Chapter 18: Ecoregion Not Classified: Hawai'i Experimental Tropical Forest, Hawai'i

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Introduction

This chapter is a review and synthesis of research conducted at Hawai'i Experimental Tropical Forest (HETF) on stream nutrients and biological responses. It is intended to inform national and regional water quality regulatory agencies, such as the U.S. Environmental Protection Agency and the Hawai'i Department of Land and Natural Resources (DLNR), about existing results of relevant scientific studies that are available at HETF, and to identify future field and synthetic research of potential use to regulatory agencies that might be conducted at HETF.

Site Description

HETF was established in 2007 by the U.S. Forest Service (USFS), and Hawai'i DLNR, Division of Forestry and Wildlife, and Division of State Parks. The HETF is composed of two units, both located on the Island of Hawai'i: the Laupāhoehoe Wet Forest (LWF) (4990 ha) and the Pu'u Wa'awa'a Dry Forest (PWDF) (15 736 ha). HETF is located on DLNR-managed lands with the following designations: forest reserve and natural area reserve in LWF and forest bird sanctuary, forest reserve, and state parks in PWDF.

The LWF (lat. 19° 56' 13.74" N, long. 155° 16' 37.08" W) is located on the eastern flank of Mauna Kea Volcano from 500 to 2000 m elevation (fig. 18.1). The vegetation is a tropical montane forest dominated by native 'ōhi'a (*Metrosideros polymorpha* Gaudich.) and koa (*Acacia koa* A. Gray) trees, although at its lower boundary, LWF has been heavily invaded by the exotic strawberry guava tree (*Psidium cattleianum,* Afzel. ex Sabine). Mean annual rainfall ranges from 2900 to 4060 mm/yr across steeply sloped forested headwater basins that are underlain by 4,000- to 250,000-year-old weathered tephra. Predominant soils are composed of moderately to well-drained hydrous, ferrihydritic/amorphic, isothermic/isomesic Acrudoxic Hydrudands of the 'Akaka, Honoka'a, Maile, and Pi'ihonua soil series

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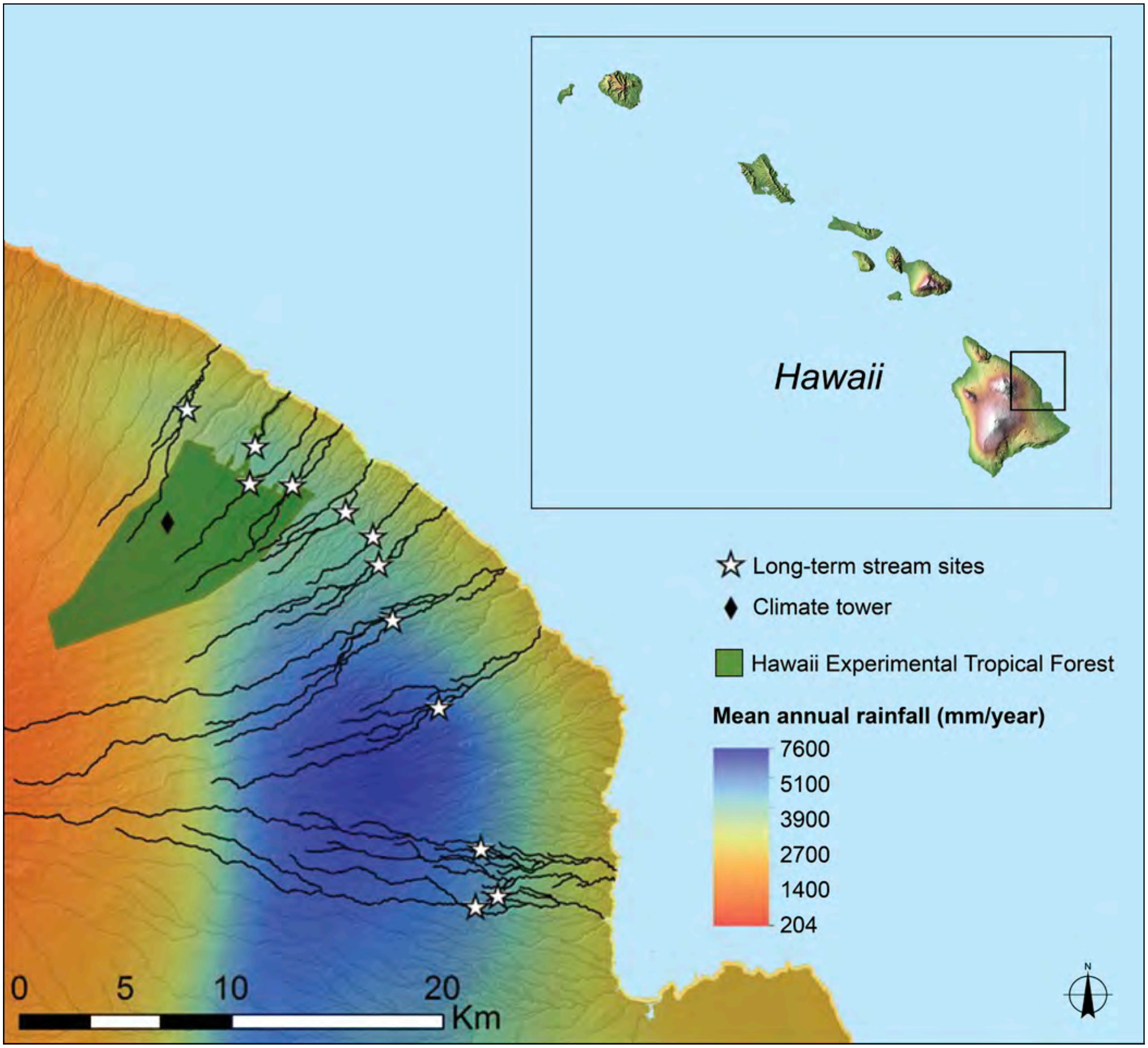

Figure 18.1—Permanent research stream sites in the Climate Change and Pacific Island Water Resources study along the North Hilo Coast of Hawai'i Island, including those located in the Laupāhoehoe Wet Forest of the Hawai'i Experimental Tropical Forest. Stream study sites shown are (N-S) Ka'awali'i, Manowai'ōpae, Kaiwilahilahi, Pāhale, Makahiloa, Manoloa, Waikaumalo, 'Uma'uma, Kolekole, Kapu'e, Pa¯hoehoe, and Honoli'i.

(Litton et al. 2011). Seven major streams drain the LWF: Ha'akoa, Ka'awali'i, Kaiwilahilahi, Kilau, Laupāhoehoe, Manowai'ōpae, and Pāhale (fig. 18.1). Streams consist of a series of channel units composed of runs, riffles, and pools separated by waterfalls, cascades, or chutes. Stream slopes are typically greater than 10 percent, resulting in streambed materials that vary from gravel and cobble to bedrock and boulder, and generally lack sand and silt. Flows rapidly respond to extreme rainfall events, with base flows shifting to flashflood conditions in minutes (Larned and Santos 2000, Lau and Mink 2006, Oki 2003, Tomlinson and DeCarlo 2003). As defined by Hansen (2001), streams within LWF are naturally intermittent. They have flow during most of the year owing to short-term bank storage inputs that maintain stream base flow. Runoff from precipitation is a supplemental source of water for streamflow in these streams. During extreme dry periods, these streams may not have flowing water. At lower elevation, these streams flow year-round. A few streams within LWF have structures installed for withdrawing water, but they are in disrepair and no longer remove water. The LWF is the location of stream monitoring in HETF.

The PWDF tract of HTEF (lat. 19° 47’ 29.33” N, long. 155° 50’ 52.79” W) is located on the North Kona coast on the leeward, dry side of the Island of Hawai’i. PWDF is not a focus of this chapter because its low rainfall and permeable bedrock produce no surface streams.

