10-1-2022

A Century of Drought in Hawaiʻi: Geospatial Analysis and Synthesis across Hydrological, Ecological, and Socioeconomic Scales

Abby G. Frazier
Clark University, afrazier@clarku.edu

Christian P. Giardina
USDA Forest Service Pacific Southwest Research Station

Thomas W. Giambelluca
University of Hawaiʻi at Mānoa

Laura Brewington
Arizona State University

Yi Leng Chen
University of Hawaiʻi at Mānoa

sustainability

MDPI

Article

A Century of Drought in Hawai'i: Geospatial Analysis and Synthesis across Hydrological, Ecological, and Socioeconomic Scales

Abby G. Frazier [1,*], Christian P. Giardina [2], Thomas W. Giambelluca [3], Laura Brewington [4,5], Yi-Leng Chen [6], Pao-Shin Chu [6], Lucas Berio Fortini [7], Danielle Hall [1], David A. Helweg [8], Victoria W. Keener [4,5], Ryan J. Longman [5], Matthew P. Lucas [3], Alan Mair [9], Delwyn S. Oki [9], Julian J. Reyes [10], Stephanie G. Yelenik [11] and Clay Trauernicht [12]

[1] Graduate School of Geography, Clark University, Worcester, MA 01610, USA
[2] Institute of Pacific Islands Forestry, Pacific Southwest Research Station, U.S. Department of Agriculture, Forest Service, Hilo, HI 96720, USA
[3] Water Resources Research Center, University of Hawai'i at Mānoa, Honolulu, HI 96822, USA
[4] Global Institute of Sustainability and Innovation, Arizona State University, Tempe, AZ 85281, USA
[5] East-West Center, Honolulu, HI 96848, USA
[6] Department of Atmospheric Sciences, University of Hawai'i at Mānoa, Honolulu, HI 96822, USA
[7] Pacific Islands Ecosystems Research Center, U.S. Geological Survey, Hawai'i Volcanoes National Park, HI 96718, USA
[8] National Climate Adaptation Science Center, U.S. Geological Survey, Reston, VA 20192, USA
[9] Pacific Islands Water Science Center, U.S. Geological Survey, Honolulu, HI 96818, USA
[10] USDA Climate Hubs, Washington, DC 20250, USA
[11] Rocky Mountain Research Station, U.S. Department of Agriculture, Forest Service, Reno, NV 89509, USA
[12] Department of Natural Resources and Environmental Management, University of Hawai'i at Mānoa, Honolulu, HI 96822, USA
* Correspondence: afrazier@clarku.edu; Tel.: +1-508-793-7524

Abstract: Drought is a prominent feature of Hawai'i's climate. However, it has been over 30 years since the last comprehensive meteorological drought analysis, and recent drying trends have emphasized the need to better understand drought dynamics and multi-sector effects in Hawai'i. Here, we provide a comprehensive synthesis of past drought effects in Hawai'i that we integrate with geospatial analysis of drought characteristics using a newly developed 100-year (1920–2019) gridded Standardized Precipitation Index (SPI) dataset. The synthesis examines past droughts classified into five categories: Meteorological, agricultural, hydrological, ecological, and socioeconomic drought. Results show that drought duration and magnitude have increased significantly, consistent with trends found in other Pacific Islands. We found that most droughts were associated with El Niño events, and the two worst droughts of the past century were multi-year events occurring in 1998–2002 and 2007–2014. The former event was most severe on the islands of O'ahu and Kaua'i while the latter event was most severe on Hawai'i Island. Within islands, we found different spatial patterns depending on leeward versus windward contrasts. Droughts have resulted in over $80 million in agricultural relief since 1996 and have increased wildfire risk, especially during El Niño years. In addition to providing the historical context needed to better understand future drought projections and to develop effective policies and management strategies to protect natural, cultural, hydrological, and agricultural resources, this work provides a framework for conducting drought analyses in other tropical island systems, especially those with a complex topography and strong climatic gradients.

Keywords: drought; Standardized Precipitation Index (SPI); Pacific Islands; El Niño-Southern Oscillation (ENSO); tropical ecosystems; agricultural drought; wildfire

Citation: Frazier, A.G.; Giardina, C.P.; Giambelluca, T.W.; Brewington, L.; Chen, Y.-L.; Chu, P.-S.; Berio Fortini, L.; Hall, D.; Helweg, D.A.; Keener, V.W.; et al. A Century of Drought in Hawai'i: Geospatial Analysis and Synthesis across Hydrological, Ecological, and Socioeconomic Scales. *Sustainability* **2022**, *14*, 12023. https://doi.org/10.3390/su141912023

Academic Editor: Erfu Dai

Received: 9 August 2022
Accepted: 19 September 2022
Published: 23 September 2022

1. Introduction

Drought is a hazardous and costly natural disturbance that affects human populations worldwide [1]. Droughts affect nearly all ecosystem types, from lowland deserts to wet tropical forests [2], and the effects of drought can range from biomass loss and tree mortality in forests [3] to drinking water shortages and economic losses from a variety of sectors including tourism and agriculture [1]. In the tropical Pacific, droughts are often synchronous across vast areas, driven by large-scale modes of climate variability such as the El Niño-Southern Oscillation (ENSO; [4,5]). In the U.S. State of Hawaiʻi, most El Niño events, the warm phase of ENSO, produce atmospheric conditions that are unfavorable for rainfall [6], which results in drier-than-average boreal winter conditions [7–9].

Drought is also a prominent feature of the climate of Hawaiʻi and can cause severe effects across multiple sectors. According to Hawaiian oral traditions, dryland agricultural systems were particularly vulnerable to droughts, with some political upheavals linked directly to devastating droughts [10]. In the recent past, droughts in Hawaiʻi have reduced crop yields, caused the loss of livestock, and reduced streamflow and reservoir water levels. In turn, these changes had driven the depletion of groundwater resources and increased the extent and severity of wildland fire, with damage to terrestrial, aquatic, and nearshore habitats. Collectively, these effects translate into substantial economic losses [11], although a comprehensive economic drought analysis for the state has not been conducted. In response to drought, resource managers can impose water use restrictions, for example through emergency declarations. Droughts, or even dry spells, can contribute to conflicts between agricultural and other instream water users [11]. The severity of droughts is also likely to increase as population growth increases the total demand for freshwater [12] and as air temperature continues to increase [13]. These changes will be compounded by anticipated declines in total annual precipitation [14,15], all combining to intensify the effects of future droughts in Hawaiʻi and exacerbate an already-stressed freshwater supply.

Assessments of historical droughts are fundamental for natural resource planning and management [16,17], especially at the regional and local/municipal scales [18,19]. Due to the multi-sector nature of drought effects, a drought will mobilize actions from freshwater resource managers (e.g., boards of water supply), land managers (e.g., forestry and fire protection, wildlife, and ecosystem restoration), and agricultural (especially rainfed) producers (e.g., ranchers and dryland farmers). Efforts to anticipate and then mitigate the effects of drought require knowledge of historical drought characteristics and clearly understood definitions of drought, with the latter being especially important in planning because the definition of drought can vary among different disciplines. Drought is most often defined as the persistence of a precipitation deficit over a specific region and period of time [20], with other definitions also including the effects of the drought or indicator variables such as evapotranspiration, soil moisture, near-surface-air temperature, streamflow, groundwater level, and vegetation cover [16]. Drought can be classified as falling into one of five categories depending on effects and duration: Meteorological, agricultural, hydrological, socioeconomic, and ecological ([21,22]; Figure 1). The first three types of physical drought typically occur in sequence, while socioeconomic and ecological drought can occur at any point in a drought's progression (Figure 1). Meteorological drought is defined by the degree of dryness and the duration of the dry period. This deficiency of precipitation typically depletes soil moisture, and if a subsequent crop failure results from a lack of precipitation, this is then known as agricultural drought. When dry conditions continue to persist and eventually affect surface water and groundwater supply, this is called hydrological drought. Socioeconomic drought considers the human demand for economic goods and is defined as when societal demand for goods exceeds supply as a result of a weather-related deficit in the water supply. This can also encompass the variable effects of drought on different groups of people, with effects being determined by access to resources and other political factors, and conflicts that may arise over limited resources [23]. A relatively new drought type, "ecological drought", has been defined by Crausbay et al. [21] to characterize the direct and indirect effects of drought on natural ecosystems, with effects ranging from tree mortality [24,25] to increased fire disturbances [26]. In this study, we provide the first comprehensive review of all five drought perspectives for Hawai'i.

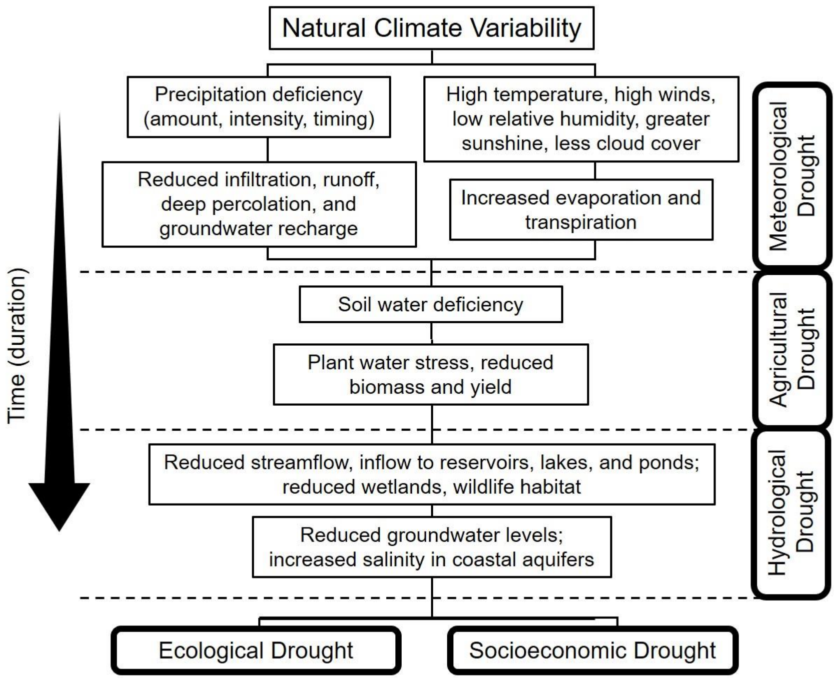

Figure 1. The general sequence for the occurrence and effects of different drought types (adapted from the National Drought Mitigation Center; https://drought.unl.edu/ (accessed on 7 August 2022)).

To facilitate effective communication within and across sectors, drought events are typically characterized by an index that combines numerical indicators into a single value. No single accepted definition, indicator, or synthesized index of drought exists, with more than 100 indices having been developed [20]. Some of the most common indices include the Standardized Precipitation Index (SPI; [27]); Palmer Drought Severity Index (PDSI; [28]); the Standardized Precipitation-Evapotranspiration Index (SPEI; [29]); the Keetch–Byram Drought Index (KBDI; [30]); the Crop Moisture Index (CMI; [31]); and the U.S. Drought Monitor (USDM; [32]). The primary source for monitoring drought in Hawai'i since 2000 is the USDM (https://droughtmonitor.unl.edu/ (accessed on 7 August 2022); Figure 2), a hybrid index that is useful for communicating drought conditions and impacts to the public. However, the relatively arbitrary spatial delineations and categorical drought values, lack of spatial detail, and short record history (only since the year 2000) limit the utility of the product for more localized or longer-term numerical analyses and applications.

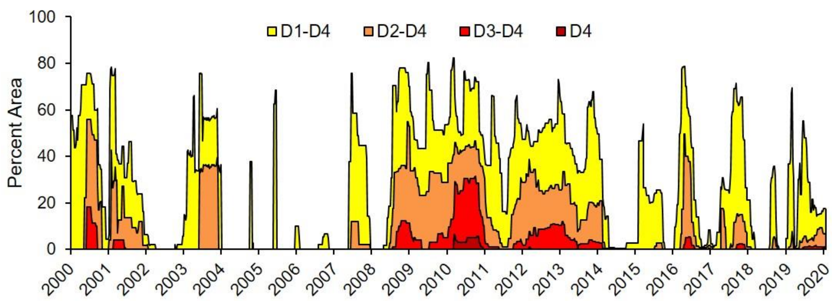

Figure 2. Hawai'i State Drought Monitor percent area time series, moderate drought (D1 category) or worse, from January 2000 through December 2019. D2 corresponds to severe drought; D3 to extreme drought; and D4 to exceptional drought. Data source: https://droughtmonitor.unl.edu/ (accessed on 30 August 2020).

In the last comprehensive drought analysis for Hawai'i, Giambelluca et al. [33] analyzed three meteorological drought indices for the period 1885–1986. The results showed that the most severe drought statewide started in September 1977 and lasted for six months; many droughts were associated with El Niño events and higher-than-normal temperatures. This report has been critical to understanding drought and its effects in Hawai'i through 1990, but the most recent three decades have seen important changes to the climate system (e.g., [13,15]). Further, several new high-resolution gridded climate datasets are now available (e.g., [34–36]), allowing for an updated analysis of historical drought conditions and effects across the State. A comprehensive analysis of drought in Hawai'i can provide information for resource managers to institutionalize the awareness of drought effects and responses to ensure that short- and long-term planning and management will be effective [37].

The objectives of this study are twofold: First, to conduct a comprehensive geospatial analysis of a new 100-year (1920–2019) gridded SPI dataset [38] to characterize historical drought in Hawai'i. Second, to review and synthesize the recent literature documenting droughts and their effects in Hawai'i. The study area of Hawai'i is described in Section 2. Methods are presented in Section 3, and results for the spatiotemporal drought analysis are given in Section 4. Section 5 contains a synthesis of the recent drought literature and a discussion of the relevance of the SPI results for different sectors. Conclusions are presented in Section 6.

2. Study Area

The main Hawaiian Islands are located in the Pacific Ocean between 18.90° N and 22.24° N latitude, and 160.25° W and 154.80° W longitude. This study considered seven of the eight major islands where climate data are available: Kaua'i, O'ahu, Moloka'i, Lāna'i, Maui, Kaho'olawe, and Hawai'i. These islands were grouped into the following four regions for analysis and discussion: Kaua'i, O'ahu, Maui Nui, and Hawai'i Island; "Maui Nui" herein refers to all islands in Maui County (Maui, Kaho'olawe, Moloka'i, and Lāna'i). The climate of Hawai'i is extremely diverse, due in part to the large elevation range (from 0 to 4205 m) and complex topography. Average annual rainfall ranges from 204 to 10,271 mm [39], with some of the steepest rainfall gradients in the world, particularly on leeward slopes (Figure 3). Prevailing surface winds are east-northeast (trade winds), and much of the rainfall is produced through orographic lifting, resulting in wet windward (east-facing) slopes and dry leeward lowlands. Annual rainfall in most areas is characterized by two distinct seasons: A wet season (November to April) and a dry season (May to October). The climate in Hawai'i is also strongly influenced by large-scale modes of natural climate variability, in particular ENSO, the Pacific Decadal Oscillation (PDO), and the Pacific North American (PNA) pattern [7,8].

Many of the early climate monitoring stations in Hawai'i were established on agricultural plantations, as growers required detailed water availability data to maximize crop yields and anticipate responses to rainfall reductions [40]. In 1980, lands devoted to agriculture and pasture lands made up 35% of the total state land area. Over the past 50 years, however, agriculture in Hawai'i has undergone substantial changes, including the closure of these large-scale monocrop plantations, a decline in the amount of actively grazed pastureland (a 31% decline between 1980 and 2015), but a rise in diversified agriculture, and an increase in commercial forestry and biotechnology [41]. With statewide initiatives to increase local food production, Hawai'i's agricultural sector will continue to play an important economic role in the coming decades.

