Chapter 1. Scope and Methodology

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1.1. Scope and General Methodology of the Assessment

This is the fifth regional report produced by the U.S. Geological Survey (USGS) as part of the national LandCarbon program (https://www2.usgs.gov/climate_landuse/land_carbon/). As with prior assessments (Great Plains, Eastern, Western, and Alaska; see, for example, Zhu and others, 2012), this assessment focuses on using best available data to quantify current and future carbon stocks and fluxes required to understand trajectories for carbon sequestration in the main Hawaiian Islands (fig. 1.1). To this end, this report considers (1) carbon stored in soils, living aboveground and belowground biomass carbon, detrital carbon in surface litter and coarse woody debris, and (2) carbon entering Hawai'i as gross primary production (GPP) and net primary production (NPP) and carbon exported to the nearshore by streams and submarine groundwater discharge (fig. 1.2). This report provides a "wall-to-wall" assessment of carbon storage and flux, as well as projected future storage and flux for the seven main Hawaiian islands of Kaua'i, O'ahu, Moloka'i, Lāna'i, Kaho'olawe, Maui, and Hawai'i, excluding the island of Ni'ihau, which is privately owned. Because there is no public access to Ni'ihau, few data for the island could be used to build carbon maps. The total area covered by this report is 16,587 square kilometers (km^2), distributed across islands in decreasing-size order: Hawai'i Island (10,432 km^2), Maui (1,884 km^2), O'ahu (1,545 km^2), Kaua'i (1,430 km^2), Moloka'i (637 km^2), Lāna'i (364 km^2), and the uninhabited Kaho'olawe (115 km^2). Ni'ihau is 180 km^2 and makes up approximately 1 percent of the State of Hawai'i's total land area, and so exclusion from the report will have negligible effects on the overall assessment.

The Energy Independence and Security Act of 2007 (EISA; 42 USC 17001) requires that current and future stores and fluxes (carbon sequestration) be assessed for all 50 states, and it identified the U.S. Department of the Interior as the lead agency charged with developing and implementing a robust methodology with the goal of quantifying (1) the amount of carbon stored in ecosystems, (2) the capacity of ecosystems to sequester carbon, and (3) the mass balance of greenhouse gas (GHG) fluxes into and out of regions of interest. The carbon assessment for Hawai'i (CAH) seeks to realize the mandate of the EISA to advance the state of knowledge on carbon storage and flux for the Hawaiian archipelago (fig. 1.3). Further, this report considers the effects of climate change and major disturbances (fire, land-use, nonnative invasions) on carbon cycling. Because of data limitations, we diverge from prior reports and consider only fluxes of carbon dioxide (CO_2), dissolved inorganic carbon (DIC), and dissolved organic carbon (DOC). We do not consider volatile organic carbon (VOC) emissions from vegetation or consider other trace gases (for example, CH_4, N_2O) that contribute to the global warming potential budget for the State of Hawai'i.

We relied on previous wall-to-wall mapping efforts to identify all major vegetation types in Hawai'i, including forests, shrublands, and grasslands distinguished according to moisture regime (dry, mesic, and wet) and ecological condition (native dominated, mostly native, and mostly nonnative). Further, we consider agricultural, urban, and aquatic systems. Details (definition, area, and distribution) for the initial vegetation and land-use and land-cover (LULC) types considered in this report are addressed in Jacobi and others (this volume, chap. 2), which relies on previous work merging a LandFIRE-enhanced Hawai'i-specific GAP product with the National Land Cover Database (NLCD; Vogelmann and others, 2001; Homer and others, 2007). The hybrid LULC product is derived from wall-to-wall LANDSAT-based remote-sensing datasets, on-the-ground mapping, pictometry (Jacobi and others, this volume, chap. 2), and professional opinion. Consequently, with the exception of the Island of Ni'ihau, this report provides spatially comprehensive data products.
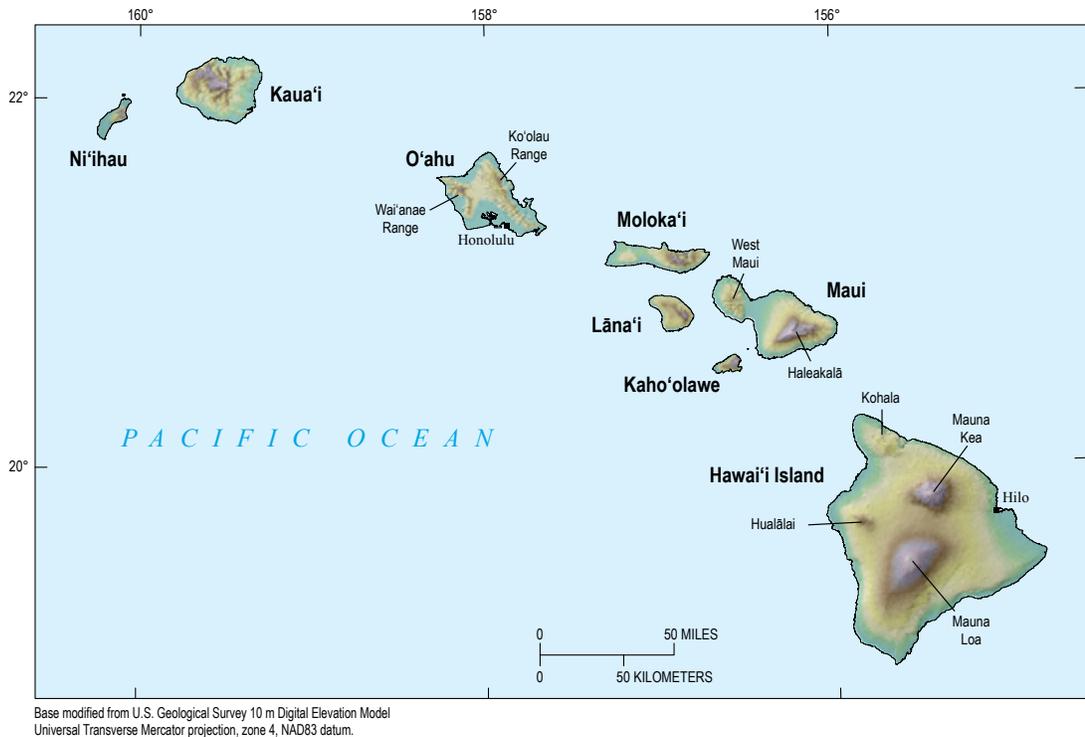
As required by the LandCarbon program and the EISA, this assessment provides both current baseline and projected future carbon storage and flux estimates with the goal of providing both the science community and policy makers an unprecedented level of understanding of the carbon-sequestration capacity of Hawaiian ecosystems. These data are essential for understanding the realistic options for carbon sequestration at the whole-state level. Here we use the term "baseline" to mean current anticipated carbon storage or flux derived from best available information, which in general was sufficient to provide moderately robust estimates to policy makers and scientists. Data used to determine baseline conditions reflect different time scales as data were collected during varying sampling campaigns during the past century; specifically, biome maps were created with vegetation data