Stream biological communities—

Hawai’i’s remoteness from continental landmasses, combined with mountainous terrain, has produced highly endemic assemblages of stream organisms. Surveys of stream fauna outside of HETF have reported that Hawai’ian streams are dominated by endemic gobies, snails, and shrimp that exhibit an amphidromous life cycle in which adults live and spawn upstream (Kinzie 1993, McDowall 1997). Freshwater floods allow shrimp larvae to drift quickly downstream to the ocean. These larvae are morphologically and physiologically adapted to live in salt water, with only days to get to the ocean, although this may differ with individual taxa (Hogan et al. 2014; Miller, n.d.). Once larvae reach the ocean, they reside in the water column and continue to eat and grow until they develop into postlarvae that then recolonize freshwater stream ecosystems. Postlarvae have special adaptations that allow them to scale waterfalls that can be greater than 300 m in height, including gobies with pelvic fins fused into suction cups (Benbow et al. 2004a), shrimp with strong claws, and limpet-like snails with muscular feet (Benbow et al. 2004b, Brasher 1997, Gorbach et al. 2012, Kinzie 1993). Invertebrate biomass is dominated by two shrimp species (Resh and deSzalay 1995). Although present, aquatic insects have lower biomass and diversity than is typical in temperate continental streams, although this varies by insect species (Benbow 2008) and across flow conditions (Benbow et al. 2005; McIntosh et al. 2002, 2003). Some trophic guilds common in temperate streams are lacking, such as the shredding guild.

Geologic nutrient inputs—

Studies done outside of HETF have found geographic patterns of geologic and atmospheric inputs of nutrients within the Hawai’ian Islands that may affect nutrient loading to HETF streams. The weathering of parent material can contribute phosphorus (P) and silicate (SiO_4^{2-}), as well as other important dissolved nutrients, although contributions vary with substrate geologic age. For example, younger, P-rich substrates can potentially provide more P to soil pore water, while older geologic substrate can provide more biologically fixed nitrogen (N) (Hedin et al. 2003, Vitousek and Farrington 1997). These patterns are not as apparent in stream water (Wiegner, n.d.), likely owing to other processes occurring within the ecosystem N cycle, such as plant uptake, denitrification, adsorption along flow paths through soils to streams, and uptake by stream organisms (Hedin et al. 2003; Wiegner et al. 2009, 2013).

Atmospheric nutrient inputs—
Atmospheric inputs are a second important source of nutrients to these watersheds. Fixed N and P are deposited from the atmosphere to land in rainfall, dust (or "dry") deposition, and cloud or fog interception (Carrillo et al. 2002, Vitousek 2004). Across the Hawai'ian Islands, atmospheric N contributions are dominated by cloud water inputs of ~5.8 kg N/ha/yr on the moist, windward side of islands, compared to biological N fixation of about 1.0 kg N/ha/yr which is more evenly distributed geographically (Vitousek 2004). Contributions of volcanically fixed N can significantly increase atmospheric deposition on volcanically active, young substrates where there are active lava flows and eruptive vents. For example, on volcanically active Hawai'i Island, total N deposition (inorganic and organic) over a 5- to 7-year period averaged 17 kg N/ha/yr, with more than 90 percent from fog interception and the rest from precipitation deposition. In contrast, N inputs from precipitation on volcanically inactive Kauai Island were only 0.2 kg N/ha/yr, although fog inputs were not measured (Carrillo et al. 2002). The high amount of N deposition on Hawai'i Island was due to thermal fixation of atmospheric N contacting erupting Kilauea lava flows (Huebert et al. 1999). When active lava flows enter seawater, aerosols can also locally increase P deposition fiftyfold in near-coast areas (Sansone et al. 2002).

Research History

In 2010, the Climate Change and Pacific Island Water Resources (CCPIWR) study was initiated by the USFS to use the North Hilo coast of Hawai'i Island as a study area to investigate how climate change will affect the ecological, hydrological, and biogeochemical function of tropical island streams. This region is well-suited as a location for a space-for-time substitution study across a rainfall gradient of 3500 mm/yr. Streams at the wetter end of the gradient represent current conditions in watersheds that provide much of the surface water for urban and agricultural areas of Hawai'i. Streams at the drier end of the gradient represent forecasted future conditions in those supply watersheds under scenarios of a drier climate.

As part of the CCPIWR study, long-term research sites were established in four streams within the LWF—Ka'awali'i, Kaiwilahilahi, Manowai'ōpae, and Pahale streams, which are continually monitored for streamflow (fig. 18.1). An additional eight streams along the north Hilo coast, located outside of HETF, are also monitored by CCPIWR. The eight watersheds outside HETF are at the wet end of the rainfall gradient and drain watersheds with native-dominated forests and minimal human disturbance. Watersheds within HETF are at the dry end of the gradient but are otherwise similar to the other CCPIWR study basins in land cover and land use. Although Parham et al. (2008) classified all CCPIWR study streams as perennial, streams at the drier end of the gradient typically have zero flow during the May to October dry season and will be referred to here as intermittent (Hansen 2001). To minimize influences of geological age, all CCPIWR study streams were selected to be on geologic substrates less than 20,000 years old.

Prior to CCPIWR, several separate research projects had been done in these streams or watersheds. Michaud and Wiegner (2011) assessed nutrient fluxes in streams along the North Hilo coast. Fish surveys have been conducted by Hawai'i's Division of Aquatic Resources in the lower reaches of Ka'awali'i, Laupāhoehoe, Kilau, Manowai'ōpae, Kaiwilahilahi, Ha'akoa, and Pāhale streams that drain HETF (Parham et al. 2008). Fish surveys in the lower reaches of Manowai'ōpae and Kaiwilahilahi investigated how the invasion by nonnative poeciliid fish affected the ecological function of native streams (Holitzki et al. 2013). Forests along this coast were sites in the Long-term Soil Age Gradient study that examined shifts in nutrient limitation along a sequence of increasing geologic substrate age across the Hawai'ian islands (Hedin et al. 2003, Vitousek and Farrington 1997). Meteorological stations had been established in Manowai'ōpae and Ka'awali'i watersheds, which monitor air temperature, rainfall, and wind. Extensive surveys using LiDAR and hyperspectral remote sensing have documented forest structure, carbon stocks, and extent of invasive plants (Asner et al. 2008, 2011). Other studies have also examined how soil carbon stocks shift along temperature gradients within CCPIWR watersheds (Litton and Giardina 2008).

Availability of publications and data—

Since the establishment of HETF in 2007, nearly 100 papers have been published on studies that have examined the biogeochemistry, floral and faunal communities, and the impacts of invasive species and climate change. A complete list of reports and publications can be found online (USDA FS 2014, 2016). Streamflow, stream chemistry, and meteorological monitoring data are currently available upon request (MacKenzie and Giardina, n.d.). Atmospheric deposition data are available in Carrillo et al. (2002) and Vitousek (2004). Information on vegetation surveys, LiDAR, and other remote images can be found in Asner et al. (2005, 2008, 2011) or from Hughes (n.d.). For data from individual studies, contact publication lead authors.

Biological Responses to Stream Nutrients N and P

Issues of Concern

Freshwater is a critical resource for human communities on islands in Hawai'i and across the Pacific. Stream water is often used as drinking water as well as for recreation, traditional and cultural practices, irrigation for crops such as taro (*Colocasia esculenta* (L.) Schott), and for aesthetic values. Hiking to and swimming in streams and waterfalls is a popular activity that attracts tourists to many islands. Island streams also play an important role in maintaining the health of coastal marine ecosystems such as estuaries and coral reefs. Unfortunately, rapid population growth and land-cover change, including urbanization, intensive agriculture, and deforestation, have resulted in substantial harm to freshwater ecosystems and nearshore marine areas. These human activities on tropical islands have often decreased water quality through increased N, P, and sediment loading to streams (Bruland and MacKenzie 2010, Golbuu et al. 2003, MacKenzie 2008, Michaud and Wiegner 2011) that can also negatively affect nearshore waters, including coral reefs (Golbuu et al. 2007, 2011; Hoover 2002).

The increased spread of invasive plants and animals across islands of the western Pacific has severely affected N and P loading to Pacific Island streams. For example, N-fixing albizia trees (*Falcataria moluccana* (Miq.) Barneby & J.W. Grimes) can significantly increase N concentrations in streams through decomposition of N-rich leaf litter (MacKenzie et al. 2013) or from subsurface flows in albizia-invaded soils (Wiegner et al. 2013). Invasive poeciliid fish also increase the amount and forms of N and P in invaded streams (Holitzki et al. 2013). Feral ungulates, such as pigs (*Sus scrofa* L.), also degrade water quality through increased nutrient, sediment, and bacteria loading (Dunkell et al. 2011a, 2011b; Sidle et al. 2006; Singer et al. 1984; Strauch et al. 2016a).

