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Hawaii and U.S. Affiliated Pacific Islands

Christian P. Giardina, Richard A. MacKenzie, and Jonathan L. Deenik

Introduction

This regional summary addresses the effects of climate change on soils of seven of the eight main Hawaiian islands (Kaua'i, O'ahu, Moloka'i, Lāna'i, Kaho'olawe, Maui, and Hawai'i), the territories of Guam and American Samoa, the Commonwealth of the Northern Mariana Islands, and the freely associated Republic of Palau, Federated States of Micronesia, and Republic of the Marshall Islands. The distribution of soil types in Hawai'i and the US Affiliated Pacific Islands (USAPI), and their sensitivity to climate change, is determined as elsewhere by soil-forming factors and their interactions (Jenny 1941; Vitousek 2004). These influences include geologic substrate age and type, temperature and precipitation, topographic features that affect hydrology and movement of sediments, vegetation occupying the site, and human impacts. For wetlands, hydric soils are shaped by available moisture, which can be dynamic, especially where water is diverted from natural wetlands for agriculture or development purposes, or in coastal areas subject to tidal inputs, storm surges, and baseline sea level rise. This understanding of climate-hydrology-soil relationships suggests that many soils will experience some change as a result of Hawai'i's changing climate.

Hawaiian Islands

The Hawaiian Islands represent a chronosequence of parent material, ranging from literally seconds-old cooling lava on the southeastern district of Puna on Hawai'i Island to the more than 4 million-year-old substrate on Kaua'i Island and of course all ages in between. In Papahānaumokuākea, or the Northwestern Hawaiian Islands, jurisdictionally a part of the state of Hawai'i but not thoroughly discussed here, coral-covered surface substrate dates back tens of millions of years. This geologically driven diversity in substrate age across the Hawaiian Islands is orthogonally married to remarkably steep gradients of temperature and moisture, from lowland deserts to montane shrublands, to alpine grasslands, to montane wet forests, and to lowland rainforests. Nearly every combination of substrate age, temperature condition, and moisture environment can be found on the Hawaiian Islands—resulting in a complex array of soil types across very short distances (Vitousek 2004).

The geographic area of the Hawaiian Islands covers 16 587 km^2 distributed across the islands as follows: Hawai'i Island (10 432 km^2), Maui (1884 km^2), O'ahu (1545 km^2), Kaua'i (1430 km^2), Moloka'i (637 km^2), Lāna'i (364 km^2), and Kaho'olawe (115 km^2)[3]. Ten of the 12 soil orders in the USDA Soil Taxonomy are found in the Hawaiian Archipelago (Fig. A16) (Soil Survey Staff 2014). Andisols are the most extensive soil across Hawai'i. Most of these soils occur on the Island of Hawai'i, the youngest and largest of the Hawaiian Islands. Much of the remaining Andisols (40 163 ha) are found on Maui Island and much smaller isolated areas on Moloka'i, O'ahu, and Kaua'i. Andisols are soils formed in volcanic ash characterized by high concentrations of short-range-order clay minerals (e.g., allophane and ferrihydrite), low bulk density, and high organic matter. We note, however, that steep rainfall gradients produce three broad categories of Andisols in Hawai'i: Udands (wet, highly weathered, low fertility Andisols), Ustands (wet/dry, moderately weathered, high fertility Andisols), and Torrands (dry, weakly weathered Andisols). The influence of rainfall on soil weathering and fertility is exemplified in the Kohala District of Hawai'i Island (Fig. A17). As described in Chadwick

[3]The eighth main Hawaiian Island, Ni'ihau, is private and lacks soil survey data.

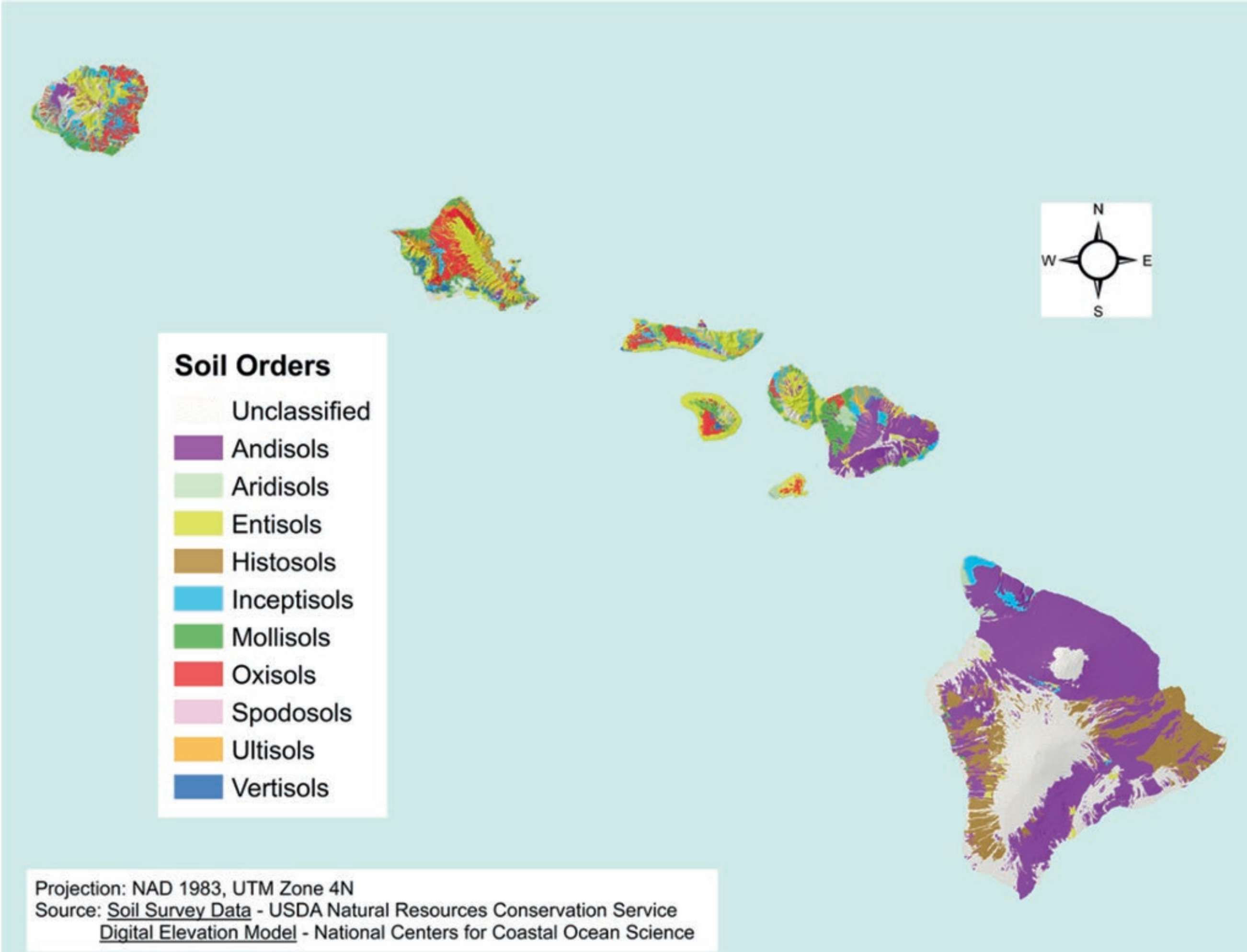

Fig. A16 Soils map of the main Hawaiian Islands (Source: University of Hawaii 2014)

et al. (2003), increasing rainfall has a dramatic effect on soil properties, producing three Andisols with distinctly different fertility capabilities. In the Torrands, found at the dry low elevations where evapotranspiration exceeds precipitation, rock weathering has proceeded slowly, creating a soil dominated by coarse materials (80% >2 mm diameter) with low clay content (<13%). The soil is rich in weatherable carbonates, which result in its alkaline pH and high base saturation, but is low in organic carbon (C) (Table A9). In the moderate weathering regime associated with moderate levels of bimodally distributed rainfall (750–1500 mm yr^{-1}), the Ustand has accumulated clay (30–40%) and substantial amounts of organic C, resulting in a near neutral soil with exceptionally high cation exchange capacity (CEC) and high base saturation. At the wet summit of Kohala Mountain, intense leaching and weathering have produced a very acidic, nutrient-depleted soil with minimal CEC and substantial amounts of soluble Al^{3+}. Torrands are also found at low elevations on the dry leeward (with respect to the prevailing trade winds) slopes of Mauna Kea and Haleakalā on Maui, while Ustands dominate the mid-elevations between Kohala and Mauna Kea and the leeward slopes of Haleakalā. The Udands are common on the wet windward slopes of Mauna Kea and the Hana region of Maui (Table A10).

