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The Pacific Drought Knowledge Exchange: A Co-Production Approach to Deliver Climate Resources to User Groups

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Abstract: Drought is a growing threat to hydrological, ecological, agricultural, and socio-cultural systems of the tropics, especially tropical islands of the Pacific where severe droughts can compromise food and water security. Overcoming barriers to knowledge sharing between land managers and researchers is a critical cross-sector strategy for engaging and mitigating or adapting to drought. Here we describe the establishment and functioning of the Pacific Drought Knowledge Exchange (PDKE), which provides users with easier access to: (1) sector- and geography-specific climate information; (2) better and more comprehensive information; (3) improved technical assistance; and (4) a more collaborative information-transfer environment through participation in knowledge co-production. We focus on our collaborative work with managers of important tropical dryland ecosystems from three distinct geographies to pilot the collaborative development of climate change, climate variability, and drought "portfolios" featuring site-specific historical and forecasted future information. This information was then used to collaboratively produce factsheets that partners used to: (i) better understand past and projected climate for specific management units; (ii) integrate new climate knowledge into management planning; and (iii) support climate-focused educational and outreach efforts. This pilot effort demonstrates the successful application of climate-focused co-production in dry tropical landscapes.

Keywords: drought; co-production; climate change; knowledge exchange; Hawaiʻi

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1. Introduction

Drought is a prominent and persistent feature of climate systems in Pacific Islands and can cause severe and sometimes long-lasting impacts to multiple sectors. Natural resource managers now identify climate change, climate variability, and drought (CCVD) as threats that need expanded attention [1]. In 2016, the USDA Forest Service (USFS) published a comprehensive synthesis report describing the effects of drought in forests and rangelands in the United States [2]. The assessment included characterization of drought impacts on forest processes and disturbances such as insect outbreaks and wildfire, and the consequences that drought can have on forests and rangelands. The report concluded that most regions of the U.S. are projected to experience a higher frequency of severe droughts and longer dry periods as a result of observed and projected increases in surface air temperatures [2]. In 2019, the USFS published a companion report that provided region-specific management options for increasing resilience to drought [3]. Chapter 5 in this report specifically addressed how the effects of drought are managed in Hawaiʻi and the United States Affiliated Pacific Islands (USAPI) [4],. Frazier et al. [4] described five attribute categories for drought [5,6]: (1) meteorological, (2) agricultural, (3) hydrological, (4) ecological, and (5) socioeconomic. These attributes form a framework for describing how a drought event is expressed and how impacts are realized across multiple sectors, including in Hawaiʻi and the USAPI. This framework was deemed useful by a wide diversity of resource managers seeking to address drought-related stressors within the context of their systems [4].

As a result of preliminary data synthesis resulting from Frazier et al. (2019) and related efforts [7], it was determined that resource managers in Hawaiʻi were interested in enhanced mechanisms for drought-focused technology and information transfer. This included improved access to high quality, site-specific CCVD-related information, a formalized organizational vehicle for the multi-directional exchange of this synthesized information, and opportunities for creative but efficient knowledge co-production. Previous efforts in Hawaiʻi to disseminate drought-related data and information have occurred primarily through guest lectures or formal presentations at workshops and meetings, presenting useful but limited opportunities for knowledge exchange about drought. These events in turn have led to informal small group meetings between researchers and resource managers to increase dialogue about drought information [8]. Partially in response to these preliminary efforts, resource managers have expressed a desire to be more actively engaged in knowledge co-production processes that shape the type, quality, and utility of drought-related products being delivered to them, including research planning and implementation [4]. Our investment into drought-related knowledge exchange reflects input from managers that there are limited opportunities to access drought-focused datasets and products—a knowledge-exchange gap resulting from the absence of a centralized, drought-focused information clearing house for serving products explicitly designed to support management planning. This gap is aggravated by the fact that most users lack familiarity with or training in the research-derived approaches to accessing, interpreting, and so using data. To address this gap, we used an established knowledge-exchange approach [7] to develop structured opportunities for local to large-scale integration of drought information into management planning and implementation for Pacific Island audiences. We specifically sought to create a mechanism to make research-driven findings about drought more accessible and useful to managers, enhancing current efforts to shape CCVD-focused planning and implementation.

Another need identified by managers is for researchers to more carefully describe and contextualize the implications of their results for meaningful use by stewardship communities [4]. More holistically, managers also describe the need for the application of co-production models to generating CCVD-relevant knowledge that can more efficiently aid in the development and implementation of management planning and policies. Meeting these needs necessarily involves the development of strong collaborations among scientists and data users and careful design and facilitation of co-production processes that lead to drought mitigation and adaptation solutions that can be used to achieve community, agency, and policy outcomes.