Dams and diversions affect water quality in Hawai'i (Brasher 2003, McIntosh et al. 2002) and across the Pacific (Leberer and Nelson 2001). For example, nearly one-third of Hawai'i's perennial streams were diverted by the late 1970s (Assessment 1990, Parrish 1978) to support the sugar industry. Today, many of these diversions still function and reduce flow in downstream reaches. Lower flows result in warmer temperatures and lower dissolved oxygen (DO) levels (Benbow et al. 2005, Leberer and Nelson 2001, McIntosh et al. 2002) that can influence biogeochemical functions in stream water and sediments (Wiegner et al. 2009). Lower flows also increase residence time, breakdown, and remineralization of organic matter (Roberts et al. 2016), producing inputs of N and P to the water column. These impacts on water quality will likely be exacerbated in a warmer and drier climate.

Increased N, P, and sediment loading from land use and invasive species decreases water quality for drinking and recreation (e.g., Strauch et al. 2014). For example, Hilo Bay has one of the largest beaches on Hawai'i Island, but less than 10 percent of people using the beach in 2001 swam owing to water quality issues (USEPA 2002). Increased N and P loading can stimulate blooms of nonnative algae that replace native algae traditionally harvested for food by humans (Lapointe and Bedford 2011). Increased algal blooms can also decrease habitat for native stream and nearshore fish (MacKenzie 2008, Smith et al. 2001).

Climate models predict that Hawai'i will become warmer and drier during this century (Mimura et al. 2007). Detailed analyses predict that leeward coasts will show the strongest drying trends, while the trade wind-dominated windward coasts will experience no change or some drying. In contrast, Timm et al. (2013) predicted fewer heavy rainfall events, which would decrease flood frequency, but not necessarily increase the number of dry days. However, the absolute magnitude of changes in rainfall timing or intensity remains uncertain (Timm et al. 2015, 2016). Based on past trends during 1950–2007, rainfall intensity has generally increased across Hawai'i. Fewer yet more intense rainfall events occurred along with a general increase in number of dry days between rainfall events (Chu et al. 2010) and an increase in streamflow intermittence (Strauch et al. 2015).

Water quantity in streams is also threatened by high water use by invasive plant species (Strauch et al. 2016b) as well as continued withdrawal of stream water to support agriculture (Oki et al. 2010). Changes in rainfall patterns and corresponding shifts in streamflow regimes and flood frequencies would probably alter stream and nearshore habitat that support many species of native fish, shrimp, and snails that are traditionally harvested by many indigenous people in Hawai'i and across the Pacific (Atwood et al. 2012, Bell 1999, Couret 1976). Impacts of rainfall changes, invasive plants, and water diversions are only expected to be exacerbated by a warmer and drier climate. However, many details of how hydrological and ecological functions in tropical streams will respond to those changing climate or land use patterns are currently unknown.

Cross-Site and Regional Studies

Almost all stream studies at HETF have been done within the context of the cross-site CCPIWR study of 12 basins on the north Hilo coast of Hawai'i Island, rather than solely on streams within HETF.

Concentrations of dissolved and total (dissolved + particulate) N and P constituents were monitored in nine of the CCPIWR streams, including three located within LWF: Ka'awali'i, Manowai'ōpae, and Pāhale. Water samples were grab-sampled from each stream once a month from June 2011 through August 2012, and analyzed for total carbon (C), N, and P nutrients and dissolved C, N, and P nutrients. For a complete description of methods used, see Wiegner et al. (2009) or Holitzki et al. (2013).

Total N (TN) was typically lower than total dissolved N, which included dissolved inorganic and organic N. This difference was attributed to microbial utilization of dissolved N that occurred in unfiltered TN samples prior to analysis (Mead 2012). This also suggests that N in our TN sample was largely in dissolved forms. Samples were collected during low flows when particulate concentrations would have been lowest, compared to stormflows that resuspend particles (Wiegner et al. 2009). Inorganic N, composed of the sum of nitrate (NO_3^-)-N and nitrite (NO_2^-)-N (referred to as ΣNO_3^-) plus ammonium (NH_4^+)-N, represented only 26.6 ± 9.8 percent standard deviation (SD) (range 16.3 to 48.8 percent) of the average monthly TN concentrations (table 18.1, fig. 18.2). The remainder of TN was primarily dissolved organic N, a complex mix of organic N compounds that have been little studied in HETF streams. Our measured concentrations of TN generally increased as flow decreased along the CCPIWR gradient when regressed against base (Q90), median (Q50), and stormflows (Q10) (table 18.2, fig. 18.2). This would have been significant if we had raised the alpha level to 0.1 and suggests that highest TN concentrations typically occurred in streams at the drier end of the CCPIWR gradient that had lower flows or were intermittent. Continued monitoring is needed to verify this pattern.

Total phosphorus (TP) was dominated by total dissolved phosphorus (TDP). TDP was strongly and negatively correlated to median streamflow (Q50) ($R = -0.73$, $p < 0.05$) and stormflows (Q10) ($R = -0.80$, $p < 0.01$) across the CCPIWR gradient. TP and TDP concentrations were generally higher in streams at the drier end of the CCPIWR gradient. In contrast, phosphate (PO_4^{3-}) was significantly and positively correlated to base (Q) ($R = 0.85$, $p < 0.01$) and median flows (Q50) ($R = 0.80$, $p < 0.01$), but not stormflows (Q10) across the CCPIWR gradient.

Hydrology has a strong influence on stream water quality as runoff and baseflow can dilute or increase the relative concentration of a nutrient, depending on its source. The negative correlations observed between N constituents, TP, and TDP and flow conditions along the CCPIWR gradient (table 18.2), as well as their higher concentrations in streams at the drier end of the gradient (figs. 18.2 and 18.3), were likely because of lower groundwater inputs, lower overall flow conditions, and resulting longer residence time of water. Lower groundwater inputs in streams at the drier end of the gradient did not dilute concentrations of N constituents, TP, and TDP. In contrast, streams at the wetter end of the gradient had higher groundwater

Table 18.1—Catchment area, flow metrics, and monthly average (±1 standard deviation) nutrient concentrations for the nine streams sampled across the North Hilo Coast of Hawai'i Island[a]

Stream	Area	Q90	Q50	Q10	ΣNO_3	PO_4^{3-}	SiO_4^{2-}	NH_4^+	TDP	TP	TDN	TN	DOC	TOC
Pāhale*	10.14	0.00	0.00	0.13	2.70	0.19	6.86	1.07	0.23	0.42	14.75	11.58	360.86	353.71
					(4.67)	(0.18)	(8.32)	(1.23)	(0.33)	(0.61)	(7.38)	(4.91)	(106.71)	(88.98)
Manowai'ōpae*	3.84	0.00	0.00	0.00	0.59	0.15	15.90	1.43	0.37	0.58	12.32	11.66	396.60	395.35
					(0.62)	(0.14)	(12.72)	(1.42)	(0.45)	(0.44)	(7.36)	(8.75)	(313.73)	(312.55)
Ka'awali'i*	33.10	0.01	0.03	0.03	2.61	0.16	23.59	1.59	0.26	0.35	13.51	11.23	247.73	246.56
					(3.58)	(0.15)	(20.43)	(1.33)	(0.39)	(0.35)	(5.12)	(3.73)	(70.59)	(76.05)
Makahiloa	9.60	0.00	0.03	0.44	1.89	0.16	8.75	1.30	0.20	0.26	16.95	8.15	332.31	304.75
					(2.56)	(0.15)	(8.76)	(1.31)	(0.34)	(0.34)	(16.29)	(3.40)	(148.84)	(115.50)
Pāhoehoe	1.30	0.03	0.05	0.13	2.43	0.17	40.94	1.05	0.20	0.15	7.14	4.91	107.58	107.57
					(1.29)	(0.12)	(37.61)	(1.62)	(0.47)	(0.42)	(6.85)	(5.31)	(92.06)	(94.27)
'Uma'uma	74.43	0.10	0.33	4.57	1.72	0.17	21.09	1.27	0.12	0.08	11.45	6.47	319.81	305.67
					(4.49)	(0.16)	(27.59)	(1.68)	(0.25)	(0.20)	(14.44)	(2.72)	(132.28)	(112.50)
Kapu'e	20.69	0.12	0.30	3.61	1.21	0.18	16.42	1.08	0.08	0.10	7.97	5.96	287.53	279.93
					(1.82)	(0.14)	(23.11)	(1.34)	(0.21)	(0.21)	(6.38)	(4.82)	(92.07)	(80.45)
Kolekole	17.23	0.15	0.29	1.81	0.76	0.20	44.11	1.24	0.13	0.04	11.57	9.14	292.07	297.27
					(1.21)	(0.16)	(63.90)	(1.40)	(0.27)	(0.16)	(10.60)	(8.11)	(149.40)	(147.50)
Honoli'i	30.36	0.40	0.71	3.51	1.23	0.23	60.00	0.96	0.10	0.14	8.06	5.05	207.63	189.87
					(1.69)	(0.12)	(60.52)	(1.69)	(0.21)	(0.29)	(7.94)	(5.29)	(64.87)	(68.84)