A closer look at Kaua‘i, with its ten soil orders, shows how the five soil-forming factors have interacted to create tremendous soil diversity on such a small island (Fig. A18). Rocky, poorly developed Entisols cover large areas of steep mountainous land in central Kaua‘i and some sandy soils on leeward coastal flats. Highly weathered, acidic Oxisols with low fertility dominate the old volcanic slopes of windward Kaua‘i. High rainfall over millennia has leached these soils of base cations, leaving behind low-CEC oxidic clays. Their productivity lies in an organic matter-rich surface horizon developed over millennia from tropical wet forest cover. After deforestation and cultivation, however, the organic matter is susceptible to rapid oxidation, and the loss of organic matter quickly renders these soils dependent on

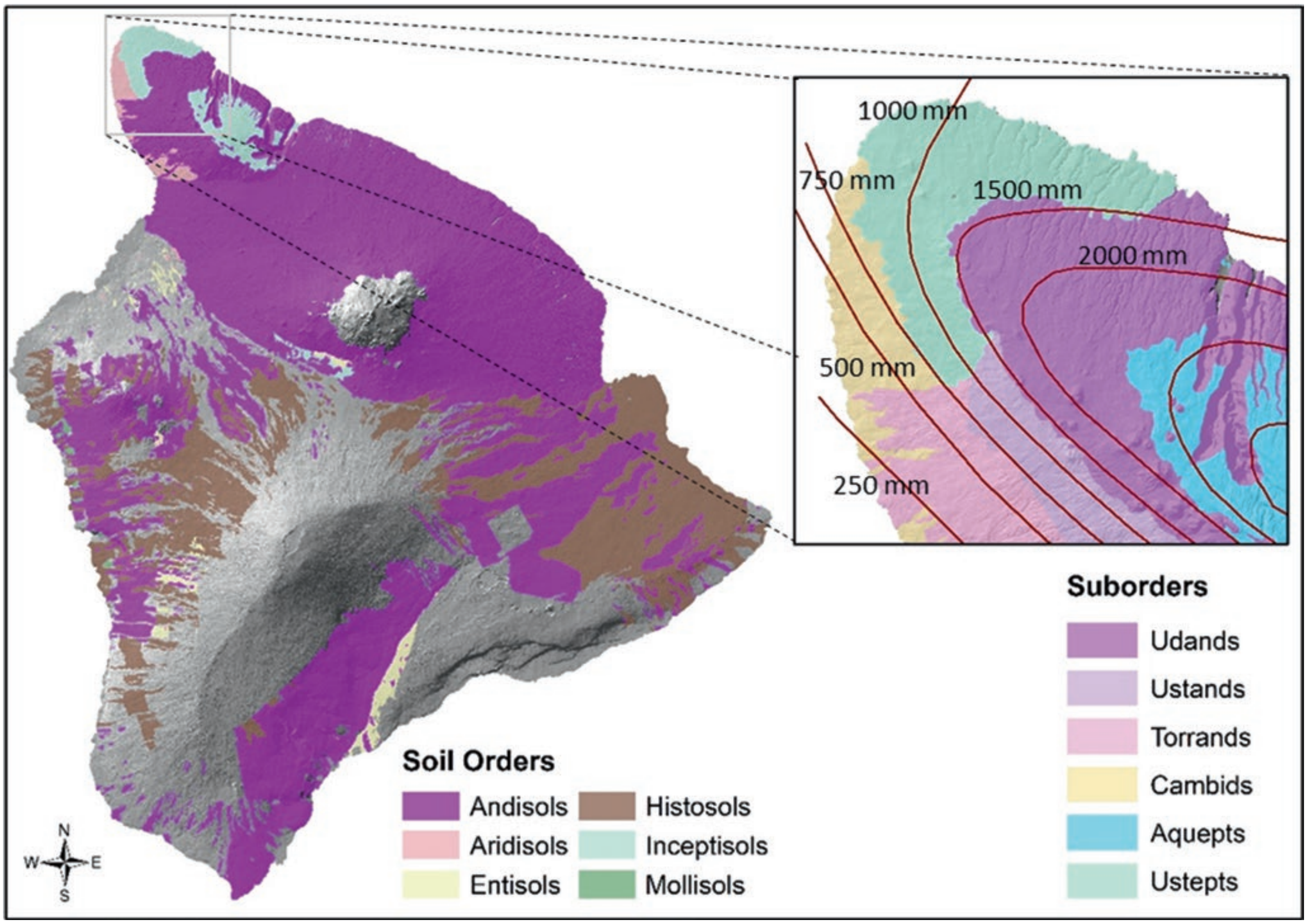

Fig. A17 Soil orders of Hawai'i Island with inset illustrating the effect of rainfall (contours) on differentiating dry (Torrands), wet/dry (Ustands), and wet (Udands) Andisols in Kohala District. Maps generated in ArcMap (ver. 10.5.1; Esri®, Redlands, CA) using SSURGO data

heavy nutrient inputs to remain productive. On the other hand, large areas of fertile Mollisols cover the lowlands of leeward Kaua'i. These soils have developed under a drier climate, which slows weathering and preserves the presence of high activity clays with ample CEC.

Three representative soils—a highly weathered Oxisol, a moderately weathered Mollisol, and a cool, wet Spodosol from the summit of Wai'ale'ale in the center of the island—illustrate some key fertility differences among Kaua'i soils. The Oxisol is strongly acidic, characterized by negligible CEC at field pH; relatively high exchangeable Al, suggesting potential toxicity; and very low base status. Together, these characteristics put this soil at the far end of the spectrum of low fertility soils. Any semblance of fertility is restricted to the surface horizon where organic matter has accumulated. The much larger value of CEC_{pH7} compared with effective cation exchange capacity (ECEC) indicates the dominance of variable-charge clay minerals, specifically iron (Fe) oxides. The Mollisol, on the other hand, is a fertile soil with high CEC throughout the profile and a high base saturation,

Table A9 Selected physical and chemical properties[a] for three Andisols found on Kohala Mountain, Hawai'i Island

Soil property (0–30 cm)	Torrands (Hapuna series)	Ustands (Waimea series)	Udands (Kehena series)
Texture	Cobbly silt loam	Silt loam	Silty clay loam
pH	8.0	7.0	4.5
OC (%)	2.1	9.6	4.54
Ca^{2+} ($cmol_c\ kg^{-1}$)	21.9	59.0	3.0
Mg^{2+} ($cmol_c\ kg^{-1}$)	15.5	12.7	1.7
K^+ ($cmol_c\ kg^{-1}$)	9.7	1.1	0.3
ECEC ($cmol_c\ kg^{-1}$)	44.8	74.0	7.3
BS (%)	80	100	10
Al^{3+} ($cmol_c\ kg^{-1}$)	0	0	2.2
Al^{sat} (%)[b]	0	0	29.7

Source: USDA NCSS n.d.

