Baseline and Projected Future Carbon Storage and Carbon Fluxes in Ecosystems of Hawai‘i
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Chapter 6. Baseline Carbon Storage and Carbon Fluxes in Terrestrial Ecosystems of Hawai‘i

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6.1. Highlights

- Carbon storage and fluxes were examined for terrestrial ecosystems on the seven main Hawaiian Islands: Hawai‘i, Maui, Moloka‘i, Lana‘i, Kaho‘olawe, O‘ahu, and Kaua‘i. Total carbon stored in terrestrial ecosystems across these islands was estimated to be 258 TgC, of which 71 percent was soil organic carbon to 1 m depth, 24 percent was live biomass (above and below ground), and 5 percent was dead biomass (a combination of litter and downed woody debris).
- Hawai‘i Island, the largest island in the Hawaiian archipelago, stored 136 TgC, which accounted for 58 percent of the total carbon storage in the State of Hawai‘i. The island of Kaua‘i had the highest carbon density (carbon storage per unit area), estimated as 23.5 kgC/m^2, followed by O‘ahu (20.5 kgC/m^2), Maui (17.1 kgC/m^2), Moloka‘i (16.1 kgC/m^2), and Hawai‘i Island (14.0 kgC/m^2).
- Live-biomass carbon storage in native forests was estimated as 32 TgC, which was 51 percent of all carbon stored as live biomass (63 TgC), followed by invaded forests (21 TgC) and alien tree plantations (6 TgC).
- Between 2003 and 2014, gross primary production (GPP) across the seven islands averaged 20.2 TgC/yr, with Hawai‘i Island accounting for 55 percent of this flux (11.2 TgC/yr). As was the case with carbon storage, the island of Kaua‘i had the highest mean annual GPP carbon flux density (GPP per unit land area), estimated at 1.85 kgC/m^2, followed by Moloka‘i (1.68 kgC/m^2), O‘ahu (1.47 kgC/m^2), Maui (1.34 kgC/m^2), and Hawai‘i Island (1.07 kgC/m^2).
- Between 2003 and 2014, the estimates of annual net ecosystem production (NEP) in terrestrial ecosystems across the seven islands averaged 2.38 TgC/yr (a positive value denotes a carbon sink). Among ecosystem types, native forests represented the largest single terrestrial carbon sink with NEP of 1.26 TgC/yr, which accounted for 53 percent of total annual carbon sequestration. Alien grasslands were estimated to be a net carbon source to the atmosphere with NEP estimated at -0.56 TgC/yr, because ecosystem respiration exceeded GPP in large areas of alien dry grasslands.

6.2. Introduction

Terrestrial ecosystems in the tropics have the potential to be major carbon sinks, yet intensive land use and development can reduce that potential or even convert these ecosystems to net carbon sources to the atmosphere. Because of its steep environmental gradients and geological history, Hawai‘i has been home to several plot- and stand-level studies examining the physical and biological controls over tropical ecosystem carbon storage and flux, with a focus on soils, live biomass, and plant productivity (Townsend and others, 1995; Torn and others, 1997; Aplet and others, 1998; Herbert and Fownes, 1999; Schuur and others, 2001; Schuur and Matson, 2001; Giardina and others, 2003; Litton and others, 2006; Selmants and others, 2014; Giardina and others, 2014). More recently several landscape-level studies on the Island of Hawai‘i have examined biotic and environmental controls on aboveground carbon density (ACD) (Asner, Hughes, and others, 2009, Asner and others, 2010, Hughes and others, 2014), including the first whole-island estimate of aboveground carbon stocks for one of the main Hawaiian Islands (Asner and others, 2011). These landscape-scale studies integrated much of the previous research conducted at the plot scale but focused on a limited set of carbon pools or fluxes.

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This chapter represents the first comprehensive assessment of terrestrial-ecosystem carbon stocks and fluxes across the main Hawaiian Islands in an effort to better understand how carbon stocks and fluxes vary by ecosystem component across islands and among ecosystem types. The goal of this chapter is to provide robust baseline estimates of carbon storage and fluxes across the Hawaiian Islands based on the best available data. This baseline data will then be used as input to predict how terrestrial carbon cycling may respond to projected future changes in land use, land cover, disturbance, and climate (see Sleeter and others, this volume, chap. 8).

Conventional carbon cycle terminology (Chapin and others, 2006) was used in this chapter and throughout this report, as noted in Giardina and others (this volume, chap. 1). Of particular relevance here is the concept of net ecosystem production (NEP), which is defined as the imbalance between gross primary production (GPP) and ecosystem respiration (R_e). For this report, NEP was estimated by subtracting R_e from GPP, therefore, a positive value indicates carbon accumulation or sequestration within an ecosystem (a net carbon sink), and a negative value indicates a loss of carbon from the ecosystem to the atmosphere (a net carbon source). This definition is consistent with that suggested by Chapin and others (2006).

6.3. Input Data and Methods

6.3.1. Carbon Storage

Input data, along with the data sources, used to estimate carbon storage in terrestrial ecosystems of Hawaiʻi are listed in table 6.1. Each input dataset was converted to a standard projection and data format. For this report, estimated carbon stocks include aboveground live-biomass carbon, live-root-biomass carbon, dead-biomass carbon (the sum of surface litter and downed woody debris carbon), and soil organic carbon (SOC). Live- and dead-biomass carbon stocks were estimated only for forests (including alien tree plantations), grasslands, shrublands, and barren-to-sparsely vegetated areas as delineated by the land-cover map from Jacobi and others (this volume, chap. 2). Collectively, these four land-cover types constitute about 88 percent of the total land area of the main Hawaiian Islands. Developed areas (6 percent of total land area), agriculture (5 percent of total land area), and wetlands (1 percent of total land) made up the remaining 12 percent of land area for which there was insufficient Hawaiʻi-specific data to estimate carbon storage in live and dead biomass. SOC data covers 100 percent of the land area on the seven main Hawaiian Islands, so we included SOC data from developed areas, agriculture, and wetlands in islandwide and statewide estimates of ecosystem carbon storage. Land-cover classes from Jacobi and others (this volume, chap. 2) were aggregated into broader categories for ease of analysis and interpretation. Specifically, all grasslands were combined into a single grassland category, all shrublands were combined into a single shrubland category, alien and mixed forest types were combined into an “invaded forest” category, and mesic and wet forests were combined into a “mesic and wet forest” category.