Nutrients measured monthly from June 2011 through August 2012 are in millimoles per liter and include sum nitrate and nitrite (ΣNO_3), phosphate (PO_4^{3-}), silicate (SiO_4^{2-}), ammonium (NH_4^+), total dissolved phosphorus (TDP), total phosphorus (TP), total dissolved nitrogen (TDN), total nitrogen (TN), dissolved organic carbon (DOC), and total organic carbon (TOC). Ka'awali'i,
* Pāhale, and Manowai'ōpae streams are three streams that drain the Laupāhoehoe Wet Forest unit of the HETF, while the remaining six streams are located along or rainfall gradient on the North Hilo Coast of Hawai'i Island.

[a] Catchment area is in square kilometers and represents that area above the study reach. Flow metrics include baseflow (Q90), medianflow (Q50), and stormflow (Q10) in units of cubic meters per second.

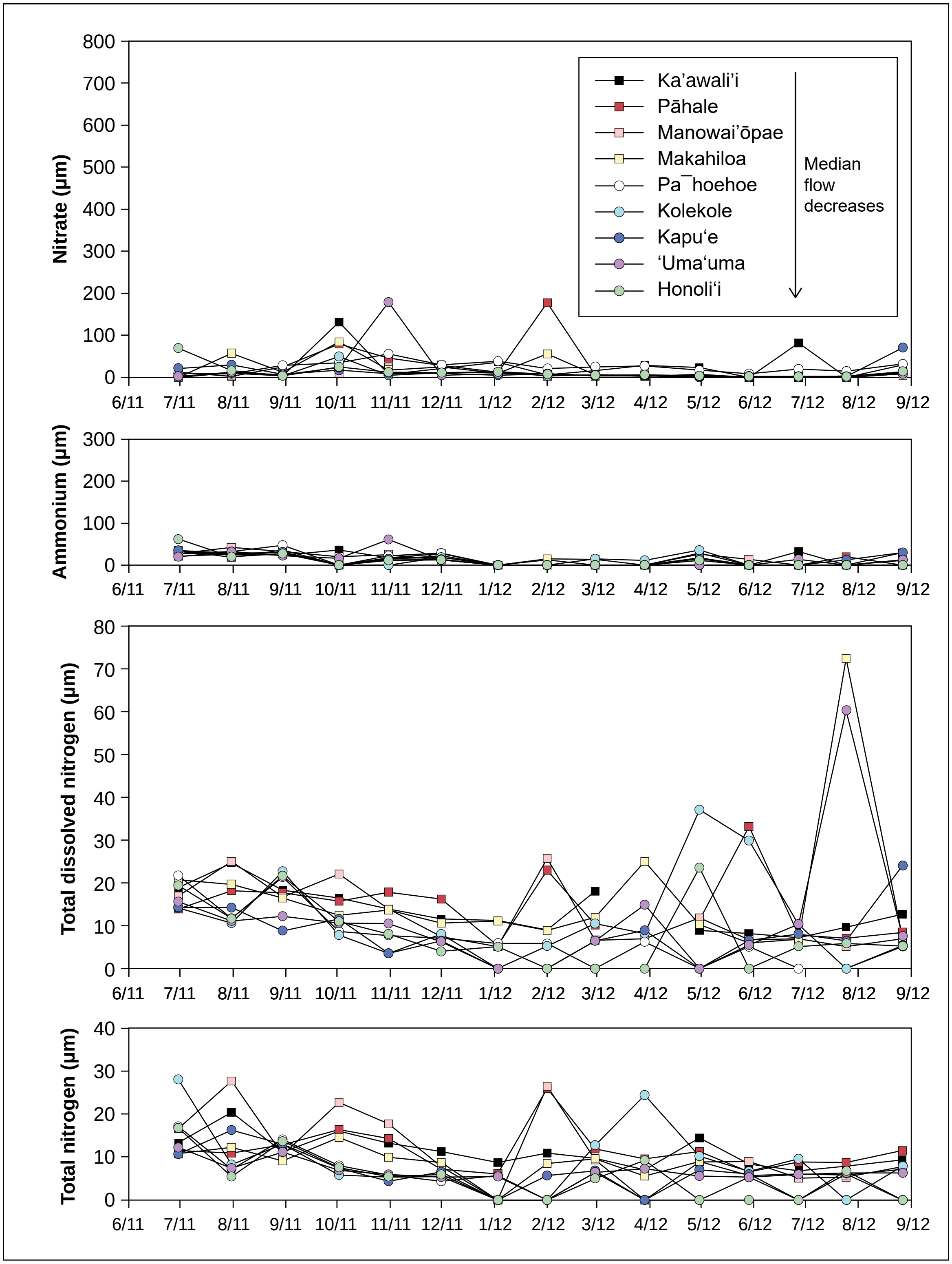

Figure 18.2—Monthly concentrations of nitrogen constituents measured from June 2011 until August, 2012.

Table 18.2—Results from Pearson's Product Moment correlation between various streamflow metrics across the Climate Change and Pacific Island Water Resources gradient, and monthly nutrient[a] concentrations averaged across the 13 months they were sampled

Nutrient[a]	Q90	Q50	Q10
ΣNO_3	-0.41	-0.43	-0.38
PO_4^{3-}	**0.85**[**]	**0.80**[**]	0.48
SiO_4^{2-}	**0.77**[*]	**0.71**[*]	0.31
NH_4^+	-0.56	-0.52	-0.39
TDP	-0.64	**-0.73**[*]	**-0.80**[**]
TP	-0.54	-0.63	**-0.70**[*]
TDN	-0.56	-0.55	-0.47
TN	-0.58	-0.63	-0.63
DOC	-0.34	-0.28	-0.05
TOC	-0.37	-0.31	-0.09

* = $p< 0.05$
** = $p< 0.01$
Q90 is low flow, Q50 is median flow, and Q10 is high flow.
[a] Nutrients include sum nitrate and nitrite (ΣNO_3), phosphate (PO_4^{3-}), silicate (SiO_4^{2-}), ammonium (NH_4^+), total dissolved phosphorus (TDP), total phosphorus (TP), total dissolved nitrogen (TDN), total nitrogen (TN), dissolved organic carbon (DOC), and total organic carbon (TOC).

inputs that diluted N concentrations (Strauch et al. 2017). Lower flows in streams at the dry end of the rainfall gradient also had longer stream water residence times. As a result, particulate organic matter in these streams have more time to break down, as opposed to being flushed downstream to the ocean (Roberts et al. 2016). Thus, the greater breakdown of particulate organic matter in streams at the drier end of the gradient may also contribute to the higher concentrations of N, TP, and TDP observed there (MacKenzie et al. 2013).

Rock weathering has been hypothesized as one potential explanation for increased concentrations of PO_4^{3-} with increased base- and median flows in streams along the CCPIWR gradient. The streams sampled within the LWF were from watersheds with geologic substrate of comparable age to the other watersheds in the CCPIWR study. Although the relatively young substrates in all these watersheds produce soils high in PO_4^{3-}, but low in N (Vitousek et al. 2009), the streams at the drier end of the gradient received less rainfall, which would have hypothetically slowed weathering rates of this P-rich rock. This could have contributed to lower stream water PO_4^{3-} concentration in drier watersheds. Another contributing factor to lower PO_4^{3-} concentrations in streams with lower Q90 and Q50 at the drier end of the gradient may be decreased groundwater inputs (Strauch et al. 2017), which is an important source of rock-derived PO_4^{3-} (Wiegner et al. 2009).