Terrestrial ecosystems in Hawai'i are known for their remarkably high levels of endemism. Given the well-recognized extreme climatic and edaphic gradients, Hawai'i's natural areas contain the majority of Holdridge life zones (bioclimatic zones), spanning tropical rain forests, arid grasslands, and alpine tundra [42]. However, since European contact in Hawai'i, the rate of species introductions has increased one-million-fold above the estimated natural rate, with non-native invasive species resulting in widespread displacement of native species [43]. The combined effects of invasive species, disease, and land cover change have severely affected native plant and animal communities in many areas of the state, resulting in a "biodiversity crisis," with native ecosystems giving way to alien-dominated ecosystems and species endangerment or extinction [44]. These diverse co-occurring threats are being exacerbated by climate change, and any further changes to drought frequency, severity, or duration will likely exacerbate effects on native species, for example, through competitive interactions with non-native invasive species (e.g., [45–47]).

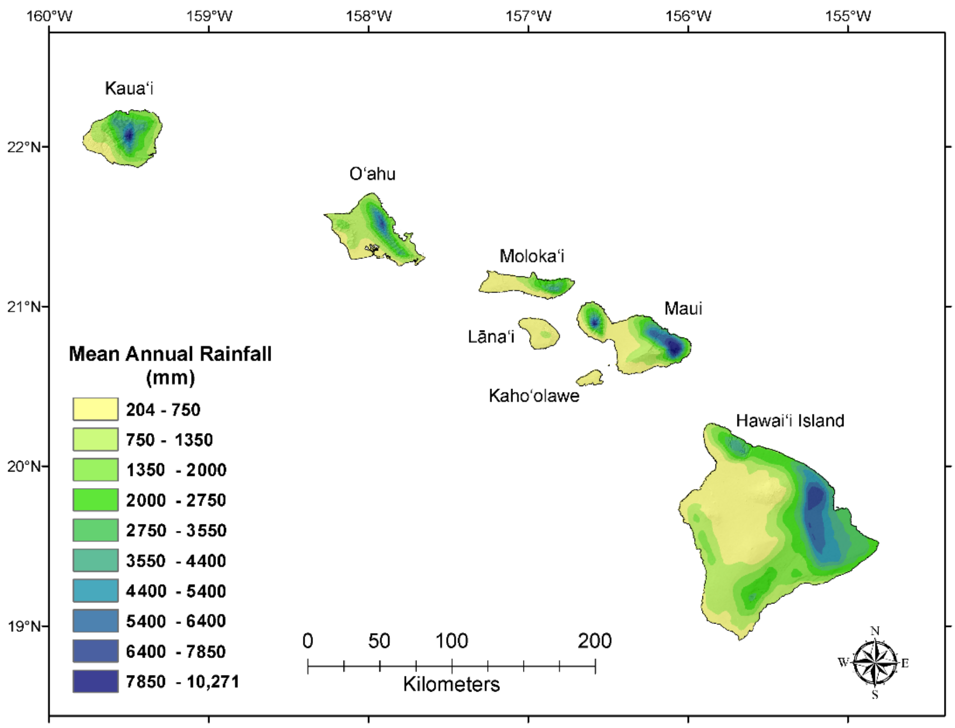

Figure 3. State of Hawai'i's average annual rainfall (1978–2007) in millimeters (http://rainfall.geography.hawaii.edu/ (accessed on 30 August 2020); Rainfall Atlas of Hawai'i [39]). "Maui Nui" refers to all islands in Maui County (Maui, Kaho'olawe, Moloka'i, and Lāna'i).

3. Materials and Methods

In 2011, the World Meteorological Organization recommended the SPI as the internationally preferred index for classifying meteorological droughts [48]. The SPI is based solely on precipitation and compares precipitation with its local multi-year average, allowing wet and dry climates to be represented on a common scale to enable comparisons. It allows the characterization of dryness (and wetness) across different timescales, which can reflect meteorological, agricultural, and hydrological drought effects [27]. A disadvantage of the SPI is that it does not consider other important variables related to droughts, such as soil moisture or potential evapotranspiration (PET; [29]). In Hawai'i, however, neither monthly nor daily gridded data exist for soil moisture and PET, and few stations measure the necessary variables, as calculating PET requires radiation, humidity, and wind speed. Therefore, indices such as the PDSI or the SPEI cannot yet be calculated in Hawai'i. The KBDI, used to monitor fire risk, is currently only calculated operationally at one location, the Honolulu Airport [11], and the State of Hawai'i is not included in many of the products available for the contiguous United States (e.g., CMI).

The input dataset used for the retrospective drought analysis presented here is a new gridded monthly SPI product created for the Hawaiian Islands for the period 1920–2019 [38]. Using a gridded monthly rainfall time series from 1990 to 2012 [34], SPI was calculated for each 250 m pixel by fitting a Gamma distribution to the original rainfall data [49,50]. Gridded results were validated using independent station-based SPI supplied by the National Weather Service and compared with the USDM. Full quality control methods and results are described in Lucas et al. [38]. In 2022, a new set of 250-m-resolution monthly rainfall grids was released for the period 1990–2019 [36]. Using the same methods as Lucas et al. [38], we calculated an updated gridded SPI using the monthly rainfall data from Frazier et al. [34] from 1920 to 1989, and data from Lucas et al. [36] from 1990 to 2019. The gridded SPI dataset (1920–2019) was calculated for 10 different timescales (from one month up to 60 months), where each new value is determined from the previous months. A 3-month SPI in August 1990, for example, compares the June-July-August (JJA) precipitation in 1990 to the JJA totals of all 100 years in the record. For this study, we analyzed the following four SPI timescales: SPI-3, SPI-6, SPI-12, and SPI-24 corresponding to the 3, 6-, 12-, and 24-month SPI timescales, respectively. Most of our results present the SPI-6 and SPI-12, as these span the timescales needed to reflect short-term to long-term precipitation patterns [51].

To examine the spatiotemporal characteristics of the SPI dataset at selected timescales, maps of average SPI by decade were calculated based on the average SPI at each 250 m pixel from 1920 to 2019. To represent drought frequency, we calculated the proportion of months in drought, which ranged from 0 months in a drought up to all months in a drought; these were then converted to a proportion. These drought frequencies were calculated by decade for four different drought category thresholds: SPI < 0 (mild drought), SPI < -1.0 (moderate drought), SPI < -1.5 (severe drought), and SPI < -2.0 (extreme drought).

Drought events were defined as periods during which the SPI values were continuously negative and reached a value of -1.0 or less [27]. The start date of each drought was determined as the date when the SPI values first fell below zero, and the end of the drought occurred when the values changed from negative to positive (after reaching a value of -1.0 or less). Drought events were calculated based on the average statewide and island time series. For each event, the start and end dates were determined, and five classic disturbance metrics were calculated to characterize each event: Duration (the number of months in drought), magnitude (the sum of SPI values during drought), intensity (the magnitude divided by the duration), peak intensity (the minimum SPI value during drought), and maximum spatial extent (maximum percentage of land area with SPI < -1.0 during the event). Droughts were ranked based on each of these five metrics, and the average of these five ranks was calculated to provide an overall ranking of droughts.

To map each drought, bi-variate maps of drought intensity and percent time in drought were produced. To display the maps, the SPI pixels were aggregated to a coarser resolution by averaging 250 m pixel values within 5 km grid cells, and these coarse-resolution raster grid cells were then converted to points. The total percent time in drought at each point location was calculated as the percentage of months in any drought category during the event years. To calculate intensity, first the number of months in each of the four drought categories (mild, moderate, severe, and extreme) was divided by the total number of months in any drought category. A weighted sum of these proportional intensities was calculated to determine the overall drought intensity at each point, with weights assigned as 0.05, 0.15, 0.30, and 0.50 from mild drought to extreme drought, respectively. The total percent time in any drought category during the years identified for each event was used to scale the size of the points, while the weighted proportional drought intensity was used to scale the color of the points.

Drought trends were analyzed by decade from 1920 to 2019, focusing on drought frequency (DF; the number of events per decade), total drought duration (TDD), and total drought magnitude (TDM). TDD and TDM are the sums of the durations and magnitudes of drought events that occurred in the considered period, expressed as the number of months for the duration, and a dimensionless severity score for magnitude [52]. These metrics were calculated based on the statewide and island-wide average time series in 10-year intervals. Linear trends were calculated for each metric over the nine decades using Student's t test at the 95% confidence level. Analysis of DF, TDD, and TDM is preferred to calculating trends on the actual SPI values (e.g., using the December SPI-12 values to represent annual trends), which would provide trends in standardized precipitation rather than drought [52].

To represent the strength and phase of ENSO, the Multivariate ENSO Index (MEI) was used [53]. The MEI was derived from six variables over the tropical Pacific and was chosen because it incorporates more information into a single variable than indices that focus only on sea surface temperatures or atmospheric pressure fields. Scatterplots between MEI and SPI were made for the wet and dry seasons to determine the relationship between ENSO and historical droughts. Seasonal SPI was calculated as the average of the SPI values during wet and dry season months for each year. To examine the relationship between wildfire and ENSO, the maximum area burned [54] was plotted for each ENSO phase, and significance between groups was assessed using the non-parametric Dunn's test [55]. The ENSO phase and intensity in each year were determined from the ranks of the average December-January-February MEI values, as this is when ENSO events are most clearly defined. To differentiate the phases and intensities of ENSO events, the rank method was used [53]. MEI values in the bottom 4% were considered Very Strong El Niño events; 4–10% were Strong El Niño events; 10–20% were Moderate El Niño events; 20–33% were Weak El Niño events; 33–67% were Neutral; 67–80% were Weak La Niña events; 80–90% were Moderate La Niña events; 90–96% were Strong La Niña events; and above 96% were considered Very Strong La Niña events.

4. SPI Analysis Results

The average SPI maps for each decade between 1920 and 2019 indicate strong decadal variability, with wet and dry decades apparent (the 1930s were generally wetter, whereas the 1970s and 1990–2019 were dry) and greater variations in the leeward (western) sides of the islands (Figure 4). Although the average calculated over the entire period would show zero values everywhere, as this is how the SPI is defined, considering individual decades show generally wetter and drier periods over the time series. These temporal patterns are also seen in the statewide average time series (Figure S1), in which several extended dry periods in the latter part of the record are notable in both the short- and long-term drought metrics (across all SPI timescales). For drought frequency, Figure 5 shows maps of the proportion of months in each decade where locations experienced moderate drought or worse (SPI < -1), severe drought or worse (SPI < -1.5), or extreme drought (SPI < -2.0), based on SPI-12. In general, all decades experienced some proportion of moderate drought months, but the last three decades showed a high proportion of both severe and extreme drought months.

A total of 28 statewide droughts were found for SPI-6 (Table S1, Figure 6), and 12 droughts were identified for SPI-12 (Table 1, Figure 6). The two highest magnitude, highest peak intensity, and longest duration droughts for both SPI-6 and SPI-12 were the 2007–2014 drought followed by the 1998–2002 drought (years based on SPI-12, Table 1). The 2007–2014 drought lasted for an unprecedented 91 months, while the second-longest drought persisted for 50 months (1998–2002; Table 1). Based on SPI-6, November and July were the most common months when droughts began, and August was the most common month of drought termination (Table S1). For the SPI-12 series, January was the most common starting month, and no droughts began or ended in the summer months (June–August) (Table 1). The droughts before 1991 align with the droughts identified by Giambelluca et al. [33]; the 1975–1978, 1952–1954, and 1983–1985 droughts (ranked third, fourth, and seventh, respectively, in Table 1) were all identified as some of the most intense and longest-lasting droughts in Hawaiʻi's history [33], although the exact months and ranks differ due to the difference in methods.

For Kauaʻi, Oʻahu, and Maui Nui, the 1998–2002 drought was more severe than the 2007–2014 drought, ranked first (Figures 7 and 8; Tables S2–S5); the 1998–2002 drought ranked second for Hawaiʻi Island (Table S2). The 2007–2014 drought ranked first for Hawaiʻi Island, second for Maui Nui, whereas on the Island of Kauaʻi, this drought ranked fourth and fifth, and on Oʻahu was ranked sixth. Although the 2007–2014 drought had a longer duration and higher magnitude for Maui Nui than the 1998–2002 drought, the latter had a much higher intensity and higher maximum and average percent area in moderate drought or worse (Figure 7, Table S3). The statewide drought ranked fourth, 1952–1954 (Table 1), was more substantial on the islands of Kauaʻi, Oʻahu, and Maui Nui (ranked third, second, and third, respectively) than on Hawaiʻi Island (ranked 10th) (Tables S2–S5).

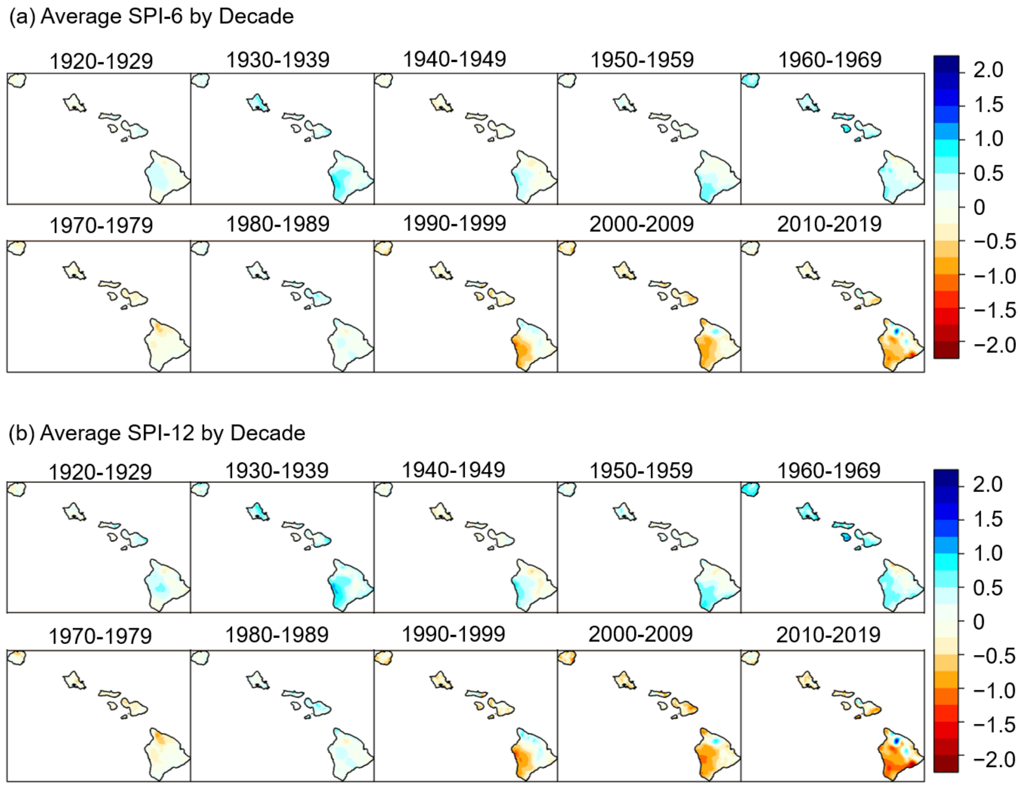

Figure 4. Average 6-month (**a**) and 12-month (**b**) SPI by decade (1920–2019) for the State of Hawaiʻi.