The strong interest expressed by Hawaiʻi resource managers and the growing threat that drought poses to natural and human systems of the Pacific make Hawaiʻi an ideal location to pilot a drought-focused knowledge-exchange collaboration between scientists and managers. Here, we, an authorship team of researchers and managers, present on our efforts to establish a formal partnership-driven co-production process for CCVD knowledge exchange in Hawaiʻi. We focus on three pilot sites representing a diversity of intact to degraded tropical dry and mesic forests. Our research objectives were to explore four key aspects of knowledge exchange: (1) how to collaboratively create easier access to drought and climate information and data; (2) how to provide better and more comprehensive information; (3) how to improve technical assistance; and (4) how to facilitate a more collaborative information-transfer environment [7]. In the process, we were able to identify a series of appropriate methods for collaboratively translating results into meaningful products that are being utilized to make resource management decisions while educating internal agency staff and reaching out to external public audiences.

2. Materials and Methods

2.1. Site Description

With funding from the Pacific Islands Climate Adaptation Science Center (PI-CASC), researchers from the East-West Center (Honolulu, HI, USA) and the USDA Forest Service (USFS) Institute of Pacific Islands Forestry (IPIF; Hilo, HI, USA) partnered with the following resource stewardship organizations to pilot the Pacific drought knowledge exchange (PDKE): Hawai'i Volcanoes National Park (HAVO); the State of Hawai'i Department of Land and Natural Resources (DLNR) Pu'uwa'awa'a Forest Reserve (PWW), which also supports the dry-forest unit of the USDA Forest Service's Hawai'i Experimental Tropical Forest (HETF); and the Mauna Kahālāwai Watershed Partnership (MKWP), a state-funded formal alliance of large land owners under the Hawai'i Association of Watershed Partnerships (www.hawp.org/ accessed on 11 July 2022). The HAVO and PWW study areas are located on Hawai'i Island and the MKWP is located on the island of Maui (Figure 1).

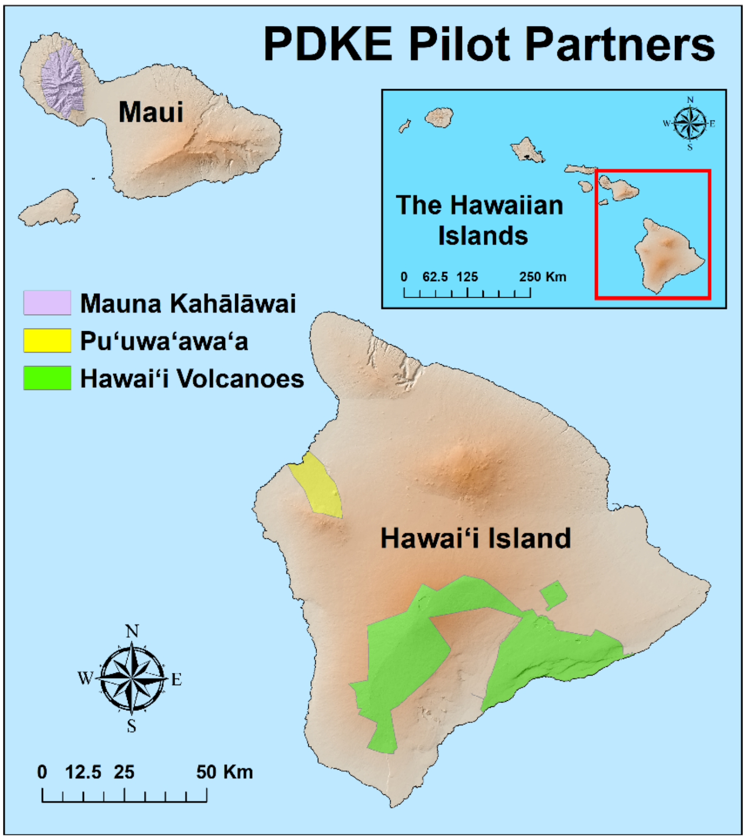

Figure 1. Drought knowledge-exchange pilot study sites in the State of Hawai'i. Orange base map shows elevation, with darker orange indicating higher elevations.

HAVO encompasses 135,675 ha of land [9] and spans elevations from sea level to 4169 m at the summit of Mauna Loa. Resource managers are responsible for a wide diversity of ecosystems from tropical dry, mesic and wet forests to arid desert, including sustaining through protection and restoration populations of 47 US Fish and Wildlife Service listed threatened and endangered species, including vascular plants, insects, mammals, reptiles, and birds [9]. This work requires substantial investments into intensive field operations to reduce the presence of invasive plants and animals, eliminate wildfire risk through ignition prevention and fuel-reduction treatments, and mitigate drought events through anticipatory management. These interacting threats—invasive species, fire, and drought—impact most of HAVO's diverse ecosystems.