[a]*OC* organic carbon, *Ca* calcium, *Mg* magnesium, *K* potassium, *ECEC* effective cation exchange capacity, *BS* base saturation, *Al* aluminum

[b]Al^{sat} = (Exchangeable Al/ECEC) × 100%

Table A10 Selected chemical properties for an Oxisol from windward Kaua'i, a Mollisol from leeward Kaua'i, and a Spodosol from the summit region of Mount Wai'ale'ale in central Kaua'i

Soil and depth (cm)	pH	Organic carbon (%)	CEC_{pH7} ($cmol_c\ kg^{-1}$)	ECEC[a] ($cmol_c\ kg^{-1}$)	Exchangeable aluminum ($cmol_c\ kg^{-1}$)	Base saturation (%)
Oxisol (Pooku series), rainfall = 3005 mm yr^{-1}						
0–38	5.2	3.88	14.6	1.6	0.3	8.9
38–48	4.7	2.43	9.6	0.3	0.1	2.0
48–76	5.0	1.58	4.8	0.7	0.1	12.5
76–100	4.8	1.10	2.6	0.1	0.1	0
Mollisol (Kekaha series), rainfall = 584 mm yr^{-1}						
0–18	7.2	2.18	44.1	43.2	0	72.0
18–35	7.0	1.72	46.7	39.1	0	84.0
35–70	6.9	1.36	44.2	36.4	0	84.0
70–110	7.0	0.69	26.7	22.0	0	83.0
Spodosol (Wai'ale'ale series), rainfall = 4445 mm yr^{-1}						
0–22	3.7	68.4	161.2	27.2	11.1	10.5
23–43	3.7	63.0	221.0	100.5	96.6	1.5
43–50	4.2	1.86	56.6	18.3	17.6	1.0
50–100	4.5	0.90	29.0	7.3	6.6	2.5

Source: USDA NCSS n.d.
[a]Cation exchange capacity (CEC) or the CEC measured at field pH

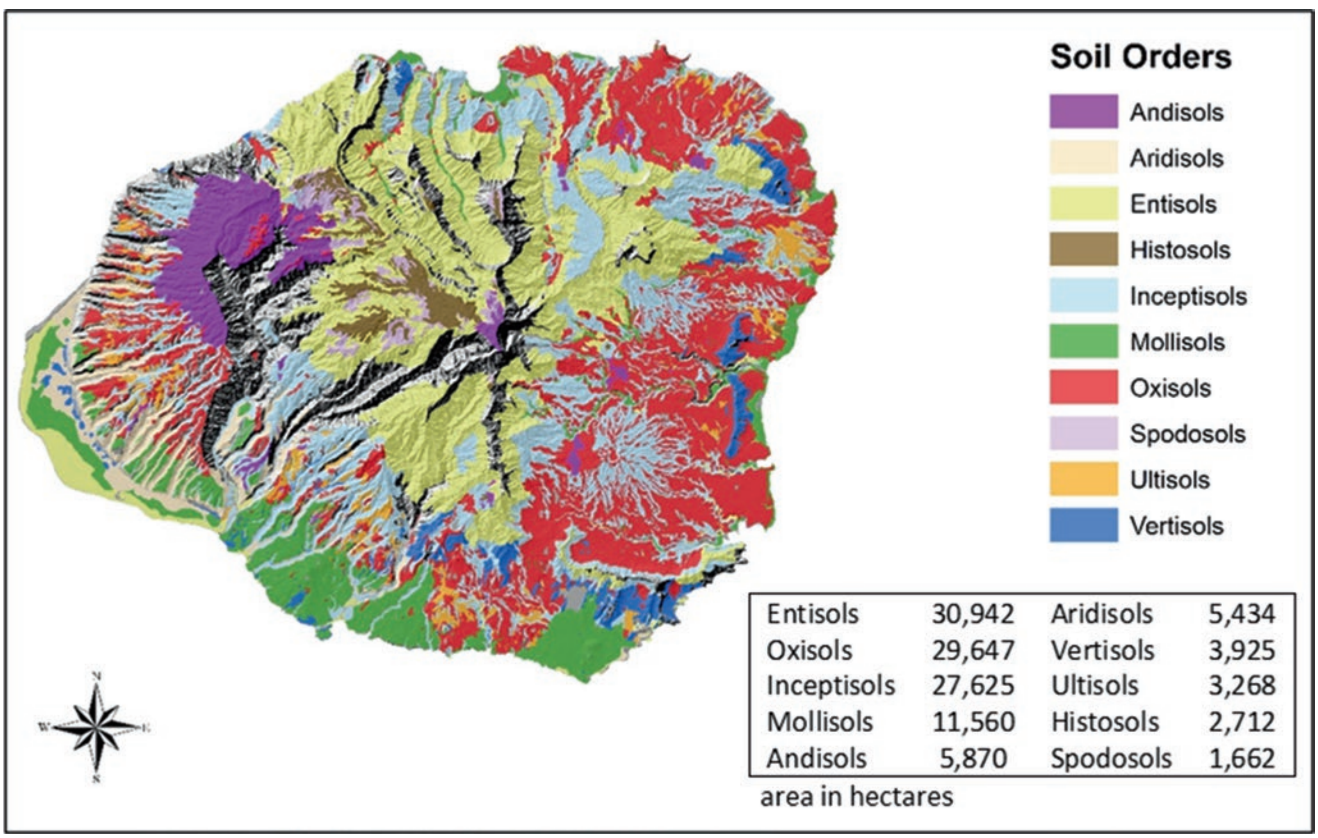

Fig. A18 The distribution of soil orders on Kaua'i and their approximate area. Map generated in ArcMap (ver. 10.5.1) using SSURGO data

indicating ample quantities of essential plant nutrients: calcium (Ca), magnesium (Mg), and potassium (K). The small differences between CEC_{pH7} and ECEC indicate the dominance of permanently charged high activity clays. This Mollisol is a prime agricultural soil known for its high productivity. The Spodosol, found in one of the rainiest locations in the world, is a poorly drained organic matter-rich, infertile soil with low base content and toxic levels of soluble

Al. Despite its very low fertility, it supports a diverse forest of rare and endemic species.

United States Affiliated Pacific Islands

The United States Affiliated Pacific Islands (USAPI) is also highly diverse with respect to soils, climate, and other characteristics but geographically much more dispersed, and the region's pedology and climate are much less studied than those of the Hawaiian Islands. The region is made up of some 2,000 separate islands and thousands more islets extending across an area larger than the continental United States. The jurisdictions of the USAPI contain an enormous variety of geologies from low-lying coral atoll islands to high volcanic islands of various ages. Because of the location of these island systems in both the northwestern and southwestern Pacific regions, with most USAPI jurisdictions north of the equator and American Samoa south of the equator, they are affected by different climate systems.

Furthermore, these jurisdictions span enormous areas of ocean, so there is no common weather pattern for the islands beyond the exposure of all jurisdictions to warm tropical temperatures and moderate to high levels of precipitation. Weather patterns, drought periods and severity, and timing and expression of large events such as El Niño vary dramatically across the USAPI. Similarly, changes in response to climate warming and drying will vary across these jurisdictions. There also are important certainties with respect to future climate-related impacts to the region. Ocean temperatures, air temperatures, and sea levels are all expected to rise. There is also a strong scientific basis for projections that cyclone events will strengthen because of a warmer, moister atmosphere, which stores more energy. Some evidence indicates that droughts in the region may be getting more severe (Polhemus 2017).

