CHAPTER 5

Managing Effects of Drought in Hawai'i and U.S.-Affiliated Pacific Islands

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INTRODUCTION: CONTEXT AND PROBLEM FRAMING

How Is Drought Expressed in Hawai‘i and the U.S.-Affiliated Pacific Islands?

Drought is a significant climate feature in Hawai‘i and the U.S.-Affiliated Pacific Islands (USAPI) (figs. 5.1, 5.2), at times causing severe impacts across multiple sectors. Below-average precipitation anomalies are often accompanied by higher-than-average temperatures and reduced cloud cover. The resulting higher insolation and evapotranspiration can exacerbate the effects of reduced rainfall. These altered meteorological conditions lead to less soil moisture. Depending on the persistence and severity of the conditions, drier soil can cause plant stress, affecting both agricultural and natural systems. Hydrological effects of drought include reductions in streamflow, groundwater recharge, and groundwater discharge to springs, streams, and near-shore environments.

The effects of drought on reduced water supply also have social and economic consequences. Therefore, drought has been defined from at least five different perspectives: (1) meteorological, (2) hydrological, (3) ecological, (4) agricultural, and (5) socioeconomic (see chapter 1). In this chapter, we explore how these drought perspectives are expressed in Hawai‘i and the USAPI, and how resource managers address drought-related stressors to their systems.

Direct and Indirect Impacts

Meteorological drought—Droughts vary in duration, frequency, extent, and severity. A region with meteorological drought is characterized by severe episodic droughts, with little or no rainfall for months, even in areas that normally have no dry season. El Niño events (the warm phase of El Niño Southern Oscillation [ENSO]) fall into this category. These moderate-frequency events are typically responsible for shorter lived but intense drought events that affect large areas.

Drought can also be expressed as infrequent but long-duration events of moderate severity, or long-term rainfall decline, where the baseline condition appears to be changing when examined on longer time scales. From the perspective of a resource manager, understanding the duration, frequency, extent, and severity of drought is critical to understanding the duration, frequency, extent, and severity of the drought

BOX 5.1
Geographic Scope

This chapter covers the State of Hawai‘i and the U.S.-Affiliated Pacific Islands (USAPI). Hawai‘i comprises eight major islands: Ni‘ihau, Kaua‘i, O‘ahu, Moloka‘i, Lāna‘i, Maui, Kaho‘olawe, and Hawai‘i. The main Hawaiian Islands are in the Pacific Ocean between 18.90°N and 22.24°N latitude, and 160.25°W and 154.80°W longitude (fig. 5.1). The climate of the Hawaiian Islands is extremely diverse, partly due to the large elevation range from 0 to 4205 m (13,796 feet), with mean annual rainfall from 200–10 270 mm (8–400 inches) (Giambelluca et al. 2013).

The USAPI comprise six jurisdictions in the Pacific Basin having special relations with the United States (see fig. 5.2). Two of these jurisdictions, American Samoa and Guam, are territories (as are the U.S. Virgin Islands), and one, the Commonwealth of the Northern Mariana Islands, is a commonwealth (as is Puerto Rico). The residents of these territories are U.S. citizens, except in American Samoa where the residents are U.S. nationals (U.S. State Department). Three other jurisdictions—the Republic of Palau, the Republic of the Marshall Islands (RMI), and the Federated States of Micronesia (FSM)—are now independent nations, but they were formerly districts of the United Nations' Trust Territories of the Pacific Islands, created after World War II and administered by the United States (U.S. State Department).

In combination, the islands in the USAPI occupy a wide range of latitude and longitude, spanning an aggregate east-west distance of over 2,700 miles (4345 km), from 20°30′N to 14°30′S and from 171°56′E to 131°07′E, which is greater than the width of the continental United States. All of these islands, except those of American Samoa, lie north of the equator in the broad region of Oceania known as Micronesia. As a result, these Micronesian islands have some general similarities in regard to their overall climate regimes and meteorological forcing mechanisms. The Samoan Islands, by contrast, lie south of the Equator, and as a result are subject to a somewhat different meteorological regime (Polhemus 2017).

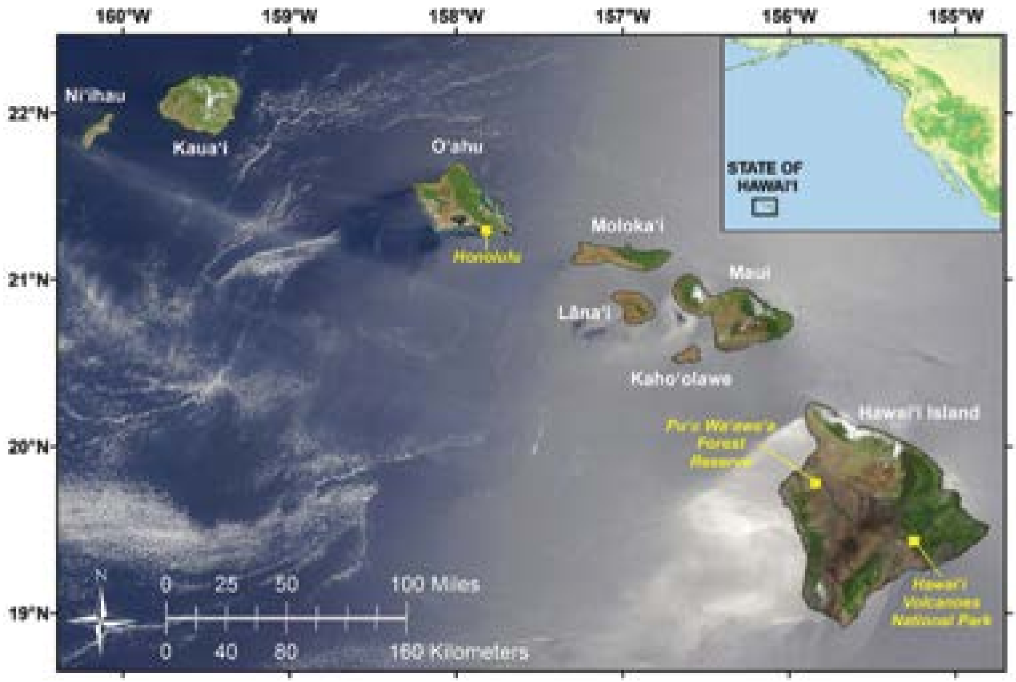

Figure 5.1—State of Hawai'i with eight major islands labeled. Background imagery: MODIS Image of Hawai'i, NASA Earth Observatory. Map: A. Frazier, U.S. Department of Agriculture, Forest Service.

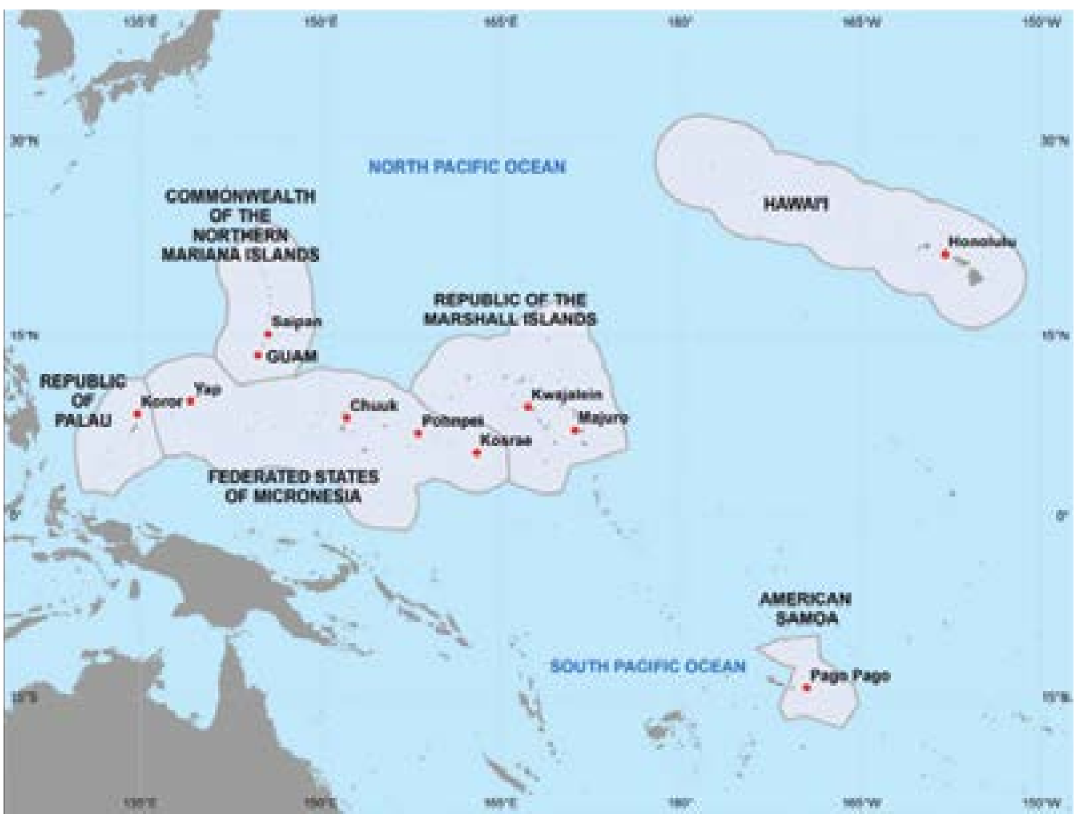

Figure 5.2—Map of the U.S.-Affiliated Pacific Islands, showing EEZ (exclusive economic zone) boundaries and locations of major islands, atolls, and cities. Map courtesy of L. Brewington, East-West Center.

response. For example, an agency's response to El Niño events, with a focus on short-lived but large-scale emergency response campaigns, may differ from a response to baseline change or an increase in the frequency of extended dry periods, with a focus on longer lived institutional, infrastructure, and personnel responses.

A long-term network of climate stations is necessary to understand and characterize meteorological drought. Rainfall has been extensively monitored in Hawai'i since the early 1900s, owing to the expansion of plantation agriculture (Giambelluca et al. 1986), while rainfall monitoring for most of the USAPI began in earnest in the 1940s, after World War II (Polhemus 2017). Because of prevailing winds, most land area in Hawai'i is characterized by a wet season from November to April and a dry season from May to October. However, dynamic features affect climate systems of the Pacific. For example, because of their tropical location, rainfall patterns in both Hawai'i and the USAPI are strongly controlled by large-scale modes of climate variability, including ENSO. El Niño events are typically associated with drier-than-average winter wet seasons and wetter dry seasons, whereas La Niña events often result in wetter-than-average wet seasons and drier dry seasons.