PWW is managed by the DLNR's Division of Forestry and Wildlife and contains over 14,164 ha of land on leeward Hawai'i Island [10]. Land managers are responsible for the protection and restoration of 24 federally listed threatened and endangered species, many of which are Hawaiʻi or Hawaiʻi Island endemics. Elevation ranges from sea level to 1981 m near the summit of Hualalai Volcano, and the unit is comprised of highly diverse dry and mesic forest as well as extensive areas of non-native and fire-prone dry grassland [10]. The unit regularly experiences severe drought [4], which, in combination with elevated fuel loads created by widespread non-native and invasive grasses and shrubs, greatly increases the risk of wildland fire. PWW contains a fenced Forest Bird Sanctuary to support populations of native birds, sustains non-native dominated rangelands used for livestock grazing, and supports a community-based subsistence forest area [10,11], hunting and other forms of public recreation.

The MKWP was formed in 1998 and includes federal, state, and private partners. It comprises over 20,000 ha of forested land on the island of Maui, with elevations spanning from sea level to 1764 m [12]. The MKWP contains over 9000 ha of critical habitat for endangered plants, with managers being responsible for protecting 30 federally listed threatened and endangered species and 146 rare species [12]. In addition, managers work to reduce the cover of invasive plants and control invasive animals, lead water and watershed monitoring, and engage wildfire prevention and awareness—especially important given that the dry leeward slopes and surrounding dry lowlands are particularly drought- and fire-prone.

2.2. Partner Engagement

The pilot partners were engaged in a knowledge-exchange process at the conceptualization stage of the PDKE project by directly contributing to writing of the PI-CASC funding proposal that supported this work. Upon receiving the funding, partners were notified, expectations and outcomes were developed, and actions and associated timelines were agreed upon. In February 2020, we held our first official in-person meetings with resource managers at HAVO and with resource managers and community members at PWW. In March 2020, due to COVID-19 travel restrictions, a virtual engagement was held with MKWP resource managers. During these meetings, the partner-groups were introduced to project objectives, shown preliminary site-specific data products, after which question and answer and conversations led to initial collaborative identification of specific goals and objectives for a co-production process. Leading up to and during these meetings, managers were asked to describe the actions they take before, during, and after drought, to continue the lessons learned conversations initiated by Frazier et al. (2019). Managers were also asked to identify perceived data needs and drought-related questions for consideration by the team. Meeting notes, taken by the PDKE team, were summarized and shared with partners for feedback. Subsequent follow-up meetings were held virtually with partners on a regular basis between April 2020 and May 2021.

2.3. Climate Change, Climate Variability, and Drought (CCVD) Portfolios

The comprehensive CCVD portfolio provided to partners after the initial engagement contained site-specific climate information extracted from available databases for partner land management areas. Data in the CCVD portfolios included: mean values of diverse climate variables; annual climate cycles; a 100-year (1920–2019) monthly rainfall and associated drought history analyses including year-to-year rainfall variability; and syntheses of dynamically and statistically downscaled future projections for rainfall and temperature under two modeled forcing scenarios for mid- and late-century. Co-production occurred through iterative review and revision, including fine-tuning the spatial extent and scale of the data products in the CCVD portfolios to best support management needs for a specific sub-geography or sub-geographies within the larger management unit.

2.3.1. Historical Climate Data

A range of available gridded climate products were utilized for this project. Mean annual and monthly rainfall (1978–2007) values were obtained from the Rainfall Atlas of

Hawaiʻi [13], which is the most comprehensive and widely used mean rainfall product in Hawaiʻi. Mean annual and monthly temperature, solar radiation, relative humidity, soil moisture, evapotranspiration and cloud fraction were obtained from the University of Hawaiʻi Geography Department's Climate of Hawaiʻi website [14]. Daily rainfall values were obtained from published gridded data products available from 1990 to 2014 [15], and extracted values were used to calculate daily statistics, including: consecutive dry days (CDD), annual CDD events, and CDD events over time. A CDD is defined as a day where accumulated rainfall was less than 0.04 in (1 mm). CDD events are defined as periods with >10 CDD's. Linear trends (1990–2014) were calculated at three different CDD thresholds (5–9 CDD, 10–19 CDD and >20 CDD); least-squares linear regression was used to determine the strength (R^2) and significance (p-value) of identified trends. Monthly rainfall data are extracted from a 100-year gridded time series (1920–2019) [16,17]. Linear trends were calculated annually and for 6-month wet (November to April) and dry (May to October) season rainfall for five different starting years (1920, 1940, 1960, 1980, and 2000) and one common end year (2019).

Individual climate station data were also utilized in this analysis. A combination of monthly [16,17] and daily [18] rainfall datasets were analyzed to identify climate stations located either within or in close proximity to management areas. Information included station name, observing entity, status (active or discontinued), period-of-coverage, completeness of the record, and accessibility of data, all of which were provided to the managers (Table 1).