Given the geologic and climatic variation across the USAPI, soils show great diversity. Differences in parent material, degree of weathering, and landscape position are the main controllers of variability. Soils on Guam cover a single main island and several very small islets, which add up to 549 km^2 of land. These soils are composed of diverse

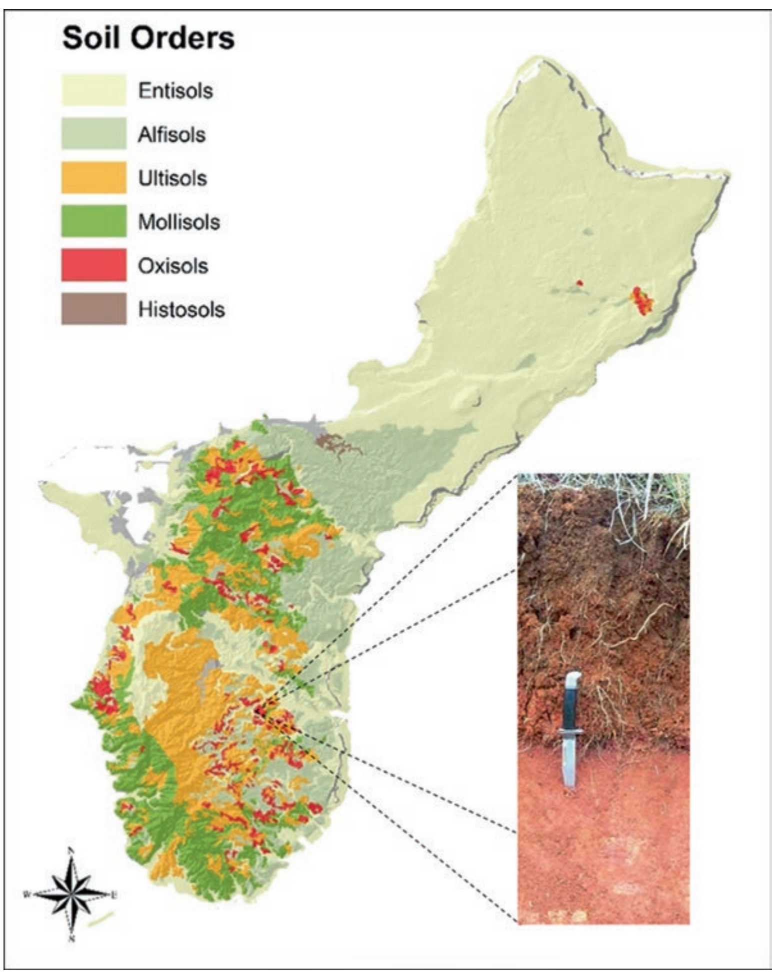

Fig. A19 The distribution of soil orders on Guam with a picture of an acidic, infertile Oxisol commonly found in the uplands of southern Guam (Photo credit: Robert Gavenda, USDA NRCS) geologies that lead to highly contrasting soils over short distances (Fig. A19). Very shallow Entisols that developed on the limestone plateaus of northern Guam are the dominant soil (27 737 ha). The soils are neutral to slightly alkaline in pH, rich in organic matter, and very high in exchangeable Ca but have accumulated gibbsite, an Al-oxide clay with high phosphorus fixation (Table A11). In stark contrast, we find Ultisols (7364 ha) and Oxisols (1728 ha) in the highly dissected and steep mountainous areas of southern Guam, which formed on old volcanic parent material now heavily weathered into acidic soils with low nutrient availability and high erosion potential. The fertility of these soils is tied to organic matter accumulation in the surface horizons (Table A11). A distinct increase in extractable Al in the subsoil results in Al saturation of 50%, which makes these soils Al toxic for many plants.

Much of southern Guam has been heavily impacted by land use conversion from forests to pasture, frequent (often arson caused) fires and hurricanes, and past military activities including bombing (Fig. A20). The result is large areas of degraded pastures and badlands from ridges to valley bottoms where the topsoil has eroded, leaving a nutrient-depleted and Al-toxic subsoil. More fertile, but very shallow, Mollisols formed in marine-deposited tuff are found in the uplands of southern Guam (6622 ha). The Northern Mariana Islands north of Guam include 474 km^2 of land over 14 islands and are geologically similar to Guam. These islands have dissected limestone plateaus and complex topography with steep and, in some places, eroded soils of volcanic origin.

Palau, located approximately 1300 km southwest of Guam, is geologically complex. It includes a mixture of older volcanic and metamorphic substrates on the large

Table A11 Selected chemical properties for an Entisol from northern Guam and an Ultisol/Oxisol and Mollisol from the volcanic uplands of southern Guam

Soil and depth (cm)	pH	Organic carbon (%)	CEC_{pH7} ($cmol_c\ kg^{-1}$)	ECEC[a] ($cmol_c\ kg^{-1}$)	Exchangeable aluminum ($cmol_c\ kg^{-1}$)	Base saturation (%)
Entisol (Guam series)						
0–6	7.1	8.57	42.7	–	0	75
6–20	7.5	5.56	26.3	–	0	76
Ultisol/Oxisol (Akina series)						
0–10	5.0	5.04	28.9	12.4	1.9	29
10–20	4.9	2.81	20.7	8.4	4.3	15
20–60	5.0	1.08	13.5	7.3	3.6	17.5
60–110	5.3	0.31	19.5	11.6	1.5	41
Mollisol (Agfayan series)						
0–10	6.4	2.66	60.3	52.4	0	87
10–20	6.7	1.36	69.7	61.5	0	88
20–50	6.7	0.61	73.5	62.0	0	87
35–50	6.9	0.85	74.2	66.5	0	90

Source: USDA NCSS n.d.
[a]Cation exchange capacity (CEC) or the CEC measured at field pH

Fig. A20 Severe erosion is common in the uplands of southern Guam. The exposed subsoil is incapable of supporting vegetation (Photo credit: Robert Gavenda, USDA NRCS) island of Babeldaob (20–40 million years before the present [Ma]), limestone parent material capping volcanic core material on smaller islands to the south, and hundreds of small, steep limestone islands farther south. Palau also includes atoll islands at its northern and southern extremes. The resulting soils are a mixture of highly weathered and acidic soils on the forested uplands and poorly drained organic matter-rich soils in the lowlands of Babadoab, minimally developed thin soils on the karst Rock Islands, and deeper and more fertile soils on the islands where substrates mix (Fig. A21). Historically, the acidic, infertile Oxisols (such as the Aimeliik series) of the Babeldoab uplands were forested and not cultivated. These soils' high acidity and excessive concentrations of soluble Al (Table A12) limit their use for agriculture. As with the Akina series on Guam, the minimal fertility of these soils resides in the organic matter-rich surface layer, and loss of this important layer leaves behind a severely degraded soil. The increasing incidence of wildfires across Babeldoab has played a strong role in denuding forested uplands, causing topsoil loss to erosion and the creation of severely degraded soils that remain exposed and difficult to revegetate. The Histosols, on the other hand, are base cation-rich organic soils that have been continuously planted to wetland taro (*Alocasia* spp.) for as long as 1,000 years. Adjacent, poorly drained organic matter-rich Inceptisols are also important agricultural soils.