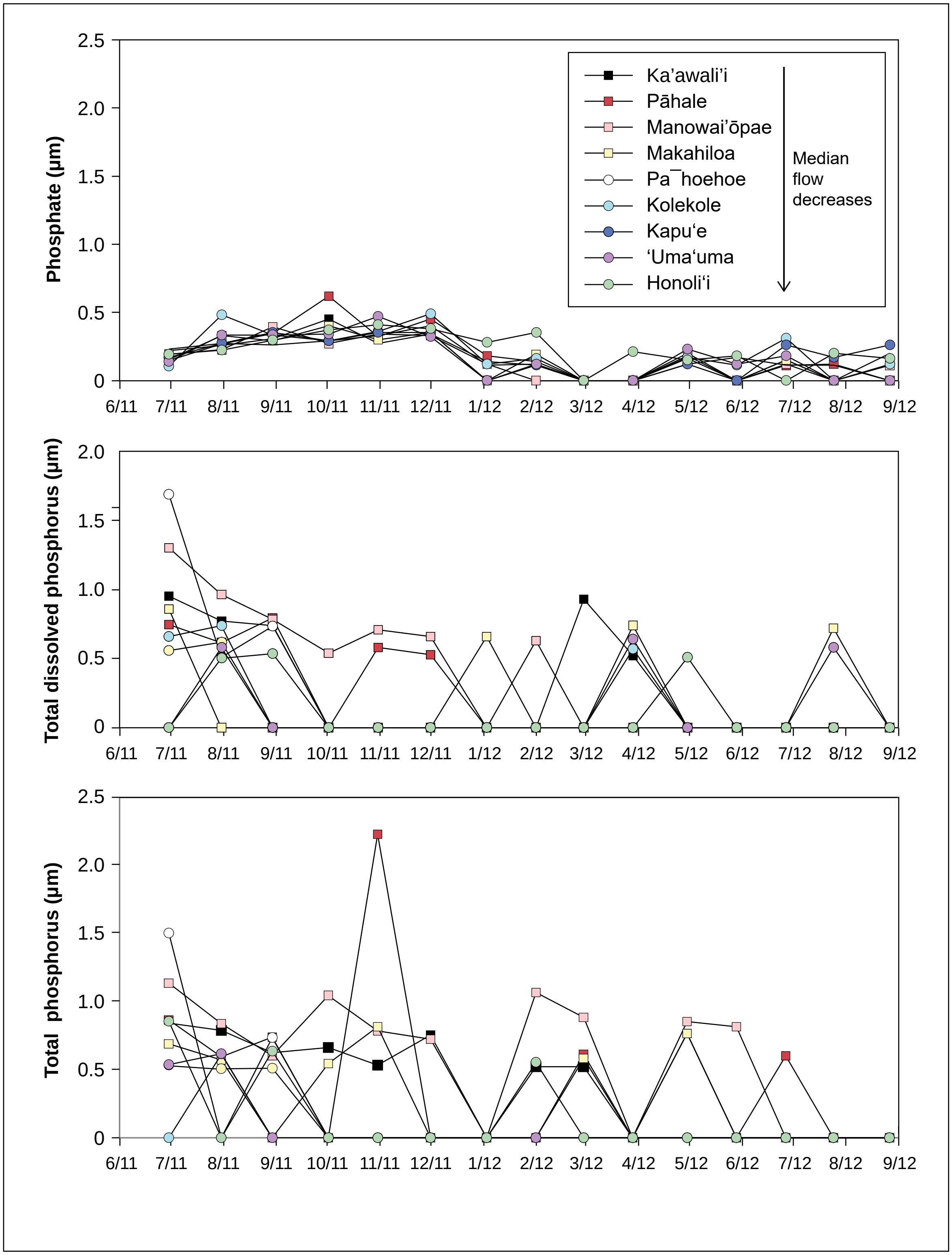

Figure 18.3—Monthly concentrations of phosphorus constituents measured from June 2011 through August 2012.

Biological activity is also probably influencing concentrations of nutrients in streams at the drier end of the gradient. Results of a nutrient spiraling study of streams across the CCPIWR rainfall gradient provide evidence that biological processes in these stream ecosystems may be limited by stream water N and P concentrations and that limitation of both nutrients may change with flow. This study used nutrient additions to measure the amount of N and P taken up by stream biota that include algae, submerged macrophytes, and microbes. Preliminary results revealed that demand for N (48.8 mg N/m^2/day) and P (37.0 mg P/m^2/day) did not vary much among perennial streams at the wetter end of the gradient (Frauendorf et al. 2019). However, in intermittent streams at the drier end of the gradient, the demand for N and P was reduced by about half and resulted in lower uptake of both these nutrients. Wiegner et al. (2013) found similar N vs. P limitation in Ainako Stream, elsewhere on Hawai'i Island. Benthic algal biomass was significantly greater on plates inoculated with both N and P than on plates inoculated with only N, only P, or uninoculated controls. While Ainako Stream differs from the CCPIWR streams because it is spring fed and on older geologic substrate, these results provide more evidence that both N and P together are limiting nutrients in perennial streams on Hawai'i Island.

A preliminary study of benthic biofilm in three CCPIWR study streams found standing stocks of benthic biofilm biomass were lower in streams at the drier end of the rainfall gradient with lower baseflows. Biofilm consist of interacting communities of autotrophs, such as diatoms and filamentous algae, and heterotrophs, such as fungi, protozoans, and bacteria. Biofilm biomass was measured as chlorophyll *a* (chl *a*, mg/m^2) and ash-free dry mass (mg/m^2) that grew on an initially bare substrate that was exposed in the stream for a known period of time. Biofilm biomass was lowest in the two streams at the drier end of the gradient that had overall lower flows than the stream at the wetter end of the gradient (Foulk et al. 2012) (fig. 18.4). In another study, benthic algal productivity, measured as chl *a* once a month for 12 months, was also significantly lower in streams at the drier end of the gradient with lower streamflows ($r^2 = 0.91$, $p < 0.05$) in four CCPIWR study streams (Frauendorf et al. 2019). Lower biofilm biomass in lower flow and intermittent streams may be due to P-limitation at low flows, or nutrient uptake may be reduced in lower streamsflows owing to a greater diffusive boundary layer for benthic algae (Finlay 2004). Regardless of the causal mechanism, patterns of benthic biofilm biomass have important implications for stream food webs, because biofilm is a major food resource for consumers, including native assemblages of shrimp, snails, gobies, and aquatic insects (Benbow et al. 2005, Brasher 1997, Kido 1996, Riney 2015). For example, benthic algae makes up 50 to 80 percent of shrimp (*Atyoida bisulcata*) diets in streams along the CCPIWR rainfall gradient (Riney 2015). A decrease in