Table 1. Data sources used in the creation of climate change climate variability and drought (CCVD)) portfolios.

Variable	Data Type	Date Range	Author	DOI/WWW
Mean RF	Gridded	1978–2007	Giambelluca et al., 2013 [13]	10.1175/BAMS-D-11-00228.1
Monthly RF	Gridded	1920–2012	Frazier et al., 2016 [16]	10.1002/joc.4437
Monthly RF	Gridded	1990–2019	Lucas et al., 2022 [17]	10.1175/JHM-D-21-0171.1
Mean TA, RH, ET, S, CF, &SM	Gridded	~1990–2012	Giambelluca et al., 2014 [14]	http://evapotranspiration.geography.hawaii.edu/ accessed on 11 July 2022
Daily RF	Gridded	1990–2014	Longman et al., 2019 [15]	10.1175/JHM-D-18-0112.1
Daily RF	Point	1990–2014	Longman et al., 2018 [18]	10.1038/sdata.2018.12
Mean Future RF	Gridded	2040–2070	Elison-Timm et al., 2015 [19]	10.1002/2014JD022059
Mean Future RF	Gridded	2080–2100	Elison-Timm et al., 2015 [19]	10.1002/2014JD022059
Mean Future RF	Gridded	2080–2100	Zhang et al., 2016 [20]	10.1175/JCLI-D-16-0038.1
Mean Future TA	Gridded	2040–2070	Elison-Timm et al., 2017 [21]	10.1002/joc.5065
Mean Future TA	Gridded	2080–2100	Elison-Timm et al., 2017 [21]	10.1002/joc.5065
Mean Future TA	Gridded	2080–2100	Zhang et al., 2016 [20]	10.1175/JCLI-D-16-0038.1

Where RF is rainfall, TA is near-surface air temperature, RH is relative humidity, ET is evapotranspiration, S is shortwave downwelling radiation, CF is cloud fraction, and SM is soil moisture.

2.3.2. Drought Calculations

Gridded monthly rainfall data from 1920 to 2019 [16,17] were used to calculate the standardized precipitation index (SPI) [22], globally one of the most widely used indices to identify and describe drought events [23]. The SPI compares precipitation with its multi-year average, and because droughts are generally defined relative to the local normal, this standardized index allows wet and dry climates to be represented on and so compared via a common scale [24]. The SPI is based solely on precipitation and allows the user to calculate drought levels for different time scales, which can reflect different types of drought including meteorological, agricultural, and hydrological drought [4] (The 12-month SPI (SPI-12) was utilized to assess long-term droughts at each site, which can provide information about Hydrological Drought, and the 3-month SPI (SPI-3) to assess short-term droughts, which is related to Agricultural Drought [6]. SPI-3 is also compared with five different phases associated with the El Niño-Southern Oscillation (ENSO) based on the Multi-variate ENSO Index (MEI [25] (strong and weak El Niño, strong and weak La Niña, and neutral).

The United States Drought Monitor (USDM) is a hybrid index that combines station-based SPI and other indicators [26]. The USDM is updated weekly and contains maps that classify drought magnitude into four categories of severity, as well as a narrative of current meteorological conditions and impacts. In this study, all available USDM data (2000–2020) for a given spatial unit in the three pilot geographies were averaged, and drought periods and severity categories were identified across the entire record. We also categorized the frequency of occurrence of each drought type over time. Other site-specific ecological data included threatened and endangered species maps [27] and fire risk based on a gridded estimate of historical fire occurrence within and in adject areas [28,29].

2.3.3. Future Climate Projections

General Circulation Models (GCMs), also called Global Climate Models, produce future projections of rainfall and temperature under multiple future greenhouse gas (GHG) scenarios. These forcing scenarios, also referred to as representative concentration pathways (RCPs), are used as input data for GCM simulations of the Earth's climate, with the two most common being RCP4.5 (reduced emissions) and RCP8.5 (high emissions). GCM output, typically with a spatial resolution of between 1° to 2.5°, is too coarse to accurately project changes in rainfall and temperature for areas with complex topography, including the small mountainous islands in the Pacific. Therefore, downscaling methods are used to relate global scale data to the local scale. Hawai'i is rarely included in national downscaled datasets, and therefore relies on a limited number of results from individual modeling groups. Here we utilized two different downscaled projections to obtain site-specific future projections of rainfall and temperature for the study sites in Hawai'i. Dynamical downscaling products are finer resolution (e.g., 1 km^2), and are created by feeding GCM output into a regional climate model (RCM) that better accounts for local topographic and atmospheric phenomena. Statistical downscaling products are created by developing a relationship between large-scale predictors and station data for a historical period and applying that relationship to GCM outputs for making future projections. We utilized end-of-century dynamically downscaled climate projections (2080–2099) for RCP4.5 and 8.5 [20]. This product is based on a tailored Hawai'i RCM [30]), and results were produced for 1 km horizontal resolution [20]. A simple delta-change bias-correction method [31] was applied to the rainfall projections to correct model outputs towards the observations (for the period 1990–2009). We also utilized mid-century (2040–2070) and end-of-century statistical projections (2070–2099) for RCP4.5 and RCP8.5 [19,21].