The Federated States of Micronesia represents some 600 islands covering 700 km^2 of land, ranging from high island volcanic islands to low-lying coral atolls. The easternmost islands of Kosrae are the youngest at just under 1 million years. The geology becomes progressively older over the 2700 km to the westernmost islands of Yap (about 14 million years old). The island of Pohnpei shows a range of soil types, from mucky sandy soils supporting dense mangrove (*Avicennia* spp.) forests that circle the shoreline to patches of highly weathered, infertile Oxisols on 7 Ma volcanic substrate (Fig. A22). Fertile Inceptisols and Alfisols have developed on more recent lava flows, which support a diverse and

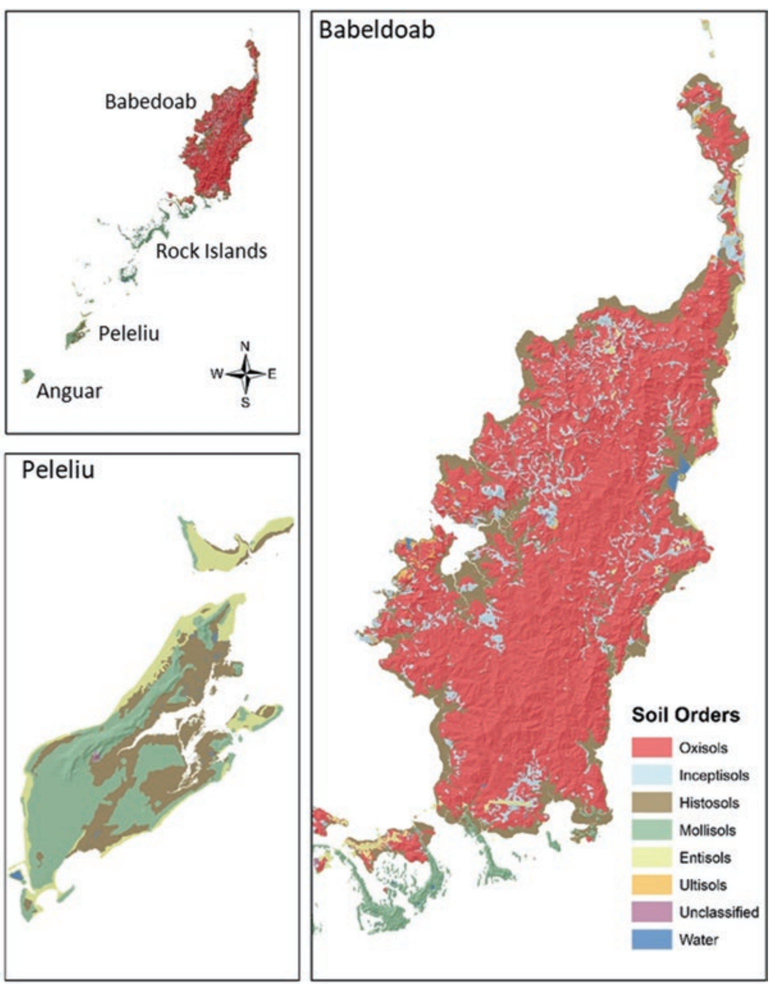

Fig. A21 The distribution of soil orders across the Palau archipelago

Table A12 Selected soil chemical properties for an Oxisol and Histosol from Babedoap Island, Palau

Soil and depth (cm)	pH	Organic C (%)	CEC_{pH7} ($cmol_c\ kg^{-1}$)	ECEC[a] ($cmol_c\ kg^{-1}$)	Exchangeable aluminum ($cmol_c\ kg^{-1}$)	Aluminum saturation[b] (%)
Oxisol (Aimeliik series)						
0–4	6.2	35.1	101	–	0	0
4–14	5.4	4.4	22.2	10.5	2.3	22
14–35	5.2	2.1	16.3	7.9	6.0	76
35–90	5.5	0.1	17.2	8.8	6.2	70
Histosol (Mesei series)						
0–12	5.5	39.8	69.8	31.7	0.2	0.6
12–40	5.0	14.9	36.6	9.1	2.0	22
40–86	5.1	15.8	31.9	7.0	0.2	3
86–150	3.8	5.8	26.1	20.9	3.1	15

Source: USDA NCSS n.d.
[a]Cation exchange capacity (CEC) or the CEC measured at field pH.
[b]%Aluminum (Al) saturation = (Exchangeable Al/ECEC) × 100%.

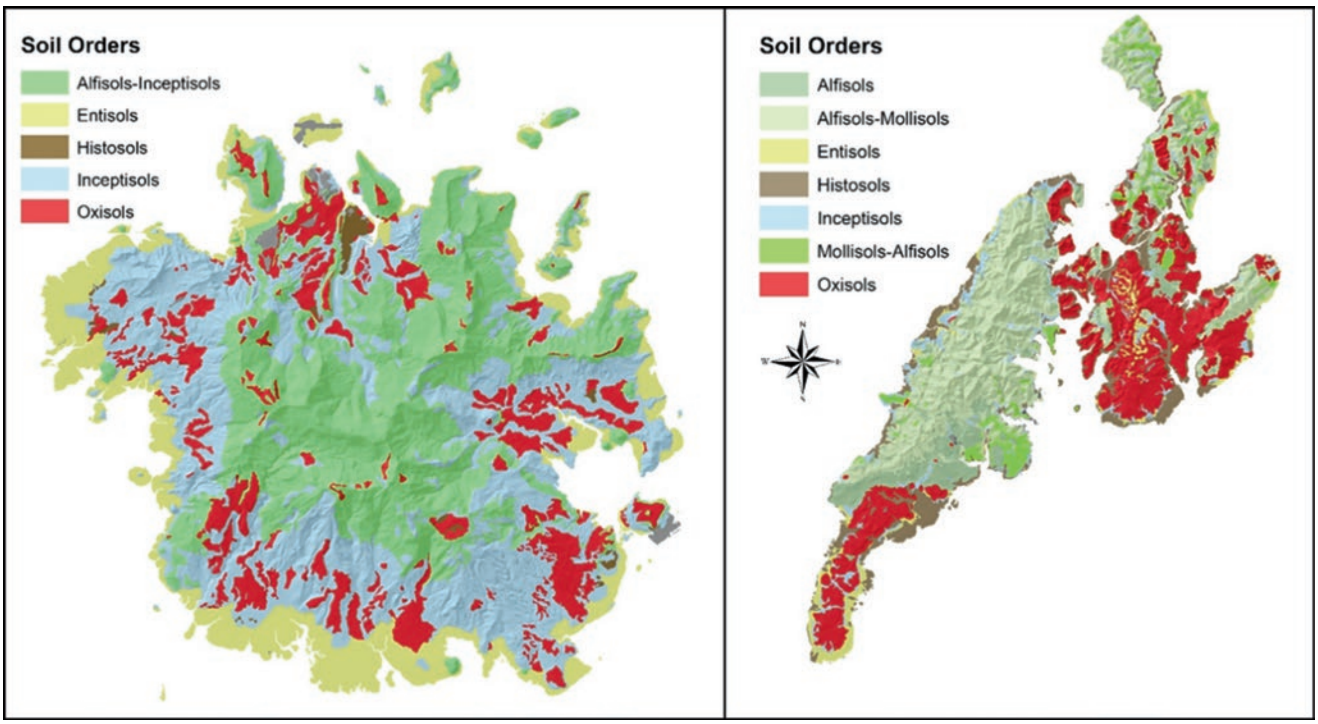

Fig. A22 The distribution of soil orders on the main islands of Pohnpei (L) and Yap (R) in the Federated States of Micronesia

productive agroforest system. Like Pohnpei, mangrove forests on mucky sandy soils fringe the island, whereas highly weathered Oxisols, low in fertility, have formed on volcanic deposits on flat bench formations of southern and eastern portions of Yap. More fertile Alfisols mixed with Mollisols have formed on older, but more resistant, metamorphic formations at the higher elevations. As discussed previously, the Oxisols are especially susceptible to degradation due to the erosional loss of organic matter-rich topsoil.