Aboveground biomass carbon of forest ecosystems for each island and forest cover type was estimated using a new map of forest ACD across the seven main Hawaiian Islands (Asner and others, 2016). The forest ACD map was constructed using a combination of airborne light detection and ranging (lidar) data from Hawaiʻi Island, freely available satellite data covering all the major islands, and the land-cover map described in Jacobi and others (this volume, chap. 2). Lidar estimates of forest top-of-canopy height (TCH) covering 3,793 km^2 over all major forest types on Hawaiʻi Island (Asner and others, 2011) was used to train a geospatial model that incorporated forest canopy fractional cover and other structural metrics derived from Landsat data as well as several environmental factors (Asner, Knapp, and others,

Table 6.1. Input data used to estimate carbon storage in terrestrial ecosystems of Hawaiʻi.

[LULC, land use and land cover]

Data category	Data type	Data source
LULC	LULC classes	Jacobi and others (this volume, chap.2)
Soils	Soil organic carbon	gSSURGO (Soil Survey Staff, 2015)
Forests, Tree plantations	Aboveground biomass carbon	Asner and others (2016)
	Litter carbon	Hawbaker and others (this volume, chap. 5)
	Downed woody debris carbon	Hawbaker and others (this volume, chap. 5)
Shrublands, grasslands	Aboveground biomass carbon	Hawbaker and others (this volume, chap. 5)
	Litter carbon	Hawbaker and others (this volume, chap. 5)
	Downed woody debris carbon	Hawbaker and others (this volume, chap. 5)

2009). This model was then applied to all the islands using the same set of canopy structural and environmental metrics to yield a multi-island map of forest TCH at 30-m spatial resolution. A landscape-level equation relating TCH to ACD was applied, resulting in a forest ACD map at 30-m resolution for the seven main Hawaiian Islands. This statewide ACD map was validated using ground-level estimates of ACD derived from Forest Inventory and Analysis plots maintained by the U.S. Department of Agriculture Forest Service that were located on Hawaiʻi Island, Maui, Molokaʻi, Oʻahu, and Kauaʻi. See Asner and others (2016) for a more detailed description of the Hawaiʻi forest ACD map.

Aboveground biomass carbon in shrublands and grasslands were estimated by multiplying median values for each biome type (from the biomass database in Hawbaker and others, this volume, chap. 5) by the land area of that biome type as delineated by the land-use and land-cover (LULC) map from Jacobi and others (this volume, chap. 2). Litter and downed-woody-debris carbon were estimated for forests, shrublands, and grasslands by taking the median values for each biome type in the biomass database from Hawbaker and others (this volume, chap. 5) and multiplying by the land area covered by that biome type.

Live-root biomass for forests and tree plantations was estimated using the power law equation listed in table 6.2 (Mokany and others, 2006). Root-to-shoot ratios of tropical grasslands are typically much lower than those of temperate grasslands (Mokany and others, 2006), and the root-to-shoot ratios of the African grass species that dominate Hawaiian grasslands are lower still because of their high biomass allocation to leaves (Williams and Black, 1994; Williams and Baruch, 2000; Neto and others, 2012). Live-root-biomass carbon of grasslands in Hawaiʻi was estimated by averaging the global median root-to-shoot ratio for tropical and subtropical grasslands (Mokany and others, 2006) with published root-to-shoot ratios of native and alien African grasses in Hawaiʻi (Williams and Black, 1994; Neto and others, 2012) and then multiplying this derived root-to-shoot ratio by the estimate of aboveground live-biomass carbon for Hawaiian grasslands (table 6.2). A similar approach was used to estimate live-biomass carbon of shrublands. The global median root-to-shoot values for shrubland and tropical arid shrubland/desert were averaged and then multiplied by the estimate of aboveground live-biomass carbon for Hawaiian shrublands (table 6.2).

Estimates of SOC to a depth of 1 m at 10-m spatial resolution were derived from the USDA Natural Resources Conservation Service (NRCS) gridded Soil Survey Geographic (gSSURGO) Database (Soil Survey Staff, 2015) for the State of Hawaiʻi. The spatial resolution of the gSSURGO dataset was resampled to 30-m raster cell size in Esri ArcGIS ver. 10.1 to align with the spatial resolution of the LULC map from Jacobi and others (this volume, chap. 2). Unlike other datasets used to estimate carbon stocks, the gSSURGO dataset covers the entire land area of the seven islands included in this report, including developed areas, agriculture areas, and wetlands. Soil organic carbon data for all land-cover types was included in islandwide and statewide estimates of SOC and total ecosystem carbon storage.

Table 6.2. Equation or ratio used to estimate live-root biomass from aboveground live biomass by ecosystem type.

[y = root live biomass; x = aboveground live biomass]

Ecosystem	Equation or Ratio	Source
Forests, Tree plantations	$y = 0.489x^{0.89}$	Mokany and others (2006)
Shrublands	1.45	Mokany and others (2006)
Grasslands	0.73	Mokany and others (2006), Williams and Black (1994), Neto and others (2012)

6.3.2. Carbon Fluxes

GPP on the seven islands included in this report was estimated using data and algorithms from the Moderate Resolution Imaging Spectroradiometer (MODIS) project (Running and others, 2004; Zhao and others, 2005). MODIS-derived estimates of GPP (MOD17) use time series of the fraction of absorbed photosynthetically active radiation (fAPAR) and regional coarse-resolution meteorological data as inputs and then use biome-specific radiation-use efficiency (ε) coefficients to translate absorbed photosynthetically active radiation (APAR) in energy units to GPP, the total mass of carbon fixed by photosynthesis per unit area per unit time. For this report, the global MOD17 algorithm was adapted by incorporating the Hawaiʻi-specific land-cover map from Jacobi and others (this volume, chap. 2), locally derived 250-m-resolution meteorological data, and 500-m-resolution MODIS ver. 6 fAPAR data processed with a specifically adapted filtering and gap-filling technique to deal with the high prevalence of clouds in some areas.

