) enhancing the quality and comprehensiveness of that information; (3) strengthening technical assistance; and (4) promoting collaborative knowledge-sharing environments (e.g., co-production). Since 2019, PDKE has made steady progress in delivering climate services tailored to resource managers' needs in Hawai'i and the broader Pacific region. Achieving such multi-sectoral knowledge exchange requires systematic, coordinated approaches that ensure stakeholder engagement, information credibility, and contextual relevance to inform decisions ranging from disaster risk management to climate-resilient development (Pulwarty and Sivakumar, 2014; Hewitt et al., 2020). The final consumers of PDKE knowledge products, tools, and outreach activities are wide-ranging, spanning multiple demographics, industries, and sectors. We identify primary end users for each product and make every effort to ensure meaningful engagement throughout the co-production process.

In alignment with the goals of the Paris Agreement (United Nations, 2015), and national efforts to build climate resilience across the United States and its Pacific Island jurisdictions (Frazier et al., 2023), climate services must be grounded in the best available science while also integrating local, context-specific knowledge to ensure relevance and usability for decision-makers (Jacob et al., 2025). Researchers at the University of Hawai'i have a long history of supporting terrestrial based weather and climate services, beginning with the establishment of the first full meteorological station on the leeward slopes of Haleakala crater on Maui in 1988 (Longman et al., 2015), and the development of the Rainfall Atlas of Hawai'i and Evapotranspiration websites which have made climatological estimates of rainfall and other climate data and maps available to the public in user friendly formats (Giambelluca et al., 2013, 2014). Local efforts have continued to expand the climate station network across the state (Longman et al., 2018) and available climate data products (e.g., Frazier et al., 2016; Longman et al., 2019; Lucas et al., 2020, 2022; Kodama et al., 2024). At present, there is an ongoing initiative to install 100 National Weather Service compliant weather stations across six islands as part of the Hawai'i Mesonet project. The research grade data collected from Hawai'i Mesonet and other stations feed directly into the Hawai'i Climate Data Portal (HCDP), where they are used to create high-resolution (250 m), gridded climate products (Longman et al., 2024). These gridded products are accessible via manual download (McLean et al., 2023) or through an application programming interface (API) that supports various programming languages (McLean et al., 2020). By developing spatially and temporally complete datasets, the HCDP provides reliable, high-quality climate information at local scales, which is critical for

effective decision-making across multiple sectors and a bedrock requirement for effective delivery of climate services.

To address the ongoing need for improved knowledge exchange in Hawai'i, the PDKE team developed two open-source, web-based DSTs designed to assist resource managers and producers in accessing climate and drought-related data products. Both DSTs have user-friendly graphical interfaces designed to streamline access to site-specific climate information and enhance the practical utility of scientific data. The goal of these DSTs is simply to support improved resource planning and decision making. These DSTs described in this manuscript are:

- 1) Climate Change, Climate Variability and Drought (CCVD) Portfolio Tool and,
- 2) Hawai'i Rangeland Information Portal (H-RIP).

The objective of this research is to introduce these two DSTs to the research community and demonstrate their value to end users in Hawai'i and beyond. The following sections provide a methodological overview of both the CCVD Portfolio Tool and H-RIP DSTs, including technical details regarding metadata management and the construction of a unified database architecture. We then present example outputs and highlight the tools' core functionalities, particularly their capabilities for visualizing and disseminating standardized meteorological and ecological data. Finally, we assess the tools' significance, strengths, limitations, and potential directions for further development and expanded application across other climate-sensitive sectors.

2 Methods: tool operationalization

2.1 CCVD portfolio tool

2.1.1 Overview

Climate data and information in Hawai'i has historically been fragmented across multiple sources, with no centralized repository and significant technical barriers limiting the ability of natural resource managers to extract relevant, site-specific information from statewide or island-wide scale products. This gap between available climate data and actionable, locally relevant information created a clear need for an integrated tool that could bridge science and management decision-making. In their analysis of drought-related concerns across Hawai'i, Frazier et al. (2019) identified a critical need among natural resource managers for co-produced, context-specific climate information to better inform management planning and policy development. This need catalyzed the creation of the CCVD Portfolio during the pilot phase of the PDKE (Longman et al., 2022). The main function of the CCVD Portfolio is to provide site-specific summaries of key climate variables for selected geographies across Hawai'i. Each 40 + page portfolio includes a wide array of synthesized data such as mean climate values for temperature, rainfall, relative humidity, soil moisture, evapotranspiration, among many others; annual temperature and rainfall cycles; over a century (1920–2025) monthly rainfall records; drought history analyses; year-to-year rainfall variability; downscaled future projections for rainfall and



This **CCVD portfolio** is a comprehensive synthesis of climate and drought information developed for any area of interest within the State of Hawaii. It is designed to provide relevant climate and drought information for a wide variety of users at the scale of one-hundred acres to whole islands. When generated, each CCVD portfolio is delivered via email as a Microsoft PowerPoint presentation of approximately 40 slides and 16MB in size. To learn more or to view sample portfolios, please visit the [PDKE website](#).

- 1) Select your area of interest (two options):
 - a) Select a predefined location by choosing from the dropdown menu then selecting on the map.
 - b) Create a custom area of interest by using the area drawing tools found at the top-left of the map.
- 2) Enter the Location name and Location short name. If you selected a pre-defined location, this will be auto-populated but can be edited if needed.
- 3) Enter the email address where the portfolio will be sent once generated.
- 4) Click the "Generate Report" button.

Select a pre-defined location

Select a pre-defined location

Location name:

?

Location short name:

?

Your email address:

your.email@example.com

An email address is required since results will be emailed to you once generated. The submit button will not be enabled until a shape is selected or drawn and all values are provided.

Generate Report

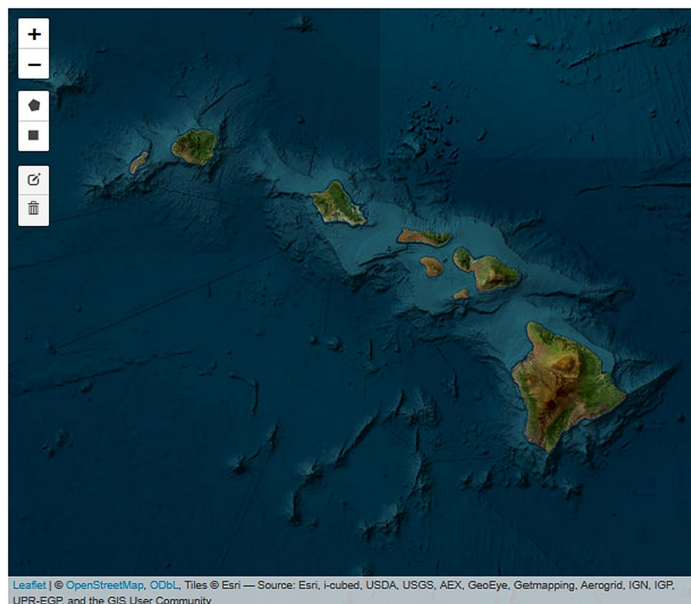


FIGURE 1
The climate change, climate variability, and drought (CCVD) portfolio tool landing page, <https://ccvd.manoa.hawaii.edu/>.

the fully integrated and automated web-based tool presented in this paper.