The Republic of the Marshall Islands covers 181 km^2 of land spread across some 1 500 000 km^2 of ocean in two parallel north-south aligned chains of islands, consisting of 5 inhabited main atoll islands, 29 low-lying atoll islands, and over 1000 islets. The highest point in the entire country is just 10 m above sea level, with most of the country less than 2 m above sea level. Natural soils of this country are therefore derived from young coral material. Soils of the coral atolls are sandy Entisols characterized by high pH and low fertility. As with the weathered Oxisols of the high volcanic islands, their fertility is associated with organic matter accumulation in the surface horizon (Deenik and Yost 2006).

American Samoa in the southern hemisphere is made of up five main volcanic islands and two coral atoll islands covering 197 km^2. The contrasting parent material and complex

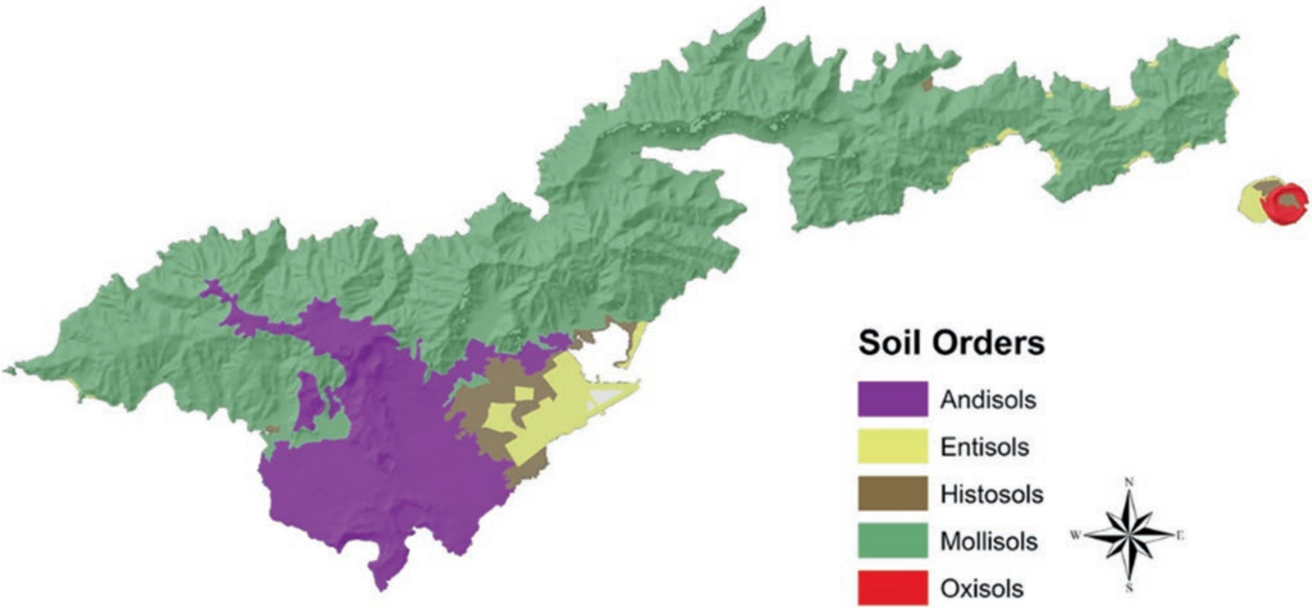

Fig. A23 The distribution of soil orders on the islands of Tutuila and Aunu'u, American Samoa

topography result in diverse soils. Fertile Mollisols dominate the steep forested mountains (10 515 ha) from the east to the west end of Tutuila (the main populated island) (Fig. A23), whereas fertile Andisols are the primary soil on the plains of southwest Tutuila (5396 ha). The Andisols formed from volcanic ash deposits laid down during posterosional volcanism. They are well-drained soils where continuous agriculture is practiced. Histosols and Entisols cover much smaller areas and are primarily in urban use.

Coastal Wetlands

We provide more detail here on coastal wetland soils because we anticipate that climate change via sea level rise will have the biggest effects on these soils. Coastal wetland soils are very deep, are very poorly drained soils, and are generally very high in organic matter. In the western Caroline Islands (e.g., Palau and Yap), mangrove soils are dominated by Histosols (Illachetomel series) (64%) composed of organic deposits derived from decomposing mangrove roots and leaf litter. The other soil series are loamy and mucky Entisols (Naniak series) (19%), composed of organic deposits and alluvium derived from volcanic material or limestone and the peaty and mucky Histosols (Chia series) (18%) composed of organic matter and coralline sand and gravel (USDA SCS 1983b; USDA NRCS 2009). In the eastern Carolines (e.g., Kosrae, Pohnpei), mangrove soils are dominated by Naniak Entisols (65%) formed from alluvium in this location-derived igneous rock. Other soils include the sandy and peaty Entisols of the Insak series (20%) and Chia Histosol soils (<15%) described earlier. Freshwater peatland forests dominated by ka (*Terminalia carolensis*) are commonly found behind mangrove forests in Micronesia, but the largest intact forest is found on the island of Kosrae. Soil types here are dominated by deep and poorly drained loamy Inceptisols of the Nansepsep series (45%) and Entisols of the Inkosr series (40%), both formed from alluvial deposits of igneous origin (USDA SCS 1982, 1983a). Soils of the Insak series are also found along coasts of American Samoa, although the predominant soil type found in mangroves are Histosols of the Ngerungor series, which is a mixture of peat, basalt, and calcareous sand (Gilman et al. 2007; USDA 1984).

In Hawai'i, coastal wetlands typically develop on soil types composed of alluvium. On Kaua'i and Oahu, these soils include the Hanalei series, an Inceptisol that is a silty clay, silty loam, or peaty silty clay alluvium derived from igneous rock. On the younger islands, wetlands form Inceptisols from mixed alluvial soils. These Tropaquepts consist of alluvium washed from soils that are formed in volcanic ash and that have a surface layer of mucky silt loam overlying a silty clay loam (USDA SCS 1972, 1973).

The organic deposits derived from decomposing roots and litter combined with the poorly drained anoxic soils and the high root to shoot ratio of these coastal forested systems has resulted in relatively high soil C content (Krauss et al. 2014; Lovelock 2008). Percent soil C content from mangroves ranges from 2.8 to 39.5% with an average of 16.4 ± 6.7% (Donato et al. 2011, 2012; Gilman et al. 2007; R.A. MacKenzie et al., unpublished data of the coauthor) and from 19.9 to 47.0% in ka peat swamps sampled on Kosrae (Chimner and Ewel 2004).

Major Threats and Impacts to Soils

Changing Climate

Hawai‘i is projected to become both warmer and generally drier, especially for leeward areas of each of the larger islands (Keener et al. 2012a, b), which have experienced significant warming (Giambelluca et al. 2008) and drying over the past century (Frazier and Giambelluca 2017). It is also expected that impacts of climate change will be strong, though varied, for the USAPI. While future air temperatures are predicted to increase, shifts in the Pacific Decadal Oscillation will result in areas with more intense storms and significantly more rainfall (e.g., Palau, Yap), whereas other areas will have longer drought periods between rain events and overall decreased rainfall (e.g., the Marshall Islands) (Polhemus 2017). We expect that climate change effects may be very large in Hawai‘i. The vulnerability of soils to these changes is driven by (1) the fast rate at which climate is changing in Hawai‘i; (2) the diversity of interacting, climate-related threats including precipitation change, invasive species, and expanding fire regimes; and (3) limited financial and technological resources to direct to adaptation or mitigation projects. These concerns will also drive impacts in the USAPI. Across the region, coastal areas of all islands are expected to be one of the most at-risk areas for increased rates of sea level rise (McLeod and Salm 2006).