The MOD17 algorithm relies heavily on accurate representations of land-cover type to apply biome-specific values of ε. Globally, the MODIS land-cover product (MOD12Q1) is accurate to within 65–80 percent, with higher accuracies in pixels that are largely homogeneous. However, Hawaiʻi is a discontinuous landmass with very heterogeneous land cover. To maximize the accuracy of land-cover-type assignment, a Hawaiʻi-specific biome map was developed by re-sampling the carbon assessment for Hawaiʻi (CAH) land-cover map (Jacobi and others, this volume, chap. 2) to 500-meter pixel resolution using the majority method in ArcGIS ver. 10.2.2 and then assigning each HIGAP vegetation type to 1 of the 16 land-cover classes in MOD12Q1. This Hawaiʻi-specific biome map represented a substantial improvement in land-cover classification compared to the MOD12Q1 product; there was only about a 50 percent agreement between the two overall, with about 86 percent agreement for broadleaf evergreen forest, 27 percent agreement for grasslands and 25 percent agreement for shrublands (table 6.1).

The MOD17 algorithm uses air temperature (T_{air}) and vapor pressure deficit (VPD) data to calculate attenuating scalars to produce a biome-specific radiation-use efficiency coefficient, ε. The biome-specific values for ε are combined with estimates of APAR to calculate GPP, where APAR is calculated as

$$APAR = \text{incident PAR} \times fAPAR$$

where incident PAR is estimated by multiplying incident shortwave radiation by 0.45, and fAPAR is the fraction of absorbed photosynthetically active radiation.

Normally, coarse-resolution Tair, VPD, and incident shortwave radiation data from the NASA GMAO dataset are used for these calculations. For this report, mean monthly Tair, VPD, and incident shortwave radiation at 250-m pixel resolution from the Climate Atlas of Hawai‘i (Giambelluca and others, 2014) were degraded to 500-m pixel resolution and used to calculate APAR and attenuating scalars for ε. Finally, the fAPAR time series was processed with an iteratively reweighted local regression filter (LOESS) to reduce noise and fill gaps caused by persistent cloud cover in some areas of the seven main Hawaiian Islands (Moreno and others, 2014). The resulting estimate of mean annual GPP represents a 10-year period from 2004 to 2013.

Estimates of R_e and NEP were calculated by modeling the relationship between GPP and R_e from literature values and applying these relationships to the MODIS-derived estimate of mean annual GPP for the seven main Hawaiian Islands. A grid of points at 500-m distance centered on each MODIS pixel was intersected with the MODIS GPP data layer, and GPP values were extracted to these points using ArcGIS ver. 10.1. Regression equations of the relationship between GPP and R_e were derived based on published values from broad-leaved evergreen forests, grasslands, and other ecosystems (table 6.3). These regression equations were applied to the GPP point values across the seven islands included in this report to estimate R_e, and NEP for each point was estimated by subtracting R_e from GPP. The grid of points with R_e and NEP values assigned was then rasterized at 500-m resolution using ArcGIS ver. 10.1.

6.4. Results and Discussion

6.4.1. Baseline Carbon Stocks

Statewide, the total carbon storage in terrestrial ecosystems of Hawai‘i, including live biomass (fig. 6.1 for forest ACD), litter, downed woody debris, and SOC (fig. 6.2), was estimated to be 258 TgC (table 6.4). Approximately 70 percent of total carbon was stored as SOC, with about 25 percent of carbon stored as live biomass (both above and below ground) and about 5 percent of carbon stored as dead biomass (litter and downed woody debris; table 6.4). Total carbon storage by island was largely a function of island area (table 6.4). Hawai‘i Island, which is larger than the combined area of the other six islands, stored the most carbon at 146 TgC, followed by Kaua‘i, Maui, and O‘ahu, each of which stored about 30 TgC (table 6.3). Kaua‘i, the oldest of the seven major islands, had the highest total ecosystem carbon density (in other words, the amount of carbon per unit area, derived from values in table 6.4) at 23.5 kgC/m^2, followed by O‘ahu (20.5 kgC/m^2), Maui (17.1 kgC/m^2), and Moloka‘i (16.1 kgC/m^2). Although Hawai‘i Island stored the most carbon

Table 6.3. Regression equations based on published values used to estimate ecosystem respiration from gross primary production by ecosystem type.