Many historical drought events have been attributed to El Niño events, which produce atmospheric conditions unfavorable for rainfall (Chu 1995). However, the relationship between El Niño events and drought is not simple: not all El Niño events result in drought, and effects differ depending on whether the El Niño is classified as Central Pacific (CP) or Eastern Pacific (EP) because the latter is characterized by more atmospheric water vapor over the eastern Pacific region (Bai 2017, Polhemus 2017). Furthermore, successive El Niño and La Niña events appear to be a dominant factor for long-duration drought events in Hawai'i (e.g., dry winter from El Niño followed by dry summer with La Niña) (Frazier 2016).

Hydrological drought—Long periods of low rainfall can reduce surface water and groundwater availability (table 5.1), leading to hydrological drought. Reduced streamflow is the first indication of the onset of hydrological drought, as prolonged precipitation deficiencies begin to affect components of the hydrological cycle. Reduced streamflow leaves less

Table 5.1—Sectors affected by drought

TYPE OF EFFECT	SECTOR OR ASPECT AFFECTED	MECHANISM	EFFECTS
Direct	Streams	Less rainfall for sustaining streamflow	Less streamflow and groundwater recharge, more conflict over water use
Indirect	Stream habitat	Higher stream temperatures, less connectivity, threatened stream fauna	Higher management cost for species identified as threatened or endangered; potential loss of species
Indirect	Wildfire management	More wildfire activity	Spread of fire-adapted, often fire-promoting, invasive grasses and shrubs; forest degradation and species loss
Indirect	Invasive species management	Dry conditions favor invasive species that out-compete native species	Higher management cost for species identified as threatened or endangered; potential loss of species
Indirect	Pest and disease management	More pest and disease activity	Native plants vulnerable to infestation and mortality
Direct	Agriculture—farming	Less soil moisture	Crop-yield losses in rain-fed systems
Indirect	Agriculture—ranching	Reduced growth of vegetation (forage) needed by livestock	Lower livestock production, higher livestock prices
Direct	Drinking water	Less rainfall (supplying water to reservoirs, catchments, and groundwater recharge), higher water demand	Water shortages for water catchment users; voluntary water reductions
Indirect	Nearshore habitats	Wildfires expose soils to rain, increasing erosion and sediment delivery to nearshore areas	Sediment exacerbates other climate-driven stressors for nearshore reefs, e.g., warming that can cause coral bleaching and ocean acidification
Direct	Traditional cultural practices	Less rainfall and streamflow reduce available water (stream) for domestic uses and irrigation; less groundwater discharge to nearshore fishpond environment	Lower yields of traditional food sources (e.g., taro, breadfruit); lower aquaculture yields in native fishponds; negative impacts to other ceremonial and medicinal plant species
Direct	Threatened and endangered species	Lack of water	Death of endangered nēnē goslings (Hawaiian goose, *Branta sandvicensis*), and endangered plants (seedlings and adults)

water to replenish lakes and ponds, support wetland and wildlife habitats, restore reservoirs, and divert into ditch systems. As hydrological drought progresses to extreme hydrological drought, groundwater levels are reduced. Lower groundwater levels exacerbate the potential for saltwater intrusion and can negatively impact drinking water wells and nearshore and marine ecosystems that rely on the discharge of fresh groundwater.

The most important aquifers in the region consist of freshwater lenses floating on denser seawater, and the groundwater in these aquifers is sustained by deep percolation of rainfall (Giambelluca et al. 1991). Thick freshwater lenses (e.g., Pearl Harbor, O'ahu) generally are less sensitive than thin lenses to periods of low rainfall. However, increased demand for agricultural and domestic water, resulting in higher pumping rates, can cause water levels to decline and salinity of pumped water to increase. For thin aquifers (e.g., Kona, Hawai'i), the transition zone between fresh and saltwater is closer to the pump intakes. During droughts, small changes in lens thickness due to reduced recharge may increase salinity of water pumped from these aquifers (Giambelluca et al. 1991).

High islands, with their topographic complexity, larger aquifers, and perennial stream networks, have water resources that are more resilient to severe hydrological drought. Less resilient are low-lying atolls, characterized by less extensive groundwater bodies that are more vulnerable to saltwater intrusion and do not sustain perennial streams (Polhemus 2017). Low-lying islands rely heavily on rainwater catchment systems and thin freshwater lenses for water supply, making the consequences of below-average rainfall severe and immediate. Sea-level rise and increased storm activity, both manifestations of a changing climate, can cause saline contamination in these thin lenses due to marine overwash events, where saltwater percolates into soil and groundwater. Increased frequency of these saltwater inundations, and degradation of lenses themselves, interact to severely reduce recovery time for the lenses.

Freshwater ecosystems are particularly vulnerable to reduced streamflows (Gillson et al. 2012) because drought conditions reduce surface water runoff and groundwater discharge into streams (Strauch et al. 2015, 2017a). Drought may also cause increased concentrations of fecal bacteria, with higher loads immediately after rain events (Strauch et al. 2014). Reductions in streamflow limit the availability of freshwater habitat and reduce water quality (e.g., increase stream temperature, decrease dissolved oxygen), which negatively affect stream fauna (Strauch et al. 2017b). Reduced discharge of surface water and groundwater into estuaries and nearshore environments also may harm brackish and marine organisms.

Continued drought conditions force many populations—suppliers of municipal drinking water, domestic users, and agricultural irrigation systems—to rely on more expensive delivery from groundwater sources (see case study 5.1). Some traditional and customary practices of Native Hawaiian communities depend on surface water resources. These practices, including wetland cultivation of taro (*Colocasia esculenta*), gathering of aquatic and riparian species, and aquaculture, are also directly affected by drought conditions. Because Native Hawaiians and Pacific Islanders have persisted on islands for millennia, future research should evaluate historic drought management strategies that have allowed these cultures to thrive across innumerable drought events.

Ecological drought—As meteorological drought persists, soil water availability decreases, which can lead to many impacts on both natural and managed systems (table 5.1), expressed as ecological drought. In Hawai'i and the USAPI, the most common expression of ecological drought is an increase in wildfire occurrence (Polhemus 2017, Trauernicht et al. 2015). Wildfires in Hawai'i are most frequent and extensive in nonnative grasslands and shrublands, which cover approximately 25 percent of total land area in the State and account for 80 percent of annual area burned (Hawbaker et al. 2017). During more severe drought events, wildfire can also occur in native wet forests (see case study 5.2). In the USAPI, most wildfires occur in native-dominated savannas, which can be up to 10–20 percent of total land cover on many islands, and which probably developed from recurrent burning since human arrival (3,000–4,000 years BP) (Athens and Ward 2004, Dickinson and Athens 2007, Minton 2006).

In response to drought, the risk of wildfire in grasslands and savanna vegetation can increase rapidly, which then increases the vulnerability of adjacent forest. The capacity of native forests to recover after wildfire in the Hawaiian Islands and some areas in the USAPI can be significantly limited by the rapid establishment of nonnative species, many of which increase the probability of future fires (LaRosa et al. 2008, Smith and Tunison 1992).

Wildfire leads to other ecological consequences, causing higher rates of erosion from recently burned areas and increased sediment delivery to streams and nearshore areas (Minton 2006). Nutrients in post-fire ash can be mobilized and, along with soil, be transported into streams and eventually nearshore areas, with impacts to stream biota and reef communities. Wildfires also have direct effects on human communities, damaging valued resources and infrastructure. In the most severe cases, these events cause road closures and even evacuations.

El Niño events can increase wildfire danger because of reduced rainfall and increased fuels from drying vegetation. During summer months, El Niño events are typically associated with more tropical cyclone activity, with increased rainfall for the islands. These wetter summer/fall conditions increase plant productivity and biomass accumulation, including in fire-prone grasslands and savannas (Cheney and Sullivan 2008). During winter months, however, El Niño events are typically associated with drier than average conditions. Dry winter weather results in widespread senescence and curing of vegetation and reduced fuel moisture, increasing the potential for wildfire occurrence and rate of spread.

Aside from the effects of ecological drought on wildfire, understanding is limited about other effects of ecological drought on the region. Remote-sensing studies offer some evidence. Barbosa and Asner (2017) found that, although remotely sensed greenness indicators were affected by short-term drought, a significant amount of variation in greenness was explained by centennial-scale drought data. Other remote-sensing evidence shows clearly that dry forest regions "brown down" during drought events (Pau et al. 2010), and that El Niño-induced drought events can shift the position of the upper elevation forest line (Crausbay et al. 2014). Studies of species-specific animals and plants in Hawai'i have identified recent droughts as a contributing factor in the decline of endemic forest birds (e.g., the palila [*Loxioides bailleui*], a critically endangered species of Hawaiian honeycreeper) and high-elevation plant populations (e.g., the iconic Haleakalā silversword [*Argyroxiphium sandwicense* ssp. *macrocepahalum*]) (Banko et al. 2013, Krushelnycky et al. 2013, Lindsey et al. 1997). In dry forest systems, drought-pest interactions have led to tree mortality of native species (see case study 5.3). Ecophysiological studies are under way to better understand the vulnerability of native ecosystems to drought.

CASE STUDY 5.1

Drought effects on drinking water supply on Maui

Reduced rainfall from meteorological drought can have direct effects on social-ecological systems; the most obvious consequence is reduced runoff and streamflow. Streams provide important ecological services on tropical islands, including water for hydropower production, habitat for freshwater fauna, irrigation of agriculture, and potable water supply. On Maui Island, surface water is a critical source of potable water supply, supplying 26.7 percent of total water for the island. Some regions are more dependent on surface water supply than others. For example, surface water sources supply most of the water systems in upcountry Maui (84.6 percent) and west Maui (65.1 percent) (fig. 5.3). These streams are vulnerable to drought, leading to frequent declarations of stage 1 water shortages (voluntary reductions in water use), where anticipated water demand is projected to exceed available water supply by 1–15 percent. Reservoirs in these regions help buffer the water system against shifts in surface water availability. However, if drought conditions continue and water conservation measures do not limit short-term use, stage 2 or stage 3 water shortages may be declared, requiring mandatory reductions in water use.