To examine the spatial characteristics of these droughts, maps of the two worst (highest ranking) droughts on record (2007–2014 and 1998–2002, identified based on the statewide overall rank in Table 1) were plotted based on SPI-12 (Figure 8). Both droughts were severe and persistent in leeward areas of the islands. The largest spatial differences between these two droughts were seen in the windward areas of Hawaiʻi Island and Maui, which experienced less time in drought and lower drought severity during the 1998–2002 drought compared to the 2007–2014 drought. For the Islands of Kauaʻi and Oʻahu, the 1998–2002 drought was clearly more severe than the 2007–2014 drought, with both islands experiencing stronger drought intensity compared to 2007–2014 nearly everywhere, and experiencing drought for the majority of the time between 1998 and 2002 (Figure 8).

Decadal DF, TDD, and TDM all showed positive trends statewide for both SPI-6 and SPI-12 from 1920 to 2019 (Figure 9). A considerable increase in drought duration and magnitude occurred in the 1970s, and TDD and TDM continued to increase through the 1990s and 2000s. All statewide trends in TDD and TDM were significant at the 95% level, whereas trends in DF were not significant ($p = 0.08$ for SPI-12). Island-wide decadal DF, TDD, and TDM also increased, but the significance of these positive trends varied by island (Figure 8). TDD trends were significant for every island, and TDM trends were significant for all islands except Oʻahu. Kauaʻi was the only island with significant trends in DF. These results indicate that droughts in Hawaiʻi have become longer and more severe, and on Kauaʻi, also more frequent.

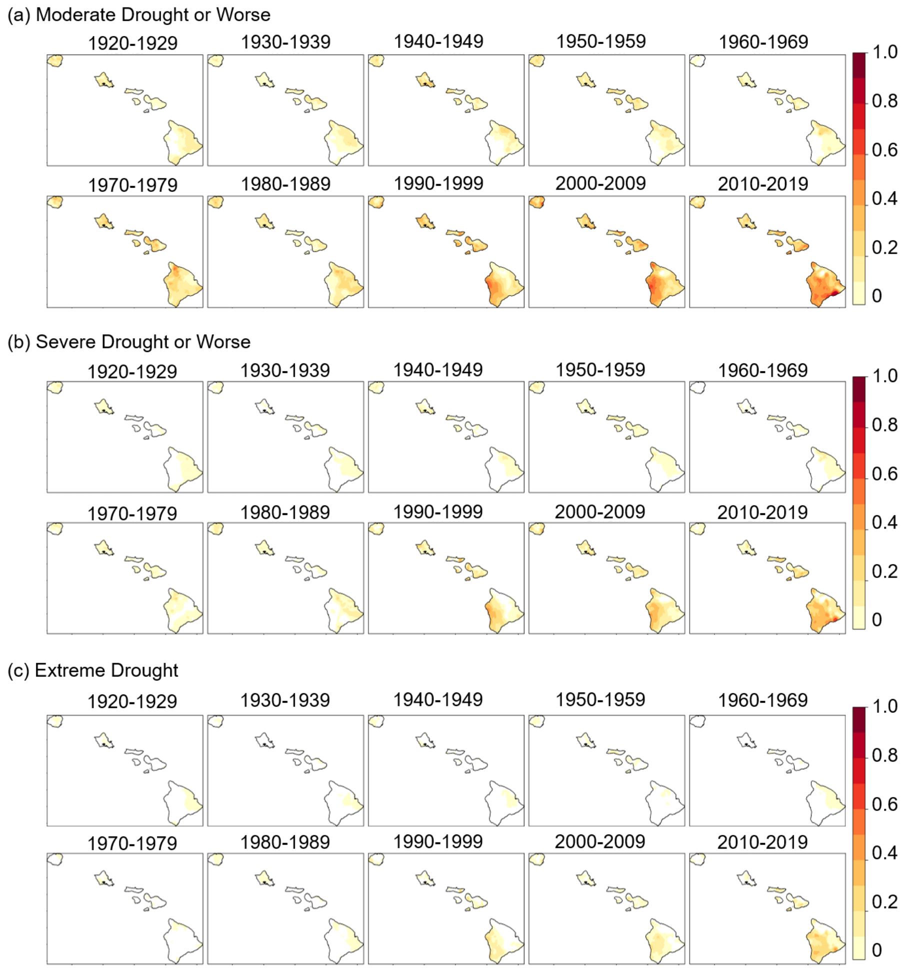

Figure 5. Proportion of months (from 0 to 1) in each decade (1920–2019) where locations experienced (**a**) moderate drought or worse (SPI-12 less than −1); (**b**) severe drought or worse (SPI-12 less than −1.5); and (**c**) extreme drought (SPI-12 less than −2.0). Zero values are shown in white.

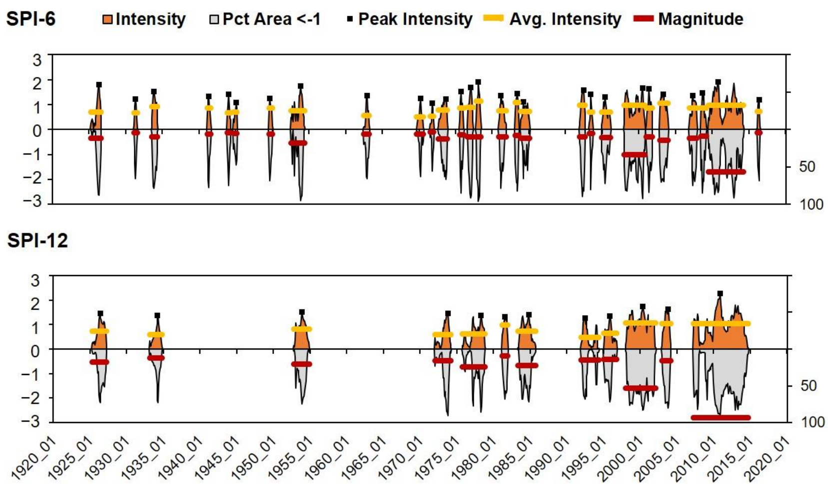

Figure 6. Droughts identified from the statewide average SPI time series (SPI-6, top panel; SPI-12, bottom panel). Intensity (absolute value of SPI values), peak intensity, average intensity, magnitude, and percent area in moderate drought or worse (SPI < −1) are shown for each drought; magnitude and percent area are shown on reverse axis.

Table 1. Statewide droughts (1920–2019) identified by average SPI-12, sorted by overall rank. Overall rank is the average of the ranks of the metrics shown here: Average intensity (absolute value of SPI values), peak intensity, duration, magnitude, and maximum percent area. Maximum percent area is the maximum percent of land area with SPI-12 < −1 during the event (moderate drought or worse).

Overall Rank	Start	End	Avg. Intensity	Peak Intensity	Duration	Magnitude	Max. Pct. Area
1	March 2007	September 2014	1.03	−2.28	91	−93.3	92.4
2	January 1998	February 2002	1.07	−1.73	50	−53.7	83.0
3	September 1975	November 1978	0.62	−1.37	39	−24.2	85.5
4	October 1952	November 1954	0.81	−1.51	26	−21.0	75.0
5	December 2002	February 2004	1.05	−1.63	15	−15.7	80.0
6	January 1972	March 1974	0.59	−1.45	27	−15.8	90.6
7	April 1983	September 1985	0.74	−1.39	30	−22.2	72.4
8	April 1925	March 1927	0.73	−1.45	24	−17.6	73.3
9	January 1995	October 1996	0.65	−1.36	22	−14.2	71.7
10	December 1991	May 1994	0.49	−1.25	30	−14.6	68.1
11	February 1933	October 1934	0.58	−1.36	21	−12.3	72.6
12	March 1981	December 1981	0.98	−1.32	10	−9.8	67.9

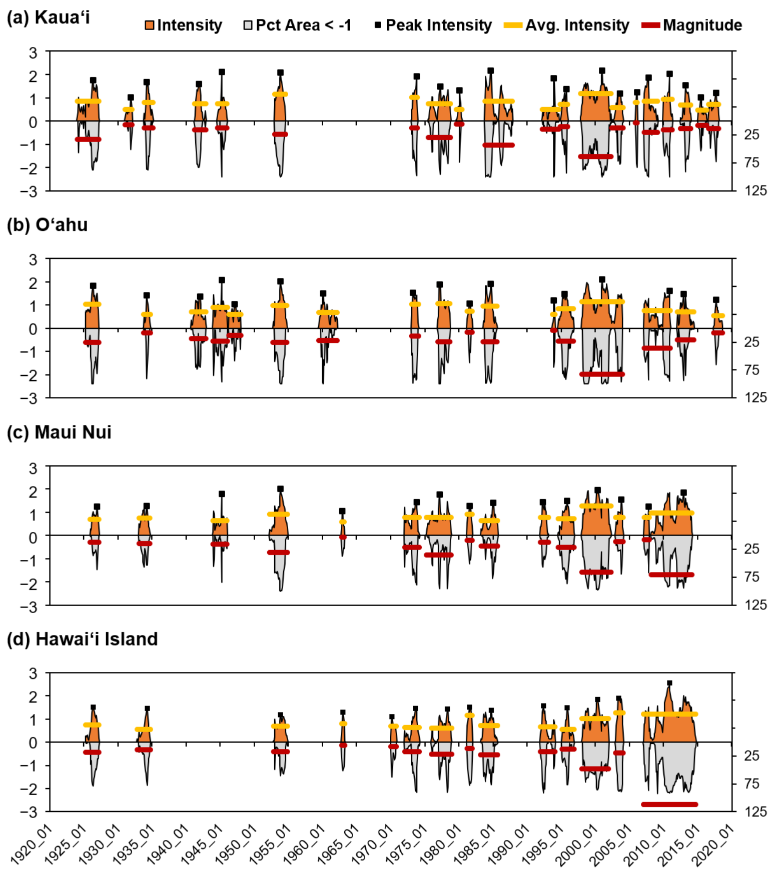

Figure 7. Droughts identified from the island average SPI-12 time series. (**a**) Kaua'i; (**b**) O'ahu; (**c**) Maui Nui; and (**d**) Hawai'i Island. Intensity (absolute value of SPI values), peak intensity, average intensity, magnitude, and percent area in moderate drought or worse (SPI < −1) are shown for each drought; magnitude and percent area are shown on reverse axis.

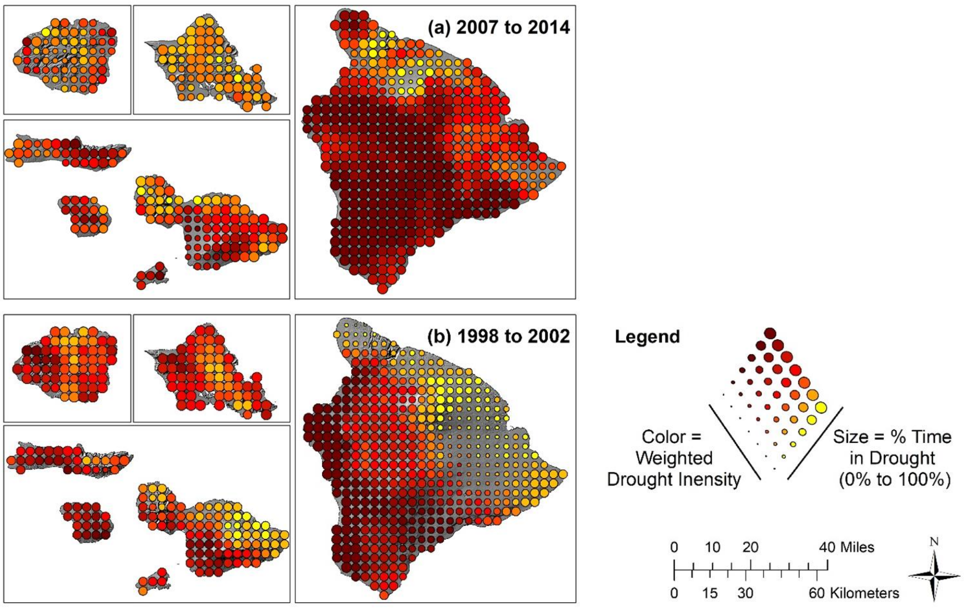

Figure 8. Drought maps based on SPI-12 for the two worst droughts (based on ranks in Table 1): (**a**) 2007–2014; (**b**) 1998–2002. Color indicates weighted proportion of drought intensity (mild drought in yellow to extreme drought in dark red). Size of points indicates proportion of time spent in drought (smallest points: 0–25% time in drought, largest points: 85–100% time in drought during drought years).

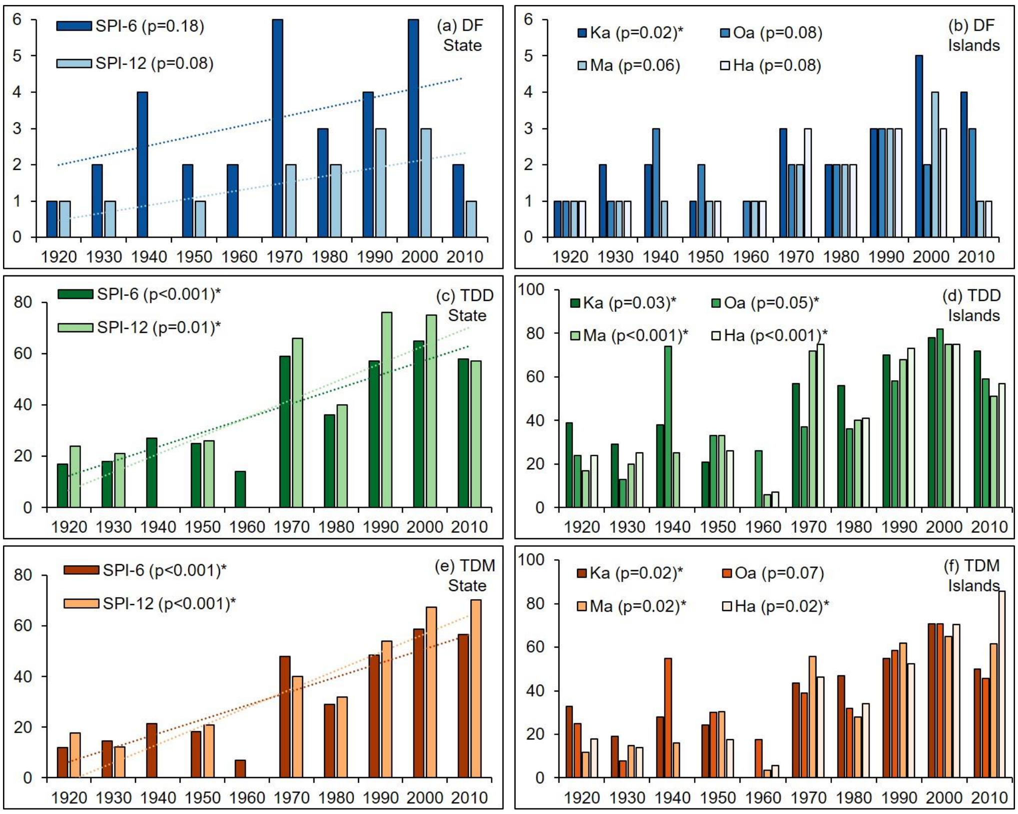

Figure 9. State and island drought frequency (DF; number of events) (**a**,**b**), total drought duration (TDD; number of months) (**c**,**d**), and total drought magnitude (TDM; unitless) (**e**,**f**) by decade from 1920–2019. Statewide trends (**a**,**c**,**e**) are shown for SPI-6 (darker colors, dashed trend line) and SPI-12 (lighter colors, solid trend line). Island trends (**b**,**d**,**f**) are shown for SPI-12; Ka = Kaua'i, Oa = O'ahu, Ma = Maui Nui, and Ha = Hawai'i Island. $p < 0.05$ indicated with asterisk *.