Initially, CCVD portfolios were created manually for the three partners engaged during the PDKE pilot (Longman et al., 2022). While useful for managers, the manual process used to create them is both labor-intensive, prone to human error, and not easily modified or replicated for new sites. As a result of a prolonged, iterative co-production process with resource managers, the need to develop a more streamlined and scalable method to generate CCVD portfolios emerged. This led to the development of a partially automated version of the CCVD Portfolio Tool, which improved efficiency but still required manual site selection and code initiation by the PDKE team. These early iterations laid the groundwork for

The CCVD Portfolio Tool is a web-based DST developed using R Statistical Software (R Core Team, 2024) that automates the creation of climate data summaries and visualizations for site specific geographies at any scale. Users can visit <https://ccvd.manoa.hawaii.edu/> to access the tool's front end and quickly create a portfolio by following simple prompts (see Figure 1). An area of interest may be chosen from a list of pre-defined layers with site specific names (Figure 2). The pre-determined layers (Table 1) were selected based

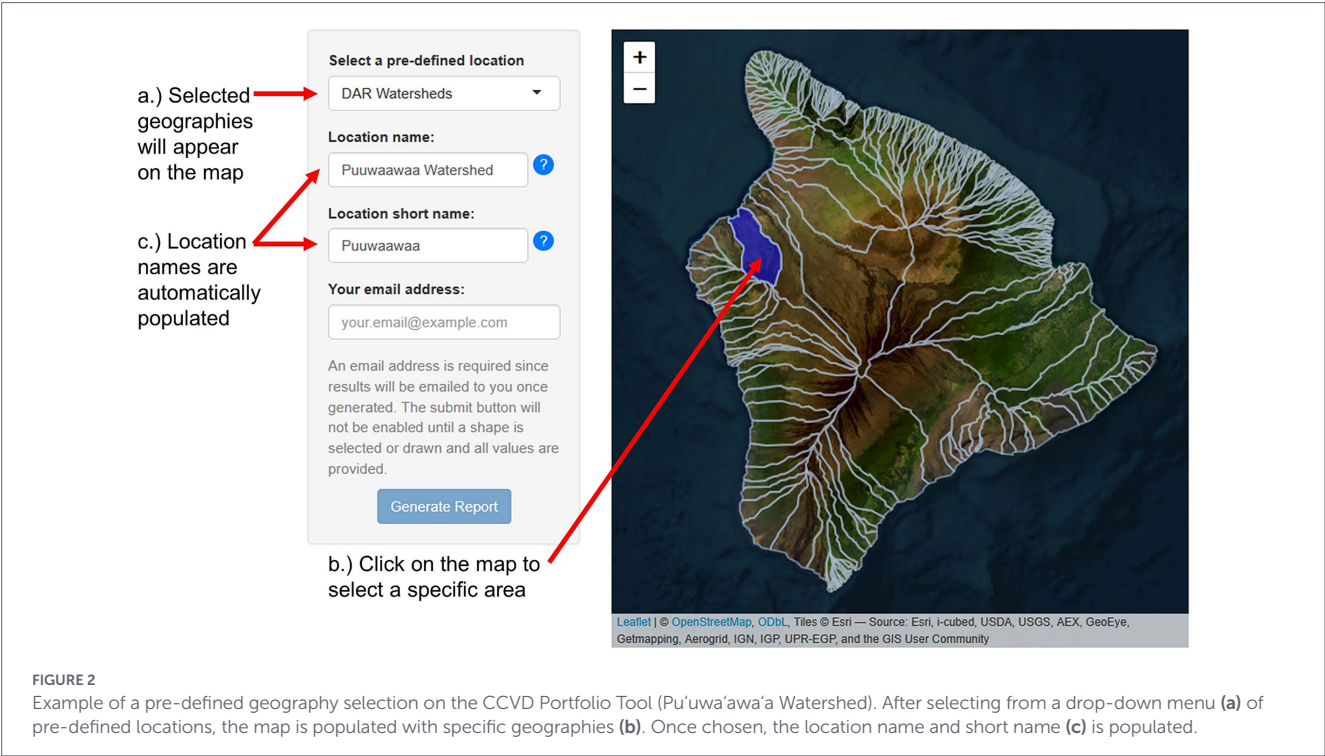


TABLE 1 List of pre-defined geographies included in the CCVD portfolio tool.

Pre-defined geography	Description
Ahupua'a	Ahupua'a (Historic Land Divisions). Created by a consultant to the Office of Hawaiian Affairs in 2024. Although not survey grade, and not checked for legal validity, the boundaries correspond to the 19th century survey maps
Aquifer sector areas	Aquifer Sector Area boundaries, as determined/defined by the State Department of Land and Natural Resources, Commission on Water Resource Management to provide a consistent basis for managing ground water resources.
Aquifer system areas	Aquifer System Area (smaller sub-region) boundaries, as determined/defined by the State Department of Land and Natural Resources, Commission on Water Resource Management to provide a consistent basis for managing ground water resources.
CWRM watersheds	Watershed Unit Boundaries for the major Hawaiian Islands—Commission on Water Resource Management (CWRM) Version
DAR watersheds	Surface water hydrologic unit boundaries for hydrologic water catchment for the main Hawaiian Islands (excluding Kaho'olawe)—Department of Aquatic Resources (DAR) Version
Elementary school areas	Elementary School Districts as of 2024
Forest reserves and sanctuaries	Various reserves, preserves, parks, etc. as of 2024
Hawaiian homelands—2022	Lands owned by the State of Hawai'i Department of Hawaiian Homelands as of October, 2022
High school areas	Hawai'i High School Districts Boundaries as of 2024
Middle school areas	Middle School District Boundaries as of 2024
National parks	Administrative boundaries of lands managed by the U.S. National Park Service
State house districts—2022	2022 Hawaii State House of Representatives District Boundaries as adopted by the State of Hawaii Reapportionment Commission in 2022
State senate districts—2022	2022 Hawaii State Senate District Boundaries as adopted by the State of Hawaii Reapportionment Commission in 2022

These geographies were included based on statewide completeness and relevance towards environmental management and education across a range of specific user interests pre-loaded geographies included in the CCVD portfolio tool.

on available GIS data from the State of Hawai'i were obtained from Hawai'i Statewide GIS program,¹ and were selected based on the

types of requests received for manual CCVD Portfolios. Custom boundaries can also be created using a set of easy-to-use draw features (Figures 3). When creating a custom polygon, users must provide both a full location name and a shortened abbreviation, which are then used throughout the portfolio in page titles, text references,