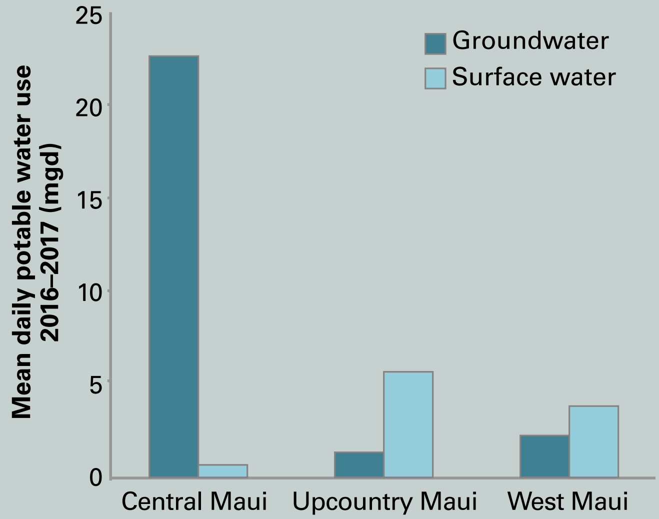

Figure 5.3—Maui County Department of Water Supply mean daily groundwater versus surface potable water use for central Maui, upcountry Maui, and west Maui regions, 2016–2017.

mgd = million gallons per day.

CASE STUDY 5.2
Drought and wildfire at Hawai'i Volcanoes National Park

During the 2002–2003 drought, relative humidity values dropped into the single digits, and wildfire spread into "safe areas" of Hawai'i Volcanoes National Park, including wet forests, with tree ferns (*Cibotium menziesii*) and uluhe ferns (*Dicranopteris linearis*) as the main carriers. Despite dozens of firefighters, miles of fuel breaks, and helicopter water drops, the fire spread into the East Rift Special Ecological Area, burning important habitat and damaging the ungulate-proof fence. Immediate action was required to replace the fence and prevent pig ingress to the area. This series of fires also impacted the lower elevation wet/mesic forest, with swordfern (*Nephrolepis multiflora*) as the main carrier. Post-fire restoration work included monitoring along with seeding and planting fire-tolerant native species. Years of lab and field trials (Loh et al. 2009) were conducted to determine which species are fire-tolerant and then to collect and bank seeds from those species (McDaniel et al. 2008). Future projects will re-survey the plots to examine longer term changes in community composition.

"The 2010 drought is the one that really changed the way I personally see the threat of drought. It was shocking to walk into the 'Ōla'a area of the park and see the forest floor dusty and the ferns crispy and dry. This is a place you usually don't venture to without rubber boots, rain gear, and Rite-in-the-Rain paper (see fig. 5.4). It made an impact on me to see how vulnerable the rare wet forest species are to extended dry periods. Some of these species are represented by only a handful of individuals, or in the case of the jewel orchid (*Anoectochilus sandvicensis*), a single patch. If their patch of forest suddenly cannot support them they could be extirpated—or if the park has the bulk of the individuals, extinct."—*Sierra McDaniel, Botanist, Hawai'i Volcanoes National Park*

Figure 5.4—'Ōla'a area of Hawai'i Volcanoes National Park during normal conditions. (Photo by S. McDaniel, National Park Service)

Predrought management:

- **Other stressors:** manage other stressors, e.g., remove ungulates, control invasive species (some nonnative species like strawberry guava [*Psidium cattleianum*] have higher transpiration rates), test rat control measures on a small scale
- **Fire:** establish and maintain fuel breaks, reduce fuels, bank fire-tolerant seeds, monitor fuel conditions
- **Monitoring:** establish monitoring plots for community change in subalpine and wet forest (Inventory & Monitoring [I&M]), map rare species
- **Rare species:** expand rare plant populations across ecological range, provide ex situ storage

Management during drought:

- Implement fire prevention including closures
- Supplement food/water for endangered bird species, e.g., nēnē (Hawaiian goose, *Branta sandvicensis*)
- Increase frequency of fence inspections because of added pressure on fences from animals seeking greener forage
- Adjust restoration activities (e.g., no planting)
- Continue invasive plant control (typically), but may need to suspend treatment of alien grasses if conditions are too dry and they are not photosynthetically active
- Increase predator trapping

Management after drought:

- If a fire occurred, conduct post-fire restoration with fire-tolerant native species (see fig. 5.5)
- Possibly replace rare species
- Use I&M data to evaluate long-term vegetation changes and formulate response

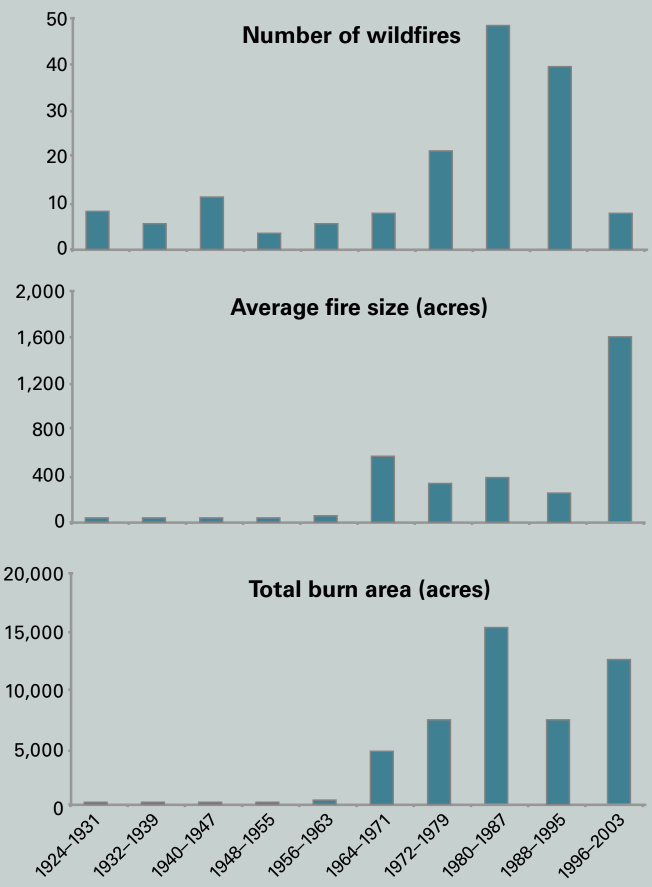

Figure 5.5—In Hawai'i Volcanoes National Park, fires are increasing in frequency, size, and total area burned.

CASE STUDY 5.3

Coping with drought at Pu'u Wa'awa'a Forest Reserve

2010 Drought

"The 2010 drought was particularly severe at Pu'u Wa'awa'a Forest Reserve (PWW). Everything looked gray and brown without a hint of green in the kikuyu grass (*Pennisetum clandestinum*) anywhere. Dust was blowing in the wind, it was really hot and sunny almost every day without the usual afternoon cloud cover, and the forest looked parched. There wasn't a lot of vegetation on the Pu'u Wa'awa'a cinder cone because most of it had died or was dormant, and there seemed to be stick forests everywhere (mostly dead māmane [*Sophora chrysophylla*], fig. 5.6). There were very few insects, and our vegetable garden (on irrigation of course) was very productive and did extremely well as compared to today where everything seems to get eaten by invertebrates. There were also no State staff around because everyone was fighting the large wildfire at Pōhakuloa Training Area up on Saddle Road."
— *Elliott Parsons, Coordinator of the Pu'u Wa'awa'a Forest Reserve*

Figure 5.6—Dead māmane trees (*Sophora chrysophylla*) in a brown field of dead kikuyu grass (*Pennisetum clandestinum*), September 2010. (Photo by E. Parsons)

Management during drought:

- General: PWW was shut down for public access for at least 6 months to reduce wildfire threat, large public events such as the 2011 Run for the Dry Forest were canceled, and research access was curtailed as well.
- Cattle grazing to reduce fire fuel loads: The State Division of Forestry and Wildlife issued special use permits (1-year revocable permits) for cattle grazing to reduce fountain and kikuyu grass biomass outside of fenced restoration/protection areas. Some cattle in the area were unhealthy because of lack of forage, nutrients, and water, and many died. New high-elevation areas were opened up during the drought where cattle had previously been kept out to allow for forest recovery. In this area, dozens of native koa (*Acacia koa*) trees had grown, ranging from a few feet to 10–15 feet high. Cattle heavily browsed the smaller koa trees; today, only the trees that were at least 10 feet tall at the time are still standing.
- Endangered and vulnerable species:
  - Endangered A'e trees (*Zanthoxylum dipetalum* var. *tomentosum*) were individually fenced (the last 10 wild trees left are at PWW, see fig. 5.7). Some of the invasive plants around the base of the trees were removed, and ooze tubes were set up to water the trees over a period of a couple weeks. The ooze tubes were refilled every month from a water tank in the back of the work truck. Seeds were collected whenever they were found.
  - Supplemental food was provided for nēnē (Hawaiian goose, *Branta sandvicensis*) at the main nesting site because drought had largely eliminated forage (kikuyu grass).

Figure 5.7—Supplemental watering and fencing of A'e (*Zanthoxylum dipetalum* var. *tomentosum*), endemic to Hualālai area and highly endangered. (Photos by E. Parsons)

- Monitoring: New monitoring programs were started including:
  - Surveys for endangered plants.
  - Resurvey for all endangered plants in the proposed Kauila-Halapepe conservation unit.
  - A halapepe (*Chrysodracon hawaiiensis*) survey across the reserve, begun when the Forest Service found that the agricultural pest banana moth (*Opogona sacchari*) had infested these trees. The survey included identifying the banana moth and individually tagging a large number of halapepe to follow their fate over time.
  - A naio (false sandalwood, *Myoporum sandwicense*) monitoring study, to evaluate the impact of the newly invasive thrips (*Klambothrips myopori*) on tree health (see fig. 5.8).
  - A survey of invasive tree tobacco (*Nicotiana glauca*) use by the endemic and endangered Blackburn's sphinx moth (*Manduca blackburni*).
- Restoration work, including weed removal and outplanting of dryland forest species and mixed mesic species, required hand watering multiple times a month to keep them alive until rainfall arrived.