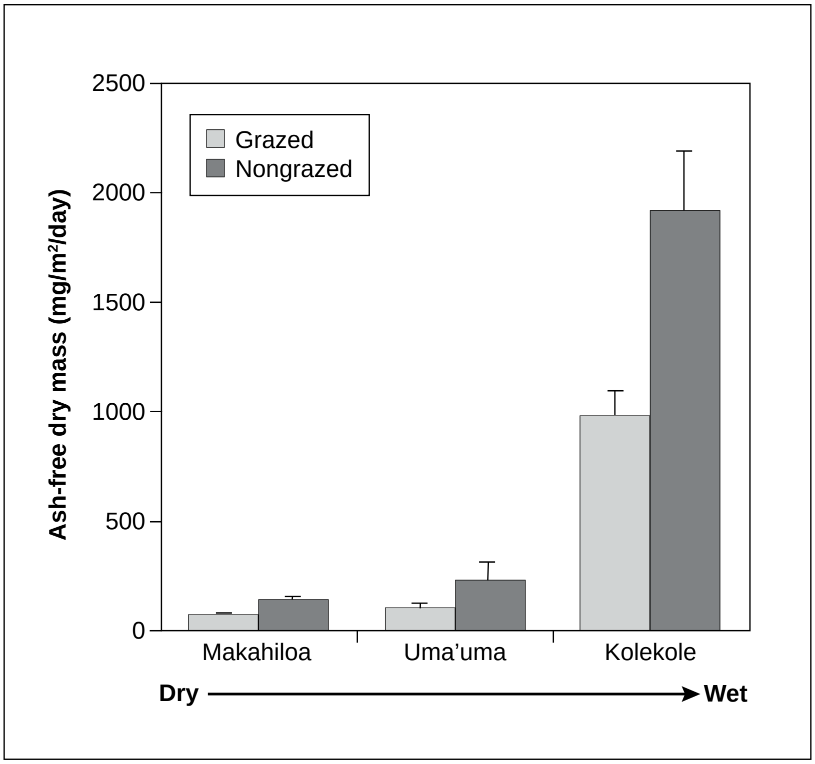

Figure 18.4—Ash-free dry mass (AFDM; mg/m^2/d) of periphyton collected from grazed and nongrazed plates in streams across the Climate Change and Pacific Island Water Resources study rainfall gradient. Grazed AFDM is significantly different in the Kolekole stream, located at the wet end of the gradient, but not different in the Uma'uma (UMA) or Makahiloa streams at the drier end of the gradient. Grazed and nongrazed AFDM plates are only different from each other in the Kolekole stream. Reproduced with permission from Foulk et al. (2012).

shrimp density, size, and body condition in streams at the drier end of the gradient may be explained, in part, by decreased benthic algal biomass in lower flow streams (Tingley 2017).

Other Factors Relevant to Biological Responses to Stream Nutrients N and P

Streamflow has been continuously monitored with stream gages that were installed by the USFS in 2010–2011 in 11 of the 12 CCPIWR basins, including three streams within HETF. The stream gage in the 12th stream, Honoli'i, was installed and has been maintained by U.S. Geological Survey since 1911 (station 16717000). The recently installed gages were sited in stable reaches, and no changes have been observed in streambed conditions over 4 to 5 years (Gore 2007, Turnipseed and Sauer 2010).

Rainfall and air temperatures have been monitored across the CCPIWR watersheds since 2011. Comparing watersheds across the rainfall gradient, as mean annual rainfall (MAR) decreased, relative rainfall intensity (maximum daily rainfall/median daily rainfall) increased, and days with zero rainfall increased, streams had more days with zero flow, and baseflow receded more quickly to no flow between rains. Low, median, and high streamflows as well as flashiness (frequency of stormflows exceeding two times that of Q50) and flow stability (Q90:Q50) all increased with increasing MAR. Flow variability (Q10:Q90) decreased with increasing MAR. This suggests that if MAR decreases with climate warming, streamflow in Hawai'ian watersheds will decrease and become less stable and flashier. These expected changes in flow conditions with warming climate have implications for the reliability of water supply to downstream users and for the quality of habitat for aquatic organisms, including the amphidromous fish and invertebrates that dominate these streams (Strauch et al. 2015).

Dose-Response Studies

Studies of dose response to N and P are currently underway in streams draining the LWF as part of the CCPIWR study, but results are not yet available. Nutrient demand is being measured using nutrient injections of NH_4^+, NO_3^-, and PO_4^{3-} into streams, along with a conservative tracer of sodium chloride (Covino et al. 2010). The study is examining how shifts in streamflow affect ecosystem nutrient demand, consisting of the amount of dissolved N and P required by a defined area of the benthos, and the proportion of the aquatic ecosystem demand that is supplied through remineralization by dominant stream taxa, including shrimp, caddisflies (*Cheumatopsyche analis*), and various species of chironomids.

Reference Watersheds

As conservation lands, the seven major watersheds in the LWF are currently managed for minimal onsite human disturbance and will remain in that status in perpetuity. Streamflow from four of these reference watersheds, Ka'awali'i (1420 ha), Manowai'ōpae (100 ha), Kaiwilahilahi (1510 ha), and Pahale streams (1000 ha) (fig. 18.1), have been monitored since 2011. Permanent forest monitoring plots and a climate monitoring tower are also located within these reference watersheds (Inman-Narahari et al. 2010, Litton et al. 2011).

Intact native Hawai'ian forests make up 60.8 percent (range 43 to 77 percent) of vegetative cover on LWF reference watersheds (Parham et al. 2008). Like other remaining native Hawai'ian forests, vegetation is dominated by native 'ōhi'a and koa forest (Asner et al. 2005). Legacies of past land use that persist in small portions of these watersheds include nonnative tropical ash (*Fraxinus uhdei* (Wenz.) Lingelsh) and eucalyptus (*Eucalyptus* spp.) plantations and, at lower elevations, abandoned sugarcane fields now dominated by invasive strawberry guava or managed as pasture. Feral pigs are common in the reference watersheds (Maly and Maly

2006).

These forests were and continue to be considered sacred to native Hawai'ians. Traditionally, they cautiously collected resources such as wood, other plant materials, and birds, and probably had minimal impacts on soil and vegetation. Since Western contact, the upland sections of these watersheds were grazed by domestic sheep and cows, and koa trees were selectively harvested, but these practices were discontinued when the state granted these lands conservation status. Collection of culturally important plants and hunting are currently permitted in these watersheds (Maly and Maly 2006).

Responses to Management and Natural Disturbances

Streams draining LWF were part of a larger study by Holitzki et al. (2013) that quantified disturbances caused by introduced invasive fish in six streams with similar land use histories, including the lower reaches of Kaiwilahilahi and Manowai'ōpae streams, downstream of HETF. Average ΣNO_3, TN, and total organic carbon (TOC) yields were eight, six, and five times higher, respectively, in three streams invaded by poeciliid fish compared to poeciliid-free streams dominated by native species. Benthic biofilm ash-free dry mass was 1.5 times greater in poeciliid-invaded streams, which may have been related to the higher levels of N in these streams.

Invasive plants with associated N-fixing bacteria can also contribute dissolved nutrients to Hawai'ian streams. For example, leaf litter breakdown from the invasive N-fixing albizia tree can significantly increase stream water concentrations of $NO_3^- + NO_2^-$ (MacKenzie et al. 2013, Wiegner et al. 2013).

A study by Strauch et al. (2016b) modeled streamflow under various climate change and invasive species-spread disturbance scenarios in 88 watersheds across Hawai'i, including all watersheds in the LWF. Decreases in base-flow yield (Q90Y) and stormflow yield (Q10Y) in response to declines in annual rainfall dwarfed effects of projected temperature increase or exotic plant species invasion. Wetter watersheds had greater annual flow reductions than currently drier ones. Effects of decreased MAR were accentuated when combined with strawberry guava invasion and warming temperature. Modeling management to restore invaded forests by removing all strawberry guava reduced the impacts of climate change on streamflow. The study concluded that, while potential changes in precipitation from climate change in the Hawai'ian Islands are likely to exert significant impacts on streamflow, managing invasive vegetation might provide strong mitigating benefits (Povak et al. 2017).

Reliability and Limitations of Findings

Results from HETF probably apply to other watersheds on the windward sides of Hawai'i, Maui, or Molokai Islands that have similar climate, geology, geological age, and land use history. In areas that are dissimilar to HETF, or where a high degree of accuracy is required, it might be beneficial to consider validation studies or monitoring to test how well HETF results predict local conditions.

Research Needs

The research needs of highest priority to the water quality regulatory community related to N and P that could be filled at HETF include: additional detailed measurements of the composition of the aquatic biological communities in reference streams under natural background conditions, and identification of the threshold levels and response times of these communities to increased stream water N and P. Filling this gap would be important to the regulatory community because it would provide science-based data that could be used by Hawai'i's Commission on Water Resources Management and the Clean Water Branch of the Department of Public Health to develop water quality standards and land management regulations that protect the integrity of intact aquatic ecosystems. Filling that need at HETF would require future research that included continued monitoring of nutrients in stream waters and performing regularly repeated stream surveys of reference stream biological communities, including benthic algal biofilm, macrophytes, macroinvertebrates, and vertebrates. Studies to identify threshold levels would also be required using increased stream N and P to elicit significant biological responses. Such studies would include comparing HETF streams to otherwise similar streams that have higher nutrient levels, and studies of biological responses to controlled nutrient additions of N and P, together and separately, in stream reaches and in artificial stream microcosms.