To examine the relation between ENSO and drought, plotting the smoothed MEI time series with the SPI-12 time series showed that many dry periods (negative SPI) were preceded by the onset of El Niño conditions. For example, the 1997/98 El Niño event preceded the 1998–2002 drought (Figure 10). However, not all droughts have been preceded by El Niño events (e.g., 2012–2013 drought conditions), and not all El Niño events have led to droughts (e.g., 1987/88 El Niño). The 2007–2014 drought was associated with a moderate El Niño event in 2009/10; however, the dry conditions began prior to this event and persisted through two La Niña events from 2010 to 2012. The relation between seasonal SPI and the MEI show that wet season (November to April) correlations were negative, indicating that El Niño events were associated with drier-than-average wet season conditions, and La Niña events with wetter-than-average wet seasons (Figure 11). In the dry season months (May to October), the correlations were positive, indicating that ENSO events had the opposite effect on rainfall (El Niño events associated with wetter dry seasons, La Niña events associated with drier dry seasons). It is also notable that the dry season correlations are stronger than the wet season correlations (Figure 11).

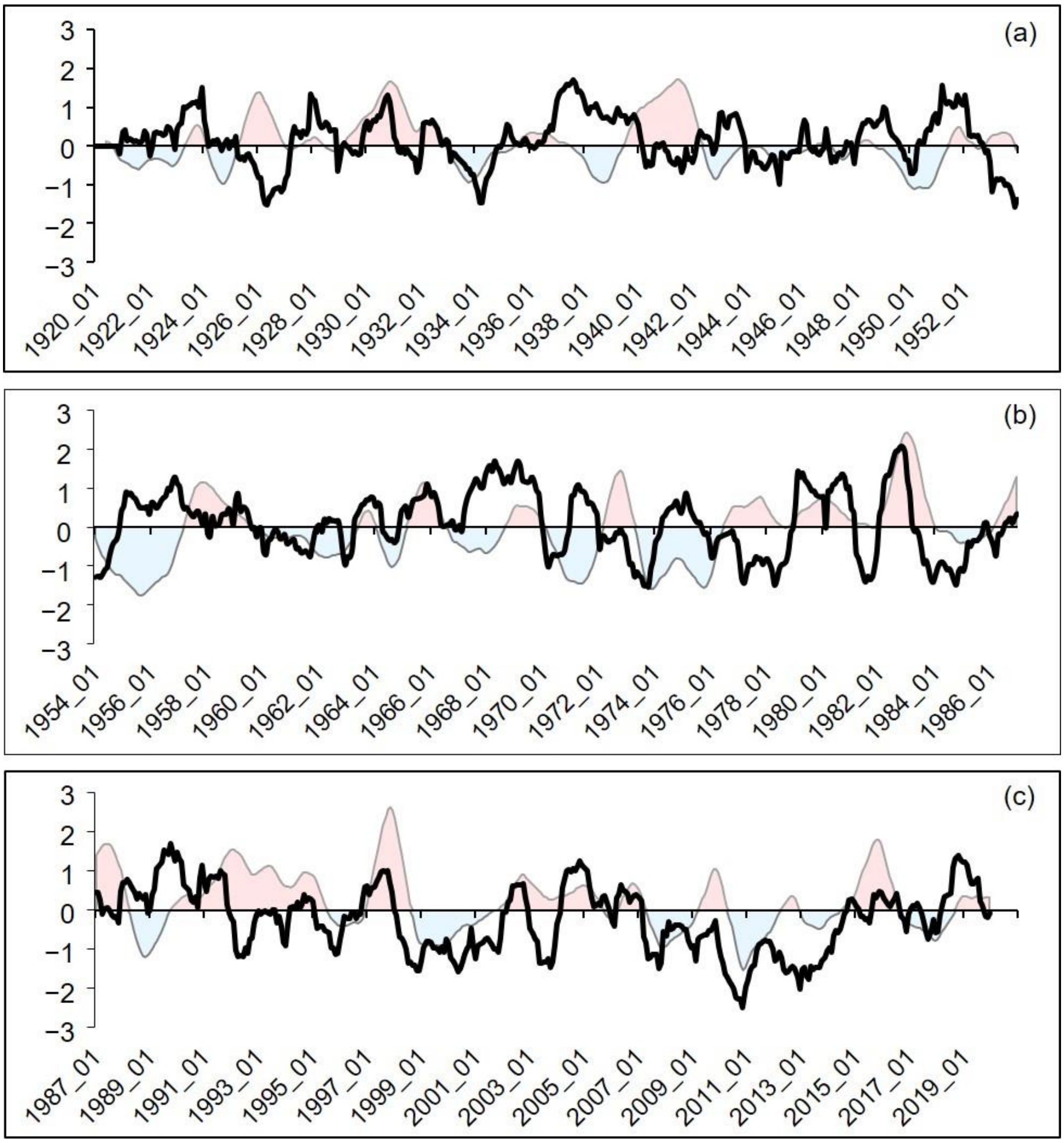

Figure 10. Time series of average monthly statewide SPI-12 plotted with the decadally smoothed MEI time series. (**a**) 1920–1953; (**b**) 1954–1986; (**c**) 1987–2019. Positive MEI (El Niño conditions) are shown in pink, negative MEI (La Niña conditions) are shown in blue.

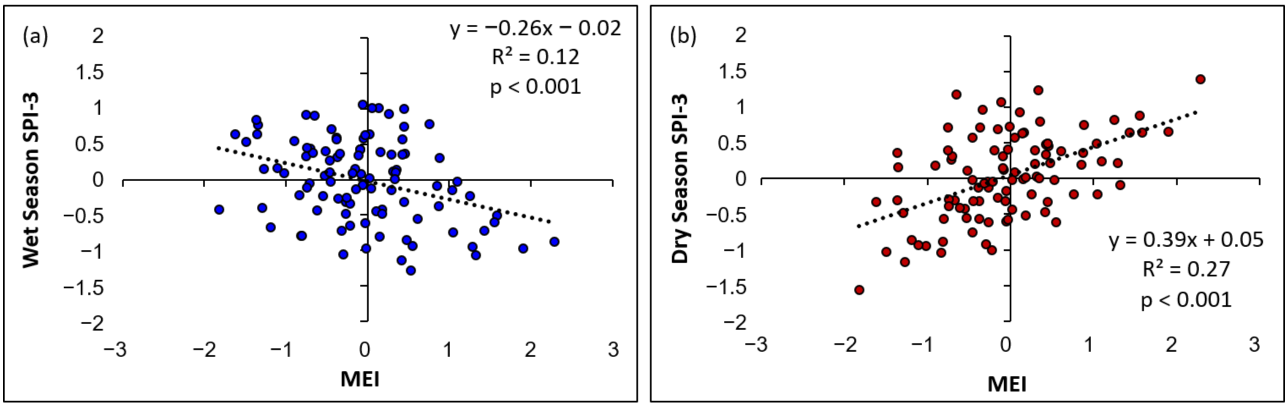

Figure 11. Scatterplots of 1920–2019 (**a**) wet season (November–April) and (**b**) dry season (May–October) SPI-3 plotted with annual MEI (based on the year from July to June of the following year). Positive values of MEI correspond to El Niño conditions, whereas negative values indicate La Niña conditions. Both relationships are statistically significant according to Student's *t* test.

5. Synthesis and Discussion

5.1. Meteorological Drought

The results in Section 4 provide a new spatially explicit drought analysis for the past century. Since the previous meteorological drought analysis by Giambelluca et al. [33], several studies have documented long-term drying trends for Hawai'i in both annual and seasonal rainfall [7,15,56–60]. The years 2010 and 2012 were the driest statewide since formal record-keeping began in 1920 [34], and as we show here, these years were part of the worst statewide drought in the last century (Figure 6, Table 1). Based on a 500-year reconstruction of winter rainfall, a drying trend has also been evident over the past 160 years [57]. Further, a significant upward trend in consecutive dry days has been occurring since the 1950s, particularly in already-dry leeward areas, and the number of rainless days per year has been increasing in high elevation areas [61–63]. Our results show that these trends have been occurring since the 1920s and have persisted through 2019 (Figure 9). Only two previous studies had directly analyzed drought metrics for Hawai'i. Koch et al. [64] spatially interpolated rainfall and temperature maps for the period 1920 to 2007, which were then used to develop different drought products, including annual drought frequency grids for different drought intensity levels (mild, moderate, severe, and extreme). The range of variability in drought frequency was small within each intensity class, although results showed a slightly higher frequency of mild and moderate drought on the leeward sides of most islands. McGree et al. [52] calculated SPI-12 using data from 24 stations in Hawai'i to examine decadal trends DF, TDD, and TDM for the period 1951–2010. Overall, results showed positive but largely non-significant trends in these drought metrics on both the leeward and windward sides of the islands, and similar trends were found across the Pacific Islands region. Our analysis revealed significant increases in these same metrics calculated from the gridded SPI dataset from 1920 to 2019 at the 95% level (Figure 9), indicating that over this longer period, droughts have become detectably more severe and longer lasting.

It has long been recognized that a strong relationship exists between ENSO and wet season rainfall in Hawai'i [7–9,65]. Most El Niño events correspond with above-average dry season rainfall in Hawai'i (Figure 11), due in part to increased tropical cyclone activity [66], followed by below-average wet season rainfall, although again, not all droughts have been associated with an El Niño event [67], and not all El Niño events have led to drought (Figure 10). Conversely, La Niña events typically lead to below-average dry season rainfall and above-average wet season rainfall (Figure 11), although a 40-year drying trend in La Niña wet season rainfall in Hawai'i is now evident [60], which could help explain the weaker correlations found between ENSO and wet season SPI (Figure 11). Correlations between rainfall and ENSO have historically focused on the winter wet season e.g., [65]; however, as indicated in Figure 11, dry season drought conditions are also strongly related to ENSO, with SPI-3 having a higher correlation with MEI in the dry season than in the wet season. Summer rainfall in Hawaiʻi has been understudied to date, and additional work is needed to describe dry season rainfall variability [68]. The effects of El Niño on seasonal rainfall vary depending on whether the El Niño event is classified as a warm pool Central Pacific (CP) type or a cold tongue Eastern Pacific (EP) type, with EP events leading to drier conditions in the wet season, and CP events resulting in near-normal wet season conditions in Hawaiʻi [69,70]. Sequential El Niño and La Niña events also appear to be a dominant factor for long-duration droughts in Hawaiʻi (e.g., a drier wet season from El Niño followed by a drier dry season with La Niña) [71]. Recent evidence has called into question the stability of teleconnection patterns in the Pacific [72–76], which has important implications for predicting drought. How these relationships between ENSO and Hawaiian rainfall will change with future warming is still unknown. However, some research indicates that the frequency and intensity of El Niño events will increase significantly [77,78], which could lead to an increased frequency of extreme drought in Hawaiʻi. The unprecedented 2007–2014 drought identified here was not clearly driven by ENSO, however, and this has led to more questions about the mechanisms that drive multi-year droughts in Hawaiʻi. [73].

5.2. Agricultural Drought

Rain-fed fields and pasture lands are the most vulnerable to drought effects in Hawaiʻi, although if a drought persists, irrigated areas also can become vulnerable. State agencies can implement mandatory water conservation measures at county and local levels to reduce the amount of water used for irrigation [11,79]. During drought, ranchers lose pasture and forage resources, which can force them to purchase expensive supplemental feed and, under more severe conditions, reduce herd size. These responses, along with increased cattle mortality and reduced calving rates, lead to large revenue losses with consequences for livelihoods and industry sustainability. For example, the 1980–1981 drought resulted in $1.4 million in losses for Hawaiʻi-based farmers and ranchers [11]. During the 2000–2002 drought, all counties were designated as primary disaster areas by the U.S. Secretary of Agriculture, which requires at least eight consecutive weeks of the Severe Drought (D2) level on the USDM (Figure 2); statewide cattle losses alone were estimated at $9 million [11]. Between 2008 and 2016, the state lost approximately $44.5 million in cattle production and more than 20,000 head of cattle due to drought. Recovery to 2008 levels was estimated to not occur until 2029 (assuming no additional drought-related disasters), with Hawaiʻi continuing to lose $4–6 million dollars in annual production (M. Thorne, University of Hawaiʻi, written communication, 1 August 2019).

Many U.S. farmers and ranchers are able to capitalize on federal insurance programs such as the USDA Risk Management Agency (RMA) and disaster relief programs such as the Farm Service Agency (FSA) Disaster Assistance Program, which includes the Noninsured Crop Disaster Assistance Program (NAP), the Livestock Forage Disaster Program (LFP), and the Livestock Indemnity Program (LIP) [80,81]. In the RMA program, drought has been the number one cause of crop loss for Hawaiʻi, resulting in over $9.7 million in payouts since 1996, with excessive rain as a distant second driver of crop loss ($2.1 million in payouts; Figure 12a; [80]). The insured crops that have experienced the largest payouts due to drought in the past 10 years have been macadamia nuts ($8 million) and coffee ($1 million) [80]. Annually, fruits and tree nuts, including macadamias, are valued at over $140 million, yet macadamia nut yield decreased between 1996 and 2018 [82]. For uninsured crops, the NAP paid out $23.8 million between 2010 and 2018 (Figure 12b; [81]). Despite the relatively small annual crop insurance payouts compared to the annual production value of Hawaiian agricultural commodities, RMA and FSA programs remain important safety nets for producers and ranchers, especially for small-scale farms that may be more vulnerable to extreme weather and climate conditions. Hawaiʻi's agricultural production shows a distinct trend toward concentration on smaller farms [82]. The two livestock disaster programs have paid out even more in recent years. Between 2008 and 2018, the LFP paid out over $50 million to ranchers in the state who suffered grazing losses due to drought, and over the same period, the LIP paid out almost $800,000 for ranchers who lost livestock, defined as livestock sold at a lower price or livestock deaths (Figure 12b; [81]). Between 1996 and 2018, these programs have paid out a total of over $84.5 million in drought relief to State of Hawaiʻi producers.