Figure 5.8—Invasive Myoporum thrips (*Klambothrips myopori*, inset) in Hawai'i infesting naio (*Myoporum sandwicense*, false sandalwood), resulting in galling, dieback, loss of foliage, and eventually tree death. (Photos by E. Parsons)

Management after drought:

- Public access was reopened in 2011 after some rainfall returned.
- Permitted cattle grazing is still occurring on a rotating basis to reduce fire fuel loads around existing fenced conservation units. This decision has consequences for grass biomass in some areas, but not all sensitive ecological areas have been fenced yet to exclude ungulates including cattle.
- A new $5.5 million capital improvement project was begun in 2017 to fix a large water catchment system, reline an upper elevation reservoir, and send water down to a lower elevation reservoir where fire threat is greater. This project will reduce wildfire threat during future droughts by adding a large amount of water for restoration, firefighting, and cattle grazing.
- Mapping all of the four-wheel-drive ranch roads was initiated to aid managers and fire fighters, and large fire fuel breaks have been created in several areas.
- The individual fencing for A'e trees is being maintained and seeds are being collected, but the ooze tubes are no longer needed.
- Seeds of as many native species as possible were collected and deposited in the Hawai'i Island Seed Bank for future restoration efforts and to guard against loss of genetic diversity from mortality due to drought and wildfire.
- The monitoring programs initiated during the drought are all ongoing. However, about 50 percent of the halapepe trees were lost since 2011. Signs of banana moth infestation were present during 2012–2013, but the massive tree die-off did not occur until 2013–2014, suggesting a possible lag between drought effects on native plants and mortality. Around 10–20 percent of the tagged naio trees were lost to thrips damage, and mortality was likely exacerbated by drought.
- Native plant survival during the drought was high, probably because of consistent supplemental watering. Some of the wild endangered plants that disappeared entirely during the drought have regenerated from the seed bank (e.g., *Hibiscus brackenridgei*) but are suffering from pests.

Lessons learned:

- There is a need to improve water infrastructure, create better mobile monitoring tools, survey all roads and threatened, endangered, and rare (TER)species, and have a better drought and fire plan in place before the next drought cycle.
- Cattle-grazing operations in forests with native plants are complicated during drought. Many regenerating koa trees were likely lost to cattle. Although cattle are used for fire-fuel reduction, they may create more problems through trampling, erosion, soil loss, and subsequent invasion by exotic plants during severe drought than they solve.
- Loss of the top vegetation layer from drought and ungulates (e.g., cattle, feral sheep, goats) led to erosion, loss of topsoil, and invasion by many weeds during and after the drought. Large thickets still remain of invasive apple of Sodom (*Solanum linnaeanum*) and tree tobacco that colonized large areas during the 2010 drought.
- Some TER plants that disappear during drought may come back if there is a seed bank and plants are protected by fencing (e.g., *Hibiscus brackenridgei*).
- Native trees were probably weakened during drought, leading to infestation by different pests. A lag may occur between when trees become stressed and infested and when they die.
- Many weed issues that were not a problem during drought became problematic afterwards. For example, Tinaroo glycine (*Glycine wightii*) was not a problem during drought but is now a huge problem in the dryland fenced areas.
- Monitoring of certain species and resources is easier during drought because foot surveys are easier when surveyors are less impeded by dense vegetation. Roads can be seen clearly on satellite imagery during drought but not as easily afterwards. Drought is the time to find roads, look for native trees, and do anything that requires moving easily over the landscape.
- More information is needed on which species can be recovered after drought or fire using seed-scattering methods.
- Finally, restoration is possible during drought. There is less weedy plant biomass to remove and far fewer pests that harm outplants. Therefore, if irrigation or hand watering is possible, at least some dryland forest plants can do well.

Agricultural drought—In an agricultural setting, irrigated systems are less vulnerable to short-term agricultural drought, but they become susceptible when water supplies decline or become too costly to buy or transport. By comparison, rain-fed fields, orchards, and pastures are the most vulnerable to agricultural drought, experiencing reduced crop yields, ground cover, and pasture productivity. For pastoral systems, these reductions can in turn affect livestock operations, often causing managers to reduce herd sizes as forage production declines.

In Hawai'i, drought impacts are most severe on non-irrigated agriculture and pasture lands supporting livestock. In 1953, a severe drought across the islands reduced pineapple production on Moloka'i by 30 percent and resulted in substantial loss of cattle. The drought of 1980–1981 was declared a disaster, causing at least $1.4 million in cattle and agricultural losses. Drought emergencies in 1996, 1998–1999, and 2000–2002 caused heavy damage to agriculture and especially the cattle industry, with losses estimated at $6.5–9.4 million (CWRM 2005). The high-value vegetable-growing regions of Kamuela (Hawai'i Island) and upcountry Maui, which rely on aging ditch systems to divert stream water, are especially vulnerable to droughts. The drought of 1983–1985, for example, reduced crop production in Kamuela by 80 percent.

Droughts in the USAPI occur less frequently than in Hawai'i, but recent research indicates an increase in frequency and severity of El Niño-driven drought events (McGree et al. 2016, Polhemus 2017). The drought of 1983 was especially severe, causing 80- to 95-percent losses to taro and cassava (*Manihot esculenta*) in Palau. The El Niño drought of 1997–1998 significantly reduced harvests of important subsistence crops across the Federated States of Micronesia (FSM), including taro, coconut (*Cocos nucifera*), breadfruit (*Artocarpus altilis*), banana (*Musa acuminata*), yam (*Dioscorea alata*), and sweet potato (*Ipomea batatas*). Coconut production declined by 20 percent and did not recover to predrought production levels for 5 years. In the Republic of the Marshall Islands (RMI), the 1982–1983 and 1997–1998 droughts severely impacted agriculture, decimating nearly 50 percent of food crops across the central, southern, and western atolls. The 1997–1998 drought cut coconut production by more than 80 percent; as in the FSM, production took almost 5 years to rebound. More recently, drought conditions that began in 2012 across the northern Marshall Islands culminated in a declaration of a state of disaster in the Marshalls in 2013, persisting through 2016 (Polhemus 2017). The recent droughts in the Marshalls have severely impacted breadfruit production.

Non-irrigated pasture land devoted to the livestock industry in Hawai'i covers 761,420 acres, equivalent to approximately 83 percent of Hawai'i's active agricultural land area. Pasture lands in low rainfall areas (<30–50 inches per year) are already marginal for forage production and so are more vulnerable to droughts than in higher rainfall areas. A substantial portion of Hawai'i's pasture land is found in these drought-vulnerable regions: on Hawai'i Island, pastures in low rainfall areas occupying 291,100 acres (51 percent of Hawai'i pasture lands); 42,370 acres on Maui (57 percent of Maui pasture lands); and 23,353 acres on Kaua'i (39 percent of Kaua'i pasture lands) (Fukumoto et al. 2015, 2016a, 2016b). Within the agricultural sector, the livestock industry is often the first and most severely impacted because most ranch lands are non-irrigated and occur in low-rainfall zones that are immediately affected by lack of rainfall.

The high-value vegetable production areas of upcountry Maui (Olinda and Kula) and Hawai'i Island (Waimea) are also vulnerable to drought because the irrigation systems servicing both areas cannot provide adequate water during frequent dry periods. In the USAPI, where the vast majority of agriculture is rain-fed, droughts have severe impacts on food production and local food security. The impacts are most severe on atolls where freshwater resources are already limited and in low-lying agricultural systems; for example, taro and swamp taro (*Cyrtosperma chamissonis*) are vulnerable to salinization (Taylor et al. 2016).

Socioeconomic drought—The complete range of social and economic impacts of drought depends on the aggregate physical characteristics of drought and the characteristics of the resources and social systems exposed to drought. Low reservoir levels, thinning freshwater lenses, and saltwater intrusion can lead to water shortages. These are most often managed through water restrictions, typically voluntary but in some cases mandatory, and are applied to both residential and agricultural sectors. Water shortages can result in millions of dollars of lost revenue in the agricultural sector as well as millions of dollars in costs of relief assistance during water shortage emergencies (CWRM 2017, Polhemus 2017).

Other human dimensions of drought, such as physical and mental health problems, interpersonal conflict, loss of educational opportunities, and loss of cultural traditions are more difficult to quantify (Finucane and Peterson 2010). Cultural impacts that continue after an acute or prolonged drought include stress on agriculture (subsistence or economically important) and soils, changes in nearshore fisheries, change in accessibility of important freshwater heritage sites (springs and seeps), lack of key plant and animal species used in cultural practices, and even forced migration (Sproat 2016, Taylor et al. 2016). Human communities, and the ecosystem services on which they rely, regularly recover from the impacts of drought (Weir et al. 2017), although the speed and ability with which they recover depends on the geography of the island, specific resources, governance system, the general socioeconomic status of the area, and other stresses (Adger et al. 2013).

For communities that rely on subsistence agriculture and fishing, recovery can be particularly difficult (Taylor et al. 2016). Within subsistence communities, atoll residents who depend on shallow groundwater aquifers for their irrigation and potable freshwater may suffer harsh consequences. For example, if wells in shallow aquifers are over-pumped and infiltrated with saltwater during or after drought, they may remain brackish or never recover enough to be a potable supply (van der Brug 1986). A reduced freshwater supply could affect both the ability of a community to remain in that location and its ability to irrigate agricultural crops. Coastal fisheries and reefs that are integral for both subsistence and the social structure of a community can be set back long after drought events because droughts can shift estuarine and coastal fish species composition (Gillson et al. 2012), slow flushing times and increase the chance of algal blooms (Alber and Sheldon 1999), and alter coastal vegetation communities for years afterward (White and Alber 2009). In Hawai'i, traditional loko i'a (fishpond) aquaculture helps to cultivate fish and supports the intergenerational teaching of local fishing practices. Shifts in freshwater inputs, sediment and pollutant fluxes, salinity, and water quality after a drought can impact the function and species composition of these culturally significant systems (table 5.1).

The aftereffects of drought have significant consequences for varied sectors of the economy throughout Hawai'i and the USAPI, including tourism, agriculture, and associated commercial development. In 2011, tourism in Hawai'i comprised about 20 percent of the total adjusted gross domestic product, with estimates for agriculture ranging from 3 to 6 percent (Keener et al. 2012, Leung and Loke 2002). Both tourism and agriculture will suffer where drought intensifies saltwater intrusion and accelerates salinization of the water supply. Saltwater intrusion negatively impacts agricultural practices that rely on groundwater, but both irrigated and non-irrigated crops show lower yields during and after a drought (CWRM 2017). Drought also affects visitor industries because of the high dependency on supplies of clean freshwater. Islands that rely on ecotourism operations are further affected because of drought-related consequences to the ecosystems that are the focus of the tourist experience. For example, after the 2015–2016 El Niño drought event in the Pacific, the Republic of Palau experienced a large spike in the mortality of moon jellyfish (*Aurelia aurita*) and golden jellyfish (*Mastigias papua etpisoni*) in Jellyfish Lake, a major tourist attraction. Mortality was attributed to reduced freshwater flows and other potential interacting ecological impacts (PEAC Center 2016a).