2.4. Factsheets and Other Products

The PDKE team worked collaboratively with individual partners to develop factsheets, presentations, webinars, and other relevant outreach and education resources. Additional peer-reviewed literature was also used to support the production of these resources. A graphic designer was contracted to professionally design the factsheets including collaborative development of original artwork and figures. The team did not enter the partner engagements with a pre-determined set of products or product designs, and instead worked with the managers to identify site-specific needs for tailored data products.

3. Results

The PDKE team met individually and regularly with resource managers at HAVO and PWW over the course of the project period, and less frequently with MKWP staff. For HAVO and PWW, meetings focused on refining and finalizing the CCVD portfolios, developing associated data products, and disseminating information to larger audiences within and outside of partner organizations. While all three partners showed interest in engaging a co-development process for generating drought-related products, engagements were more extensive and intensive with HAVO and PWW. In contrast to in-person kick-off meetings with HAVO and PWW, COVID-19 became a concern in early 2020, and so a virtual kickoff meeting was held with resource managers at MKWP in March, with one follow up meeting in July 2020. Despite reduced opportunities for engagement, MKWP was provided with a CCVD portfolio for their entire land management area and technical assistance on how to use and interpret the content. Due to the more involved co-production process with HAVO and PWW, we focus on these two efforts in the next two sections of this manuscript.

The final comprehensive CCVD portfolio is the product of interactions between the members of the PDKE team and resource managers. One of the first challenges of the CCVD process was translating the data to a meaningful scale. While some larger-scale data are useful to visualize and analyze at the whole unit level, most management activities take place in smaller units that are prioritized for and so receive most management investments—for example, the Fire Management Units (FMUs) in HAVO. These smaller areas are both more tractable for planning by resource managers and more homogenous with respect to climate variables captured in the portfolios. As all gridded products utilized in these analyses have a spatial resolution of 250 m, there is still an opportunity to use the products to capture smaller scale spatial variability across these smaller management units designed to address specific management objectives. For HAVO, resource managers decided that using an existing delineation of FMUs, which are based on vegetation characteristics, would be useful for diverse management applications. In some cases, FMUs contained lands that were not contiguous or spanned significant climatic or vegetation diversity, requiring additional disaggregation into what are now referred to as Climatic Sub-Units (CSU). For PWW, we worked with resource managers to develop a different approach as there were no pre-defined management CSU scale delineations in this area. To establish CSUs for PWW, we worked with managers to identify established land divisions of interest (e.g., Kiholo State Park, the main Pu’u or cinder cone that is located in the east part of the unit, and the Forest Bird Sanctuary), and several other sub-units based on mean annual rainfall obtained from the gridded climatology [13]. In total, 12 CSUs are identified for HAVO, and 9 CSUs were identified for PWW (Figure 2).

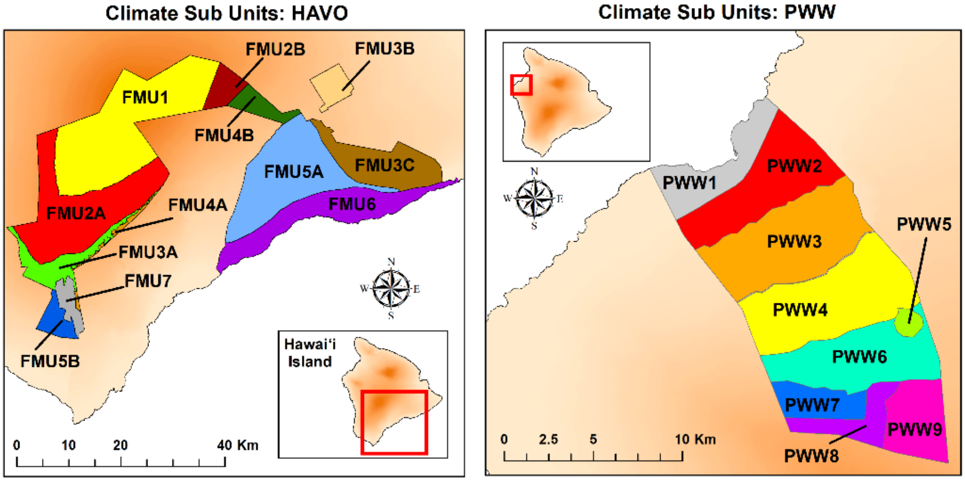

Figure 2. Climate sub-units (CSU) identified for Hawai‘i Volcanoes National Park (HAVO; **left**) and Pu‘uwa‘awa‘a (PWW; **right**), both on Hawai‘i Island.