1 <https://planning.hawaii.gov/gis/>

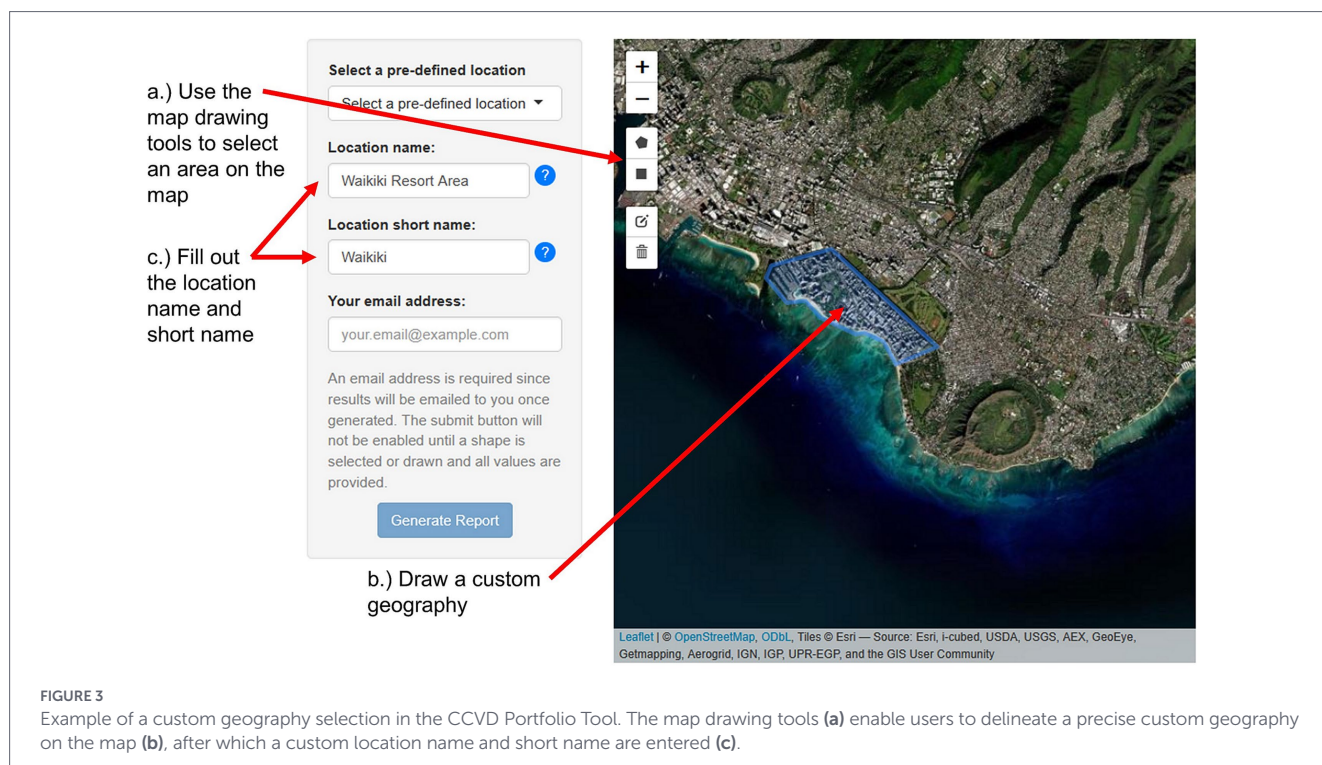


FIGURE 3

Example of a custom geography selection in the CCVD Portfolio Tool. The map drawing tools (a) enable users to delineate a precise custom geography on the map (b), after which a custom location name and short name are entered (c).

and figure captions. After selecting or creating the desired location, users enter an email address to receive the generated portfolio. Once submitted, the tool extracts climate data from multiple spatial datasets, computes statistics and trends, and generates maps, figures, and descriptive text which is delivered as a Microsoft PowerPoint file. Portfolio generation typically takes less than 1 h, though larger areas may require more processing time. To secure reliable transmission, the CCVD Portfolio is retrieved via a download link that is sent to the user via email.

The primary goal of these demonstration activities was to increase awareness of the CCVD Portfolio Tool and to gather informal input as part of an ongoing co-production process. While hundreds of individuals were engaged across these activities, formal feedback tracking was not employed during this phase of tool development. Nonetheless, the tool has since seen meaningful adoption across multiple user groups: educators have integrated portfolio outputs into classroom instruction, natural resource managers are using portfolios to inform planning and policy decisions, and extension agents are leveraging the tool to communicate climate science to broader audiences. Formal user evaluation mechanisms are currently being developed to better capture and incorporate feedback in future iterations.

The back-end functionality is implemented in R using a comprehensive suite of packages detailed in [Supplementary Table 1](#). The front-end uses the R Shiny framework ([Chang et al., 2024](#)) and is deployed on a Jetstream2 ([Hancock et al., 2021](#)) instance running Ubuntu ([Canonical Ltd., 2025](#)). It incorporates leaflet for interactive mapping, sf for spatial data handling, and additional R packages (shiny and leaflet.extras) for web interface functionality and visualization. A set of Python scripts, scheduled via cron jobs, perform automated maintenance tasks: one removes outdated files after 1 week to manage storage, while another retrieves the latest rainfall data. The

source code for the portfolio is openly available on GitHub² and is currently implemented as a platform-independent web application. Licensing restrictions for non-academic use should be verified via the repository or with the development team.

The final version of the web design was co-produced with end users using a range of methods. First, the PDKE team used several online and in-person meetings to showcase the tool to collaborating agencies and partners. Second, the team acquired an exhibitor booth at the annual Hawai'i Conservation Conference held in Honolulu, HI, July 22–24, 2025, to showcase the tool to a broader audience. Meeting attendees were asked to create a portfolio on their own and to provide feedback on their experience. Finally, between July and September 2025, the team demonstrated the tool to a range of end users including high school teachers, students, lawmakers, colleagues, friends, and family to gain additional insight on how functionality and content might be improved.

2.2 Hawai'i rangeland information portal (H-RIP)

2.2.1 H-RIP overview

The H-RIP was developed in response to the significant and recurring impacts of drought on Hawai'i's ranching sector. Rain-fed rangelands in Hawai'i are typically located in drier upland and leeward areas of the state, making them highly vulnerable to drought. While prolonged dry periods can compromise irrigated lands ([Frazier et al., 2022](#)), Hawai'i's leeward rangelands have experienced the most dramatic declines in baseline rainfall and the largest increases in

² <https://github.com/landyachtz05/PDKE.git>

drought frequency, severity, and duration. Drought conditions are especially challenging because they force ranchers to purchase costly supplemental feed or reduce herd sizes at great expense. During the most severe droughts, insufficient rainfall can greatly increase cattle mortality and reduce calving rates, resulting in substantial economic losses and threatening the long-term sustainability of the industry (Frazier et al., 2022).

Between 2008 and 2018, the USDA's Livestock Forage Disaster Program paid out over \$50 million to Hawai'i ranchers for grazing losses and nearly \$800,000 for livestock losses (Frazier et al., 2022). Drawing on the Grassland Productivity Forecast ("Grass-Cast"; Peck et al., 2019) as inspiration, the PDKE team began designing a DST in 2020 to address drought-related challenges confronting Hawai'i's ranchers. Through a series of stakeholder meetings, and in partnership with the USDA Natural Resources Conservation Service (NRCS), the University of Hawai'i at Mānoa, the Hawai'i Cattlemen's Council (HCC), and the National Oceanic and Atmospheric Administration (NOAA), the team engaged the ranching community directly to identify key drought-related data needs. These collaborative exchanges with ranchers and extension agents shaped a beta version of H-RIP, released in 2022, built around a forage production model developed by Thorne (2011) using forage growth estimates based on grass type and rainfall in Hawai'i. Rancher feedback from stakeholder consultations during this beta phase focused primarily on front-end functionality improvements and the addition of plain language explanatory text, both of which were incorporated to improve usability. H-RIP was subsequently updated in 2023 to integrate the NRCS 528 PIA-Prescribed Grazing Tool Forage Yield Model (Ogoshi et al., 2025), which builds on and improves upon the Thorne (2011) approach to simulating forage growth based on local rainfall conditions and grass type.

Officially released in 2024, H-RIP gives ranchers across Hawai'i accessible, TMK-scale, site-specific information to support climate-smart decision-making and build drought resilience at the scale of individual ranches. To use H-RIP, ranchers can access four core features: (1) a near-real-time climate dashboard with site-specific rainfall, temperature, and drought data; (2) a 3-month rainfall outlook based on the current ENSO phase; (3) forage growth projections over 1–6 months based on forage type and pasture condition; and (4) annual summaries of rainfall, vegetation, and drought indicators.

2.2.2 Forage production tool

The 528 Forage Production Tool, embedded within the H-RIP, was developed by the USDA Natural Resources Conservation Service (NRCS) Hō'olehua Plant Materials Center in collaboration with NRCS rangeland specialists to improve the accuracy and utility of grazing management planning in the Pacific Islands Area (Ogoshi et al., 2025). In building on a long history of better understanding forage production in Hawaii (Thorne, 2011; May, 2014) and based on the NRCS Grazing Management Conservation Practice Standard, Code 528 [NRCS (Natural Resources Conservation Service), 2018], the tool was developed to provide a science-based approach for estimating forage availability, calculating livestock forage demand, and maintaining a sustainable forage-animal balance. It allows users to adjust grazing plans based on pasture condition, soil type,

climate data, and herd characteristics, supporting adaptive management and ecological resilience. A key feature of the tool is its regionally calibrated forage production model, which was developed through multi-year field studies and the evaluation of five existing models plus a custom-built ensemble model. After years of testing and analysis Ogoshi et al. (2025) concluded that the ensemble model provided more accurate and precise results based on a range of error metrics.