Other research needs of the regulatory community, but of lower priority, that might be addressed at HETF include the following:

- How do climate change, land use, and invasive species interact to affect water quality and quantity in Hawai'i and Pacific Island streams?
- How does changing climate influence water availability through changes in groundwater recharge and surface water-groundwater interactions, and alter flood risk, especially for low-lying coastal areas?
- How does nutrient spiraling determine the fate of nutrients in Pacific Island streams, including the sources and sinks of these nutrients along a stream continuum?
- What explains differences in nutrient levels between soil pore water and stream water across geologic substrates of differing age?
- How do native fish and invertebrate assemblages in Hawai'ian streams alter nutrient dynamics and affect the algal food base?

Potential Utility to Water Quality Regulatory Agencies

Existing monitoring datasets from the HETF and the CCPIWR research platform might be useful to the regulatory community as baseline data to help identify impaired waters under section 303(d) of the Clean Water Act of 1977 (33 U.S.C. s/s 1251 et seq.) by providing data on stream conditions in relatively undisturbed Hawai'ian headwater streams, or as a baseline for assessing impacts on streams of land use change and invasive species. Data can also be used for the development of total daily maximum load (TMDL) source assessments for Hawai'i. These data might also be used by regulators to set guidelines for restoration and conservation of impaired waters to increase the resilience of these watersheds to stressors and improve their capacity to provide clean and plentiful water for the humans, plants, and sensitive Hawai'ian stream and nearshore ecosystems.

Key points:

- The CCPIWR monitoring network has found relationships between measurements of stream water concentrations of P and total N and flow that suggest there are hydrologic, geologic, and biological processes that influence stream nutrients.
- In streams with perennial flows, initial results indicate that stream water N and P together limit aquatic biological communities, but with intermittent flow in streams at the drier end of the CCPIWR gradient, demand for both N and P declined by nearly half, and biofilm biomass production may be both N and P limited.
- Maintaining native-dominated forests or restoring degraded ones to native-dominated forests have potential to mitigate climate change impacts on water quantity and quality of Hawai'ian streams.
- The highest priority research need of the regulatory community that could be filled at HETF includes continued water quality monitoring, detailed surveys of aquatic biological communities, and studies to identify thresholds of N and P enrichment that elicit biological responses in these stream communities.
- Existing datasets and research results from HETF and the regional CCPIWR study have strong potential to be useful to regulatory agencies as a scientific base for developing regulations that protect beneficial uses of Hawai'ian streams and nearshore waters.

Biological Responses to Stream Nutrients Other Than N and P

To date, the nutrients other than N and P that have been studied in HETF streams have been SiO_4^{2-}, dissolved organic carbon (DOC), TOC, and dissolved organic matter (DOM).

Issues of Concern

There are no major water quality issues related to nutrients other than N and P in Hawai'i. Diatoms that are an important component of benthic biofilms require SiO_4^{2-} as a nutrient. Silicate is also useful as a tracer for groundwater. DOC is a concern in Hawai'ian streams. Although it is not a nutrient for the purposes of this report, DOC is an energy source for aquatic food webs, and, in excess, can degrade water quality by stimulating heterotrophic respiration and depressing DO in water bodies (Atwood et al. 2010, Johnson and Wiegner 2014, Larned et al. 2008). Increased urban development and agriculture can increase the bioavailability of DOC (Seitzinger et al. 2002, Wiegner and Seitzinger 2004), and changes in streamflow from climate warming, stream water withdrawals, and their combination may also affect future loads of bioavailable DOC in Hawai'ian streams.

Cross-Site and Regional Studies

Silicate is a nutrient that is monitored in the streams of the CCPIWR study. Measured SiO_4^{2-} concentrations were generally higher in higher flow CCPIWR streams and were strongly and positively correlated to baseflows (see table 18.2). Silicate is a product of rock weathering, similar to PO_4^{3-}. The positive correlation of SiO_2^{2-} with baseflow across the CCPIWR gradient may indicate lower rates of rock weathering of SiO_2^{2-} in basins with drier climates or smaller groundwater inputs.

Silicate concentrations from CCPIWR (range 6.86 to 60 mmol/L) (table 18.1, fig. 18.5) were at the lower end of the global range reported for streams and rivers (range 8.9 to 320 mmol/L) (Fulweiler and Nixon 2005, Li et al. 2007, MacKenzie 2008, Turner et al. 2003). Because SiO_4^{2-} dissolution is temperature dependent, concentrations of dissolved silicate are usually higher in tropical than in temperate streams (Turner et al. 2003). Derry et al. (2005) reported that the lower concentrations in Hawai'ian streams compared to other tropical systems were likely due to biological uptake of SiO_2^{2-} by diatoms.

Other Factors Relevant to Responses to Stream Nutrients Other Than N and P

Dissolved organic matter—

The measured average (± SD) TOC concentration across all streams (275.6 ± 86.0 mmol/L, range 107.6 to 395.4 mmol/L) was typically lower than the average DOC (283.6 ± 87.0 mmol/L, range 107.6 to 396.6 mmol/L) (fig. 18.5, table 18.1). Similar to N, this was attributed to microbial utilization of DOC that occurred in the unfiltered TOC samples prior to sample analysis (Mead 2012). TOC showed no apparent patterns with flow and was largely composed of DOC. Factors that control DOM concentrations in Hawai'ian streams are not well understood. DOM sources to Pacific Island streams likely include soil pore water, leaf litter leachate, and benthic algae exudates (MacKenzie 2008, Wiegner et al. 2009), but how these sources result in observed stream DOC concentrations is not currently known. Michaud and Wiegner (2011) found that DOM in Hawai'ian streams was generally not correlated to MAR, human population density, or percentage of agricultural land. Similarly, modeling C fluxes from lotic systems across the main Hawai'ian Islands did not explain stream DOC concentrations (MacKenzie et al. 2017).

Dose-Response Studies

Dose-response studies for nutrients other than N and P have not been conducted at HETF.

Reference Reaches

SiO_4^{2-}, DOC, and TOC were monitored monthly from June 2011 to August 2012 in the three streams draining HETF reference watersheds (table 18.1).

Responses to Management and Natural Disturbances

There have been no studies at HETF for nutrients, other than N and P, or studies of DOM in response to management or natural disturbances.

Reliability and Limitations of Findings

Results of studies of nutrients other than N and P from HETF probably apply to other watersheds on the windward sides of Hawai'i, Maui, and Molokai Islands that have similar climate, geology, geological age, and land use history. In areas that are dissimilar to HETF, or where a high degree of accuracy is required, we suggest considering validation studies or monitoring to test how well HETF results predict local conditions.