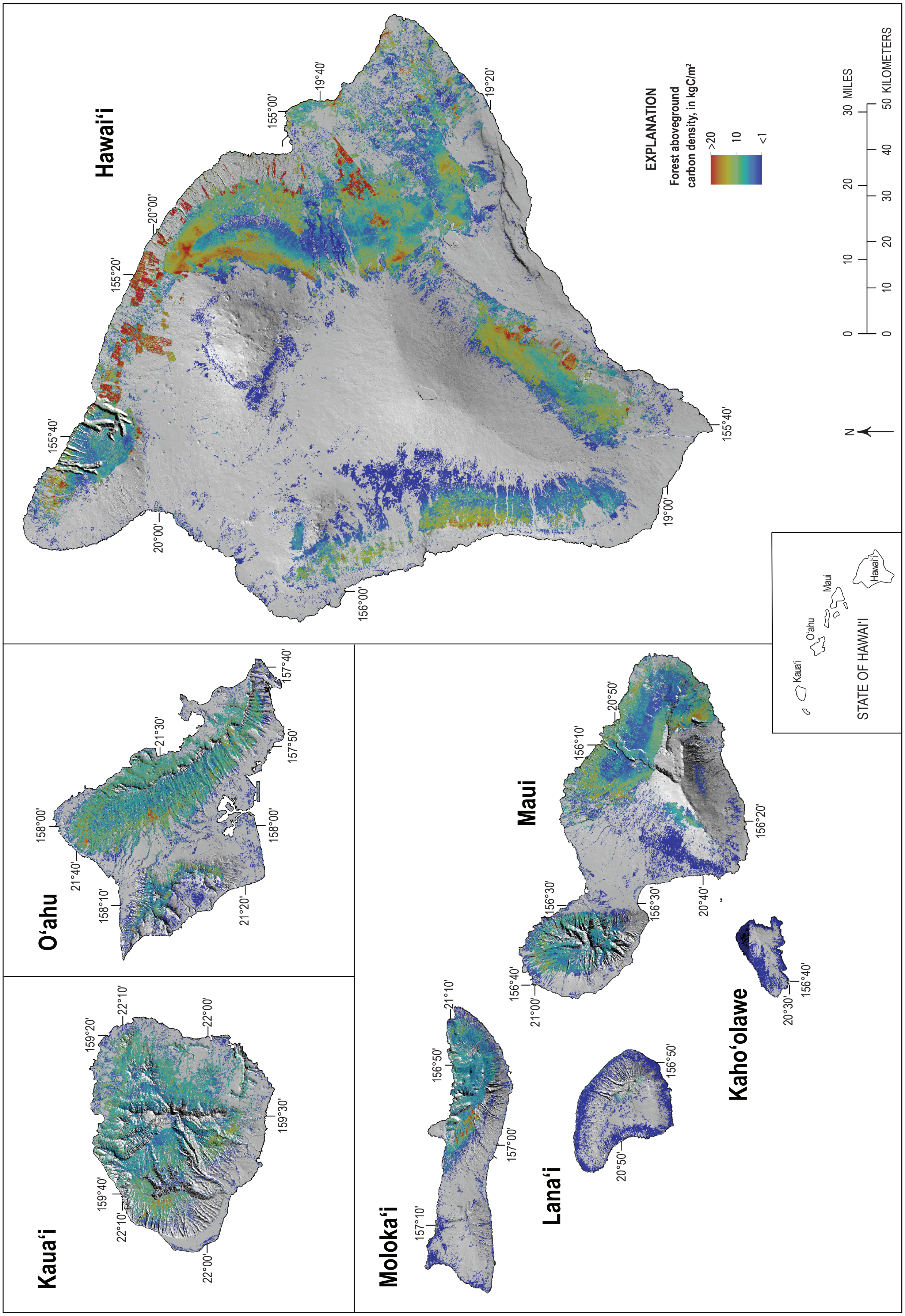
[R^2, ordinary least squares coefficient of determination; N, sample size; R_e, ecosystem respiration; GPP, gross primary production]

Ecosystem	Equation	R^2	N	Source
Forests, Tree plantations	$R_e = 1.048 \times GPP - 0.5078$	0.81	25	Lasslop and others (2010), Yuan and others (2011)
Shrublands	$R_e = 0.8767 \times GPP - 0.0839$	0.77	145	Lasslop and others (2010)
Grasslands	$R_e = 0.8325 \times GPP + 0.4091$	0.80	45	Yuan and others (2011), Wolf and others (2011)

Table 6.4. Estimates of ecosystem carbon stored in Hawai‘i by carbon pool for each island.

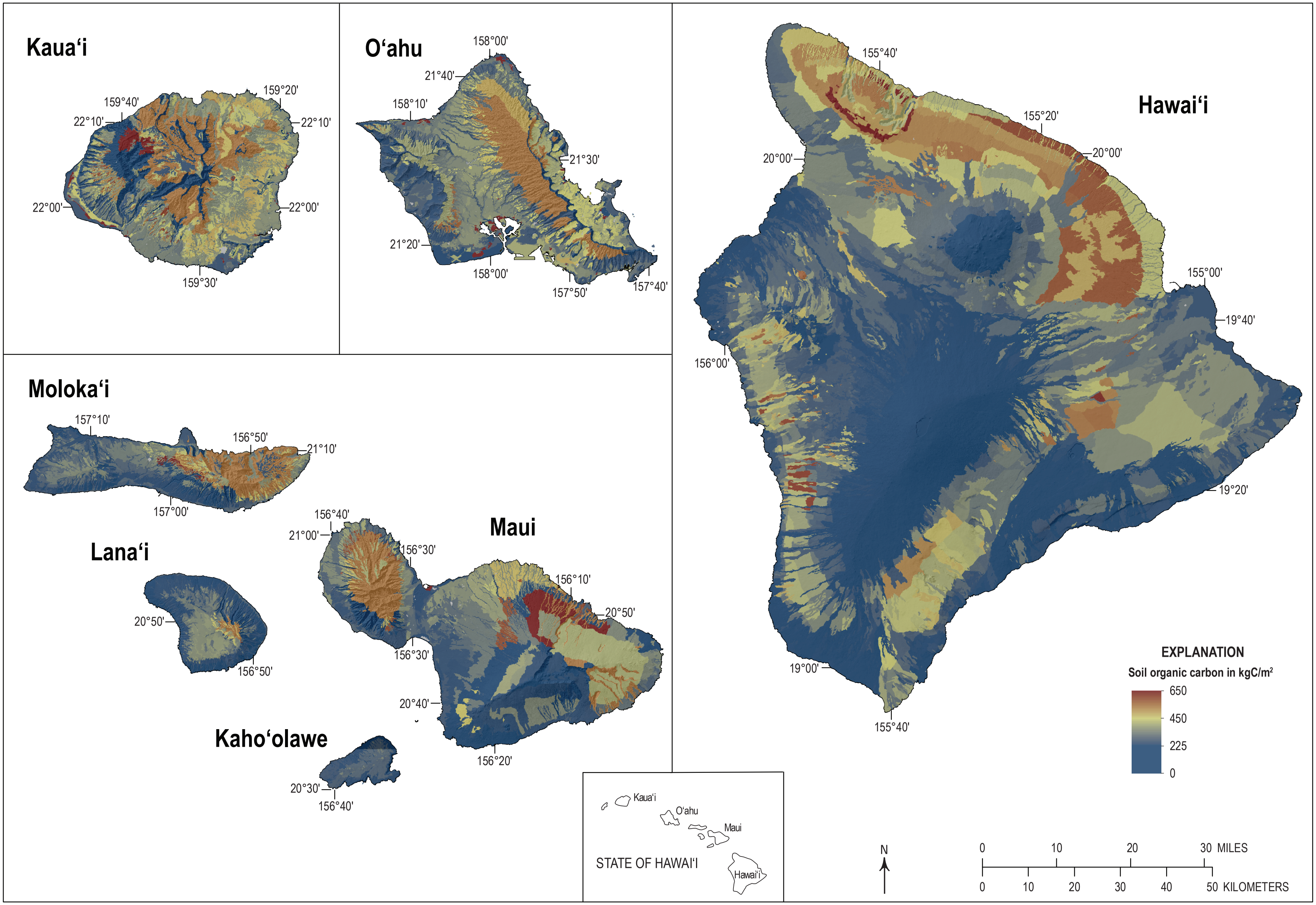
[Island-wide and total soil organic carbon (SOC) estimates include SOC data from developed areas, agriculture, and wetlands. DWD, downed woody debris; TgC, teragrams of carbon]