The 528 tool also accounts for five NRCS-recommended forage grass species (*Kikuyu*, *Pangola*, *Buffel*, *Signal*, *Guinea*), enabling planners to estimate Annual Available Forage Yields (AAFY) specific to the vegetation composition of a site. By integrating these capabilities into a user-friendly platform, the 528 tool within H-RIP supports data-driven decision-making, promotes rangeland sustainability, and enhances the application of conservation practices across the Pacific Islands' diverse ecosystems.

2.2.3 The Hawai'i rangeland information portal design and functionality

To launch H-RIP, visit³ from any internet-connected device including smartphones, tablets, or laptops. Upon arriving at the landing page, users will find two primary features. To get started, navigate to the upper portion of the page labeled "Ranch Selection" to choose a geography of interest (Figure 4). Using the interactive map, select an island of interest from the drop-down menu or zoom into an area of interest using the scroll feature. The individual islands all contain a series of equal size markers with spatial resolution of 0.01° (~1km). Each marker represents a unique ranch or area of interest. A uniform size marker is used to protect the privacy of the ranches. Additionally, markers can be added to the map at any time using the H-RIP site selection form. Each marker is given a unique 3-digit ranch ID (RID) number that bears no relationship to ranch ownership or full perimeter. The 1 Km threshold was chosen as an appropriate resolution for estimates of pasture characteristics based on stakeholder feedback. There is no limit to how many markers can be added to the map.

The lower portion of the H-RIP landing page provides a snapshot of current climate conditions across Hawai'i through three interactive widgets: (1) The Oceanic Niño Index (ONI) gauge displays the current status of the El Niño-Southern Oscillation (ENSO), updated monthly on the 8th of each month, using data from NOAA's Climate Prediction Center; (2) The [windy.com](https://www.windy.com) widget shows a dynamic wind and 24-h weather forecast map; and (3) The current U.S. Drought Monitor Map which shows weekly drought conditions across the state⁴ (Figure 5).

2.2.3.1 Climate dashboard

Each individual ranch page within the H-RIP provides tailored, site-specific data to support climate-informed decision-making. Once end users select a geography (RID) of interest from the interactive map on the home page, they will be redirected to an individual ranch page with site specific information (Figure 6). The first section of the page is a dynamic dashboard that serves as a central hub for daily and monthly climate conditions at that site. The dashboard contains information

³ <http://hrip.manoa.hawaii.edu/>

⁴ <https://droughtmonitor.unl.edu/>

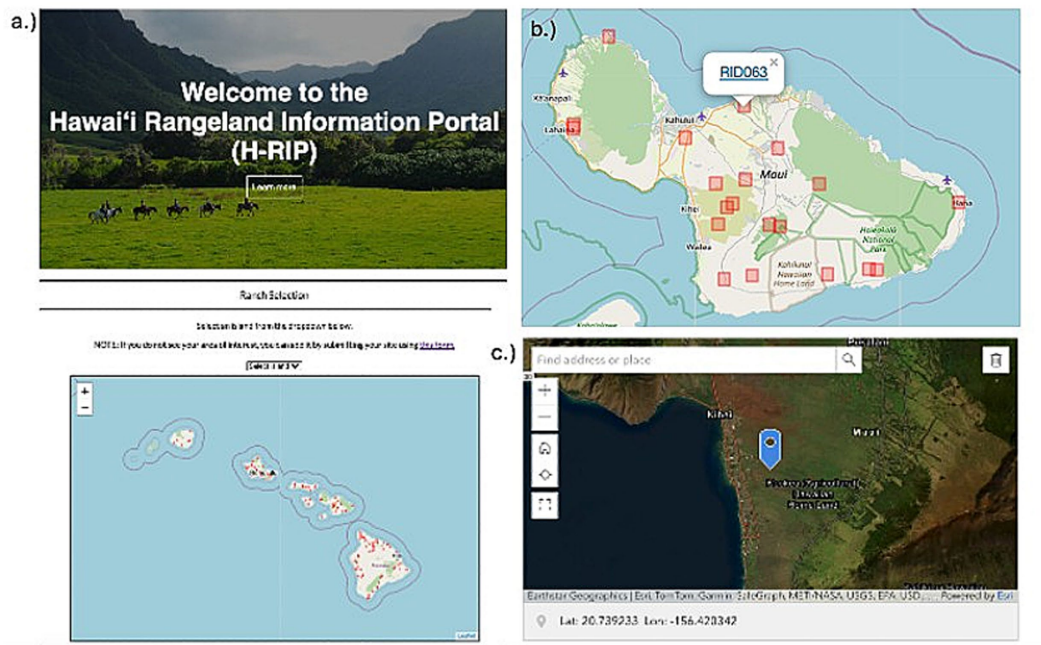


FIGURE 4

(a) H-RIP landing page with statewide interactive site-selection map; (b) Maui Island with ranch red box markers and example of a selected ranch Identifier (RID); (c) Ranch Site Selection form.

about rainfall and temperature obtained from near-real-time gridded products produced on the HCDP. End users may toggle between daily and monthly estimates of these variables and statistics will update accordingly. Imperial units are used to display both rainfall and temperature data. For monthly rainfall, data are presented in absolute (total rainfall) and relative anomaly (percent from normal). Above average total rainfall (positive anomalies) are indicated by a green check mark and below average total rainfall (negative anomalies) are indicated by a red check mark. The total number of dry days (daily rainfall < 0.04 in) that occurred during the month are displayed. For monthly temperature, average temperature is shown with an absolute anomaly (degrees Fahrenheit above or below normal for that month). Monthly average minimum and maximum surface air temperature are also shown. For daily rainfall, yesterday's total rainfall is given as well as a current consecutive dry day counter.

The monthly rainfall is also used to generate drought time series using the Standardized Precipitation Index at a 3-month time-step (SPI-3) for the past 12 months (SPI-12). The axis on the graph is labeled as "Drought" or "No Drought" (instead of SPI) to improve clarity to the end-user. Current drought severity conditions are given based on thresholds defined by the USDM drought monitor. The U.S. Drought Monitor (USDM) defines drought severity using percentile-based thresholds ranging from D0 (Abnormally Dry) to D4 (Exceptional Drought), corresponding roughly to the 30th, 20th, 10th, 5th, and 2nd percentiles of historical conditions (NDMC, n.d.).

The final portion of dashboard is the ENSO gauge. Using the current ONI value obtained from the NOAA Climate Prediction Center (2025), one of five possible ENSO phase classifications (Strong El Niño, Weak El Niño, Neutral, Weak La Niña, and Strong La Niña) is determined based on pre-defined thresholds. Periods with ONI values above +0.5 °C indicate El Niño conditions, with weak El Niño ranging from +0.5 °C to +0.9 °C and strong El Niño exceeding +1.5 °C. Conversely, values below

−0.5 °C signify La Niña conditions, with weak La Niña between −0.5 °C and −0.9 °C and strong La Niña at −1.5 °C or lower. ONI values between −0.4 °C and +0.4 °C are considered neutral conditions (NOAA Climate Prediction Center, 2025). Note that the ONI is the primary metric used to classify the five phases of the El Niño–Southern Oscillation (ENSO) based on sea surface temperature anomalies in the Niño 3.4 region (NOAA Climate Prediction Center, 2025).

Historical monthly rainfall information related to the most recent month as well as to the current ENSO phase classification are provided directly below the ENSO gauge. The long-term monthly average is labeled as "Historical Avg," then the historical average for that month as it relates to the current ENSO phase is given, and finally, the historical minimum as it relates to that ENSO phase is given.