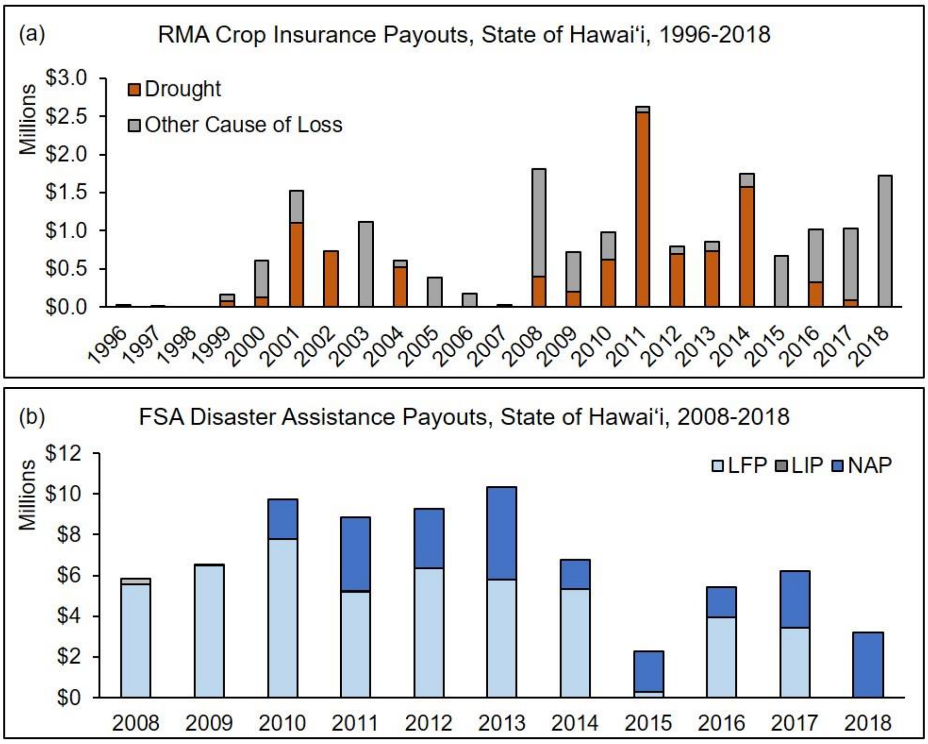

Figure 12. (**a**) Crop insurance indemnities (payouts) by year for the State of Hawaiʻi from 1996 to 2018 from the USDA Risk Management Agency (RMA, [80]), separated by cause of loss: Drought versus all other causes of loss. (**b**) Farm Service Agency (FSA) Disaster assistance payouts by year for the State of Hawaiʻi from 2008 to 2018 are shown for three programs: Livestock Forage Disaster Program (LFP), Livestock Indemnity Program (LIP), and the Noninsured Crop Disaster Assistance Program (NAP) [81].

5.3. Hydrological Drought

The first indication of hydrological drought is reduced streamflow [22], which decreases the water available to support stream and wetland habitats, agricultural irrigation, cultural practices, watershed processes, and reservoir recharge. Groundwater discharge and surface water runoff into streams are also reduced during drought [83,84], which can result in higher concentrations of fecal bacteria in streams immediately following rain events [85]. Because groundwater systems commonly have substantial storage, they might not respond immediately to meteorological drought. During extended dry periods, streamflow in perennial streams is sustained by groundwater discharge. Thus, meteorological drought might not immediately affect streamflow in some areas. As hydrological drought progresses, groundwater recharge and water levels are eventually reduced. For example, estimates of groundwater recharge across several of the main Hawaiian Islands indicate that island-wide recharge rates declined by 23% to 38% during five-year historical drought periods when compared to baseline conditions [86–89]. Groundwater in Hawaiʻi is mainly found as a convex-shaped layer, or basal lens, floating on and displacing denser saltwater, and at higher elevations in inland dike-impounded systems. Thicker freshwater lenses such as the Pearl Harbor aquifer on Oʻahu are generally less sensitive to substantive salinity changes caused by periods of low rainfall compared to thinner lenses. However, higher pumping rates due to increased demand will cause the basal water table to decline [90], and this can lead to saltwater intrusion. Thinner aquifers such as those in coastal areas of the western part of Maui are more vulnerable to increased salinity during droughts [91]. For these thin lenses, the transition zone between freshwater and saltwater is closer to the pump intakes, and thinning of the freshwater lens due to reduced recharge possibly coupled with increased pumpage during droughts may lead to increased salinity in the pumped water [33]. Lower groundwater levels exacerbate the potential for saltwater intrusion, which negatively affects the drinking and agricultural water supply. Over the past century, stream base flows have declined statewide [92], likely the result of decreased groundwater recharge, making Hawaiʻi's aquifers more vulnerable to saltwater contamination during periods of severe drought.

5.4. Ecological Drought

Ecological drought in Hawaiʻi commonly drives an increase in wildland fire occurrence [93–95]. Wildland fires in Hawaiʻi are most extensive in dry and mesic non-native grasslands and shrublands, which cover 24% of the total land area in the state and account for approximately 80% of annual area burned [96], although, under severe drought conditions, wildfires have affected native wet forests [97,98]. During drought, wildfire risk in grasslands increases rapidly, making drought an important contributor to the invasive grass–wildfire cycle [95,99]. Land use transitions from active agriculture to fallow areas dominated by non-native fire-prone grasses and shrubs [41] combined with recurring droughts are expected to increase the risk of future wildfires in Hawaiʻi [100]. The relation between wildfire and El Niño occurrence in Hawaiʻi is particularly apparent (Figure 13; [26]). The dry season typically experiences relatively high rainfall before an El Niño event (Figure 11b), which increases standing stocks of live biomass [100]. As an El Niño event progresses, drought conditions establish during the wet season (Figure 11a). This causes widespread senescence and rapid curing of vegetation (e.g., browning and drying), which drives an increase in wildfire danger. During the 1997–1998 very strong El Niño event, for example, over 37,000 acres burned across the state, including several large fires in the usually wet Puna district of eastern Hawaiʻi Island [101]. Although more large fires occur on average during El Niño years, large fires can occur during neutral or La Niña years (Figure 13). Heavy rainfall in recently burned areas aggravates wildfire effects by rapidly eroding exposed soils, often delivering large quantities of ash-infused sediment to streams where it affects stream fauna [95,102]. Because of short ridge-to-reef distances, much of this sediment ultimately is deposited in nearshore areas [95] where it affects coral reef communities [103].

Freshwater ecosystems are particularly vulnerable to drought, and stream fauna are negatively affected by reductions in streamflow through the limited availability of freshwater habitat, loss of hydrological connectivity, and reduced water quality [104–108]. Reduced surface water and groundwater inputs into nearshore environments may also have negative effects on organisms in brackish and marine environments [105]; however, more research is needed to evaluate the effects of reduced groundwater discharge on nearshore ecosystems, including threatened anchialine ponds [109].

Forest responses to drought have been characterized from remote sensing analyses, which have shown that dry forest areas in the state "brown down" during droughts [110], and strong reductions in canopy greenness and volume have been observed on Hawaiʻi Island as a result of long-term precipitation declines [111]. Field-based evidence indicates that El Niño-induced droughts determine upper elevation forest lines [112,113]. Drier conditions have been linked to the mortality of the Haleakalā silversword (*Argyroxiphium sandwicense* subsp. *macrocephalum*), an iconic and endangered high-elevation endemic plant [63,114]. Extreme drought can also cause mortality among some of the dominant native woody species [115,116], with insect infestations during drought leading to native tree mortality in dry forest areas [97]. Drought tolerance of native species has been documented, with some native grass species having greater drought tolerance than invasive species (e.g., [117]), and other tolerance variations found across different elevation, moisture, and light conditions [118–122]. Drought causes invasive ungulates (e.g., feral pigs, goats, deer, and sheep) to change their foraging patterns in search of food and encroach into residential and agricultural areas, causing erosion and damage to infrastructure and crops [11,79,97]. The simultaneous threats of drought, wildfire, and browsing pressure from ungulates have resulted in drastic range reductions for endangered Hawaiian bird species such as the palila (*Loxioides bailleui*) [123,124].

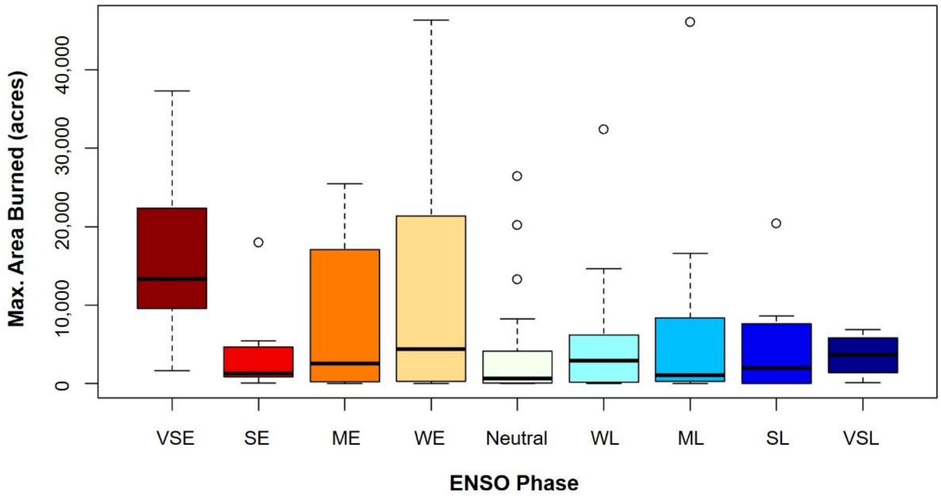

Figure 13. Boxplots of maximum area burned (acres) in Hawaiʻi during ENSO phases, 1904–2021. ENSO phases are separated by intensity levels: VSE = Very Strong El Niño, SE = Strong El Niño, ME = Moderate El Niño, WE = Weak El Niño, WL = Weak La Niña, ML = Moderate La Niña, SL = Strong La Niña, and VSL = Very Strong La Niña. Differences between groups were not statistically significant at the 95% level.

5.5. Socioeconomic Drought

The full extent to which drought affects social and economic systems depends not only on the physical characteristics of the drought, but also on the characteristics of the resources and systems exposed to the drought. Water shortages can occur, prompting state and county agencies to make declarations to implement voluntary or mandatory water conservation measures. On Oʻahu, both voluntary conservation measures and city policies such as the low flow toilet ordinance (1993) helped to mitigate drought effects in the 1998–2002 drought [125]. The cost of water transport and any crop or livestock production losses can result in significant income losses for farmers and ranchers, higher food prices for consumers, unemployment, decreased land prices, population migration, and mental and physical stress [11,126]. In some cases, federal insurance programs could mask or buffer the true financial impacts of crop losses; moreover, increased hedging by farmers on crop insurance may inadvertently reduce their cash flow and ability to respond to other disasters [127].

Drought can increase threats to public health and safety from water shortages, wildfires, and even mosquito-borne diseases. An estimated 30,000 to 60,000 residents in Hawaiʻi use rainwater catchment systems for drinking water [128] and are the most directly affected by drought and water shortages. Approximately 99% of domestic water used in Hawaiʻi comes from groundwater [129]. Future freshwater stress is expected to be particularly acute for island populations as evaporative demand increases and recharge rates are reduced [130–132], which, in combination with increased sea levels, will likely enhance saltwater intrusion into groundwater [5,129]. Wildfires have direct effects on human communities as they can damage infrastructure and other valued resources, and in some cases, can result in road closures, power outages, and evacuations. Additionally, for public health, droughts can result in more localized breeding sites for mosquitoes as streams dry and leave behind pockets of standing water, contributing to an increased risk of mosquito-borne diseases such as the 2001–2002 dengue outbreak in Hawaiʻi [133]. All of these may have negative effects on tourism, although the direct and indirect effects of drought on tourism have not been explicitly studied for Hawaiʻi.

Other human dimensions of drought, such as loss of educational opportunities, physical and mental health problems, interpersonal conflict, and loss of cultural traditions, are not easy to quantify [134]. Drought directly affects traditional and customary practices of native Hawaiian communities that rely on freshwater resources. These practices can include wetland cultivation of taro (*Colocasia esculenta*), gathering of aquatic and riparian species, traditional fishpond aquaculture, changes in nearshore fisheries, and changes in the accessibility of important freshwater heritage sites (springs and seeps) [11,97,135]. The socioeconomic effects of drought in Hawaiʻi are understudied to date; more research would be beneficial to identify the full range of direct and indirect socioeconomic effects of drought, and how these effects vary across communities.

5.6. Looking Ahead

Novel categories of drought are emerging due to anthropogenic climate change, expanding human water use, and land use change (e.g., "Hotter Drought" [136]; "Flash Drought" [137]; "Human Induced" or "Human Modified Drought" [138]; and "Transformational Ecological Drought" [21]). These new forms of drought are increasingly difficult to anticipate and manage [139]. Whether droughts in Hawaiʻi are beginning to show characteristics reflective of anthropogenic influence is unclear. However, the frequency, intensity, and duration of droughts were all higher in the second half of the study period (Figures 6, 7 and 9), with the two longest duration and most severe droughts in Hawaiʻi occurring since 1998. Although the 2007–2014 drought was unprecedented over the past century (Figures 2 and 6), detecting an anthropogenic signal at small spatial scales such as that of the Hawaiian Islands is difficult, and at this time, evidence indicates that rainfall changes in Hawaiʻi are still predominantly driven by large-scale modes of natural variability [8,73]. Regardless, these multi-year, severe droughts have serious biophysical and socioeconomic effects on many sectors across the state. Work is ongoing to create a near-real-time gridded SPI dataset for Hawaiʻi using products from the new Hawaiʻi Climate Data Portal to allow for real-time monitoring and analysis [140]. Since 2019, Hawaiʻi has continued to experience severe and extreme drought conditions (see USDM https://droughtmonitor.unl.edu/ (accessed on 7 August 2022)), highlighting the need for an SPI dataset that is updated in near-real time.

This study identified long-term trends and synthesized the effects of drought at the landscape scale, which provides a critical baseline that can be utilized when designing projects or adaptation strategies. If these regional trends of increasing frequency, intensity, and duration continue in Pacific Islands (Figure 9; [52,141]), resource managers may wish to proactively and comprehensively plan and design drought-resilient management systems. Modeling studies of future conditions have shown that drier future climate conditions [14] will result in lower groundwater recharge in already water-stressed leeward areas [132], and appropriate land management strategies can help mitigate the effects [142]. For example, ranchers in Hawaiʻi and other areas of the tropical Pacific may benefit from early planning for drought by cultivating hardy, drought-tolerant grass varieties, and manage groundwater supply for pasture irrigation to ensure continuous forage supply [143]. Understanding historical patterns, as well as future projections, helps to provide justification for investing in adaptation strategies that promote resilience to drought. A retrospective, lessons-learned approach to engaging in drought planning can also lead to powerful insights about preparing for future droughts [97,144]. Indigenous peoples living in drought-prone areas have accumulated knowledge over many generations about how to persist and even thrive during droughts. Where possible, engaging traditional knowledge to inform actions will represent an important strategy for future drought mitigation and resilience efforts [145,146]. In addition, natural resource managers have identified several barriers they face when trying to find and incorporate drought data, products, and information in Hawaiʻi. The recently developed Pacific Drought Knowledge Exchange (PDKE) project seeks to address this need and has demonstrated how a co-production approach and site-specific climate data (including the gridded SPI dataset [38]) and information can be utilized to inform planning decisions that address adaptation concerns [147]. Researchers and resource managers can collaborate closely to coproduce usable and actionable drought science to better navigate future novel drought conditions [147,148].