On isolated atolls, cascading impacts from natural disasters, such as severe drought followed by storms or saltwater intrusion, can produce mounting negative effects across different measures of socioeconomic well-being, such as public health, education, and food security (Hernández-Delgado 2015). In the 1982–1983 drought event in the Republic of the Marshall Islands (see case study 5.4), daily freshwater rationing was reduced to 1 gallon per day per person (van der Brug 1986); subsequent drought events have been associated with gastrointestinal illness and conjunctivitis (WHO 2015). Drought can lead to lower incomes at the individual and community level, where agriculture both provides subsistence and supplements household income and commercial sales (Bell and Taylor 2015, Friday et al. 2017). In American Samoa, where the tuna cannery traditionally employed over 1,500 workers, drought conditions required importing freshwater at high cost to support continued cannery operations (Dworsky and Crawley 1999).

CASE STUDY 5.4
Drought and ENSO predictions in the Marshall Islands

The Republic of the Marshall Islands (RMI) lies north of the equator in the western North Pacific Ocean (fig. 5.2) and consists of 29 atolls with over 1,100 individual islands and islets. The tropical Pacific location of RMI makes it sensitive to variations caused by the El Niño-Southern Oscillation (ENSO), affecting rainfall, sea level, and tropical cyclone activity. El Niño is a strong predictor of meteorological drought in this region and allows skillful predictions of drought events, with lead times up to 9 months. The low-lying nature of these atolls and their dependence on rainwater catchment systems for drinking water make them highly vulnerable to prolonged periods of below-average rainfall (Holding et al. 2016, Polhemus 2017). The major RMI population centers, on Majuro and Kwajalein Atolls, are both served by international airports whose runways also serve as rainfall catchments that feed centralized water delivery systems (Polhemus 2017). During periods of low rainfall, these systems must be supplemented by water from reverse osmosis units and wells. Wells often rapidly become brackish from overuse.

During the drought of 1982–1983, the water supplies on Majuro became extremely depleted, and water service from the central delivery system was restricted to 2 hours each morning and evening; in February 1983, it was then cut back even further, to 1 hour every third day. By May 1983, this system was so depleted that water deliveries were primarily reserved for use at the hospital, with the populace relying largely on shallow wells hastily developed by the government. On the other more remote atolls, which rely on small catchments and shallow wells, the water supply situation became acute, with daily rations reduced to 1 gallon per day per person (van der Brug 1986). During the drought, rainfall at both Kwajalein and Majuro from January through May was only 13 percent of the long-term averages for each location.

In 1994, after recognizing the strong relationship between climate variability and drought in the USAPI, the NOAA National Weather Service (NWS), along with the University of Hawaiʻi and other partners, established the Pacific ENSO Applications Center

Figure 5.9—Public Works in Majuro, Marshall Islands, established freshwater "filling stations" around the atoll to help people access water during the extended drought of 2015–2016. Majuro Atoll Local Government is delivering reverse osmosis-produced drinking water from the College of the Marshall Islands to these filling stations April 9, 2016. (Photos courtesy of the Marshall Islands Journal)

Figure 5.10—Dying pandanus trees (*Pandanus tectorius*) during drought on Mejit Atoll, Marshall Islands, May 2013. (Photo courtesy of Moana Marine, http://moanamarine.com/projects/)

(PEAC) (Schroeder et al. 2012); the name was changed to Pacific ENSO Applications Climate (PEAC) Center in 2007. The mission of the PEAC Center is to monitor ENSO conditions, provide tailored products for planning and management including advisories and outlooks, prepare a 3-month outlook every month, and make skillful long-lead, ENSO-based rainfall and sea-level forecasts. The PEAC Center also provides periodic education and event warning outreach.

During the El Niño of 1997–1998, which resulted in severe water rationing in Majuro and other Pacific Islands, the PEAC Center proactively worked to help people by providing preemptive information about the impact of El Niño. By April 1997, the PEAC Center had successfully predicted dry conditions for early 1998, and by July the predictions indicated that this event would be comparable to the 1982–1983 event. The PEAC Center scheduled in-person outreach visits with each island and assisted in the development of drought response plans. The PEAC Center also contacted the Federal Emergency Management Agency (FEMA), which assisted RMI in developing and submitting presidential declaration requests (Schroeder et al. 2012).

Drought continues to plague the Marshall Islands (figs. 5.9 and 5.10), with acute socioeconomic drought effects seen again in 2015–2016, when a state of drought disaster was declared for the northern atolls of the RMI (Polhemus 2017). Total rainfall at Majuro from October 2015 to July 2016 was the driest 10-month period in the 62-year historical record at that station (PEAC Center 2016b). The PEAC Center and local NWS offices are critical partners in helping local government officials to prepare for drought events and have worked to lessen the socioeconomic drought impacts across the region.

Identifying and Quantifying Future Drought Risk in Hawai'i and USAPI

Limitations—Hawai'i and the USAPI have small land areas (~500 km wide in Hawai'i) that are poorly captured in general circulation models (GCMs) because these models typically use 100-km horizontal grid spacing or greater for simulations. Tall islands, including the main Hawaiian Islands, have complex topography and extremely spatially diverse climate patterns that vary greatly over short distances. However, a GCM may represent all major Hawaiian Islands in only a few grid cells (Lauer et al. 2013), which is too coarse to accurately simulate these complex climate patterns (Elison Timm et al. 2015). To overcome this issue, a technique known as "downscaling" is needed to derive local- and regional-scale information (<3-km horizontal grid spacing) from larger scale models. Downscaling uses two main approaches: dynamical downscaling (DDS) and statistical downscaling (SDS). Dynamical downscaling uses regional climate models, while SDS develops statistical relationships between large-scale atmospheric variables and local/regional climate variables (empirical data), then applies the relationships to predictors from global models (IPCC 2013).

Downscaling accuracy varies with location, season, parameter, and boundary conditions. Uncertainty can arise from many areas: resolution, model complexity, method chosen, observational uncertainty in evaluation data and parameterizations, choice of model domain, and boundary data (driving data). For Hawai'i, both DDS and SDS products are available to predict future temperature and rainfall (Elison Timm 2017, Elison Timm et al. 2015, Zhang et al. 2016), but other climate variables are available only from DDS (Lauer et al. 2013, Zhang et al. 2016). For the USAPI, only DDS products are being developed, and only for some islands (Polhemus 2017).

Future projections—Future temperatures in Hawai'i are expected to increase (Elison Timm 2017, Lauer et al. 2013, Zhang et al. 2016), and the trade wind inversion is projected to become more frequent, resulting in drying, particularly at high elevations (Longman et al. 2015, Zhang et al. 2016). If atmospheric moisture increases, windward areas are expected to show slight increases or no changes in precipitation, while leeward areas are projected to experience significant drying (Elison Timm et al. 2015, Zhang et al. 2016). Even if rainfall does not change in the future, temperatures will continue to rise, and drought severity and frequency in the future will increase because of greater evaporative demand. However, with the

BOX 5.2
Measures of drought

In Hawai‘i, the U.S. Drought Monitor (USDM) (Svoboda et al. 2002) is a widely used drought resource. The USDM is a weekly product with contributions from local authors who synthesize empirical data, drought indices, and drought impact reports from local informants to develop a map depicting drought conditions across Hawai‘i. U.S. Drought Monitor maps show drought intensities ranging from D0 (Abnormally Dry) to D4 (Exceptional Drought) as well as associated impacts.

Other indices such as the Standardized Precipitation Index (SPI) and the Keetch-Byram Drought Index (KBDI) are available for Hawai‘i, but are limited in their spatial and temporal coverage. The KBDI, for example, is publicly available for only one station in the State, at the Honolulu Airport (although KBDI is calculated by individual agencies like the National Park Service using data from nearby stations). For example, the National Park Service uses KBDI as part of the National Fire Danger Rating System (NFDRS) through data collected at Remote Automated Weather Stations (RAWS) at Kalaupapa, Haleakalā, and Hawai‘i Volcanoes National Park. Keetch-Byram Drought Index values are calculated through the Wildland Information Management System (WIMS) program. At this time, indices like the Palmer Drought Severity Index (PDSI) cannot be calculated because of insufficient data on soil moisture and evapotranspiration in Hawai‘i.

The USDM was made available for the USAPI in April 2019. Before this product was released, however, a widely used source of drought information for Pacific Islands is the Pacific ENSO Applications Climate (PEAC) Center. The PEAC Center, developed in 1994, is a partnership among multiple institutions, including the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS), the University of Hawai‘i–School of Ocean and Earth Science and Technology, and the University of Guam–Water and Environmental Research Institute (Schroeder et al. 2012). The mission of the PEAC Center is to “conduct research and develop information products specific to the USAPI on the ENSO climate cycle, its historical impacts, and latest long-term forecasts of ENSO conditions, in support of planning and management activities in such climate-sensitive sectors as water resource management, fisheries, agriculture, civil defense, public utilities, coastal zone management, and other economic and environmental sectors of importance to the communities of the USAPI” (https://www.weather.gov/peac/). See case study 5.4 for more information about the PEAC Center and its role in drought preparedness and management in the USAPI.

already-dry, drought-prone leeward areas projected to become drier, these leeward areas are expected to be at high risk for drought in the future. In addition to the regional projections from downscaled models, the strong link between ENSO and drought in this region allows us to use global ENSO projections to infer potential changes to drought in Hawai‘i and the USAPI. The frequency of extreme El Niño events is projected to increase (Cai et al. 2014, Wang et al. 2017), which will likely result in more extreme drought in the region.

PREDROUGHT MANAGEMENT

Water Infrastructure

Predrought management practices can improve resilience to drought and mitigate the impacts of drought if they are implemented before the onset of drought. The Hawai‘i Drought Plan (CWRM 2017) recommends seven broad categories or mitigation actions that could reduce the impacts of drought:

- Statewide and island-wide water resources monitoring, drought forecasting, and impact assessments
- Development of water sources
- Increasing freshwater security
- Public education awareness and outreach
- Watershed protection partnerships
- Legislation
- Land-use planning

This section will cover water infrastructure for agriculture, drinking water, and forest/wildland fire suppression. Management options for water infrastructure before drought focus on increasing water capture and storage capacity, improving delivery efficiencies, securing backup/alternative water sources, improving end-user efficiencies, and providing education and outreach. Regardless of sector, other predrought management options also include drought response plans that outline actions to take once a drought event occurs (table 5.2).