2.2.3.2 Rainfall projection

The second section of each H-RIP ranch page presents a three-month rainfall forecast based on the current ENSO phase and the historical rainfall data at the site. We chose to use an "almanac" approach based on historical data instead of forecast data for two reasons. First, forecast data for Hawai'i are limited, and what products do exist are relatively coarse resolution and are not able to capture the extreme climate gradients experienced in the state. Second, during our conversations with ranchers we found that they are generally more comfortable with the almanac approach rather than predictive (course resolution) models. The rainfall forecast is therefore derived from historical rainfall records spanning from 1920 to the most recent month, which are separated into the five ENSO phases to derive historical relationships across all phases. For each phase, the average and minimum monthly values for each month. We do not show maximum rainfall values only to reduce the amount of data shown on the graph. The resulting forecast provides an almanac-style perspective, displaying three key metrics for the current and next two consecutive months: (1) average rainfall historically observed for each month

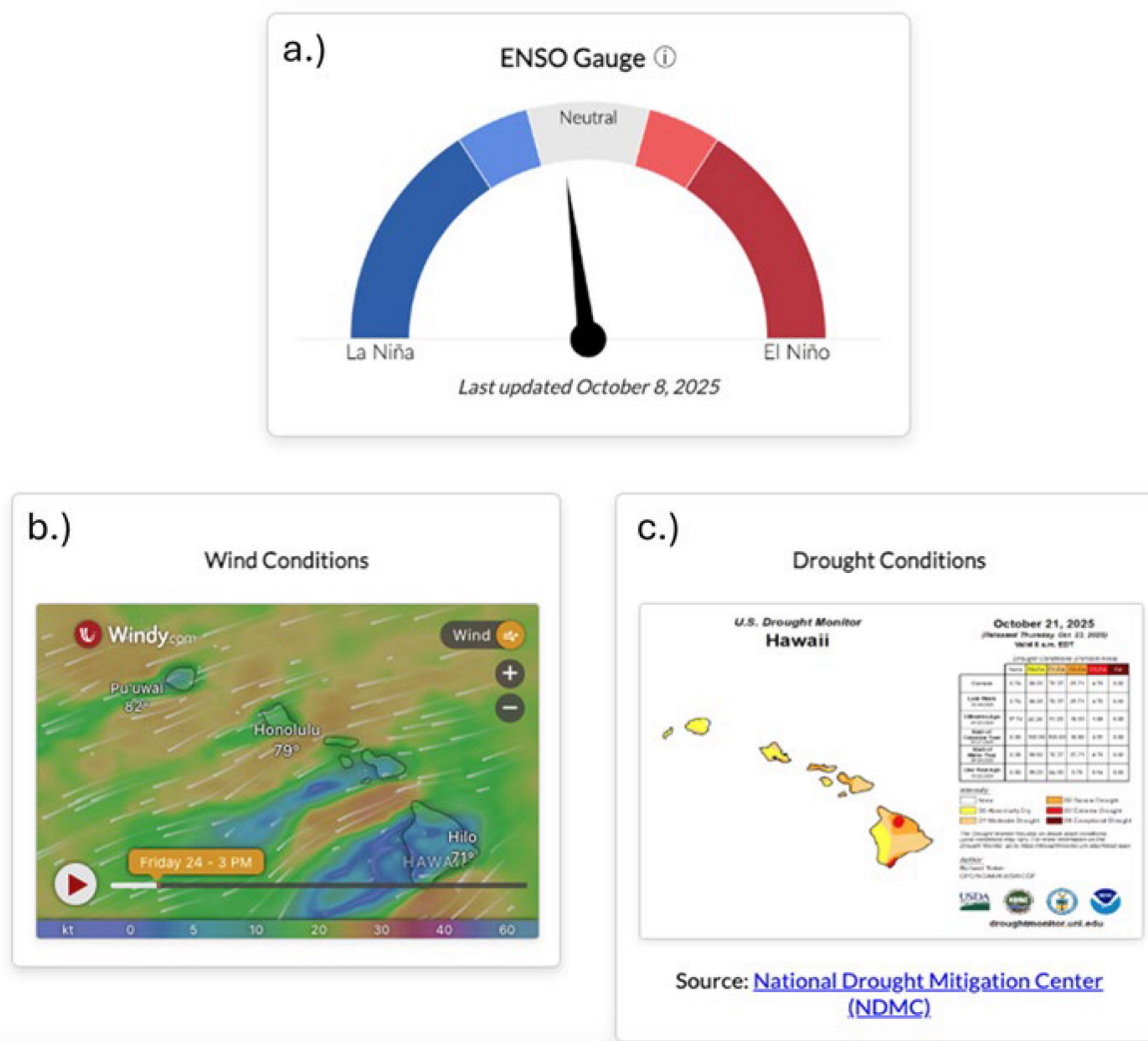


FIGURE 5

Lower portion of the H-RIP home page with state-wide climate information includes the current (a) Current El Niño Southern Oscillation (ENSO) phase based on the current NOAA Oceanic Niño Index (ONI) value; (b) map of current wind conditions from [windy.com](#) and (c) the current U.S. Drought Monitor map for Hawaii.

regardless of ENSO phase, (2) average rainfall historically observed during the current ENSO phase, and (3) the minimum rainfall historically observed during the current ENSO phase (Figure 7).

2.2.3.3 Forage production tool

The third section of the ranch page provides a forage production estimate tailored to user-defined conditions. Ranchers are prompted to input two key pieces of information specific to their site: the dominant grass type which is selected from a drop-down menu and current pasture condition (Figure 8). The five grass types available in the drop-down menu are selected based on the NRCS 528 tool described above. Pasture conditions subjective and based on a rancher's assessment of the pasture in relation to available forage. Based on these two inputs, the 528-tool embedded in the H-RIP will generate a forage production estimate for the next 1 to 6 months based on projected ENSO phase rainfall. Outputs are expressed in pounds per acre, as well as the percentage difference from normal forage production for the same months based on the projected average and minimum rainfall for the current

ENSO phase. There is also an option to view this same information for the prior 5 months.

2.2.3.4 Average climate conditions

The fourth section of the ranch page, titled "Average Climate Conditions," offers a deeper look at four key environmental datasets: monthly rainfall (1920–present), monthly temperature (1990–present), monthly NDVI (Normalized Difference Vegetation Index; 2000 to present), and monthly drought using the 3-month standardized precipitation index (1920–present). For rainfall, temperature and NDVI datasets, users can view a high-resolution map showing last month's values at the island scale with ranch area highlighted and a 12-month graph showing a line of monthly values comparing each month's data to long-term monthly averages, and a full time series of all available historical data. Rainfall, temperature, and NDVI data are sourced from the Hawai'i Climate Data Portal (Longman et al., 2024), while evapotranspiration data are provided via Google Earth Engine (Running et al., 2017). This section gives ranchers the ability to monitor local trends and variability over time, supporting informed decision-making for pasture and herd management.