Longer-duration and higher-intensity droughts have brought attention to drought in a way that now points to the importance of higher-level responses that address policy and large-scale resource management practices. Although residents are aware that Hawaiʻi is home to areas that are among the wettest on Earth, many areas of the State are highly vulnerable to drought, in particular, the dry, leeward parts of all islands, and the duration and severity of droughts have increased over the past century. This has critically important implications for (i) sustaining the agricultural sector, especially rain-fed or surface-water-reliant farming and ranching; (ii) meeting the hydrological needs of municipalities and ecosystems that depend critically on groundwater; (iii) reducing the growing health and human safety effects of wildland fire, which are increasing due to an expanding cover of non-native fire-prone plants, a warming climate, and a worsening drought regime; and (iv) designing socio-ecologically based approaches to engage a future world that will be warmer and, for large areas of Hawaiʻi, likely drier. Further drought research would benefit from including real-time SPI updates, as well as additional research on ecological and socioeconomic drought effects and the opportunities for policy and management to mitigate some of these effects. To support resource management under a warmer and potentially drier future, and to understand how droughts and their impacts may change in the future as global temperatures continue to rise and the climate system becomes more variable, understanding drought and protecting water resources are important in Hawaiʻi.

6. Conclusions

Drought is a regular and natural component of the climate in Hawaiʻi with severe effects across many sectors statewide. Spatiotemporal analysis of a new gridded drought index revealed that the two worst droughts for the State of Hawaiʻi in the past century were 2007–2014 and 1998–2002, resulting in over $80 million in drought relief in the agriculture sector. The island-level analysis identified that the 2007–2014 drought was the worst for Hawaiʻi Island, whereas the 1998–2002 drought was more severe for Kauaʻi, Oʻahu, and Maui Nui. Significant trends were found in decadal drought duration and magnitude, echoing increasing drought trends across the Pacific Islands. Strong relations exist between drought, wildfire, and ENSO, with El Niño events typically leading to drier wet season conditions and greater area burned by wildfires. The assessment of current drought literature revealed large gaps in socioeconomic and ecological drought effects in Hawaiʻi, and future drought research may prioritize these areas along with real-time SPI updates. By coupling quantitative SPI analysis with a review of the economic and ecological effects of drought across different sectors, a more thorough understanding of historical drought trends can be used to better understand future projections in a given region. Although drought is experienced differently across landscapes, this combined analysis provides a framework that enables a holistic yet spatiotemporally relevant view that can contribute to more effective management.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su141912023/s1, Figure S1: SPI Time Series; Table S1: Statewide Droughts from SPI-6; Table S2: Droughts for Hawaiʻi Island; Table S3: Droughts for Maui Nui; Table S4: Droughts for Oʻahu; Table S5: Droughts for Kauaʻi.

Author Contributions: Conceptualization, A.G.F. and C.P.G.; methodology, A.G.F.; validation, A.G.F.; formal analysis, A.G.F.; data curation, A.G.F., D.H., J.J.R. and M.P.L.; writing—original draft preparation, A.G.F., C.P.G., L.B., L.B.F., V.W.K. and R.J.L.; writing—review and editing, A.G.F., C.P.G., T.W.G.,

L.B., Y.-L.C., P.-S.C., L.B.F., D.A.H., V.W.K., R.J.L., A.M., D.S.O., J.J.R., S.G.Y. and C.T.; visualization, A.G.F. and D.H.; supervision, C.P.G., T.W.G. and D.A.H.; project administration, C.P.G.; funding acquisition, C.P.G., T.W.G., D.A.H., Y.-L.C., P.-S.C., L.B.F., A.M., D.S.O. and C.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Pacific Islands Climate Adaptation Science Center (PI-CASC) Award Numbers G16PG00037 and G20PG00101, and the USDA Climate Hubs.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The rainfall data presented in this study are available on the Hawai'i Climate Data Portal (https://www.hawaii.edu/climate-data-portal/, accessed on 7 August 2022), the gridded SPI from Hydroshare (https://www.hydroshare.org/resource/822553ead1d04869b5b3e1e3a3817ec6/, accessed on 1 December 2020), and derived products on request from the corresponding author.

Acknowledgments: The authors would like to sincerely thank the Pacific Islands Climate Adaptation Science Center team for their support, especially Mari-Vaughn Johnson and Heather Kerkering, as well as Emile Elias with the USDA Southwest Climate Hub and the NOAA National Integrated Drought Information System (NIDIS).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Wilhite, D.A. Drought as a Natural Hazard: Concepts and Definitions. In *Drought: A Global Assessment*; University of Nebraska: Lincoln, NE, USA, 2000; pp. 3–18.
2. McDowell, N.; Allen, C.D.; Anderson-Teixeira, K.; Brando, P.; Brienen, R.; Chambers, J.; Christoffersen, B.; Davies, S.; Doughty, C.; Duque, A.; et al. Drivers and Mechanisms of Tree Mortality in Moist Tropical Forests. *New Phytol.* **2018**, *219*, 851–869. [CrossRef] [PubMed]
3. Breshears, D.D.; Cobb, N.S.; Rich, P.M.; Price, K.P.; Allen, C.D.; Balice, R.G.; Romme, W.H.; Kastens, J.H.; Floyd, M.L.; Belnap, J.; et al. Regional Vegetation Die-Off in Response to Global-Change-Type Drought. *Proc. Natl. Acad. Sci. USA* **2005**, *102*, 15144–15148. [CrossRef] [PubMed]
4. Lyon, B. The Strength of El Niño and the Spatial Extent of Tropical Drought. *Geophys. Res. Lett.* **2004**, *31*, L21204. [CrossRef]
5. Polhemus, D.A. *Drought in the U.S.—Affiliated Pacific Islands: A Multi-Level Assessment*; Pacific Islands Climate Science Center: Honolulu, HI, USA, 2017; pp. 1–67.
6. Chu, P.-S. Hawaii Rainfall Anomalies and El Niño. *J. Clim.* **1995**, *8*, 1697–1703. [CrossRef]
7. Chu, P.-S.; Chen, H. Interannual and Interdecadal Rainfall Variations in the Hawaiian Islands. *J. Clim.* **2005**, *18*, 4796–4813. [CrossRef]
8. Frazier, A.G.; Timm, O.E.; Giambelluca, T.W.; Diaz, H.F. The Influence of ENSO, PDO and PNA on Secular Rainfall Variations in Hawai'i. *Clim. Dyn.* **2018**, *51*, 2127–2140. [CrossRef]
9. Lyons, S.W. Empirical Orthogonal Function Analysis of Hawaiian Rainfall. *J. Appl. Meteorol.* **1982**, *21*, 1713–1729. [CrossRef]
10. Kirch, P.V. Controlled Comparison and Polynesian Cultural Evolution. In *Natural Experiments of History*; Harvard University Press: Cambridge, MA, USA, 2010; pp. 15–52.
11. CWRM. *Hawaii Drought Plan. 131. Report prepared for State of Hawaii Department of Land and Natural Resources, Commission on Water Resource Management*; One World One Water, LLC.: Honolulu, HI, USA, 2017.
12. Keener, V.W.; Helweg, D.; Asam, S.; Balwani, S.; Burkett, M.; Fletcher, C.H.; Giambelluca, T.; Grecni, Z.N.; Nobrega-Olivera, M.; Polovina, J.; et al. Hawai'i and U.S.-Affiliated Pacific Islands. In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment*; Reidmiller, D.R., Avery, C.W., Easterling, D.R., Kunkel, K.E., Lewis, K.L.M., Maycock, T.K., Stewart, B.C., Eds.; U.S. Global Change Research Program: Washington, DC, USA, 2018; Volume II, pp. 1242–1308.
13. McKenzie, M.M.; Giambelluca, T.W.; Diaz, H.F. Temperature Trends in Hawai'i: A Century of Change, 1917–2016. *Int. J. Climatol.* **2019**, *39*, 3987–4001. [CrossRef]
14. Timm, O.E.; Giambelluca, T.W.; Diaz, H.F. Statistical Downscaling of Rainfall Changes in Hawai'I Based on the CMIP5 Global Model Projections. *J. Geophys. Res. Atmos.* **2015**, *120*, 92–112. [CrossRef]
15. Frazier, A.G.; Giambelluca, T.W. Spatial Trend Analysis of Hawaiian Rainfall from 1920 to 2012. *Int. J. Climatol.* **2017**, *37*, 2522–2531. [CrossRef]
16. Mishra, A.K.; Singh, V.P. A Review of Drought Concepts. *J. Hydrol.* **2010**, *391*, 202–216. [CrossRef]
17. Giri, S.; Mishra, A.; Zhang, Z.; Lathrop, R.; Alnahit, A. Meteorological and Hydrological Drought Analysis and Its Impact on Water Quality and Stream Integrity. *Sustainability* **2021**, *13*, 8175. [CrossRef]
18. Li, M.; Cao, F.; Wang, G.; Chai, X.; Zhang, L. Evolutional Characteristics of Regional Meteorological Drought and Their Linkages with Southern Oscillation Index across the Loess Plateau of China During 1962–2017. *Sustainability* **2020**, *12*, 7237. [CrossRef]

19. Uwimbabazi, J.; Jing, Y.; Iyakaremye, V.; Ullah, I.; Ayugi, B. Observed Changes in Meteorological Drought Events During 1981–2020 over Rwanda, East Africa. *Sustainability* **2022**, *14*, 1519. [CrossRef]
20. Zargar, A.; Sadiq, R.; Naser, G.; Khan, F.I. A Review of Drought Indices. *Environ. Rev.* **2011**, *19*, 333–349. [CrossRef]
21. Crausbay, S.; Ramirez, A.R.; Carter, S.L.; Cross, M.S.; Hall, K.R.; Bathke, D.J.; Betancourt, J.L.; Colt, S.; Cravens, A.E.; Dalton, M.S.; et al. Defining Ecological Drought for the Twenty-First Century. *Bull. Am. Meteorol. Soc.* **2017**, *98*, 2543–2550. [CrossRef]
22. Wilhite, D.A.; Glantz, M.H. Understanding: The Drought Phenomenon: The Role of Definitions. *Water Int.* **1985**, *10*, 111–120. [CrossRef]
23. Wilhite, D.A.; Buchanan-Smith, M. Drought as Hazard: Understanding the Natural and Social Context. *Drought Water Cris. Sci. Technol. Manag. Issues* **2005**, *3*, 29.
24. Allen, C.D.; Breshears, D.D. Drought-Induced Shift of a Forest-Woodland Ecotone: Rapid Landscape Response to Climate Variation. *Proc. Natl. Acad. Sci. USA* **1998**, *95*, 14839–14842. [CrossRef]
25. McDowell, N.; Pockman, W.T.; Allen, C.D.; Breshears, D.D.; Cobb, N.; Kolb, T.; Plaut, J.; Sperry, J.; West, A.; Williams, D.G.; et al. Mechanisms of Plant Survival and Mortality During Drought: Why Do Some Plants Survive While Others Succumb to Drought? *New Phytol.* **2008**, *178*, 719–739. [CrossRef]
26. Chu, P.-S.; Yan, W.; Fujioka, F. Fire-Climate Relationships and Long-Lead Seasonal Wildfire Prediction for Hawaii. *Int. J. Wildland Fire* **2002**, *11*, 25. [CrossRef]
27. McKee, T.B.; Doesken, N.J.; Kleist, J. The Relationship of Drought Frequency and Duration to Time Scales. In Proceedings of the Eighth Conference on Applied Climatology, Anaheim, CA, USA, 17–22 January 1993.
28. Palmer, W.C. *Meteorological Drought*; Res. Pap. No. 45.; US Department of Commerce, Weather Bureau: Washington, DC, USA, 1965; Volume 58.
29. Vicente-Serrano, S.M.; Beguería, S.; López-Moreno, J.I. A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index. *J. Clim.* **2010**, *23*, 1696–1718. [CrossRef]
30. Keetch, J.J.; Byram, G.M. A Drought Index for Forest Fire Control. In *Research Paper*; US Department of Agriculture, Forest Service, Southeastern Forest Experiment Station: Asheville, NC, USA, 1968; Volume 35.
31. Palmer, W.C. Keeping Track of Crop Moisture Conditions, Nationwide: The New Crop Moisture Index. *Weatherwise* **1968**, *21*, 156–161. [CrossRef]
32. Mark, S.; Lecomte, D.; Hayes, M.; Heim, R.; Gleason, K.; Angel, J.; Rippey, B.; Tinker, R.; Palecki, M.; Stooksbury, D.; et al. The Drought Monitor. *Bull. Am. Meteorol. Soc.* **2002**, *83*, 1181–1190. [CrossRef]
33. Giambelluca, T.W.; Nullet, M.A.; Ridgley, M.A.; Eyre, P.R.; Moncur, J.E.T.; Price, S. *Drought in Hawaii*; Department of Land and Natural Resources, Commission on Water Resource Management: Honolulu, HI, USA, 1991; Volume 232.
34. Frazier, A.G.; Giambelluca, T.W.; Diaz, H.F.; Needham, H.L. Comparison of Geostatistical Approaches to Spatially Interpolate Month-Year Rainfall for the Hawaiian Islands. *Int. J. Climatol.* **2016**, *36*, 1459–1470. [CrossRef]
35. Longman, R.J.; Frazier, A.G.; Newman, A.J.; Giambelluca, T.W.; Schanzenbach, D.; Kagawa-Viviani, A.; Needham, H.; Arnold, J.R.; Clark, M.P. High-Resolution Gridded Daily Rainfall and Temperature for the Hawaiian Islands (1990–2014). *J. Hydrometeorol.* **2019**, *20*, 489–508. [CrossRef]
36. Lucas, M.P.; Longman, R.J.; Giambelluca, T.W.; Frazier, A.G.; Mclean, J.; Cleveland, S.B.; Huang, Y.-F.; Lee, J. Optimizing Automated Kriging to Improve Spatial Interpolation of Monthly Rainfall over Complex Terrain. *J. Hydrometeorol.* **2022**, *23*, 561–572. [CrossRef]
37. Vose, J.M.; Peterson, D.L.; Luce, C.H.; Patel-Weynand, T. *Effects of Drought on Forests and Rangelands in the United States: Translating Science into Management Responses*; U.S. Department of Agriculture Forest Service, Washington Office: Washington, DC, USA, 2019; pp. 1–227.
38. Lucas, M.P.; Trauernicht, C.; Frazier, A.G.; Miura, T. Long-Term, Gridded Standardized Precipitation Index for Hawai'i. *Data* **2020**, *5*, 109. [CrossRef]
39. Giambelluca, T.W.; Chen, Q.; Frazier, A.; Price, J.P.; Chen, Y.-L.; Chu, P.-S.; Eischeid, J.K.; Delparte, D.M. Online Rainfall Atlas of Hawai'i. *Bull. Am. Meteorol. Soc.* **2013**, *94*, 313–316. [CrossRef]
40. Giambelluca, T.W.; Nullet, M.A.; Schroeder, T.A. *Rainfall Atlas of Hawaii*; Department of Land and Natural Resources, Division of Water and Land Development: Honolulu, HI, USA, 1986; Volume 267.
41. Perroy, R.L.; Melrose, J.; Cares, S. The Evolving Agricultural Landscape of Post-Plantation Hawaii. *Appl. Geogr.* **2016**, *76*, 154–162. [CrossRef]
42. Asner, G.; Elmore, A.; Flinthughes, R.; Warner, A.; Vitousek, P. Ecosystem Structure Along Bioclimatic Gradients in Hawaii from Imaging Spectroscopy. *Remote Sens. Environ.* **2005**, *96*, 497–508. [CrossRef]
43. Juvik, S.P.; Juvik, J.O. *Atlas of Hawaii*; University of Hawaii Press: Honolulu, HI, USA, 1998.
44. Sakai, A.K.; Wagner, W.L.; Mehrhoff, L.A. Patterns of Endangerment in the Hawaiian Flora. *Syst. Biol.* **2002**, *51*, 276–302. [CrossRef] [PubMed]
45. Camp, R.J.; Loh, R.; Berkowitz, S.P.; Brinck, K.W.; Jacobi, J.D.; Price, J.; McDaniel, S.; Fortini, L.B. Potential Impacts of Projected Climate Change on Vegetation Management Strategies in Hawaii Volcanoes National Park. *Park Sci.* **2018**, *34*, 22–31.
46. Lucas, F.; Price, J.; Jacobi, J.; Vorsino, A.; Burgett, J.; Brinck, K.; Gon, S.; Koob, G.; Paxton, E. A Landscape-Based Assessment of Climate Change Vulnerability for All Native Hawaiian Plants. In *Technical Report HCSU-044*; Hawaii Cooperative Studies Unit University of Hawaii at Hilo: Hilo, HI, USA, 2013; Volume 134.