Agriculture—Reservoirs are the most important infrastructure solution to buffer agricultural and municipal systems from drought. However, the capacity of current infrastructure to effectively buffer this sector from prolonged drought is limited by small reservoir sizes and losses due to seepage and evaporation. The collapse of large-scale plantation agriculture during the 1980s and 1990s greatly reduced reservoir maintenance and management. As a result, many reservoirs throughout the State of Hawaiʻi are no longer in compliance with State code and have been taken out of service.

Hawaiʻi's sugar plantation legacy left many operational surface water irrigation systems across the State. These systems are supplied by water diverted from streams. Most systems are privately owned and continue to serve agricultural needs, and a few also serve drinking water needs. However, many systems are nearly a century old and need continual maintenance and repair. Some systems traverse lands with different owners, which adds complexity to maintaining these systems.

Drinking water—Much of Hawaiʻi's population relies on 135 regulated public water systems to deliver potable water to their homes and businesses. Over 90 percent of these systems are supplied by surface water, and the rest are supplied by groundwater wells (see case study 5.1). Drought affects utilities supplied by surface water faster (weeks to months) than utilities supplied by wells because most aquifers in Hawaiʻi have large storage capacities and may respond slowly to changes in rainfall (months to years). Further, throughout Hawaiʻi and the USAPI, many especially rural households depend on catchment water (CWRM 2017, Polhemus 2017). People can depend on these self-supplied systems directly for drinking water, particularly in USAPI, and they are also important water resources for other domestic uses.

Forest/wildland fire—Water for wildland fire suppression usually comes from nearby freshwater sources such as reservoirs, lakes, and other open water sources. However, many fires occur in dry areas with limited access to these water sources. Portable dip tanks supported by water-hauling tenders/tankers are a key resource for fire suppression in areas without available surface water or municipal water. In some areas, helicopter dip tanks are constructed near reservoirs or fire hydrants to facilitate water pick-ups. Hawaiʻi Volcanoes National Park constructed dip tanks in multiple locations, with one tank near sensitive park

Table 5.2—Predrought management options for improving water infrastructure and conservation

OBJECTIVE/SECTOR	AGRICULTURE	DRINKING WATER	FOREST/WILDLAND FIRE
Increase water capture and storage capacity	Expand and add reservoirs; increase supply from stream diversions and wells; line reservoirs	Add new wells or increase pumping capacity; expand/add reservoirs	Expand/add reservoirs; establish new dip tank sites; pre-position equipment in high-risk areas
Improve delivery efficiencies	Enclose or line open-ditch systems; detect and repair leaks; establish ditch cleaning and maintenance programs	Conduct water audits; detect and repair leaks; create main line replacement programs; manage pressure	Establish dip tanks and helicopter landing pads near critical areas
Secure backup and alternative sources	Construct wells; secure agreements for recycled water where feasible; explore storm-water capture	Construct backup wells; maintain replacement pumps/parts locally; use desalination	Secure agreements with landowners to use water sources
Improve end-use efficiencies	Use efficient irrigation methods (drip irrigation); seasonally adjust irrigation schedules; mulch; use conservation tillage	Implement customer water conservation programs (e.g., incentives, conservation rates, give-away and direct replacement programs)	Develop maps of critical infrastructure (e.g., fire roads, water sources, locked gates, equipment)
Outreach/education	Workshops for conservation practices; university extension service programs	Media advertising; water conservation contests; Fix-a-Leak Week[a]	Pre-fire season stakeholder planning meeting;[b] fire prevention campaign; Wildfire LOOKOUT![c]

[a]U.S. Environmental Protection Agency annual awareness campaign, which can be used by local water utilities.

[b]Although this does not directly improve end-use efficiency of water, this planning meeting can help firefighters coordinate response and equipment between organizations and make more efficient use of equipment, personnel, and water resources.

[c]Annual pre-fire season campaign headed by Department of Land and Natural Resources and Hawaiʻi Wildfire Management Organization (http://www.hawaiiwildfire.org/lookout/).

resources. These tanks are filled by rainfall catchment and supplemented by water hauling. In the summer of 2017, they were used successfully to suppress a rapidly spreading wildfire within the park.

Closing of sugar plantations and recent Hawai'i State dam safety regulations pose a challenge to keeping and maintaining reservoirs operational and filled for agriculture and firefighting uses. Saltwater from the ocean is not typically used for firefighting because it kills plants and can render the soil toxic for existing or recovering plants.

Wildfire

Strong drought events are closely linked with large fire years across the USAPI, when large percentages of total land area have burned on Palau, Guam, and the drier islands of the FSM. Drought and fire are also linked in Hawai'i, but they interact differently across Hawaiian landscapes. The Hawaiian Islands are more climatically diverse than any other USAPI, with a much stronger presence of nonnative, fire-prone vegetation (Trauernicht et al. 2015). Regardless of how drought affects fire danger, preparing for wildfire before a drought is critical to mitigate its impacts (table 5.3). Preparation includes (1) building up or maintaining fire suppression and emergency responder capacity and readiness and (2) preparedness at the level of individuals, households, communities, and large landowners and land managers.

Response—The capacity for firefighters to respond quickly to wildfires is essential to minimize suppression costs and fire damage (Lee et al. 2013). Municipal fire departments are typically first to respond to wildfires in the Pacific region, but they are primarily trained and equipped to fight structural fires. Many forestry agency staff are trained and equipped for wildland firefighting, but they must be called away from regular duties to fight a fire, which can lengthen response times. The National Park Service and U.S. Fish and Wildlife Service use continental U.S. firefighting resources on extended-duration incidents through a Master Cooperative Wildland Fire Management and Stafford Act Response Agreement. For other organizations, firefighters have identified two top priorities to maintain readiness and build cooperative relationships among agencies: (1) provide wildland-specific equipment (e.g., engines and water tenders with off-road capabilities) and (2) create training opportunities, especially those involving cross-agency participation (Gollin and Trauernicht, in press). Regardless of fire danger level or wildfire incident size, resources for fire suppression equipment and supplies are limited, and any equipment coming into Hawai'i to support fighting of fires needs to be shipped long distances. Mutual Aid Agreements and shared jurisdictions can facilitate joint responses by multiple agencies on fires, especially on larger, multi-day incidents.

Preparation—Planning for wildfire incidents by homeowners, landowners, and land managers involves (1) identifying hazards, valued resources, and mitigation opportunities; (2) developing evacuation procedures, especially for large landholdings; and (3) creating maps and other documents to communicate this information with fire responders.

Most fires on islands are caused by human activities, but there are also occasional lightning-strike fires and, on Hawai'i Island, lava-caused ignitions (e.g., fig. 5.11). The dry conditions that accompany drought are a primary cause of fires, but wildfire hazards also include high wind, low relative humidity, high ignition frequency, and unmanaged vegetation. Of these, ignitions and vegetation can be actively managed. Ignition risk can be mitigated somewhat by restricting access to high-risk or high-priority areas and restricting high-risk activities (e.g., operating machinery, welding) during drought (see

BOX 5.3
Historical and recent drought in Hawai'i

In Hawai'i, the 2010 drought was one of the worst on record. According to the U.S. Drought Monitor, at least 40 percent of Hawai'i experienced severe drought (category D2) or worse for 35 consecutive weeks in 2010. For about half the State, severe drought or worse occurred from July 2008 through January 2014. This drought was associated with a Central Pacific (CP) El Niño event in 2009/10, and caused the U.S. Department of Agriculture to designate all four counties in Hawai'i as Primary Natural Disaster Areas. Drought consequences included lost crop and livestock production, encroachment of feral ungulates into agricultural areas, and wildfire occurrences on every island (Pierce and Pickett 2014), even in wet forest areas, as well as post-fire rain events that caused significant erosion and sediment delivery to nearshore areas.

Figure 5.11—Aerial view of lava-ignited fire in June 2007 at Hawai‘i Volcanoes National Park. (Photo courtesy of National Park Service)

Invasive Species below). Another way to reduce ignition risk is to properly inform the public, the source of mostly accidental but also intentional ignitions.

Reducing vegetation-based fuels is another action that landowners and managers can take to mitigate drought effects on wildfire risk. Fuel loads and fuel continuity can be reduced by lowering hazardous fuels through restoration (invasive species removals and the planting of native species), establishing fuel breaks, targeted livestock grazing, and prescribed burning. All of these steps can reduce the size of wildfires and the intensity and speed at which they burn and spread (e.g., Oliveira et al. 2016, Prichard et al. 2017, Taylor 2006). However, higher intensity animal grazing can expose more soil, increasing the incidence of erosion when rains resume as well as causing impacts to remnant native vegetation. Fuel breaks are most effective at stopping fires when they provide access and defensible space for firefighters (Syphard et al. 2011). Adaptations in the built environment are also important (Penman et al. 2014), especially when extreme fire weather (e.g., very high winds and low relative humidity) reduce the effectiveness of fire breaks and strain suppression capacity (Arienti et al. 2006, Cheney and Sullivan 2008). Other ways to reduce fire impacts and facilitate fire response include increasing water availability; fireproofing homes and buildings; and improving roads, access, and signage.

Outreach—Science communication and outreach efforts are essential to increase the adoption of best practices for pre-fire planning and fuels management, and these are being implemented in three main ways. First, forestry agencies throughout the region have worked to various extents on public education about wildfire safety. More recently, the Hawai‘i Wildfire Management Organization (HWMO) and the Wildland Fire Program with University of Hawai‘i (UH) Cooperative Extension have increased the technical support and resources available on fire planning for the public and land managers throughout the region.

The HWMO has expanded the number of Community Wildfire Protection Plans and Firewise-certified communities throughout Hawai‘i State and on Guam. HWMO also partners with UH Cooperative Extension and the U.S. Department of Agriculture (USDA) Forest Service Institute of Pacific Island Forestry (IPIF) on the Pacific Fire Exchange (PFX), a regional partnership for the exchange of fire science knowledge funded by the Joint Fire Science Program. The HWMO and PFX have co-developed fire preparedness technical guides and workshops that promote landscape-scale, cross-boundary planning and resource sharing to maximize the effectiveness of pre-fire mitigation efforts. Finally, IPIF and USDA Forest Service Region 5 Fire and Aviation Management also have been funding multifaceted research and management projects in fire-prone areas of Hawai‘i, and in Guam, Palau, and the FSM, including fire history mapping, landscape restoration, shaded fuel break establishment, and fire prevention through education and outreach.