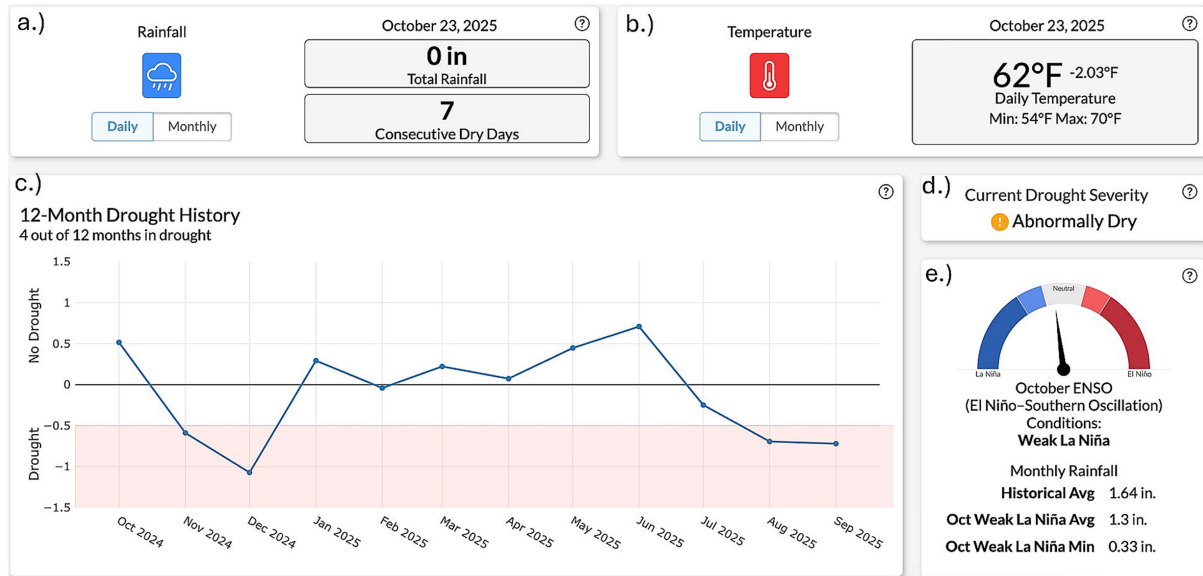


FIGURE 6

Climate dashboard for RID063 on October 23rd, 2025: (a) daily rainfall absolute value (in.) and consecutive dry-day counter; (b) daily temperature absolute value (°F), temperature anomaly from long term average, minimum and maximum daily surface air temperature; (c) 12-month drought history using the 3-month Standardized Precipitation index (SPI -3); (d) Current drought conditions based on monthly SPI-3; (e) ENSO gauge with corresponding rainfall during that month and historical average and minimum rainfall during the current ENSO phase.

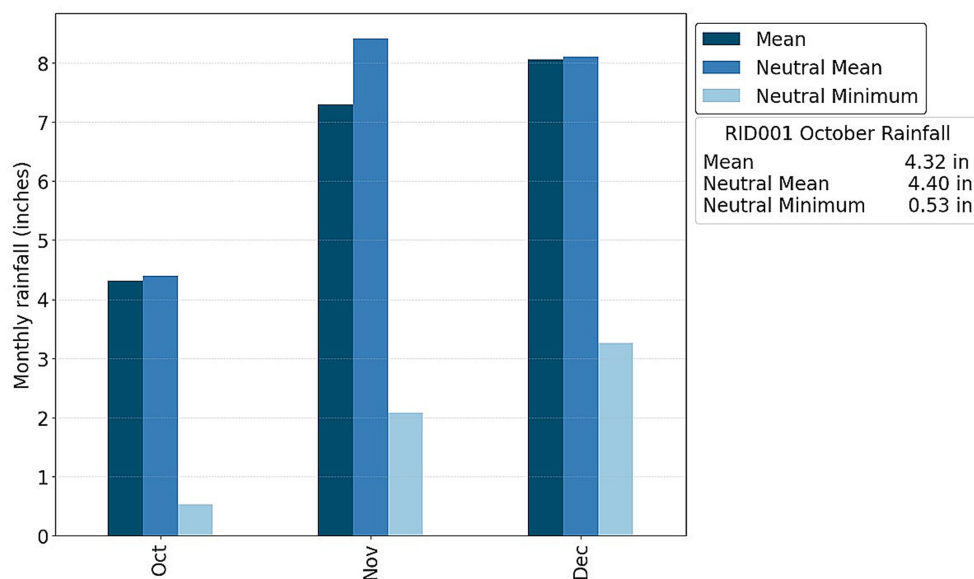


FIGURE 7

Projected monthly rainfall displaying current month (October, 2025) next 2 months (November and December, 2025) based on historical data (1920-to most recent month) for a sample location in Hawaii (RID063). Based on the current ENSO phase (Neutral, El Niño, or La Niña), bars show the historical mean monthly rainfall received at this location during all years ("Mean"), the mean rainfall during the ENSO phase years ("Neutral Mean"), and the minimum rainfall during the ENSO phase years ("Neutral Minimum").

2.2.4 H-RIP tool programing

The H-RIP is a web-based decision-support tool designed to provide ranchers with climate-driven insights for forage production and resource management. The system's back end is primarily built using "Python" (Python Software Foundation, 2025), which handles climate data retrieval, analysis, and forage growth modeling.

For each update cycle, H-RIP downloads climate data from the HCDP as GeoTIFF files. The Python processing pipeline loops through all registered ranches, extracting relevant climate variables for each ranch boundary. This analysis produces historical statistics, figures, and CSV data products, which are stored in individual directories. Each ranch's data set then feeds into its respective website.

Select the following for your location and click submit:

Grass Type:

Forage Condition:

Ranch may select:

a.) Pasture grass type (five options)

b.) Forage conditions (Improved or unimproved)

FIGURE 8
Selection menu for user defined inputs to the 528-forage production tool.