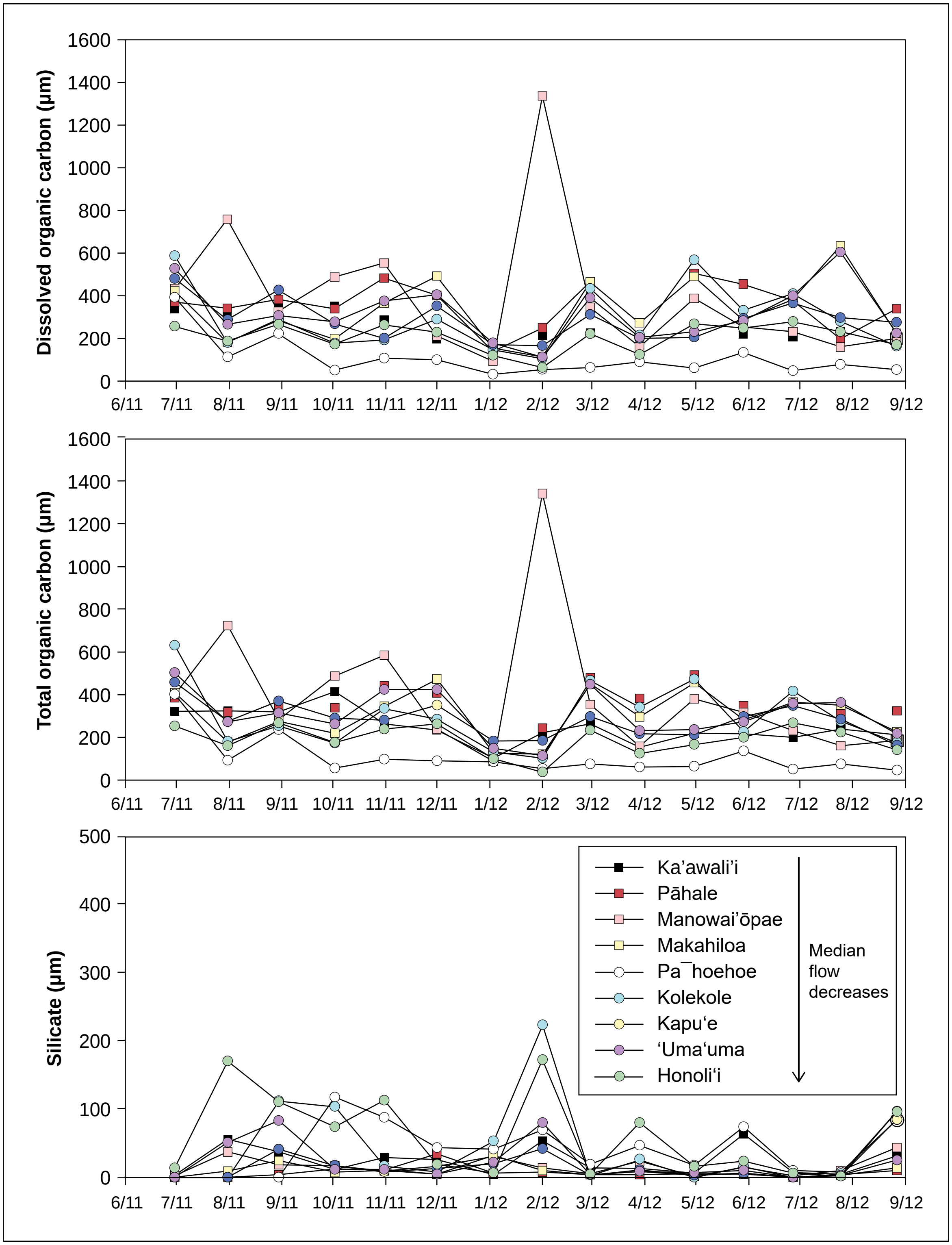

Figure 18.5—Monthly concentrations of carbon constituents and silicate measured in streams across the Climate Change and Pacific Island Water Resources study stream flow gradient from June 2011 until August 2012.

Research Needs

The research need of highest priority to the regulatory community, related to nutrients other than N and P, that could be filled at HETF would be a better understanding of carbon processing in tropical island streams, especially more detailed information on the sources and fate of dissolved inorganic and organic C and particulate organic C in undisturbed Hawai'ian headwater streams, both perennial and intermittent. These carbon sources drive important metabolic processes in streams and nearshore waters (MacKenzie et al. 2017). A better understanding of the sources, the dynamics, and processes that control these C constituents would help regulatory agencies to develop more effective rules for the management of DOC loading in Hawai'ian watersheds to protect beneficial uses of these waters. More scientific understanding of DOC dynamics in relatively undisturbed headwaters might be particularly useful as a baseline for assessing impacts of development in more disturbed streams. Filling this research need at HETF would require continued monitoring of LWF streams for DOC and total C (dissolved + particulate), turbidity, as well as additional studies to distinguish between labile and recalcitrant forms of DOC in stream water. In addition, process-oriented studies would be needed to investigate what processes control stream water DOC, including sources of stream C, such as instream vs. surface runoff vs. groundwater, and sinks of C, such as stream metabolism and volatilization. The intermittent streams in LWF in the drier parts of the rainfall gradient have potential to be especially useful for understanding whether processes controlling DOC in intermittent streams are different from controls in perennial streams.

Another research need of regulatory agencies that might be addressed at HETF, although of lower priority, would be to study how land use change and invasive plants and animals affect sediment inputs and retention times within flashy Hawai'ian streams.

Potential Utility to Water Quality Regulatory Agencies

Existing datasets from HETF and the CCPIWR study on background levels of sediment and nutrients other than N and P from undisturbed reference watersheds and their hydrologic response to intense rainfall events might be used by regulatory agencies to model what amounts of these constituents streams carry into estuarine and nearshore environments under natural conditions. Such information about water quality in undisturbed Hawai'ian streams might be helpful for developing enforceable, science-based TMDL limits.

Key points:

- Nutrients other than N and P are not currently associated with water quality concerns in this region.
- DOC provides an important energy source that supports culturally and economically important fisheries, but, in excess, can degrade water quality.
- Sources, sinks, and composition of stream DOC are not currently well understood in Hawai'ian streams.
- The highest priority research need of regulatory agencies not directly related to N and P that might be filled at HTEF is a better understanding of the sources, sinks, and composition of DOM in Hawai'ian streams under reference conditions.

Overview and Synthesis

The HETF is a newly established experimental forest that contains four watersheds that are part of the regional CCPIWR study. The concept behind the wider study is that streams in drier watersheds might predict hydrological, biogeochemical, and ecological responses of streams in wetter watersheds that are currently important water resources for Hawai'i, if the climate becomes drier under the influence of climate change. This information also provides insight into how reduced water quantity from invasive plant species or water withdrawals will affect Hawai'ian streams. This research has potential to benefit the water quality regulatory community by providing a scientific basis for anticipating how future climate or land use conditions may affect stream water quantity and quality and aquatic biotic communities in the streams of Hawai'i. This science is likely to be useful for developing regulations and management that will increase the resilience of Pacific Island streams and watersheds that are subject to these stressors.

Monitored watersheds in HETF represent reference conditions in headwater basins dominated primarily by undisturbed native forests at the drier end of the regional rainfall gradient. These sites provide regulators with measures of stream conditions under nearly pristine conditions that may serve as a natural baseline for developing water quality criteria and for TMDL modeling.

Important research results from the regional study suggest that aquatic communities in Hawai'ian headwater streams may be limited by both N and P in high rainfall areas with higher flows and that N and P demand is reduced in streams in drier areas with lower flows. Lower benthic algal biomass measured in streams in low rainfall basins may suggest P limitation of biofilms in these streams and explain the smaller body size and reproduction of native shrimp, a dominant macroinvertebrate in these headwater streams. Existing datasets on stream hydrology and stream water nutrients are potentially useful to regulatory agencies for setting water quality standards for nutrients.

Research needs of highest priority for regulatory agencies that might be filled at HETF were identified as studies of aquatic biotic communities in reference streams and threshold levels of stream nutrient enrichment that elicit significant responses in those communities, along with investigations of the sources and fates of dissolved organic and inorganic carbon compounds in HETF streams.

Results from HETF and the wider CCPIWR study are of scientific importance because their findings have potential to be applicable to streams with similar watershed characteristics, such as substrate geological age, rainfall, and elevation, found across the Hawai'ian Island chain and other mountainous islands of the tropical Pacific. Other potentially interesting scientific outcomes might also arise if cross-comparisons were made between HETF and the studies of the rainforest watersheds at Luquillo Experimental Forest (chapter 17) on Puerto Rico, another mountainous, tropical island with analogous though different aquatic species and land uses.

Key points:

- HETF is part of the long-term, regional CCPIWR study investigating the potential impacts of climate change on streams that are important sources of surface water for human populations and natural ecosystems on the north Hilo coast of Hawai'i Island.
- CCPIWR focuses on stream water quantity and quality, including stream nutrient levels, and aquatic biological communities composed of many species endemic to the Hawai'ian Islands.
- Effects of exotic invasive plants and animals and urban development are also under investigation.
- Research needs of highest priority to regulatory agencies that might be filled at HETF were identified as a better understanding of aquatic biotic communities in undisturbed reference streams and their responses to increased nutrient levels, and a characterization of the composition, sources, and fates of DOC in streams.
- Existing datasets and research results from HETF and the CCPIWR study have strong potential to be useful to regulatory agencies for developing regulations and programs to better protect beneficial uses of streams and nearshore marine ecosystems in Hawai'i and other mountainous tropical islands.

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