Invasive Species

Invasive nonnative (alien) species encompass an increasingly wide range and diversity of organisms, from microbial organisms (e.g., fungal and bacterial pathogens) to plants (e.g., small fire-prone grasses, large nitrogen-fixing canopy dominants) to animals (e.g., plant-eating insects, omnivorous foraging rodents, forest-modifying ungulates). Not surprisingly, invasive alien species can have wide-ranging impacts on ecosystem composition, structure, function, and dynamics. Across biome types, efforts to build ecological and social resilience to drought by managing invasive alien species are complicated by variations in (1) invasive species encountered, (2) the types of effects that invasive species can exert on watersheds and water supply, and (3) the individual and interactive responses of these organisms to changing environmental conditions. Conversely, the many co-benefits to drought-focused management of invasive alien species include enhanced native biodiversity, often improved health and increased human safety (in the case of fire), and other biocultural benefits, such as continued access to cultural and economic goods and services provided by native species.

Predrought management of invasive species (table 5.3) is most effective with a clear understanding of the hydrological benefits of invasive species management, whether by increasing water supply in previously invaded wet systems or by reducing erosional threats in previously fire-prone drier systems. For example, in wet systems that are heavily invaded by or have the potential to be invaded by strawberry guava (*Psidium cattleianum*), management of this alien invader can support ecological, botanical, and hydrological objectives (Balzotti and Asner 2017, Strauch et al. 2017a). To this end, Povak et al. (2017) used distributed hydrological modeling (after Strauch et al. 2017a) within a decision-support framework to build a tool to support efficient watershed stewardship on Hawai'i Island's windward wet forests, with a focus on invasive alien plant species removal.

This modeling tool identified those 250-acre hydrological units that, if either treated for strawberry guava or protected from invasion by strawberry guava, would provide the largest hydrological benefits to managers. The tool also considered other factors in constructing restoration or protection priorities. For example, each unit was scored with respect to the kind of conservation protection the land parcel received, how easy the parcel is to access, and any conservation co-benefits of restoration protection. In this case, drought was addressed indirectly by first considering the implications of reduced water supply, then maximizing opportunities for targeting management to those areas most likely to positively affect water supply (wet forests of Hawai'i Island).

Water-demanding invasive plant species can be targeted, with physical and chemical methods for removal of incipient populations or with biocontrol agents for extensive populations. Because drought management is fundamentally landscape management, drought-relevant management of invasive species ideally also considers and operates at landscape scales.

Agriculture

Well-managed pastures in good condition (i.e., high plant diversity with a range of growing seasons and rooting depths) are better adapted to withstanding the negative effects of drought (table 5.3). Pasture management entails regulating the intensity, frequency, and timing of grazing (Howery 1999). Moderate grazing intensity, carefully spaced over time, ensures that a pasture does not suffer from overgrazing. Overgrazing, including reduced root biomass and growth, prevents the ability of plants to extract soil resources and ultimately reduces aboveground growth and forage production. Moderate grazing, in contrast, maintains adequate root growth, enabling plants to extract soil moisture even during drought. More forage biodiversity in the pasture ensures a range of forages with varying tolerance to drought and a range of rooting depths, both of which promote vegetative coverage of the soil. Maintaining soil cover, even during drought, improves recovery once rains return by increasing infiltration and percolation, reducing evaporation, and preventing erosion.

In irrigated row-cropping systems, one strategy to counter the negative effects of reduced rainfall is to build and maintain soil organic matter. Soil organic matter increases soil water retention and increases plant-available water in the soil. Another way to reduce evaporative water loss from the soil surface is to use natural (wood chips) and synthetic (plastic cover) mulches. Although building and maintaining soil organic matter is a cornerstone of soil health and resiliency, this alone cannot overcome the destructive effects of drought on crop productivity. On the other hand, biodiverse agroforest-cropping systems developed in the islands of the USAPI are much better able to withstand and recover from drought because these systems are characterized by high plant diversity, with many varieties having more tolerance to drought and salinity.

MANAGEMENT OPTIONS DURING AND AFTER DROUGHT

To address the impacts of drought in an island system, diverse responses are needed to meet specific ownership, partnership, and county or larger State needs. The nature of these responses must recognize that municipality needs might conflict with agricultural needs, and both of these may conflict with the needs of native species in diverse ecosystems, including streams, forests, shrublands, and grasslands.

The duration, extent, frequency, and severity of a drought will affect how recovery proceeds. For areas that rarely experience drought, recovery from a severe drought of long duration will be different from areas that experience frequent droughts of short duration and moderate severity (see Barbosa and Asner 2017 for an ecological example). Once a drought event is over and rainfall returns to normal patterns, sectors will recover differently both spatially and temporally. Sustaining or reestablishing ecosystem services while recovering from drought depends on many factors, including type of harm done to an ecosystem, its accessibility for recovery efforts, resources available, and postdrought weather conditions. Postdrought reports, which can inform both drought recovery and drought preparedness actions, should document impacts, response actions, and effectiveness of preparation and response.

Water Resources

Stream fauna—Once streamflow returns, native stream fauna rapidly (within 1–12 months) recolonize stream habitats that connect to the ocean. As examples, after the 2014 restoration of ridge-to-reef streamflow in Wailuku River on Maui, native snails (hihiwai, *Neretina granosa*) were observed returning upstream from the ocean. Within 1 month of restored streamflow on Honomanu Stream, Maui, in 2016, both hihiwai and oopu nopili (*Sicyopterus stimpsoni*) were observed recruiting upstream (Skippy Hau, pers. comm.[1]). However, the control of nonnative species is critical for restoring native stream ecosystems. For example, during drought, nonnative Tahitian prawn (*Macrobrachium lar*) will populate pool environments, consuming detritus and preying on native species. Restoring streamflow using water diverted from other streams might also transport nonnative species, spreading their distribution and increasing the transmission of diseases they carry.

Infrastructure—During recovery from drought, managers and landowners can focus on restoring water infrastructure to predrought capacity, but this requires several considerations. Water-use restrictions should be lifted with caution to ensure that system capacity can effectively meet postdrought high water demand. Lowered flows during drought may have caused sedimentation and water quality issues in surface water ditch systems and reservoirs. Unused portions of irrigation systems may become desiccated from lack of water. Low reservoir levels may expose portions of these reservoirs to plant growth or erosion, which need to be addressed before filling. Guidelines for many drought recovery actions for infrastructure are like those for predrought management (tables 5.3, 5.4).

During drought, system managers and operators can carefully monitor both the water resources supplying their systems and customer consumption, quantifying streamflow and diverted water amounts along with water quality metrics. Groundwater resources should also be carefully monitored. Metrics include water withdrawn, water levels, freshwater thickness, salt-brackish-freshwater transition zone depth, pumping amounts, and chloride concentration of water pumped by wells.

Alternative water sources—Hawai'i's human population is growing, and along with it is the demand for water. This trend, together with higher awareness of environmental needs and cultural rights, has increased competition for limited natural supplies. In a future warmer climate with many land-use changes and increased pressures, use of alternative resources will increasingly become a key component in sustainable resource management for nonpotable needs. Alternative water sources available in Hawai'i include recycled water, gray water, storm water, and desalinated seawater.

Wildfire Prevention and Suppression

Tracking climate and weather is critical to monitoring and predicting the threat of wildfire (table 5.4). In Hawai'i, several efforts modeled off the National Fire Danger Rating System have been put forward, but strong climate gradients and insufficient information on local fuel types (Pierce and Pickett 2014) have limited the adoption of a statewide system (Burgan et al. 1974, Fujioka et al. 2000, Weise et al. 2010). The National Weather Service posts Red Flag warnings for Hawai'i and Guam when drought and weather conditions meet specific criteria (e.g., in Hawai'i: Keetch/Byram Drought Index [KBDI] >600, relative humidity [RH] <45 percent, sustained winds >20 miles per hour).

For the goal of wildfire suppression, fire danger warnings are effective only if agencies have the capacity to increase resources available for fire response. Ideally, increases in fire-related staffing are commensurate with fire danger. For example, Federal wildland firefighters with the U.S. Army Garrison will increase personnel during times of high fire danger. The National Park Service conducts fire training for most field-going personnel and equips qualified personnel with

[1] Personal communication. 2016. S. Hau, Aquatic Biologist, Hawai'i Department of Land and Natural Resources (DLNR) Division of Aquatic Resources (DAR), 101 Mā'alaea Boat Harbor Road, Wailuku, HI 96793.

Table 5.3—Predrought management options by sector

SECTOR	MANAGEMENT OPTIONS
Water resources	• Increase water capture and storage capacity. • Improve delivery efficiencies. • Secure backup/alternative water sources. • Improve end-user efficiencies. • Increase education and outreach. • Make drought response plans outlining actions to be taken once a drought event occurs.

Wildfire	• Build up or maintain fire suppression and emergency responder capacity and readiness.
	• Improve preparedness at the level of individuals, households, communities, and large landowners/land managers:
	    • Identify hazards, valued resources, and mitigation opportunities.
	    • Develop evacuation procedures.
	    • Create maps and other documents to communicate this information with fire responders.
	• Reduce vegetation-based fuels through restoration (invasive species removals with planting of native species), fuel breaks, targeted livestock grazing, and prescribed burning.
	• Establish and maintain physical (roads) or biological (green stripes) fuel breaks to help reduce the spread of wildland fires and provide access and defensible space for firefighters.
	• Increase water availability, fireproof homes and buildings, and improve roads, access, and signage.
	• Increase science communication and outreach efforts to promote adoption of best practices for pre-fire planning, fuels management, and reducing ignition risk.
	• Ensure adequate water availability for fire suppression (nearby reservoirs, lakes, and other open freshwater sources). In areas without available surface water or municipal water:
	    • Provide where possible portable dip tanks supported by water hauling tenders/tankers—a key resource for fire suppression.
	    • Consider constructing helicopter dip tanks near reservoirs or fire hydrants to facilitate water pick-ups.

Invasive/TER species	• Target water-demanding invasive plant species with physical and chemical methods for removal of incipient populations, or with biocontrol agents for extensive populations. • Reduce the number of nonnative ungulates through culling or exclusion by fencing.
Agriculture	• Ensure that pastures are well-managed and in good condition (high plant diversity with a range of growing seasons and rooting depths). Manage intensity, frequency, and timing of grazing. • Maintain soil cover, even during drought, to improve recovery once rains return to increase infiltration and percolation, reduce evaporation, and prevent erosion. • Build and maintain soil organic matter in irrigated row-cropping systems. • Use natural (wood chips) and synthetic (plastic cover) mulches to reduce evaporative water loss from the soil surface. • Use biodiverse agroforest cropping systems (i.e., with high plant diversity and with many varieties having greater tolerance to drought and salinity). • Ensure adequate reservoirs to buffer agricultural and municipal systems from drought.