Island	Area (km^2)	Aboveground live biomass (TgC)	Root live biomass (TgC)	Litter and DWD (TgC)	SOC (TgC)	Total ecosystem carbon (TgC)
Hawai‘i	10,453	24.6	10.7	6.5	104.3	146.1
Kaho‘olawe	115	0.2	0.1	0.1	0.4	0.8
Kaua‘i	1,428	6.0	2.4	1.3	23.8	33.5
Lana‘i	365	0.3	0.1	0.2	2.1	2.7
Maui	1,898	5.5	2.2	1.4	23.4	32.5
Moloka‘i	672	1.7	0.8	0.4	7.9	10.8
O‘ahu	1,539	5.9	2.4	1.2	22.0	31.5
Total	16,470	44.2	18.7	11.0	184.0	257.9



Shaded-relief base modified from U.S. Geological Survey National Elevation Dataset, 2015.

Figure 6.1. Maps showing forest aboveground carbon density (ACD) for the State of Hawai‘i (data from Asner and others, 2016). kgC/m^2, kilograms of carbon per square meter.



Shaded-relief base modified from U.S. Geological Survey National Elevation Dataset, 2015.

Figure 6.2. Maps showing soil organic carbon (SOC) to 100-cm depth for the State of Hawai‘i; the data were derived from the gridded Soil Survey Geographic (gSSURGO) Database (Soil Survey Staff, 2015). kgC/m^2, kilograms of carbon per square meter.

overall, its estimated carbon density of 14 kgC/m^2 was low compared to other islands because approximately 27 percent of its total land area (~2,800 km^2) is classified as “bare ground” consisting of alpine tundra and relatively recent lava flows with sparse vegetation and little to no soil development (see Jacobi and others, this volume, chap. 2). Only Kahoʻolawe and Lanaʻi (~7 kgC/m^2 each), both relatively arid islands with long histories of land-cover conversion, had carbon densities lower than Hawaiʻi Island.

Native mesic and wet forests stored the highest amount of total carbon among ecosystem types, estimated as 96.3 TgC. Approximately 61 percent of the total carbon in native mesic and wet forests was in soil, 33 percent in live biomass, and 6 percent in dead biomass (table 6.5). In contrast, grasslands, shrublands, and bare ground, which together cover nearly three times the total area of native mesic and wet forests, combined to store a total of only 67.9 TgC, about 30 percent less than in native mesic and wet forests (table 6.5). Total carbon of invaded mesic and wet forests was about half the total carbon stored in native mesic and wet forests (49.6 TgC), primarily because invaded mesic and wet forests covered about half the total land area of native mesic and wet forests. Of total carbon in invaded mesic and wet forests, approximately 56 percent was in soil, 39 percent was in live biomass, and 5 percent was in dead biomass—a distribution similar to that of native mesic and wet forests. Invaded mesic and wet forests had a similar overall carbon density as native mesic and wet forests (31 and 32 kgC/m^2, respectively). Native and invaded dry forests also had similar total carbon densities, estimated as 7.6 and 8.3 kgC/m^2, respectively, but invaded dry forests had a higher proportion of total carbon in live biomass (24 percent) compared to native dry forests (13 percent). Alien tree plantations had the highest total carbon density of any ecosystem type, estimated as 45.7 kgC/m^2, but constituted a relatively small land area (243 km^2) (table 6.5). In contrast, bare ground covered the largest land area of the ecosystem types listed in table 6.5, but had the lowest estimated total carbon density at 1.9 kgC/m^2.

6.4.2. Baseline Carbon Fluxes

Mean annual GPP of terrestrial ecosystems in the State of Hawaiʻi was estimated as 20.2 TgC/yr for the years 2003–2014 (fig. 6.3; table 6.6). Approximately 88 percent of the carbon fixed annually by GPP was respired back to the atmosphere (17.8 TgC/yr) as the combination of autotrophic and heterotrophic respiration. Terrestrial ecosystems of Hawaiʻi

Table 6.5. Estimates of ecosystem carbon stored in Hawaiʻi by carbon pool for each ecosystem type.