There is compelling evidence that in the past few decades, increases in mean annual air temperature for Hawai‘i’s native ecosystems have exceeded the global average rate of increase (Giambelluca et al. 2008). There is also strong evidence for drying over the past century (Frazier and Giambelluca 2017). Below-average precipitation has had an impact on watershed hydrology (Keener et al. 2012a); streamflows have decreased by 10% in the past half-century compared to the previous 50 years (Oki 2004), in line with model projections for moisture responses to warming (Safeeq and Fares 2011). Dynamical downscaling for the Hawaiian Islands projects further warming and drying. These changes will be accompanied by increased periodicity of a smaller total rainfall amount, hence more intense rain events separated by longer periods of dry weather (Chu and Chen 2005; Chu et al. 2010; Norton et al. 2011). Forecasting further indicates stronger periodicity and stronger reductions in total rainfall in the drier leeward areas of Hawai‘i.

Fire

Most direct effects of climate change on soils will take millennia to be manifested as soil development and responses to change are typically very slow, but there is a high likelihood that soils may change more rapidly in response to interactions between climate change and other threats. For example, novel fire regimes are expanding into new areas because of invasion by fire-prone exotic grass and shrub species, including fountain grass (*Cenchrus setaceus*), common gorse (*Ulex europaeus*), and guinea grass (*Urochloa maxima*). Such invasive species have dramatically magnified fire danger not only in Hawai‘i (D’Antonio and Vitousek 1992; Trauernicht et al. 2015) but also across portions of the USAPI, especially Guam, Palau, and parts of the Federated States of Micronesia (Fig. A24). These accelerating invasions are also complicat-

Fig. A24 Fire-prone nonnative grasses and shrubs, like those shown here in Hawai‘i Volcanoes National Park, cover 25% of Hawai‘i’s land area, and with expanding cover of these weeds, a warming and drying climate is exacerbating the wildfire threat across the Pacific region, especially Hawai‘i, Guam, the Northern Mariana Islands, and the Federated States of Micronesia (Photo courtesy of the National Park Service) ing fire management, a situation that is further exacerbated by warmer and drier conditions.

The combined effects of these threats have been devastating to native dry and mesic forests of Hawai‘i and mesic to wet forests in the more strongly seasonal areas of the USAPI. In Hawai‘i, these forests are converted by fire to nonnative grasslands, with important impacts to soil. For example, introduced fire regimes result in fire events that kill native trees and their roots (Cabin et al. 2002); consume organic matter on the soil surface; consume organic matter in the top few centimeters of mineral soil, releasing large amounts of nutrients (Giardina et al. 2000); and kill soil flora and fauna (Døckersmith et al. 1999). Combined, these fire-related impacts reduce soil organic matter, arguably the most important component of tropical soils, and render them vulnerable to rapid degradation.

In the USAPI, fires have converted forests to savanna ecosystems that are dominated primarily by native fire-adapted species. In contrast to Hawai‘i, savanna of the USAPI will be colonized by woody tree species and, with sufficient time (decades) between fires, savanna will return to native forest (Donnegan et al. 2007). In Hawai‘i, where fire return intervals are long, nonnative woody species will typically invade nonnative grasslands (Cordell et al. 2002). Immediately following fire, freshly exposed soils are the most vulnerable to rain events, which can cause significant erosion of the unprotected soils. Because of the compact nature of watersheds in Hawai‘i and throughout the USAPI, rain-on-fire events can quickly move soil from upper watershed areas into coastal or nearshore areas. Critically, once invaded and burned, nonnative grasses in Hawai‘i or native savanna in the USAPI will occupy a site and drive a novel largely anthropogenic fire cycle that will repeatedly burn an area, with each burn further degrading soils.

Soil Moisture Changes

Though it is widely known that nearly all native-dominated dry ecosystems in Hawai‘i are invaded or have been converted to grasslands by fire, it is less appreciated that most mesic and wet forests in Hawai‘i have also been invaded by nonnative species, and in large areas, invasions are very dense (Asner et al. 2005, 2008). Remnant long-lived trees such as ohia (*Metrosideros polymorpha*) can persist in the overstory for many decades, thereby delaying complete conversion of a site to nonnative condition. But when an individual dies, the complete absence of native species recruits results in full occupation of gaps by nonnative species. Thus, wet forest soils are subject to both climate change and climate change interactions with invasive plants. Specifically, plant invasions increase plant and stand water use (Cavaleri and Sack 2010; Strauch et al. 2017), with increases in water use being magnified under warmer and drier conditions (Strauch et al. 2017). The combined effects of climate change-induced drying and plant invasions reduce soil moisture and hinder potential reestablishment of native plant communities.

On longer timesteps, climate-accelerated plant invasions can displace native vegetation within a few decades, fundamentally changing forest structure, rainfall interactions with soils, sediment delivery to streams, and overall watershed hydrology. According to the census of Hawai‘i and forests recently completed by the USDA Forest Service’s Forest Inventory and Analysis program (USDA FS 2018), the nonnative strawberry guava (*Psidium cattleianum*) is now the most common tree in Hawai‘i. Total estimated stem numbers exceed that of Hawai‘i’s most common native tree, ohia. Guava has a wide variety of hydrological effects on soils, including decreased soil moisture and very different litter inputs that are likely to affect soil organisms and both biological and physical processes.

Sea Level Rise

By far the biggest climate-related impacts to the region’s soils will be in low-lying areas affected by sea level rise, more intense storms, and altered hydrology due to altered rainfall patterns and warmer temperatures. Conservation and restoration of USAPI coastal forests are especially important given the large role that they play in many islands’ subsistence economies. Conservation of these systems is also important for mitigation of impacts from climate change and increased nutrient and sediment runoff. For example, the high C content in coastal forested wetland soils, coupled with their high productivity and waterlogged anaerobic condition, results in massive amounts of relatively permanent C stocks. Carbon stocks from USAPI coastal forested wetlands range from 700 to 870 Mg C ha^{-1} with an average of 780 ± 320 Mg C ha^{-1}. These forests represent about 10% of forest cover in the USAPI but contribute up to 30% of total island C stocks (Donato et al. 2012). This is largely due to soil C, which makes up more than 80% of total C stocks in these coastal forests. This C can provide funding through C markets for the conservation and restoration of coastal forested wetlands and the many ecosystem services that they provide.

Conservation of coastal wetlands is also important as these ecosystems reduce sediment and nutrient loading to valuable nearshore ecosystems, such as seagrass beds and coral reefs. Coastal forests can reduce sediment input to coral reef ecosystems by as much as 30% (Golbuu et al. 2003; Victor et al. 2004). Soils in coastal wetlands can also reduce phosphorus (P) and nitrogen (N) loads that can result in eutrophication of nearshore waters. Sorption values for P from coastal wetland soils around Hawai‘i were as great or greater than values reported from intact wetlands in the Midwest and on the east coast (Bruland and De Ment 2009). These wetlands also appear to play an important role in removal of N loads (Bruland and MacKenzie 2010).

Forest, Wetland, and Agricultural Products

Compared to elsewhere in the Asia Pacific region, coastal wetlands in the USAPI remain relatively intact. Selective harvesting of trees occurs in mangroves for cooking fuel or for house timber and in ka forests for canoes (Balick 2009). Fish and crabs are also harvested from mangroves, and the organic rich soils of freshwater peat swamps support banana (*Musa* spp.), sugarcane (*Saccharum officinarum*), and soft taro (*Colocasia esculenta*) agroforestry. Combined, coastal wetlands provide up to 60% of the median household income on the island of Kosrae (Conroy et al. 2011; Drew et al. 2005; Naylor and Drew 1998). In Hawai‘i, coastal wetlands were traditionally converted into loko i`a kalo, irrigated agriculture plots with raised islands for growing taro, a dominant form of starch consumed by Hawaiian peoples. Interspersed among these islands were ponded areas that were also used for capturing and raising aholehole (*Kuhlia sandvicensis*) and `o`opu fish (*Eleotris sandwicencis, Awaous stamineus*) (Kikuchi 1976).