Resource managers identified ways that CSU-scale information would be useful for informing on-the-ground management activities, for example the timing of weed control or fuel-reduction treatments. They also expressed interest in how to use finer temporal resolution data to address operation questions—for example, the timing of outplanting during restoration. We refer to this scale as the planting sub-unit (PSU) scale. The PDKE team worked with managers to identify specific projects that could be addressed or improved with PSU scale data. By utilizing temperature and rainfall projectionsresource managers can use data products to identify suitable candidate sites for outplanting and stewardship activities.

An example of this targeted PSU approach involved working with HAVO resource managers to identify suitable times for outplanting the endemic Āhinahina or Mauna, Loa Silversword (*Argyroxiphium kauense*). The co-production process is demonstrative of the operational relevance of our knowledge-exchange efforts because the Silversword is extremely sensitive to even small variations in climate [32]. Concerned with efficiently directing resources to specific PSUs, resource managers were interested in identifying the rainfall and temperature thresholds for species of concern to better inform conservation and restoration decisions, which we supported by identifying seasons with the lowest likelihood of short-term drought. At PWW, resource managers are utilizing information at the CSU and PSU scales to develop a community-based subsistence forest area (P-CBSFA) stewardship plan [10,11] for the PWW cone to help them understand which plants may do best under projected future climate for this area and which may be negatively impacted by changing climate. This engagement is also supporting efforts to understand where, for example, climate envelopes for tropical mesic forest may transform into a drier climate envelope more suited to tropical dry forest, and how such changes could affect culturally and ecologically important plant species being selected for biocultural restoration.

Outputs from our analyses are being used to inform decisions about what, where, how, and when to plant, for example by integrating statistically determined probabilities for inter-annual variation in climate. In total, three PSUs were identified for HAVO, and four PSUs were identified for PWW (Figure 3).

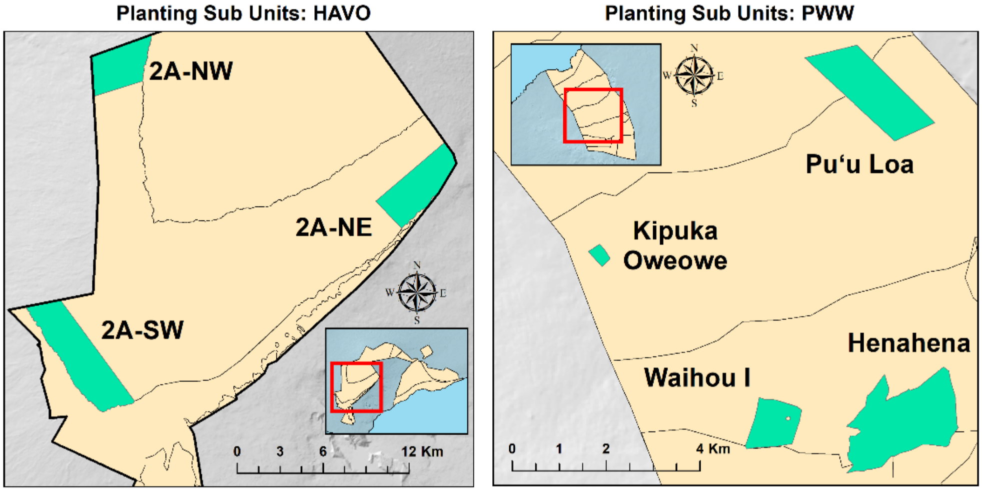

Figure 3. Planting sub-units within climate sub-units identified for Hawai‘i Volcanoes National Park (**left**) and Pu‘u wa‘awa‘a (**right**), both on Hawai‘i Island.

Our engagement with resource managers with HAVO and PWW led to the development of a series of factsheets for these geographies, which included information obtained from the CCVD portfolio process from existing literature and through consulting with partner staff and other experts. The PDKE team worked closely with a graphic designer and each partner to co-develop factsheets covering four topics with the following titles: (1) The Impacts of El Niño, (2) Future Climate Projections, (3) Historical Drought Occurrence, and (4) Fire Occurrence and Risk. Factsheets at the two sites were developed for different purposes. At HAVO, resource managers were most interested in developing the factsheets for staff trainings. There was additional interest in using them to raise public awareness during a visitor's experience in the park. Emphasis was placed on presenting the information in a way that highlighted the need to address climate stressors without causing despair in the face of what can seem to be overwhelming stewardship challenges. HAVO plans on using the figures from the factsheets to build out web-based climate resources.