47. Vorsino, A.E.; Fortini, L.B.; Amidon, F.A.; Miller, S.E.; Jacobi, J.D.; Price, J.P.; Gon, S., 3rd; Koob, G.A. Modeling Hawaiian Ecosystem Degradation Due to Invasive Plants under Current and Future Climates. *PLoS ONE* **2014**, *9*, e95427. [CrossRef] [PubMed]
48. Michael, H.; Svoboda, M.; Wall, N.; Widhalm, M. The Lincoln Declaration on Drought Indices: Universal Meteorological Drought Index Recommended. *Bull. Am. Meteorol. Soc.* **2011**, *92*, 485–488. [CrossRef]
49. Beguería, S.; Vicente-Serrano, S.M. *SPEI: Calculation of the Standardised Precipitation-Evapotranspiration Index*; R Package Version 1.7; R Project: Vienna, Austria, 2017.
50. R Core Team. *R: A Language and Environment for Statistical Computing; R Foundation for Statistical Computing: Vienna, Austria, 2013.*
51. World Meteorological Organization. *Standardized Precipitation Index User Guide*; Svoboda, M., Hayes, M., Wood, D., Eds.; WMO-No. 1090; World Meteorological Organization: Geneva, Switzerland, 2012.
52. McGree, S.; Schreider, S.; Kuleshov, Y. Trends and Variability in Droughts in the Pacific Islands and Northeast Australia. *J. Clim.* **2016**, *29*, 8377–8397. [CrossRef]
53. Wolter, K.; Timlin, M.S. El Niño/Southern Oscillation Behaviour since 1871 as Diagnosed in an Extended Multivariate ENSO Index (MEI.Ext). *Int. J. Climatol.* **2011**, *31*, 1074–1087. [CrossRef]
54. Selmants, P.C.; Sleeter, B.M.; Liu, J.; Wilson, T.S.; Trauernicht, C.; Frazier, A.G.; Asner, G.P. Ecosystem Carbon Balance in the Hawaiian Islands under Different Scenarios of Future Climate and Land Use Change. *Environ. Res. Lett.* **2021**, *16*, 104020. [CrossRef]
55. Dunn, O.J. Multiple Comparisons Using Rank Sums. *Technometrics* **1964**, *6*, 241–252. [CrossRef]
56. Diaz, H.F.; Giambelluca, T.W. Changes in Atmospheric Circulation Patterns Associated with High and Low Rainfall Regimes in the Hawaiian Islands Region on Multiple Time Scales. *Glob. Planet. Chang.* **2012**, *98–99*, 97–108. [CrossRef]
57. Diaz, H.F.; Wahl, E.R.; Zorita, E.; Giambelluca, T.; Eischeid, J.K. A Five-Century Reconstruction of Hawaiian Islands Winter Rainfall. *J. Clim.* **2016**, *29*, 5661–5674. [CrossRef]
58. Kruk, M.C.; Levinson, D.H. Evaluating the Impacts of Climate Change on Rainfall Extremes for Hawaii and Coastal Alaska. In Proceedings of the 24th Conference on Severe Local Storms, Savannah, GA, USA, 27–31 October 2008.
59. Longman, R.J.; Diaz, H.F.; Giambelluca, T.W. Sustained Increases in Lower-Tropospheric Subsidence over the Central Tropical North Pacific Drive a Decline in High-Elevation Rainfall in Hawaii. *J. Clim.* **2015**, *28*, 8743–8759. [CrossRef]
60. O'Connor, C.F.; Chu, P.-S.; Hsu, P.-C.; Kodama, K. Variability of Hawaiian Winter Rainfall During La Niña Events since 1956. *J. Clim.* **2015**, *28*, 7809–7823. [CrossRef]
61. Chu, P.-S.; Chen, Y.R.; Schroeder, T.A. Changes in Precipitation Extremes in the Hawaiian Islands in a Warming Climate. *J. Clim.* **2010**, *23*, 4881–4900. [CrossRef]
62. Kruk, M.C.; Lorrey, A.M.; Griffiths, G.M.; Lander, M.; Gibney, E.J.; Diamond, H.J.; Marra, J.J. On the State of the Knowledge of Rainfall Extremes in the Western and Northern Pacific Basin. *Int. J. Climatol.* **2015**, *35*, 321–336. [CrossRef]
63. Krushelnycky, P.D.; Loope, L.L.; Giambelluca, T.W.; Starr, F.; Starr, K.; Drake, D.R.; Taylor, A.D.; Robichaux, R.H. Climate-Associated Population Declines Reverse Recovery and Threaten Future of an Iconic High-Elevation Plant. *Glob. Chang. Biol.* **2013**, *19*, 911–922. [CrossRef]
64. Koch, F.H.; Smith, W.D.; Coulston, J.W. Drought Patterns in the Conterminous United States and Hawaii. In *Forest Health Monitoring: National Status, Trends, and Analysis 2012*; Potter, K.M., Conkling, B.L., Eds.; Asheville, North Carolina: Gen. Tech. Rep. SRSGTR-198; US Department of Agriculture, Forest Service, Southern Research Station: Ashville, NC, USA, 2014; pp. 49–72.
65. Chu, P.-S. Hawaiian Drought and the Southern Oscillation. *Int. J. Climatol.* **1989**, *9*, 619–631. [CrossRef]
66. Chu, P.-S.; Wang, J. Tropical Cyclone Occurrences in the Vicinity of Hawaii: Are the Differences between El Niño and Non-El Niño Years Significant? *J. Clim.* **1997**, *10*, 2683–2689. [CrossRef]
67. Chu, P.-S.; Nash, A.J.; Porter, F.-Y. Diagnostic Studies of Two Contrasting Rainfall Episodes in Hawaii: Dry 1981 and Wet 1982. *J. Clim.* **1993**, *6*, 1457–1462. [CrossRef]
68. Luo, X.; Wang, B.; Frazier, A.G.; Giambelluca, T.W. Distinguishing Variability Regimes of Hawaiian Summer Rainfall: Quasi-Biennial and Interdecadal Oscillations. *Geophys. Res. Lett.* **2020**, *47*, 23. [CrossRef]
69. Hsiao, F. Island Effects on Rainfall over the Hawaiian Islands with Mountaintops Below Trade Wind Inversion. Ph.D. Thesis, University of Hawaii at Mānoa, Honolulu, HI, USA, 2020.
70. Lu, B.-Y.; Chu, P.-S.; Kim, S.-H.; Karamperidou, C. Hawaiian Regional Climate Variability During Two Types of El Niño. *J. Clim.* **2020**, *33*, 9929–9943. [CrossRef]
71. Frazier, A.G. The Influence of Large-Scale Modes of Climate Variability on Spatiotemporal Rainfall Patterns and Vegetation Response in Hawaii. Ph.D. Thesis, University of Hawaii at Mānoa, Manoa, HI, USA, 2016.
72. Coats, S.; Smerdon, J.E.; Cook, B.I.; Seager, R. Stationarity of the Tropical Pacific Teleconnection to North America in CMIP5/PMIP3 Model Simulations. *Geophys. Res. Lett.* **2013**, *40*, 4927–4932. [CrossRef]
73. Eischeid, J.K.; Hoerling, M.P.; Quan, X.-W.; Diaz, H.F. Diagnosing Hawaii's Recent Drought. *J. Clim.* **2022**, *35*, 3997–4012. [CrossRef]
74. McAfee, S.A. Consistency and the Lack Thereof in Pacific Decadal Oscillation Impacts on North American Winter Climate. *J. Clim.* **2014**, *27*, 7410–7431. [CrossRef]
75. Wang, B.; Luo, X.; Liu, J. How Robust Is the Asian Precipitation–ENSO Relationship During the Industrial Warming Period (1901–2017)? *J. Clim.* **2020**, *33*, 2779–2792. [CrossRef]

76. Yeh, S.-W.; Cai, W.; Min, S.-K.; McPhaden, M.J.; Dommenget, D.; Dewitte, B.; Collins, M.; Ashok, K.; An, S.-I.; Yim, B.-Y.; et al. ENSO Atmospheric Teleconnections and Their Response to Greenhouse Gas Forcing. *Rev. Geophys.* **2018**, *56*, 185–206. [CrossRef]
77. Wang, B.; Luo, X.; Yang, Y.-M.; Sun, W.; Cane, M.A.; Cai, W.; Yeh, S.-W.; Liu, J. Historical Change of El Nino Properties Sheds Light on Future Changes of Extreme El Nino. *Proc. Natl. Acad. Sci. USA* **2019**, *116*, 22512–22517. [CrossRef]
78. Wang, G.; Cai, W.; Gan, B.; Wu, L.; Santoso, A.; Lin, X.; Chen, Z.; McPhaden, M.J. Continued Increase of Extreme El Niño Frequency Long after 1.5 °C Warming Stabilization. *Nat. Clim. Chang.* **2017**, *7*, 568–572. [CrossRef]
79. KHNL. Drought Conditions Plaguing Parts of Maui County, Big Island. 2012. Available online: https://www.hawaiinewsnow.com/story/17354594/drought-conditions-plaguing-parts-of-maui-county-big-island/ (accessed on 30 August 2020).
80. Reyes, J.J.; Elias, E. Spatio-Temporal Variation of Crop Loss in the United States from 2001 to 2016. *Environ. Res. Lett.* **2019**, *14*, 074017. [CrossRef]
81. USDA. *U.S. Department of Agriculture Farm Service Agency (FSA) Disaster Assistance Program*; USDA: Washington, DC, USA, 2019.
82. Rehkamp, S.; Roberts, M.J.; MacDonald, J.M. *The Agricultural Economic Landscape in Hawaii and the Potential for Future Economic Viability*; UHERO Brief: Honolulu, HI, USA, 2021.
83. Strauch, A.M.; Giardina, C.P.; MacKenzie, R.A.; Heider, C.; Giambelluca, T.W.; Salminen, E.; Bruland, G.L. Modeled Effects of Climate Change and Plant Invasion on Watershed Function across a Steep Tropical Rainfall Gradient. *Ecosystems* **2017**, *20*, 583–600. [CrossRef]
84. Strauch, A.M.; MacKenzie, R.A.; Giardina, C.P.; Bruland, G.L. Climate Driven Changes to Rainfall and Streamflow Patterns in a Model Tropical Island Hydrological System. *J. Hydrol.* **2015**, *523*, 160–169. [CrossRef]
85. Strauch, A.M.; MacKenzie, R.A.; Bruland, G.L.; Tingley, R.; Giardina, C.P. Climate Change and Land Use Drivers of Fecal Bacteria in Tropical Hawaiian Rivers. *J. Environ. Qual.* **2014**, *43*, 1475. [CrossRef] [PubMed]
86. Engott, J.A. *A Water-Budget Model and Assessment of Groundwater Recharge for the Island of Hawaii*; U.S. Geological Survey Scientific Investigations Report 2011–5078; Department of the Interior, US Geological Survey: Washington, DC, USA, 2011; Volume 53.
87. Engott, J.A.; Johnson, A.G.; Bassiouni, M.; Izuka, S.K.; Rotzoll, K. *Spatially Distributed Groundwater Recharge for 2010 Land Cover Estimated Using a Water-Budget Model for the Island of Óahu, Hawaii*; U.S. Geological Survey Scientific Investigations Report 2015–5010; Department of the Interior, US Geological Survey: Washington, DC, USA, 2017; Volume 49.
88. Johnson, A.G.; Engott, J.A.; Bassiouni, M.; Rotzoll, K. *Spatially Distributed Groundwater Recharge Estimated Using a Water-Budget Model for the Island of Maui, Hawaii, 1978–2007*; U.S. Geological Survey Scientific Investigations Report 2014–5168; Department of the Interior, US Geological Survey: Washington, DC, USA, 2018; Volume 64. [CrossRef]
89. Oki, D.S.; Engott, J.A.; Rotzoll, K. *Numerical Simulation of Groundwater Availability in Central Molokaí, Hawaii*; U.S. Geological Survey Scientific Investigations Report 2019–5150; U.S. Geological Survey: Menlo Park, CA, USA, 2020; Volume 95. [CrossRef]
90. Izuka, S.K. *Effects of Irrigation, Drought, and Ground-Water Withdrawals on Ground-Water Levels in the Southern Lihue Basin, Kauai, Hawaii; U.S. Geological Survey Scientific Investigations Report 2006-5291; U.S. Geological Survey: Menlo Park, CA, USA, 2006; p. 52.* [CrossRef]
91. Gingerich, S.B.; Engott, J.A. *Groundwater Availability in the Lahaina District, West Maui, Hawaii*; U.S. Geological Survey Scientific Investigations Report 2012–5010; U.S. Geological Survey: Menlo Park, CA, USA, 2012; Volume 90. [CrossRef]
92. Bassiouni, M.; Oki, D.S. Trends and Shifts in Streamflow in Hawaii, 1913-2008. *Hydrol. Process.* **2013**, *27*, 1484–1500. [CrossRef]
93. Dolling, K.; Chu, P.-S.; Fujioka, F. A Climatological Study of the Keetch/Byram Drought Index and Fire Activity in the Hawaiian Islands. *Agric. For. Meteorol.* **2005**, *133*, 17–27. [CrossRef]
94. Dolling, K.; Chu, P.-S.; Fujioka, F. Natural Variability of the Keetch–Byram Drought Index in the Hawaiian Islands. *Int. J. Wildland Fire* **2009**, *18*, 459–475. [CrossRef]
95. Trauernicht, C.; Pickett, E.; Giardina, C.P.; Litton, C.M.; Cordell, S.; Beavers, A. The Contemporary Scale and Context of Wildfire in Hawaii. *Pac. Sci.* **2015**, *69*, 427–444. [CrossRef]
96. Hawbaker, T.J.; Trauernicht, C.; Howard, S.M.; Litton, C.M.; Giardina, C.P.; Jacobi, J.D.; Fortini, L.B.; Hughes, R.F.; Selmants, P.C.; Zhu, Z. Wildland Fires and Greenhouse Gas Emissions in Hawaii. In *Baseline and Projected Future Carbon Storage and Carbon Fluxes in Ecosystems of Hawaii*; US Geological Survey Professional Paper 1834; U.S. Geological Survey: Menlo Park, CA, USA, 2017; pp. 57–73. [CrossRef]
97. Frazier, A.G.; Deenik, J.L.; Fujii, N.D.; Funderburk, G.R.; Giambelluca, T.W.; Giardina, C.P.; Helweg, D.A.; Keener, V.W.; Mair, A.; Marra, J.J.; et al. Chapter 5: Managing Effects of Drought in Hawaii and U.S.-Affiliated Pacific Islands. In *Effects of Drought on Forests and Rangelands in the United States: Translating Science into Management Responses*; Peterson, J.M., Luce, D.L., Patel-Weynand, C.H., Vose, T., Eds.; U.S. Department of Agriculture Forest Service, Washington Office: Washington, DC, USA, 2019; pp. 95–121.
98. Tunison, J.T.; D'Antonio, C.M.; Loh, R.K. Fire and Invasive Plants in Hawaii Volcanoes National Park. In Proceedings of the Invasive Species Workshop: The Role of Fire in the Control and Spread of Invasive Species, Fire Conference 2000: The First National Congress on Fire Ecology, Prevention, and Management, Tallahassee, FL, USA, 27 November–1 December 2000.
99. Nugent, A.D.; Longman, R.J.; Trauernicht, C.; Lucas, M.P.; Diaz, H.F.; Giambelluca, T.W. Fire and Rain: The Legacy of Hurricane Lane in Hawaii. *Bull. Am. Meteorol. Soc.* **2020**, *101*, E954–E967. [CrossRef]
100. Trauernicht, C. Vegetation-Rainfall Interactions Reveal How Climate Variability and Climate Change Alter Spatial Patterns of Wildland Fire Probability on Big Island, Hawaii. *Sci. Total Environ.* **2018**, *650*, 459–469. [CrossRef]
101. Trauernicht, C. El Niño and Long-Lead Fire Weather Prediction for Hawaii and Us-Affiliated Pacific Islands. Pacific Fire Exchange (PFX), PFX Fact Sheet 2015_1. 2015. Available online: http://www.c4gts.org/wp-content/uploads/2020/05/El-nino-Pacific-Island-wildfires-Pacific-Fire-Exchange-2015.pdf (accessed on 30 August 2020).