Higher air temperatures and lower rainfall (Frazier and Giambelluca 2017; Giambelluca et al. 2008; Keener et al. 2012b) will have adverse effects on coastal wetland soils of Hawai‘i and the USAPI through greater soil salinity. Increased salinity will result from rising sea level and will be exacerbated by lower water tables and freshwater inputs due to increased drought frequency (Scavia et al. 2002). Rising salinity levels will severely limit food productivity because the key food crops (e.g., taro, banana) grown in the coastal lowlands are typically sensitive to soil salinity (Day et al. 2008; Field 1995). Warmer and drier conditions will also expose coastal soils to aerobic conditions that increase decomposition as well as nutrient loss through oxidation and subsequent reflooding (Burkett and Kusler 2000; Chimner and Ewel 2004; Morrissey et al. 2014). Increased decomposition of peat soils results in subsidence in coastal ecosystems, making these areas increasingly vulnerable to seawater inundation (Krauss et al. 2014; Rogers et al. 2014). Alternatively, increased precipitation can increase soil productivity by reducing salinity and osmotic stress of plants and trees (Clough et al. 1982; Ellison 2000). Increased precipitation can also increase peat and sediment accumulation in coastal ecosystems through increased delivery of sediments from flooding, peat production through root growth, and organic matter accumulation from litter inputs (Rogers et al. 2014; Sanders et al. 2016; Scavia et al. 2002). This process has allowed mangroves and salt marshes to keep up with sea level rise in the past (Ellison and Stoddart 1991; Rogers et al. 2014) as well as migrate inland (Eslami-Andargoli et al. 2009). We note, however, that prolonged flooding can also result in the loss of wetland plants and thus belowground productivity.

Invasive plants are likely to have a negative impact on coastal wetland soils of Hawai‘i and the USAPI, although little research has been conducted on this topic. Vegetation from 40 wetlands sampled across the five main Hawaiian Islands was dominated by nonnative species, representing more than 60% of the species sampled (Bantilan-Smith et al. 2009). In continental United States wetlands, this kind of invasion had a negative impact on soil properties (Zedler and Kercher 2004), yet no studies have examined these relationships in Hawai‘i and USAPI coastal systems. Preliminary results from Hawai‘i have shown that the invasion by mangroves can significantly increase C content of coastal soils (R.A. MacKenzie, unpublished data of the coauthor).

Sea level rise is the factor expected to have the greatest negative impact on coastal ecosystems. Mangroves are dynamic systems that play a critical role in protecting island ecosystems from a rising sea level by (1) maintaining the forest floor relative to sea level through root growth and sediment trapping and (2) migrating with a rising sea level to more inland locations suitable for soil formation and forest growth (Krauss et al. 2014). However, there appear to be strong geologically driven differences across the USAPI in resilience to sea level rise. Stratigraphic records from the USAPI revealed that high-island mangrove ecosystems were able to keep up with past rates of sea level rise of 4.5 mm yr^{-1}, whereas low-island mangroves were not able to keep up with rates of 1.2 mm yr^{-1} (Ellison and Stoddart 1991). Thus, high-island mangrove systems are thought to be more resilient to current rates of sea level rise (2.0–4.0 mm yr^{-1}) than low-island mangroves. This difference may be related to (1) greater sediment inputs from high-island watersheds, which allow these coastal forests to trap larger amounts of sediment and maintain their elevation and (2) greater high-island diversity of inland sites for mangrove migration.

We anticipate that similar patterns will emerge with current high rates of sea level rise for low atoll islands of the USAPI but also of Papahānaumokuākea (the Northwestern Hawaiian Islands). We expect low islands to be more sensitive to sea level rise than high islands, adding burdens and further reducing the socioecological resilience of these low islands and their soils to sea level rise. Further, a rising sea level will result in longer salt water inundation periods for soils, salinity shifts, and increased coastal erosion. While many wetland plants are adapted to live in extreme conditions that occur from inundation, such as waterlogged and anoxic hydric soils, many plants cannot tolerate inundation, especially with higher salinity water, for extended periods of time. Permanent flooding of coastal areas will also alter soils by decreasing oxygen availability and increasing the amount of reduced elements (e.g., Fe, manganese) that can lead to plant stress and decreased plant growth, reproductive output, and productivity of some plant species (Pezeshki and DeLaune 2012). These conditions can also result in the release of P and N bound to wetland soils, potentially increasing nutrient loading to nearshore coral reefs or seagrass beds

(Bruland and De Ment 2009). Loss of vegetation from flooding can result in peat collapse through the decomposition of root material or leaching of organic matter, lowering the elevation of the wetland, and creating flooded conditions again (Day et al. 2008).

Increased flooding from sea level rise and from storm surges of increased severity and frequency can also impact the elevation of coastal soils through the deposition of new sediments or erosion of coastal edges. The latter can lead to the redistribution and deposition of sediments or vegetation wrack elsewhere in the systems (Fagherazzi et al. 2012; Morton and Barras 2011). Either can have positive or negative effects. Small amounts of sediment benefit coastal wetlands by contributing to vertical soil building through deposition on the marsh or mangrove surface. In contrast, large quantities of sediment delivered to low-saline marshes can smother and kill vegetation (Guntenspergen et al. 1995). Quantifying how fast the elevation of coastal ecosystems is rising relative to sea level rise is an important research need. Research and monitoring can identify areas that may be resilient to sea level rise. These areas may be sequestering C at a faster rate than less productive systems and thus require special conservation designation to protect the many ecosystem services that are provided by coastal soils. Less productive areas that are not keeping up with sea level rise and are sequestering C at a slower rate may require a more proactive restoration and management action (reforestation, hydrologic restoration) in order to protect them.

Key Findings

- Soils of Hawaii and the USAPI represent a remarkable gradient in soil-forming factors and, hence, soil types, complicating efforts to develop management solutions for global change-related challenges to soil health. There remains a need for improved knowledge about how synergistic effects of rising sea level, changing climate, expanding invasive species cover, and increased exposure to novel fire regimes all affect soil resources of the Pacific.
- Recent advances in knowledge of invasive species, drought, and fire have expanded capacity to inform decisions regarding soil changes that accompany novel fires—the frequency, severity, and extent of which are increasing as climate warms, rainfall becomes more variable, and the cover of fire-promoting invasive species increases. While understanding of both the drivers of these disturbances and their often multiplicative effects on soils has greatly increased, strategies are needed for successfully reducing fires and their impacts, especially during periods of high fire danger.
- Hawai'i and the USAPI are home to a number of the Earth's plant and animal biodiversity hotspots, including a remarkable diversity of nearshore coral habitats, as well as an enormous diversity of cultural systems strongly connected to soils via traditional management systems. These are all affected by impacts to watershed condition and soil erosional processes and by sea level rise. Likely future changes for the region include (1) elevated fire impacts to watersheds; (2) expanded agricultural land use, which elevates erosional processes; and (3) continued rise in sea level and salt water intrusion events, which drastically alter soil tilth and compromise ecosystem health. Preventing human-caused fires across the region and enhancing coastal forest cover on low-lying islands remain important areas that require enhanced management attention.
- Soils and soil-building processes are critical in maintaining and protecting coastal habitats that support indigenous populations of flora and fauna and humans.

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