At PWW, managers are most interested in using the factsheets to raise community awareness, especially with respect to drought and fire risk, which are persistent and dominant challenges to restoration of this tropical dry landscape. Resource managers at PWW are engaged with several community groups that promote environmental stewardship and which are actively engaged in education and outreach activities in the area. For these individuals, the factsheet process involved the iterative exchange of ideas over several months. Each factsheet underwent multiple internal reviews by diverse audiences including community members. The PDKE team and managers worked with the graphic designer to develop original artwork and figures to capture site-specific concerns and feedback on topographical features, flora, and fauna.

4. Discussion

In this paper, we document how formation of the PDKE has developed approaches that enable knowledge co-production and exchange with important conservation partners in Hawaiʻi. We illustrate how our co-production model works in practice by analyzing interactions with three partners, two of whom became strongly involved in an extended and diverse co-production process. We note that this co-production process was affected by what were dramatic COVID-related changes in field and office operations, which affected pilot partners and the PDKE team. Despite this global-scale organizational disruption, the PDKE team adopted a virtual approach that allowed the team to maintain clear and regular communication with HAVO and PWW resource managers. In turn, virtual communications allowed resources managers to efficiently invest time and energy to support co-production of the various described products. In contrast, managers with MKWP had less time for supporting co-production, but still received and utilize PDKE products. Critically, the PDKE team had previously worked with the HAVO and PWW partners [4]), and this previous work could have been the driver for their higher level of engagement. This difference among partners may indicate the importance of developing relationships among researchers and managers, and that the strength of these partnerships may indicate the promise of successful co-production [33]. Conversely, the PDKE team realized a wide range of co-production approaches reflecting different degrees of engagement, which previous studies have described as: contractual, consultative, collaborative, and collegial [34]. Each of these levels can support co-production objectives, and not having expectations about degree of engagement allowed the PDKE team to be flexible and adaptive.

One of the lessons learned through the pilot project was the importance of communicating responsibilities and time commitments with potential new partners at the onset of engagement. While obvious, the more time that managers were able to spend engaging in co-production, the more diversified and tailored the outputs became. For HAVO and PWW, much of the co-production process involved narrowing the geographic focus of the portfolios from the entire stewardship area (e.g., all of HAVO) to CSUs, and ultimately PSUs of particular interest to managers. While looking at landscape-scale data was useful, especially for education and outreach purposes both within the organizations and for outfacing communications with the public, managers were keenly concerned with how management actions could be influenced at the sub-unit scale. Having discussions about geographic scope/scale as well as the location of ongoing and proposed stewardship activities helped to guide data acquisition, processing, and development of visualization graphics.

Co-production of the CCVD portfolios required determining which data and at what scale data were most relevant to meeting individual partner needs. Viewed superficially, this detailed process conflicted with a longer-term goal of efficiently producing CCVD portfolios. However, co-production resulted in portfolios of greatest value to managers, with ownership of the portfolios being more evenly distributed among team members. We did however work to increase efficiencies. Initially, CCVD portfolios were generated individually with figures compiled by hand into a PowerPoint presentation. As the project progressed, we developed an automated approach to produce portfolios and so increase ease of modification and application to new sites. This increase in utility also led to more consistent formatting and easier production but limited the amount of data that could be included for a given site, complicating automated products for sites with different data needs occurring at different scales. As the PDKE began to scale-up with new partners, initial discussions increasingly involved identifying which data are important and should be included in the site-specific portfolios.

A common theme in CCVD portfolio development has been to directly ask decision makers what type of information they need to address their management actions [35]. This approach relies on the decision makers being willing and able to articulate this need [36]. In this study we found that identifying quantitative and qualitative data that could be used for management decisions and outreach required both direct and indirect approaches. In some instances, managers were able to communicate exactly what they needed, while in other instances, the PDKE team shared a range of products and potential ways to interpret and visualize data. Overall, we determined that the creation of decision-relevant metrics required a mix of direct and indirect engagements to capture the data and information needs of the partners and translate them into useful and meaningful products.

The PDKE improved communication mechanisms through a formalized and iterative feedback process between researchers. The mechanisms for information exchange included: (1) regular virtual meetings to discuss project goals and manager needs; (2) a smooth transfer of science and information that directly addresses management and policy needs (e.g., factsheets and CCVD portfolios); (3) organized information with clear explanations, (4) the creation of opportunities for one-on-one practitioner–researcher exchanges that address issue- or site-specific needs, and the establishment of a centralized clearinghouse of drought-related knowledge and information (http://www.soest.hawaii.edu/pdke/ accessed on 11 July 2022). The PDKE team has effectively built a collaborative information-transfer environment by bridging across multiple agencies and entities to improve coordination on the delivery of climate change, climate variability, and drought-related information to users. To date, we have built a strong partnership that includes a wide range of local, regional, and national organizations.