102. Brasher, A.M.; Wolff, R.H.; Luton, C.D. *Associations among Land Use, Habitat Characteristics, and Invertebrate Community Structure in Nine Streams on the Island of Oahu, Hawaii, 1999–2001*; U.S. Geological Survey, National Water-Quality Assessment Program: Reston, VA, USA, 2004; pp. 1–47.
103. Stender, Y.; Jokiel, P.L.; Rodgers, K.S. Thirty Years of Coral Reef Change in Relation to Coastal Construction and Increased Sedimentation at Pelekane Bay, Hawai'i. *PeerJ* **2014**, *2*, e300. [CrossRef]
104. Clilverd, H.M.; Tsang, Y.-P.; Infante, D.M.; Lynch, A.J.; Strauch, A.M. Long-Term Streamflow Trends in Hawaii and Implications for Native Stream Fauna. *Hydrol. Process.* **2019**, *33*, 699–719. [CrossRef]
105. Hau, S. Hīhīwai (Neritina Granosa Sowerby) Recruitment in 'Īao and Honomanū Streams on the Island of Maui, Hawaii. *Bish. Mus. Bull. Cult. Environ. Stud.* **2007**, *3*, 171–181.
106. McIntosh, M.D.; Benbow, M.E.; Burky, A.J. Effects of Stream Diversion on Riffle Macroinvertebrate Communities in a Maui, Hawaii, Stream. *River Res. Appl.* **2002**, *18*, 569–581. [CrossRef]
107. Strauch, A.M.; MacKenzie, R.A.; Tingley, R.W. Base Flow-Driven Shifts in Tropical Stream Temperature Regimes across a Mean Annual Rainfall Gradient. *Hydrol. Process.* **2017**, *31*, 1678–1689. [CrossRef]
108. Tsang, Y.-P.; Tingley, R.W.; Hsiao, J.; Infante, D.M. Identifying High Value Areas for Conservation: Accounting for Connections among Terrestrial, Freshwater, and Marine Habitats in a Tropical Island System. *J. Nat. Conserv.* **2019**, *50*, 125711. [CrossRef]
109. Tribble, G.W. *Ground Water on Tropical Pacific Islands: Understanding a Vital Resource*; Geological Survey: Reston, VA, USA, 2008; Volume 1312.
110. Pau, S.; Okin, G.; Gillespie, T.W. Asynchronous Response of Tropical Forest Leaf Phenology to Seasonal and El Niño-Driven Drought. *PLoS ONE* **2010**, *5*, e11325. [CrossRef] [PubMed]
111. Barbosa, J.M.; Asner, G.P. Effects of Long-Term Rainfall Decline on the Structure and Functioning of Hawaiian Forests. *Environ. Res. Lett.* **2017**, *12*, 094002. [CrossRef]
112. Crausbay, S.D.; Frazier, A.G.; Giambelluca, T.W.; Longman, R.J.; Hotchkiss, S.C. Moisture Status During a Strong El Niño Explains a Tropical Montane Cloud Forest's Upper Limit. *Oecologia* **2014**, *175*, 273–284. [CrossRef]
113. Christoph, L.; Schulte, M. Microclimatological Investigations in the Tropical Alpine Scrub of Maui, Hawaii: Evidence for a Drought-Induced Alpine Timberline. *Pac. Sci.* **1991**, *45*, 152–168.
114. Krushelnycky, P.D.; Starr, F.; Starr, K.; Longman, R.J.; Frazier, A.G.; Loope, L.L.; Giambelluca, T.W. Change in Trade Wind Inversion Frequency Implicated in the Decline of an Alpine Plant. *Clim. Chang. Responses* **2016**, *3*, 1. [CrossRef]
115. Lohse, K.A.; Nullet, D.; Vitousek, P.M. Effects of Extreme Drought on Vegetation of a Lava Flow on Mauna Loa, Hawaii. *Pac. Sci.* **1995**, *49*, 212–220.
116. Weller, S.G.; Cabin, R.J.; Lorence, D.H.; Perlman, S.; Wood, K.; Flynn, T.; Sakai, A.K. Alien Plant Invasions, Introduced Ungulates, and Alternative States in a Mesic Forest in Hawaii. *Restor. Ecol.* **2011**, *19*, 671–680. [CrossRef]
117. Goergen, E.; Daehler, C.C. Factors Affecting Seedling Recruitment in an Invasive Grass (*Pennisetum Setaceum*) and a Native Grass (*Heteropogon Contortus*) in the Hawaiian Islands. *Plant Ecol.* **2002**, *161*, 147–156. [CrossRef]
118. Barton, K.E.; Jones, C.; Edwards, K.F.; Shiels, A.B.; Knight, T. Shiels, and Tiffany Knight. Local Adaptation Constrains Drought Tolerance in a Tropical Foundation Tree. *J. Ecol.* **2020**, *108*, 1540–1552. [CrossRef]
119. Westerband, A.C.; Bialic-Murphy, L.; Weisenberger, L.A.; Barton, K.E. Intraspecific Variation in Seedling Drought Tolerance and Associated Traits in a Critically Endangered, Endemic Hawaiian Shrub. *Plant Ecol. Divers.* **2020**, *13*, 159–174. [CrossRef]
120. Craven, D.; Gulamhussein, S.; Berlyn, G. Physiological and Anatomical Responses of Acacia Koa (Gray) Seedlings to Varying Light and Drought Conditions. *Environ. Exp. Bot.* **2010**, *69*, 205–213. [CrossRef]
121. Michaud, J.; Cordell, S.; Cole, T.C.; Ostertag, R. Drought in an Invaded Hawaiian Lowland Wet Forest. *Pac. Sci.* **2015**, *69*, 367–383. [CrossRef]
122. Krushelnycky, P.D.; Felts, J.M.; Robichaux, R.H.; Barton, K.E.; Litton, C.M.; Brown, M.D. Clinal Variation in Drought Resistance Shapes Past Population Declines and Future Management of a Threatened Plant. *Ecol. Monogr. Ecol. Monogr.* **2019**, *90*, 1. [CrossRef]
123. Banko, P.C.; Camp, R.; Farmer, C.; Brinck, K.W.; Leonard, D.L.; Stephens, R.M. Response of Palila and Other Subalpine Hawaiian Forest Bird Species to Prolonged Drought and Habitat Degradation by Feral Ungulates. *Biol. Conserv.* **2013**, *157*, 70–77. [CrossRef]
124. Banko, P.C.; Hess, S.C.; Scowcroft, P.G.; Farmer, C.; Jacobi, J.D.; Stephens, R.M.; Camp, R.J.; Leonard, D.L.; Brinck, K.W.; Juvik, J.O.; et al. Evaluating the Long-Term Management of Introduced Ungulates to Protect the Palila, an Endangered Bird, and Its Critical Habitat in Subalpine Forest of Mauna Kea, Hawaii. *Arct. Antarct. Alp. Res.* **2014**, *46*, 871–889. [CrossRef]
125. Smith, C.D.M. *2016 Water Master Plan*; Honolulu Board of Water Supply: Honolulu, HI, USA, 2016; Volume 216.
126. Anderson, C.L.; Piscolish, M.; Henly-Shepard, S. Summary Report: Outcomes from Integrating Socioeconomic Assessments to Build Community Resilience in Mitigating Drought in Hawaii. In Proceedings of the 92nd American Meteorological Society Annual Meeting, New Orleans, LA, USA, 22–26 January 2012; pp. 1–9.
127. Reyes, J.J.; Elias, E.; Haacker, E.; Kremen, A.; Parker, L.; Rottler, C. Assessing Agricultural Risk Management Using Historic Crop Insurance Loss Data over the Ogallala Aquifer. *Agric. Water Manag.* **2020**, *232*, 106000. [CrossRef]
128. Macomber, P. *Guidelines on Rainwater Catchment Systems for Hawaii*; College of Tropical Agriculture and Human Resources, University of Hawaii at Mānoa: Manoa, HI, USA, 2010.
129. Gingerich, S.B.; Oki, D.S. *Ground Water in Hawaii*; U.S. Geological Survey: Menlo Park, CA, USA, 2000; Volume 6.

130. Holding, S.; Allen, D.M.; Foster, S.; Hsieh, A.; Larocque, I.; Klassen, J.; Van Pelt, S.C. Groundwater Vulnerability on Small Islands. *Nat. Clim. Chang.* **2016**, *6*, 1100–1103. [CrossRef]
131. Karnauskas, K.B.; Donnelly, J.P.; Anchukaitis, K.J. Future Freshwater Stress for Island Populations. *Nat. Clim. Chang.* **2016**, *6*, 720–725. [CrossRef]
132. Mair, A.; Johnson, A.G.; Rotzoll, K.; Oki, D.S. *Estimated Groundwater Recharge from a Water-Budget Model Incorporating Selected Climate Projections, Island of Maui, Hawaii*; U.S. Geological Survey Scientific Investigations Report 2019–5064; CABI Publishing: New York, NY, USA, 2019; Volume 46.
133. Kolivras, K.N. Changes in Dengue Risk Potential in Hawaii, USA, Due to Climate Variability and Change. *Clim. Res.* **2010**, *42*, 1–11. [CrossRef]
134. Finucane, M.L.; Peterson, J. *Human Dimensions of Drought in Hawaii. An Exploratory Study of Perceptions of and Responses to Drought Risk*; East-West Center: Honolulu, HI, USA, 2010; pp. 1–12.
135. Sproat, D.K. An Indigenous People's Right to Environmental Self-Determination: Native Hawaiians and the Struggle against Climate Change Devastation. *Stanf. Environ. Law J.* **2016**, *35*, 157.
136. Allen, C.D.; Breshears, D.D.; McDowell, N.G. On Underestimation of Global Vulnerability to Tree Mortality and Forest Die-Off from Hotter Drought in the Anthropocene. *Ecosphere* **2015**, *6*, 1–55. [CrossRef]
137. Otkin, J.A.; Svoboda, M.; Hunt, E.D.; Ford, T.W.; Anderson, M.C.; Hain, C.; Basara, J. Flash Droughts: A Review and Assessment of the Challenges Imposed by Rapid-Onset Droughts in the United States. *Bull. Am. Meteorol. Soc.* **2018**, *99*, 911–919. [CrossRef]
138. Van Loon, A.F.; Gleeson, T.; Clark, J.; Van Dijk, A.; Stahl, K.; Hannaford, J.; Di Baldassarre, G.; Teuling, A.; Tallaksen, L.M.; Uijlenhoet, R.; et al. Drought in the Anthropocene. *Nat. Geosci.* **2016**, *9*, 89–91. [CrossRef]
139. Crausbay, S.D.; Betancourt, J.; Bradford, J.; Cartwright, J.; Dennison, W.C.; Dunham, J.; Enquist, C.A.; Frazier, A.G.; Hall, K.R.; Littell, J.S.; et al. Unfamiliar Territory: Emerging Themes for Ecological Drought Research and Management. *One Earth* **2020**, *3*, 337–353. [CrossRef]
140. McLean, J.; Cleveland, S.B.; Dodge, M.; Lucas, M.P.; Longman, R.J.; Giambelluca, T.W.; Jacobs, G.A. Building a Portal for Climate Data—Mapping Automation, Visualization, and Dissemination. *Concurr. Comput. Pract. Exp.* **2021**, e6727. [CrossRef]
141. McGree, S.; Herold, N.; Alexander, L.; Schreider, S.; Kuleshov, Y.; Ene, E.; Finaulahi, S.; Inape, K.; MacKenzie, B.; Malala, H.; et al. Recent Changes in Mean and Extreme Temperature and Precipitation in the Western Pacific Islands. *J. Clim.* **2019**, *32*, 4919–4941. [CrossRef]
142. Brewington, L.; Keener, V.; Mair, A. Simulating Land Cover Change Impacts on Groundwater Recharge under Selected Climate Projections, Maui, Hawaii. *Remote Sens.* **2019**, *11*, 3048. [CrossRef]
143. Adhikari, M.; Longman, R.J.; Giambelluca, T.W.; Lee, C.N.; He, Y. Climate Change Impacts Shifting Landscape of the Dairy Industry in Hawaii. *Transl. Anim. Sci.* **2022**, *6*, xac064. [CrossRef] [PubMed]
144. Longman, R.J.; Peterson, C.L.; Baroli, M.; Frazier, A.G.; Cook, Z.; Parsons, E.W.; Dinan, M.; Kamelamela, K.L.; Steele, C.; Burnett, R.; et al. Climate Adaptation for Tropical Island Land Stewardship: Adapting a Workshop Planning Process to Hawaii. *Bull. Am. Meteorol. Soc.* **2022**, *103*, E402–E409. [CrossRef]
145. Kagawa, A.K.; Vitousek, P.M. The Ahupuáa of Puanui: A Resource for Understanding Hawaiian Rain-Fed Agriculture. *Pac. Sci.* **2012**, *66*, 161–172. [CrossRef]
146. Lincoln, N.; Ladefoged, T. Agroecology of Pre-Contact Hawaiian Dryland Farming: The Spatial Extent, Yield and Social Impact of Hawaiian Breadfruit Groves in Kona, Hawaii. *J. Archaeol. Sci.* **2014**, *49*, 192–202. [CrossRef]
147. Longman, R.J.; Frazier, A.G.; Giardina, C.P.; Parsons, E.W.; McDaniel, S. The Pacific Drought Knowledge Exchange: A Co-Production Approach to Deliver Climate Resources to User Groups. *Sustainability* **2022**, *14*, 10554. [CrossRef]
148. Meadow, A.M.; Ferguson, D.B.; Guido, Z.; Horangic, A.; Owen, G.; Wall, T. Moving toward the Deliberate Coproduction of Climate Science Knowledge. *Weather Clim. Soc.* **2015**, *7*, 179–191. [CrossRef]