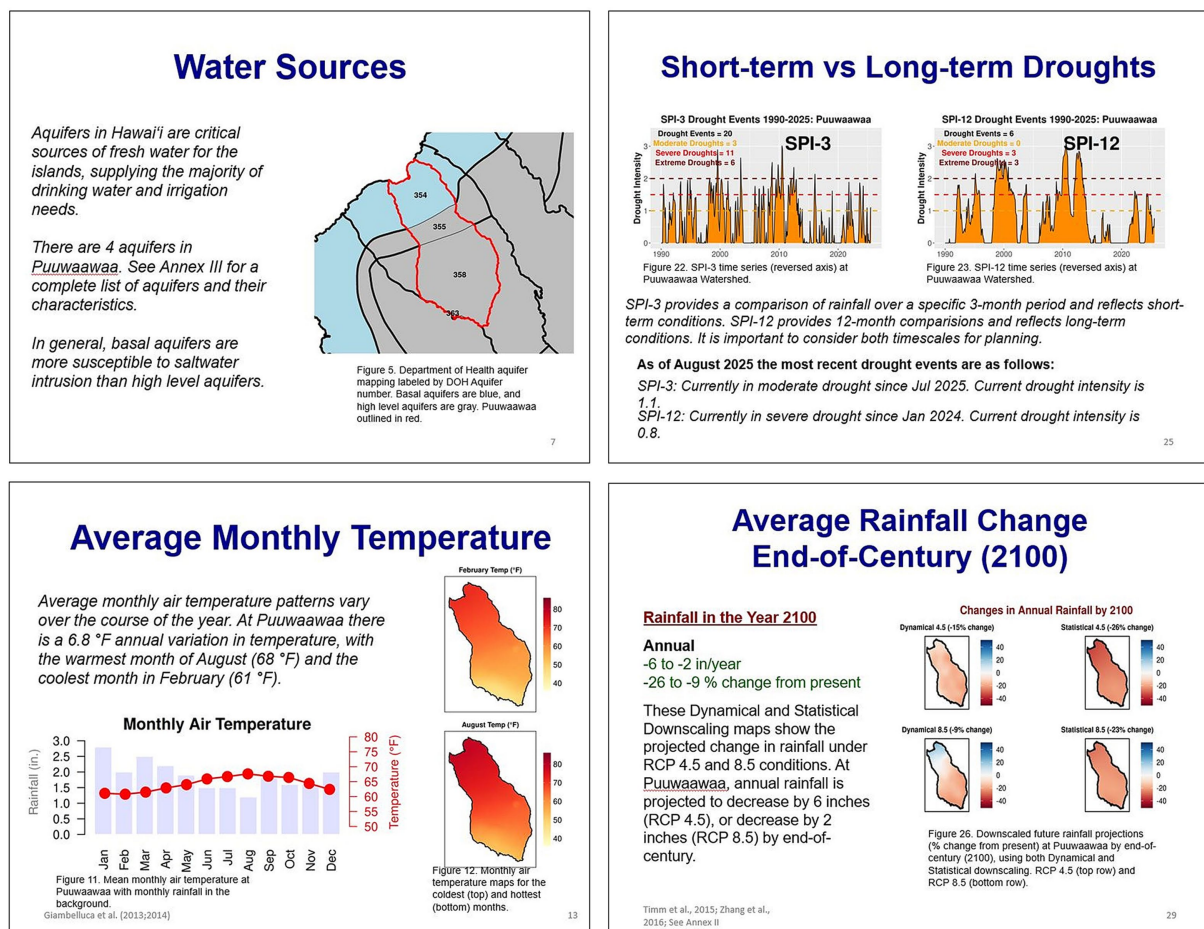


FIGURE 9
Example output slides of the CCVD Portfolio for Pu'uwa'awa'a Watershed. Slides 7 (Water Sources), 13 (Average Monthly Temperature, 25) (Short-term vs. Long-term Droughts) and 29 (Average Rainfall Change End-of-Century (2100)) shown.

The forage production estimation model, also built in Python, uses user-supplied information about grass type and pasture conditions combined with ranch-specific rainfall data to calculate forage growth potential. The results are dynamically output to the ranch websites. The back end uses the following Python packages: *pandas*, *datetime*, *numpy*, *geopandas*, *rasterio*, *rasterstats*, *matplotlib*, and *standard-precip*.

The scripts are automated via cron jobs (Unix/Linux systems), running daily or monthly depending on the dataset being updated. This ensures a continuous, scheduled processing workflow. The front-end is developed using HTML and PHP to handle user interactions and data

ingestion. The H-RIP website is hosted on a Jetstream2 (Hancock et al., 2021) instance running Ubuntu (Canonical Ltd., 2025) with Apache as the web server (The Apache Software Foundation, 2025). The source code for the H-RIP is openly available on GitHub⁵ and is currently implemented as a platform-independent web application. Licensing restrictions for non-academic use should be verified via the repository or with the development team. The H-RIP tool has also been adapted for mobile-friendly use.

⁵ <https://github.com/cherryleh/H-RIP>

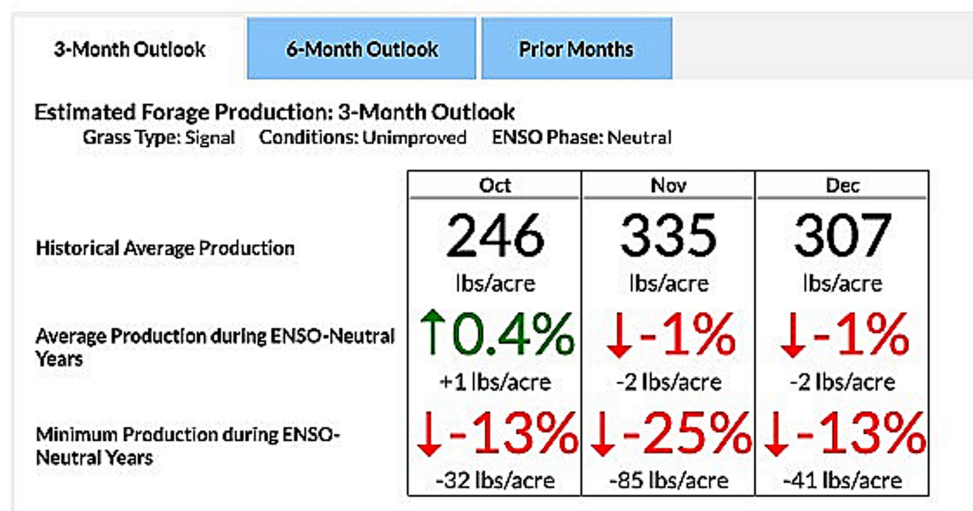


FIGURE 10

Forage production output for RID063 on October 23rd, 2025 during Neutral phase ENSO conditions for October–December 2025.

3 Results: tool outputs and performance

3.1 CCVD portfolio tool

The CCVD Portfolio Tool⁶ was officially launched in April 2025 and introduced through a series of outreach events. The current version (5.4) consists of 40 slides covering a wide range of topics including available water resources, short and long-term drought, average monthly temperatures, and future rainfall projections at end of century (Figure 9). Portfolio generation typically takes less than 30 min for smaller geographies such as school complexes, and up to 1 h for larger areas such as watersheds.

Since launch, all portfolio requests are handled exclusively through the online platform, eliminating ad-hoc requests and manual creation. This transition has reduced production costs and increased accessibility by allowing users to define their area of interest through pre-loaded geographies or custom-drawn polygons. The streamlined format has enabled more consistent outputs and quicker production, though it has also introduced challenges in tailoring data across sites with varying needs and spatial scales. Portfolio outputs have already informed a wide range of resource management decisions including habitat and species protection, restoration site identification, and planting time optimization. For instance, historical drought information guided planting decisions for the endemic Mauna Kea Silversword in Hawai'i Volcanoes National Park (Longman et al., 2022), and CCVD outputs have been incorporated into Environmental Assessments (Longman et al., 2022) and scenario planning efforts (Peterson et al., 2003; Weiskopf et al., 2020). Looking ahead, all Hawai'i Department of Education school complex areas are now preloaded as selectable geographies to support future curriculum development, and initial efforts are underway to explore portfolio development for U.S. Territories including American Samoa and Guam. The scalability of the CCVD Portfolio Tool depends on the availability of high-resolution gridded products for a defined geography.

Currently the tool is limited to gridded products covering the entire State of Hawai'i and does not yet support spatially incomplete datasets. A gridded rainfall climatology at minimum provides insights into annual cycles and seasonal variability, while longer-term datasets enable analysis of rainfall trends, drought occurrence, and relationships with modes of interannual climate variability such as ENSO.

3.2 H-RIP

The Hawai'i Rangeland Information Portal (H-RIP) was officially launched in May 2024 with the goal of providing ranchers with site-specific information about drought conditions, climate variability, and near-term forage production at the pasture scale. Following the steps outlined in Section 2.2.2, users receive three- and six-month forage production outlooks based on statistical relationships between rainfall and ENSO phase (Figure 10). To improve accessibility, the tool deliberately avoids technical jargon describing conditions as "Drought" or "No Drought" rather than using Standardized Precipitation Index terminology, and presenting rainfall as deviations from normal rather than absolute totals.

The rollout of H-RIP began with a soft launch targeted at the ranching community, followed by formal outreach events, training workshops, and a tutorial video with step-by-step instructions. A highlight of these efforts was the demonstration at the Hawai'i Cattlemen's Council Annual Meeting in Waikoloa, where ranchers were encouraged to add monitoring points to the interactive map and trained to interpret site-specific forage projection estimates.

Users should be aware of uncertainties associated with the data and information the tool provides. We have high confidence in the interpolated rainfall products based on the rigorous methodology and error metrics presented by Lucas et al. (2022). For forage production, Ogoshi et al. (2025) demonstrated that a model ensemble approach produces more accurate and precise results than any single production model, with an average bias of 34%, supporting medium confidence in these estimates.

The scalability of H-RIP depends on the availability of high-resolution gridded rainfall and temperature products, with a 30-year rainfall time series considered optimal for calculating the Standardized

⁶ <https://ccvd.manoa.hawaii.edu>

Precipitation Index (SPI). The forage production model is currently specific to Hawai'i; application in other geographies would require development of a site-specific production model.