The knowledge products produced during the PDKE pilot have already been utilized by resource managers at the pilot sites. At HAVO, information on consecutive dry days was used to determine optimal planting times for an endemic species, while other climate information has been incorporated into an Environmental Assessment that is currently in preparation. At PWW, the CCVD portfolio was used in a climate adaptation planning workshop and information for one of the CSUs was incorporated into the natural resource section of a land stewardship plan which was developed in 2021. Factsheets from both sites are currently being translated into ʻŌlelo Hawaiʻi (the Hawaiian language) for use by cultural organizations and Hawaiian language-immersion charter schools, and to normalize the use of ʻŌlelo Hawaiʻi (Hawaii's other official language) within conservation and restoration.

The information within the CCVD portfolios is also valuable for use in decision support, for example, via scenario planning [37,38] whereby manager–researcher teams evaluate a range of future scenarios in order to understand risks and prioritize management actions in the face of uncertainty [39,40]. Scenario planning techniques are increasingly being used by managers as a climate change adaptation tool when uncertainty is high and when multiple competing climate models predict a set of plausible, but divergent, possible futures [41,42]. Given the high uncertainty in future climate, especially rainfall projections in Hawaiʻi where small land area makes predictions difficult [19,20,43], the PDKE CCVD portfolios add critical information as raw material to support important conservation and restoration planning discussions.

Within international science and policy, there is a growing expectation that shifting towards co-production will enable science to have greater impact on sustainable development outcomes [44]. The co-production of knowledge can also lead to more actionable science by engaging partners to share in its design and implementation, with a shared and informed goal of achieving better outcomes for society [45]. To this end, and more broadly, the PDKE is addressing several of the United Nations sustainable development goals (SDGs), especially the goals aligned with natural resource management [46]. The PDKE directly supports SDGs by equipping managers with the best available science and tools to perform various activities to improve watershed protection, enhance freshwater security, control invasive species, and restore native species.

The PDKE was successful in creating a formal, iterative communication and co-production process to foster next-generation knowledge exchange between the research community and resource manager user groups, thereby expanding the utility of research on climate and drought. The benefits of this enhanced knowledge co-production and exchange for the effectiveness of conservation and restoration actions in the drought prone often dry and mesic landscapes of Hawaiʻi and the USAPI will require multiple years to evaluate. However, we attribute initial successful co-production to the well-developed and ongoing relationships between scientists and partners, which have ensured two-way communication and helped to maintain a focus on the utility of data products and the efficiency of their production. Partner enthusiasm provides an important metric for the success of this pilot project and provides motivation for expanding this work.

5. Conclusions

Given the lessons learned provided by our partners, we have a clear direction for advancing PDKE efforts into the future, including: (1) the establishment of a formal alliance-focused governance structure for PDKE operations that brings together various partners interested in leading drought knowledge exchange in the region; (2) an update to the CCVD portfolio that incorporates new data from the Hawaiʻi Climate Data Portal (HCDP; [47] (3) the development of a website where products can be assimilated for easy access and dissemination; (4) scaling up the pilot to include more partners in Hawaiʻi; and (5) extending PDKE efforts into the USAPI and eventually the broader Pacific, so that data, information, and lessons learned can be exchanged across the Pacific Basin. While co-production has been shown to have high transaction costs in terms of money, time, and commitment that complicates efforts to scale up [48], in the case of the PDKE, these investments have resulted in high degree of data utilization. The development of an automated approach to the CCVD portfolio has enhanced efficiency and so lowered costs, and created a mechanism by which many partners can see immediate benefits of engagement. This entry point can set the stage for next steps. Further, numerous lessons learned, reflected in newer versions of the CCVD portfolio, are passed directly to new partners, which can help streamline future engagements. It is too soon to evaluate the extent to which resource managers will be able to utilize PDKE data products for adapting to andmitigating against drought.

To meet the PDKE objectives, we are developing a formal alliance-based organizational model that is designed to guide future activities. The most immediate next steps will be continued engagement with key partners to synergize co-production and deliver drought-related information to the region, including: the Pacific Islands Climate Adaptation Science Center (PI-CASC), the NOAA National Integrated Drought Information System (NIDIS) and Regional Integrated Sciences and Assessments (RISA), the USDA Southwest Climate Hub (SCH) including the USDA Forest Service and National Resource Conservation Service (NRCS), and other regional and local partners. The development of a formal alliance will bring together a range of regional, national, and state agencies that can provide both financial and technical support to the PDKE team. The PDKE team also plans on using lessons learned from the pilot project to improve on services and products in future stakeholder engagements.

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