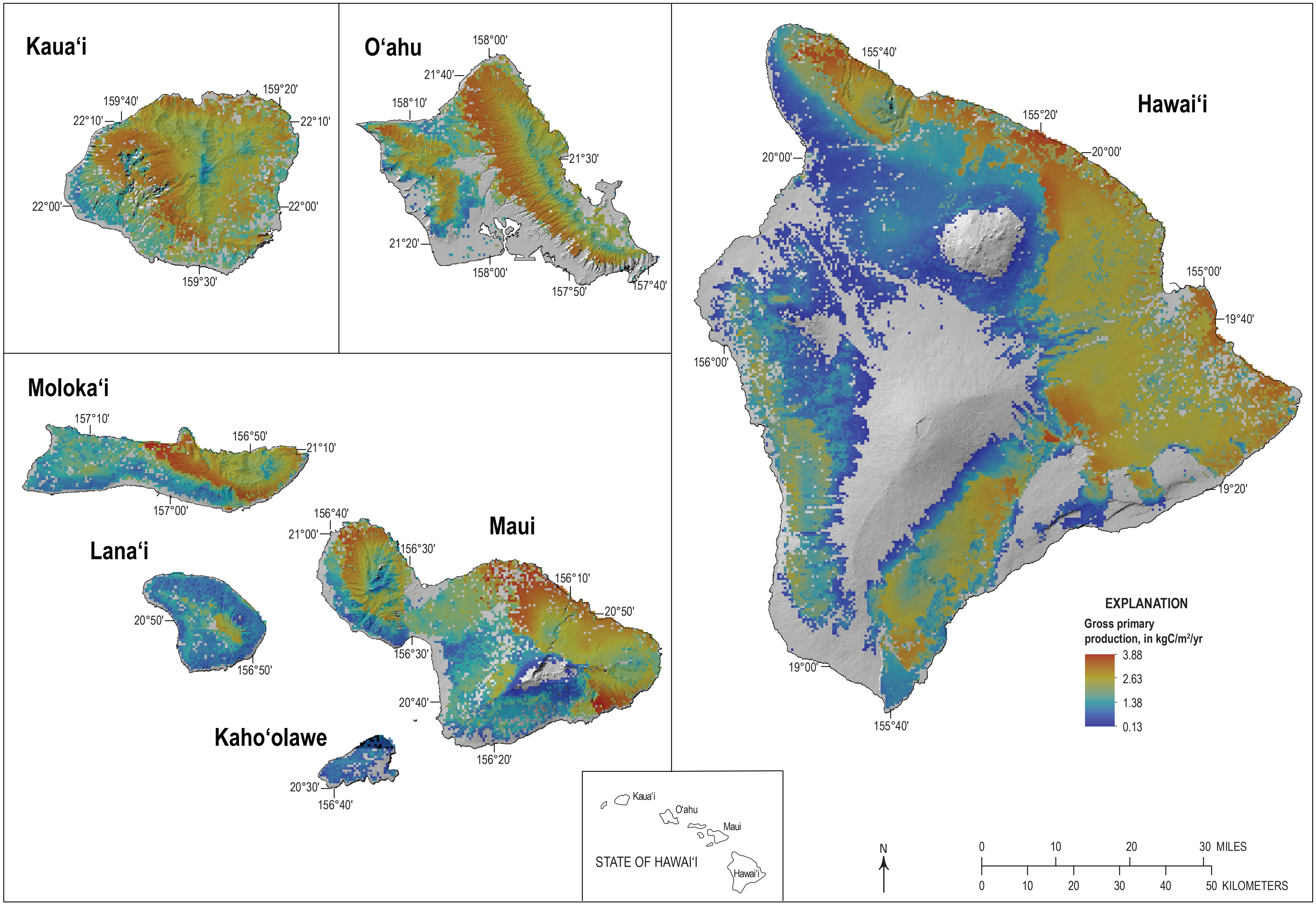
[DWD, downed woody debris; SOC, soil organic carbon; TgC, teragrams of carbon]

Ecosystem	Area (km^2)	Aboveground live biomass (TgC)	Root live biomass (TgC)	Litter and DWD (TgC)	SOC (TgC)	Total ecosystem carbon (TgC)
Native dry forest	302	0.2	0.1	0.2	1.8	2.3
Invaded dry forest	635	1.0	0.5	0.5	3.6	5.6
Native mesic–wet forest	3,148	22.8	9.0	5.6	58.9	96.3
Invaded mesic–wet forest	1,529	13.9	5.3	2.7	27.6	49.5
Alien tree plantations	243	4.4	1.6	0.3	5.1	11.4
Shrublands	2,719	1.2	1.7	1.0	20.6	24.5
Grasslands	2,783	0.7	0.5	0.6	35.6	37.4
Bare (sparse vegetation)	3,111	< 0.1	< 0.1	0.1	5.7	5.9
Total	14,470	44.2	18.7	11.0	158.9	232.9

Table 6.6. Estimates of gross primary production, ecosystem respiration, and net ecosystem production by island.

[Data are mean annual fluxes for the years 2004–2013. GPP, gross primary production; *R*e, ecosystem respiration; NEP, net ecosystem production; TgC/y, teragrams of carbon per year]

Island	Area (km^2)	GPP (TgC/y)	R_e (TgC/y)	NEP (TgC/y)
Hawaiʻi	10,453	11.19	10.02	1.17
Kahoʻolawe	115	0.06	0.05	0.01
Kauaʻi	1,429	2.64	2.29	0.35
Lanaʻi	365	0.37	0.32	0.05
Maui	1,898	2.54	2.25	0.29
Molokaʻi	672	1.13	0.93	0.20
Oʻahu	1,539	2.26	1.94	0.32
Total	16,470	20.19	17.81	2.38



Shaded-relief base modified from U.S. Geological Survey National Elevation Dataset, 2015.

Figure 6.3. Maps showing annual gross primary production (GPP) for the years 2004–2013 in the State of Hawai'i; the data were derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) with modified land cover based on the map from Jacobi and others (this volume, chap. 2) and local meteorological estimates from Giambelluca and others (2014). $kgC/m^2/yr$, kilograms of carbon per square meter per year.