4 Discussion

4.1 The need for locally relevant climate decision support tools

Despite growing demand for climate services to inform decision-making, critical gaps persist in the relevance, accessibility, and uptake of tools among the communities they are designed to serve. As [Ikendi et al. \(2025\)](#) found in their investigation of extension technical service providers, the most commonly cited shortfalls in existing tools include limited data translation, insufficient local granularity, low community participation in tool development, and a persistent disconnect between what researchers build and what practitioners actually need. As [Findlater et al. \(2021\)](#) note, there is often a gap between the aspirational promise of climate services and their real-world application, with many tools focusing more on delivering better data than on enabling better decisions. In Hawai'i, natural resource managers, ranchers, and conservation practitioners have faced a persistent shortage of accessible, site-specific climate information tailored to their operational realities. The CCVD Portfolio and H-RIP tools were developed specifically to address this gap not as generic data delivery platforms, but as purpose-built solutions designed around the distinct information needs of their respective user communities.

The CCVD Portfolio Tool addresses the need for synthesized, site-specific climate information to support habitat management, restoration planning, and adaptation across a wide range of land stewardship contexts. H-RIP was developed in direct response to the significant and recurring economic impacts of drought on Hawai'i's ranching sector, where timely, pasture-scale information on forage production and rainfall variability can mean the difference between proactive management and costly reactive responses. Both tools were intentionally designed to meet these practical needs through intuitive, web-based platforms that prioritize accessibility, ease of use, and local relevance ([Lieske, 2015](#)) marking a significant step toward more meaningful and actionable climate services in the region.

4.2 Co-production as process

While the development of these tools was driven by clearly identified user needs, co-production was the process that ensured those needs were met effectively. Rather than merely consulting stakeholders for *ad hoc* feedback, the PDKE team actively engaged resource managers in an ongoing dialogue to identify what types of information they needed to support their decisions, a process that hinges on users' ability and willingness to articulate their needs ([Briley et al., 2015](#); [Jagannathan et al., 2021](#)). Co-production processes are iterative and relational, involving trust-building, capacity development, shared understanding, and the creation of jointly developed outputs ([Ostrom, 1996](#); [Kruk et al., 2017](#); [Bojovic et al., 2021](#)). These processes require climate service providers to design products that are not only timely and reliable but also accessible and tailored to real-world decision contexts ([Christel et al., 2018](#); [Jacob et al., 2025](#)). The long-standing relationships between the PDKE team and its partners played a crucial role in

enabling this kind of sustained co-development, fostering mutual respect, two-way communication, and a continuous focus on utility.

Both tools have undergone significant revisions in direct response to user feedback collected through outreach events, direct communication, and one-on-one consultations. Partner enthusiasm has served as a key indicator of success and continues to motivate further refinement and expansion. The co-development process behind both DSTs ensures that the services are not only scientifically robust but also context-specific, fit-for-purpose, and responsive to the real-world needs of their intended users. For the CCVD Portfolio Tool, these users include natural resource managers, conservation practitioners, land stewards, and educators across Hawai'i. For H-RIP, they are ranchers, extension agents, and USDA partners working directly with the ranching community. As highlighted by [Jacob et al. \(2025\)](#) and reinforced by [Ikendi et al. \(2025\)](#), the usefulness, usability, and uptake of climate services depend on sustained, iterative engagement between providers and the full range of end users — not just researchers and scientists — the development of timely and reliable products, and a genuine commitment to accessibility. As [Ikendi et al. \(2025\)](#) and [Ranjan et al. \(2020\)](#) document among conservation professionals, understanding how and why practitioners choose to use (or not use) decision support tools is essential to designing resources that actually serve their needs. The collective contributions of these user communities have fostered a sense of shared ownership and trust that is essential for transformational adoption.

While co-production is widely recommended, it remains underutilized despite its demonstrated ability to produce more actionable science and better societal outcomes ([Lemos et al., 2018](#); [Jacob et al., 2025](#)). Recognizing that climate service users are a diverse group with varying goals ranging from economic to ecological and cultural outcomes makes the need for tailored participatory approaches even more critical ([Jacob et al., 2025](#)). The experiences with the CCVD Portfolio and H-RIP illustrate how collaborative, user-centered design can result in more trusted, useful, and impactful climate services. Trust-building between researchers and users, and a shared understanding of decision-making contexts, are vital ingredients for moving climate services beyond data delivery toward more effective, equity-centered resource management.

5 Conclusion

Looking ahead, the experiences with the CCVD Portfolio and H-RIP point toward a broader opportunity to advance co-produced, locally relevant climate services across the Pacific Islands region and beyond. As both tools continue to mature and expand their user communities, the co-production model applied here offers a replicable framework for translating climate science into actionable decision support that centers the needs of practitioners, builds lasting partnerships, and positions climate services as essential infrastructure for resilience across diverse sectors and geographies.

The CCVD Portfolio and H-RIP DSTs represent important advancements in the delivery of climate services for resource managers and agricultural producers in Hawai'i, including the ranchers, land managers, conservation practitioners, and extension agents who were directly engaged throughout the co-production process. Together, they enhance the state's capacity to respond to drought and climate variability by

providing access to site-specific, near-real-time information through user-friendly, web-based platforms. Both tools were designed with the explicit goal of delivering tailored climate data that can serve locations not co-located with an active weather station, by leveraging a spatially continuous gridded database and intuitive visual interfaces, with data presented in plain language formats to maximize accessibility and support informed, on-the-ground decision-making. While real-world adoption across multiple user communities suggests these design goals are being realized, we acknowledge that a formal socioeconomic evaluation of tool use and impact has not yet been conducted, and we recognize that web-only delivery and English-only interfaces may limit access for some potential users. In Hawai'i, NRCS and extension staff have served as important intermediaries working directly with producers to demonstrate tool use or share outputs on their behalf partially mitigating the web access limitation, and to date no demand for language translation has been identified, though we recognize this may reflect barriers to engagement rather than absence of need.

As of this writing, all major components of both tools have been openly released on GitHub and integrated into scalable cloud-based workflows. Both tools have been refined through ongoing stakeholder engagement, including outreach events, demonstrations, and direct communication with end users. While this engagement has been formative and has driven meaningful improvements, we acknowledge that systematic collection and analysis of user feedback data was not employed during these phases. Establishing formal user evaluation mechanisms including structured feedback protocols and metrics of tool adoption and impact is a recognized priority as both tools continue to mature. These efforts will provide the empirical foundation needed to more rigorously assess tool effectiveness and equity of access. With funding secured for at least two more years of maintenance and development, the CCVD Portfolio and H-RIP are well-positioned to continue contributing to a more resilient and climate-informed future for Hawai'i's natural resource managers and agricultural producers.

Data availability statement

Both the H-RIP and CCVD Portfolio tools are open-source web applications available online via the following URLs respectively: <http://hrip.manoa.hawaii.edu/>; <https://ccvd.manoa.hawaii.edu/>.

Author contributions

RL: Funding acquisition, Project administration, Writing – original draft, Supervision, Formal analysis, Software, Writing – review & editing, Resources, Data curation, Investigation, Visualization, Conceptualization, Methodology, Validation. DF: Validation, Data curation, Writing – review & editing, Methodology, Investigation, Writing – original draft, Formal analysis, Visualization, Software. CH: Investigation, Methodology, Data curation, Writing – review & editing, Software, Validation, Visualization, Formal analysis, Writing – original draft. JG: Software, Visualization, Writing – review & editing. AF: Conceptualization, Funding acquisition, Writing – review & editing, Methodology, Project administration. CG: Project administration, Conceptualization, Methodology, Funding acquisition, Supervision,

Writing – review & editing. JP: Supervision, Conceptualization, Writing – review & editing, Funding acquisition, Project administration. SC: Methodology, Writing – review & editing, Software, Supervision, Project administration. JM: Writing – review & editing, Methodology, Conceptualization, Funding acquisition.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fclim.2026.1768549/full#supplementary-material>

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