TER = Threatened, endangered, and rare.

Table 5.4—Drought and postdrought management options by sector

SECTOR	MANAGEMENT OPTIONS
Water resources	• Restore water infrastructure to predrought capacity. ◦ Assess water quality in surface water ditch systems and reservoirs. • Control nonnative species to restore native stream ecosystems. • Lift water-use restrictions cautiously to ensure that system capacity can effectively meet high water demand. • Carefully monitor groundwater resources, including water withdrawn, water levels, freshwater thickness, salt-brackish-freshwater transition zone depth, pumping amounts, and chloride concentration of water pumped by wells. • To inform drought recovery and future drought preparedness, write a postdrought report to document drought impacts, describe drought response actions taken, and evaluate effectiveness of drought preparation and response. • Consider use of alternative water resources for sustainable resource management for nonpotable needs (recycled water, gray water, storm water, desalinated seawater).
Wildfire	• Restrict access to high-risk or high-priority areas, or restrict high-risk activities (operating machinery, welding) during drought to mitigate ignition risk. • Track climate and weather to monitor and predict the threat of wildfire. • Ensure that agencies have the capacity to increase resources available for fire response. • Consider using fire danger rating systems to support prevention efforts by (1) informing the public about hazardous conditions and (2) justifying to agencies and landowners the need to restrict access and activities to reduce the chance of ignitions. • Scale up wildfire-prevention messaging in response to drought, a relatively low-cost, potentially high-impact mitigation strategy. ◦ Use signage and media including radio for wildfire prevention campaigns, especially when El Niño development allows longer range forecasting of drought conditions.

Invasive/TER species	• Protect TER species:
	  ◦ Enhance fire prevention (reduce fuel conditions and number of ignitions).
	  ◦ When ignitions cannot be prevented, increase investment in fire suppression.
	  ◦ Reduce the number of nonnative ungulates through culling or exclusion by fencing.
	  ◦ Target fencing of individuals or groups of individuals of nonnative ungulates.
	  ◦ For TER species of greatest concern, provide supplemental water through irrigation systems or even hand watering (see case studies 2, 3).
	• Plant TER species back into the wild, taking future droughts/climate into consideration as to where, when, and how TER enrichment planting and restoration are done.
	  ◦ Select genotypes that are more resistant to drought for outplanting, better able to cast shade, or more competitive with aggressive nonnatives.
	  ◦ Strategically locate plantings within or adjacent to areas that already are managed for other objectives.

Agriculture	• Ranchers may move or cull herds, slaughter cattle, or wean calves early. • Farmers may harvest early, plant less thirsty crops, prioritize irrigation, apply mulch, and pump more groundwater. • Use traditional knowledge to inform response actions. • Monitor reservoir, stream, and well levels more often. • Seek authorization to convert and use nearby wells for emergency water, facilitating use for private reservoirs; coordinate installation and use of standpipes for ranchers for livestock drinking water; use military surplus equipment to transport equipment and/or water to drought-stricken areas. • Coordinate and facilitate access to Federal assistance programs, low-interest State loans, and Federal crop loss programs and agriculture loans.

TER = Threatened, endangered, and rare.

firefighting gear during periods of elevated fire danger. Other agencies, however, especially in the USAPI, often lack additional personnel or equipment to increase suppression readiness during times of high fire danger.

Another way to support prevention efforts is with fire danger rating systems. These not only inform the public about hazardous conditions, but they also reduce the chance of ignitions by justifying to agencies and landowners the need to restrict access and activities.

In the USAPI, scaling up messaging on wildfire prevention in response to drought is a relatively low-cost, potentially high-impact mitigation strategy (table 5.4). Nearly all wildland fires on Pacific Islands are human-caused (Trauernicht et al. 2015). Preventable wildfires cause losses that vastly exceed the cost of prevention education (Prestemon et al. 2010). Wildfire prevention campaigns using signage, the media, and radio occur across the USAPI, especially when El Niño development allows longer range forecasting of drought conditions.

In Hawai'i, the 2015–2016 El Niño event provides an example of using science communication to spur agency response to a climatic event in the context of wildfire prevention. In November 2015, the Pacific Fire Exchange produced a fact sheet outlining the link between El Niño and increased fire activity (Trauernicht 2015). Many agencies—the University of Hawai'i Cooperative Extension, Hawai'i Wildfire Management Organization, and the National Weather Service—used this fact sheet to approach local wildfire-coordinating groups. The outcome was the development of the statewide Wildfire LOOKOUT! campaign, spearheaded by the Hawai'i Department of Land and Natural Resources and endorsed by over 20 Federal, State, and county agencies. In addition to an annual kick-off media event coinciding with the nationally recognized Community Wildfire Preparedness Week (the first week of May), the campaign has a web page (www.hawaiiwildfire.org/lookout) with fact sheets covering homeowner safety and fire occurrence in Hawai'i. To encourage media coverage of wildfire in Hawai'i, the campaign organizers also created a web page with ready-made press briefs highlighting fire mitigation projects around the State.

Endangered Species

Managing threatened, endangered, and rare (TER) species during a drought should address not only the basic water-supply needs of the species, but also elevated threats that other stressors may impose (table 5.4). Drought stressors include elevated fire danger conditions, increases in browse pressure by nonnative feral ungulates, and increases in rodent damage (e.g., bark stripping by rats). The interacting effects of multiple stressors can also increase susceptibility to disease or insect pests.

Because many TER plant species in Hawai'i occur in dry to mesic biome types (Ostertag et al. 2014) that are susceptible to drought and drought-related impacts, managing for the direct and indirect effects of drought are fundamentally a biodiversity concern. Managers are therefore tasked with reducing stress to or preventing death of TER species and are often required to manage the whole ecosystem. Managers can enhance fire prevention (reduce fuel conditions and number of ignitions), increase investment in fire suppression when ignitions cannot be prevented, reduce the number of nonnative ungulates (either by culling or exclusion by fencing), target fencing of individuals or groups of individuals, and, for the TER species of greatest concern, provide supplemental water through irrigation systems or even hand watering (see case studies 5.2, 5.3).

Although not a method that has been used by managers of the Pacific Islands, planting of TER species back into the wild probably needs to be done in a way that considers future droughts in deciding where, when, and how TER enrichment planting and restoration are done. For example, depending on genetic variation in remaining wild populations, managers could select genotypes for outplanting that are more resistant to drought, cast more shade, or are more competitive with aggressive nonnatives (table 5.4). Plantings could be located strategically based on historical and future climate trends (e.g., at the wetter end of the range limit if there has been a drying trend), and within or adjacent to areas that already are managed for other objectives. Such areas include those that are ungulate-free, receive regular fuel reduction treatments, have fire awareness and prevention promoted in adjacent communities, and have supplemental watering.

Agriculture

Farmers and ranchers respond to drought in a number of ways (table 5.4). Farmers may harvest early, plant less thirsty crops, prioritize irrigation, apply mulch, and pump more groundwater. Ranchers may move or cull herds, slaughter cattle, and wean calves early.

Both farmers and ranchers may need to pay for water deliveries and supplemental feed.

Some response actions are informed by Native Hawaiian traditional knowledge. For example, the following management strategy refers to the observations of limu (seaweed):

> *When a certain kind of limu begins to appear it's a solid sign of a drought because (it reflects) the changing water temperatures of the ocean. And so (when) these different kinds of limu began appearing they said, "Now is the time to start getting your fields ready for sweet potato." And you know these were observations of a great amount because sweet potato can stand a drought. (Finucane and Peterson 2010)*

The Hawai'i Department of Agriculture has a responsibility to manage drought and may implement a number of response actions (CWRM 2017):

- Implement more frequent monitoring of reservoir, stream, and well levels.
- Continue to notify system users regarding storage and supply conditions.
- Implement voluntary and/or mandatory water restrictions for system users.
- Seek authorization and available funding to mobilize contractors to truck water to ranches without source.
- Seek authorization to convert and utilize nearby wells for emergency water use.
- Seek authorization for use of private reservoir sources and coordinate installation and use of standpipes for ranchers for livestock drinking water.
- Advise farmers and ranchers regarding required documentation and data collection for Federal assistance and disaster relief programs.
- Coordinate and facilitate access to Federal assistance programs, low-interest State loans, Federal crop loss programs, and agriculture loans.
- Seek authorization for use of military surplus equipment to transport equipment and/or water to drought-stricken areas.

CONCLUSIONS

Hawai'i and especially the USAPI have not seen a comprehensively designed research strategy focused on identifying and developing solutions for drought-related thresholds and their interactions with other threats. Clearly, resource management can alleviate drought-related social and biophysical factors that push natural and human systems across these thresholds (Barnett and Adger 2003). Management efforts need to be expanded to engage multiple interacting stressors: invasive species, altered fire and climate regimes, pests, and pathogens. The many areas of applied drought-focused research include:

- Silvicultural management of nonnative species for watershed function
- Restoration practices that increase resilience of native ecosystems to drought and fire, including appropriate genotypes and species
- Spatial and temporal variation in the effects of drought on fire behavior, including fuel loads and the potential of management to reduce fuels
- The human dimensions of drought, wildfire, and their interactions
- Groundwater resiliency to drought and saltwater intrusion
- The genetic drought adaptation potential for TER species
- Drought-pathogen-pest interactions and spatial and temporal variation in the effects of pathogens and pests on native plants and animals
- The design of agricultural and pastoral systems that allow for more rapid accommodation of drought events while reducing sensitivity to financial loss

Many communities in Hawai'i and the USAPI have features that may make them more resilient to drought compared to some of the other regions covered by this report. Pacific Island host cultures rely on traditional knowledge developed over thousands of years and on the resulting community-based approaches, practices, tools, and institutions that have supported communities during drought periods from the distant past into the present. Traditional knowledge-based communities also are more resilient to drought because close connections exist between landowners, resource managers, and decision makers, allowing for more timely and targeted support (Barnett 2001, Mimura et al. 2007). Although crossing certain drought-related thresholds cannot be prevented, the effects may be mitigated more easily and cost effectively in the region because of these attributes.

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