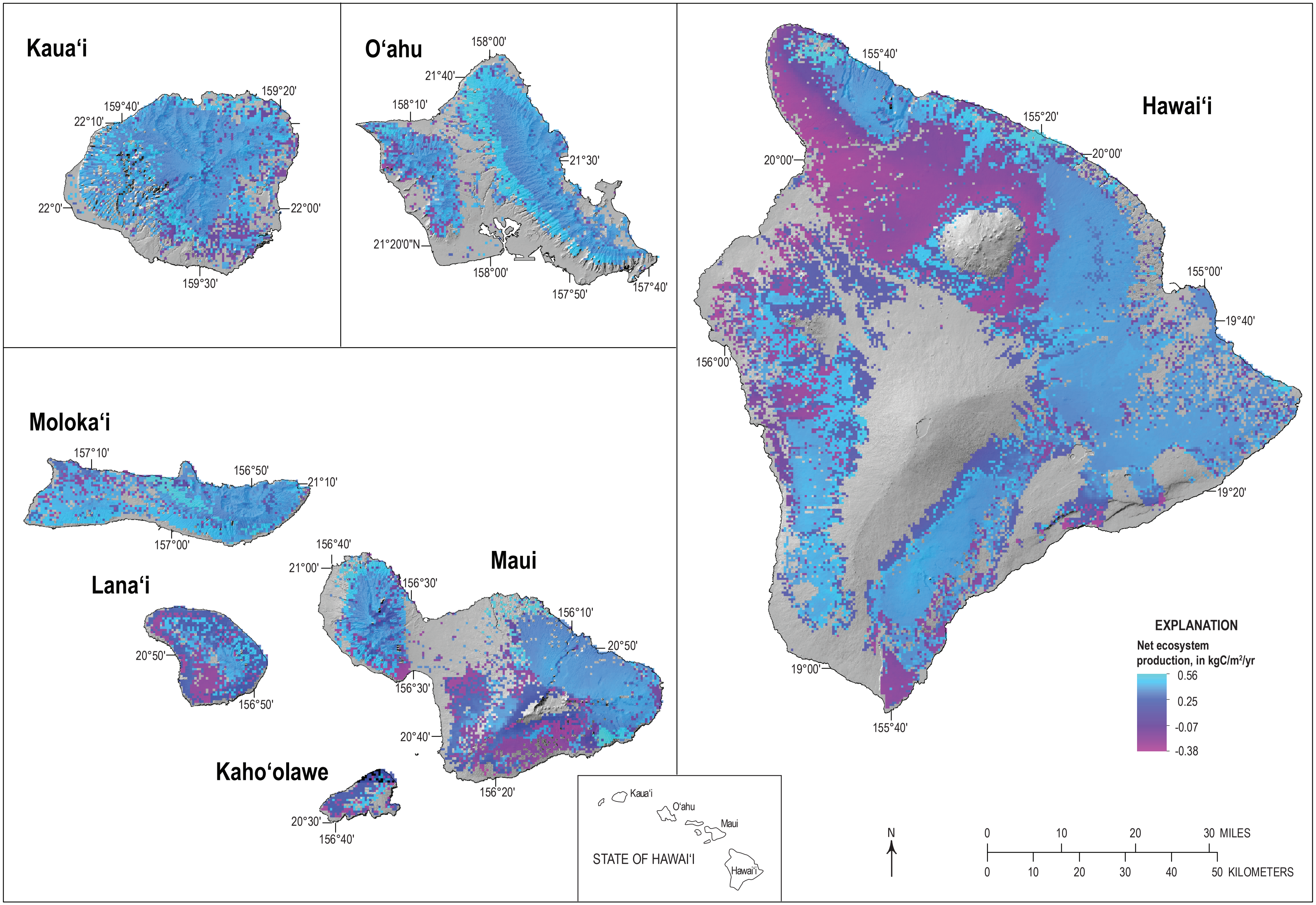
were estimated to sequester an average of 2.38 TgC/yr for the years 2003–2014. Similar to trends for carbon storage, total annual carbon fluxes by island were largely a function of island area. Hawai‘i Island, the largest of the seven islands considered in this report (~64 percent of the total land area), was estimated to have the highest mean annual GPP (11.2 TgC/yr) and R_e (10 TgC/yr) for the period 2003–2014. Hawai‘i Island was also the largest carbon sink with an estimated mean annual NEP of 1.17 TgC/yr, which represented approximately 50 percent of the total annual terrestrial-ecosystem carbon sink of the seven main Hawaiian Islands. Maui, O‘ahu, and Kaua‘i each represented approximately 8–12 percent of the total land area of the seven islands considered in this report, and each contributed approximately 10–14 percent of the estimated total carbon sink. Collectively, the islands of Maui, O‘ahu, and Kaua‘i accounted for about 37 percent of both GPP and NEP. Kaua‘i had the highest GPP carbon flux density (carbon flux per unit area), estimated at 1.85 kgC/m^2/yr. Although Hawai‘i Island exhibited the highest total GPP, its estimated GPP carbon flux density was only 1.1 kgC/m^2/yr, approximately 40 percent lower than that of Kaua‘i. Only Lana‘i (1.0 kgC/m^2/yr) and Kaho‘olawe (0.5 kgC/m^2/yr) had lower GPP carbon flux densities than Hawai‘i Island. Carbon-sink strength per unit area (NEP carbon flux density) followed a similar pattern; Kaua‘i was estimated to have the highest carbon-sink strength per unit area (NEP carbon flux density = 0.25 kgC/m^2/yr), and Kaho‘olawe had the lowest carbon-sink strength per unit area (NEP carbon flux density = 0.09 kgC/m^2/yr).

Native mesic and wet forests accounted for approximately 35 percent of total terrestrial GPP, and invaded mesic and wet forests and grasslands each accounted for 16–18 percent of total GPP (table 6.7). Native mesic and wet forests represented the largest carbon sink of any ecosystem type, accounting for approximately 50 percent of estimated mean annual NEP for the years 2003–2014 (table 6.7). In contrast, grasslands were estimated to be a net carbon source to the atmosphere for the years 2003–2014 because R_e exceeded GPP in dry grasslands (fig. 6.4).

Table 6.7. Estimates of gross primary production, ecosystem respiration, and net ecosystem production by ecosystem type.

[Data are mean annual fluxes for the years 2004–2013. GPP, gross primary production; R_e, ecosystem respiration; NEP, net ecosystem production; TgC/y, teragrams of carbon per year]

Ecosystem	Area (km^2)	GPP (TgC/y)	R_e (TgC/y)	NEP (TgC/y)
Native dry forest	302	0.34	0.25	0.09
Invaded dry forest	635	0.70	0.60	0.11
Native mesic–wet forest	3,148	7.05	5.89	1.17
Invaded mesic–wet forest	1,529	3.63	3.13	0.50
Alien tree plantations	243	0.65	0.54	0.11
Shrublands	2,719	4.65	3.69	0.96
Grasslands	2,783	3.17	3.72	-0.56
Bare (sparse vegetation)	3,111	0	0	0
Total	14,470	20.19	17.81	2.38



Shaded-relief base modified from U.S. Geological Survey National Elevation Dataset, 2015.

Figure 6.4. Maps showing mean annual net ecosystem production (NEP) for the years 2003–2014 in the State of Hawai'i; the data were estimated by subtracting regression-derived estimates of ecosystem respiration (R_e) from estimates of gross primary production (GPP) derived from the MODIS satellite (see fig. 6.3.). kgC/m^2/yr, kilograms of carbon per square meter per year.

6.5. Summary, Limitations, and Uncertainty

Aside from the recently published statewide forest ACD map (Asner and others, 2016), previous efforts quantifying carbon stocks and fluxes in terrestrial ecosystems in Hawai‘i have been confined to the plot level (Herbert and Fownes, 1999; Schuur and others, 2001; Schuur and Matson, 2001; Giardina and others, 2003; Litton and others, 2006; Selmants and others, 2014; Giardina and others, 2014), the landscape level (Asner, Hughes, and others, 2009; Asner and others, 2010; Hughes and others, 2014), or, at most, the island level (Asner and others, 2011). This report represents the first comprehensive effort to quantify carbon stocks and carbon fluxes in terrestrial ecosystems across the seven main Hawaiian Islands.

Overall estimates of carbon storage are relatively well constrained, particularly data related to forest aboveground biomass carbon and SOC, but knowledge gaps exist. Estimates of forest aboveground biomass carbon were validated with statewide plot-level estimates (Asner and others, 2016). The current estimate of aboveground live-biomass carbon for Hawai‘i Island in this report (22.8 TgC) is about 20 percent lower than a previous estimate of 28.3 TgC made by Asner and others (2011). The SOC data product, which is a statewide interpolation of soil survey data points over several decades, represents the most detailed soil geographic data available for the State of Hawai‘i. In contrast, published studies that provided plot-level estimates of shrubland and grassland aboveground live-biomass carbon and dead-biomass carbon (downed woody debris and litter) were not evenly distributed across islands or climatic zones, and so the islandwide and statewide estimates of these carbon stocks should be used with caution. Shrublands in particular are poorly represented in the dataset of published values (Hawbaker and others, this volume, chap. 5) relative to their land area. However, shrubland and grassland ecosystems typically have relatively low biomass carbon densities compared to forest ecosystems, and SOC makes up the majority of ecosystem carbon in shrublands and grasslands, so uncertainty related to biomass carbon storage in shrubland and grassland vegetation types is unlikely to exert substantial influence on islandwide or statewide estimates of total ecosystem carbon storage. Estimates of live-root biomass are derived from global root-to-shoot relationships for particular ecosystem types, and so any errors in estimates of aboveground biomass carbon are propagated to estimates of belowground live biomass. In addition, although there is no evidence that native and nonnative plant species in Hawai‘i differ in their root-to-shoot ratios from plant species found elsewhere, the global root-to-shoot relationships used to estimate live-root biomass may not accurately represent those of plants growing in the Hawaiian Islands. Finally, islandwide and statewide estimates of total ecosystem carbon storage do not include estimates of live biomass, litter, and downed-woody-debris carbon in agriculture, developed areas, and wetlands, which make up about 12 percent of land area statewide. Litter and downed-woody-debris carbon are likely minimal in agriculture and developed areas, and live-biomass carbon is transitory in agricultural areas and of low density in developed areas. Soil organic carbon likely makes up most ecosystem carbon in agriculture areas, developed areas, and wetlands, but the lack of data on live biomass and detritus carbon in these areas may have resulted in an underestimate of islandwide and statewide ecosystem carbon storage and overly high estimates of the proportion of ecosystem carbon stored as SOC.

There are currently no published islandwide or statewide estimates of carbon fluxes (for example, GPP, R_e, NEP) for the State of Hawai‘i, and so it was not possible to compare current estimates to previous efforts at similar scales. However, at the plot level, Giardina and others (2003) estimated whole-ecosystem carbon budgets for Eucalyptus (*Eucalyptus saligna*) plantations in multiple 900 m^2 plots for several years on the windward side of the Island of Hawai‘i. They estimated a mean annual GPP carbon flux density of 2.95 $kgC/m^2/yr$ (Giardina and others, 2003), which is 10 percent higher than statewide MODIS-derived estimates of GPP carbon flux density for alien tree plantations (2.68 $kgC/m^2/yr$), 25 percent higher than estimates for invaded mesic-to-wet forests (2.37 $kgC/m^2/yr$), and about 30 percent higher than native mesic-to-wet forests (2.24 $kgC/m^2/yr$).

Estimates of R_e in this report are from regression equations based on the relationship between GPP and R_e derived from eddy flux towers, none of which were located in Hawai‘i (Lasslop and others, 2010; Wolf and others, 2011; Yuan and others, 2011). Therefore, statewide values of R_e and NEP may be the least well constrained of all carbon stock and flux estimates in this chapter. Plot-level estimates of R_e carbon flux density in Eucalyptus plantations from Giardina and others (2003) were higher (2.27 $kgC/m^2/yr$) than statewide estimates of R_e carbon flux density in both alien tree plantations (2.22 $kgC/m^2/yr$) and invaded mesic-to-wet forests (2.05 $kgC/m^2/yr$). However, plot-level estimates of R_e in young Eucalyptus plantations accounted for about 77 percent of GPP, whereas statewide estimates of carbon flux density for R_e in alien tree plantations and alien mesic-to-wet forests accounted for about 83–85 percent of GPP. The estimated statewide R_e carbon flux density in native mesic-to-wet forests was 1.87 $kgC/m^2/yr$, about 20 percent lower than the plot-level Eucalyptus estimates, but R_e made up a greater proportion of GPP in native mesic-to-wet forests (approximately 84 percent) than in the young Eucalyptus plantations (Giardina and others, 2003). Taken together, the comparative relationship of R_e and NEP among these forest types yields reasonable results. Older, more established forest stands should lose a greater proportion of GPP as respiration, given their higher proportion of structural tissues relative to leaf area and less efficient foliage caused by hydraulic limitation of water transport in taller trees. However, the eddy covariance technique generally underestimates R_e lost to the atmosphere on an annual basis, which may result in overestimates of NEP and annual carbon sequestration. This represents an important caveat to the estimates of R_e in this chapter, in addition to the fact that relationships between GPP and R_e are derived from eddy flux towers in ecosystems outside of Hawai‘i.

The data on ecosystem carbon stocks and fluxes presented in this chapter should prove useful to the scientific community, land managers, and policy stakeholders in a variety of applications. However, caution should be exercised when using data and conclusions in this chapter by considering the constraints and uncertainties noted above.

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