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Figure 1.1 Shaded topographic relief map showing the geographic extent of the project area, the seven main Hawaiian Islands of Hawai'i, Maui, Kaho'olawe, Lāna'i, Moloka'i, O'ahu, and Kaua'i. Ni'ihau was not included in this report.

Base modified from U.S. Geological Survey 10 m Digital Elevation Model
Universal Transverse Mercator projection, zone 4, NAD83 datum.

collected between 2000 and 2012; LULC data were derived from remote-sensing data collected in 2005; wildland-fire data were collected between 1904 and 2011; aboveground (and so belowground) biomass data reflect complex datasets collected in 2008 and 2009; soil-carbon data were based on the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) excavations conducted during the past 50 years; GPP, NPP, and ecosystem-respiration data were modeled from data collected between 2004 and 2013; and data on carbon export in streams are based on gage data collected between 1972 and 2013. The datasets used for this assessment were provided by a diverse set of partners participating in the assessment including the USGS, USDA Forest Service and NRCS, Carnegie Institution for Science, University of Hawai'i at Mānoa, State of Hawai'i Division of Forestry and Wildlife, Nature Conservancy, and other organizations.

The carbon assessment for Hawai'i relied on a complete carbon budgeting approach (fig. 1.3) that included the following features: (1) land-use and land-cover types (Jacobi and others, this volume, chap. 2) and biome and LULC maps delineating current distributions of vegetation types (Fortini and others, this volume, chap. 3); (2) modeled aboveground biomass for shrubs and grasslands, constructed and validated with biomass plots for these ecosystems types (Hawbaker and others, this volume, chap. 5); (3) remote-sensing-based quantification of aboveground biomass for forests, constructed with plane-based light detection and ranging (lidar) estimates of aboveground biomass and validated with plot data from USDA Forest Service Forest Inventory and Analysis (FIA) plots across the State of Hawai'i (Selmants and others, this volume, chap. 6); (4) modeled estimates of belowground live biomass based on generalized allometric equations linking aboveground and

belowground biomass (Hawbaker and others, this volume, chap. 5); (5) MODIS-derived estimates of GPP and NPP and statistically determined relationships between GPP and ecosystem respiration to estimate net ecosystem production (NEP) (Selmants and others, this volume, chap. 6); (6) publicly available USDA NRCS mineral soil-carbon data; (7) spatially and temporally explicit carbon storage and GHG flux estimates (Selmants and others, this volume, chap. 6); and (8) streamgauge-based modeling of inorganic and organic carbon export by stream and groundwater discharge (MacKenzie and others, this volume, chap. 7). These data sources and modeling yielded a spatially extensive (99 percent of total land area for the State of Hawai'i) estimate of current carbon storage in Hawai'i's grassland, shrubland, and forest land base.

The carbon assessment relied on the above baseline data for carbon storage and future projected vegetation (Fortini and others, this volume, chap. 3) to identify current (Selmants and others, this volume, chap. 6) and potential future carbon storage and flux (Sleeter and others, this volume, chap. 8, and Selmants and others, this volume, chap. 9). Specifically, estimates of current carbon storage were paired with projected change in biome coverage for the years 2090–2100, which in turn was based on dynamical downscaling of global circulation models (1–3-km^2 resolution for Hawai'i depending on island size). Projected biome maps were based on (1) modeling biome extent from projected climate variables of temperature and precipitation, where models are constructed from relationships between current climate and current modeled maps of biomes validated against current maps of actual biome type (Fortini and others, this volume, chap. 3); (2) Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios of climate and land use (Sleeter and others, this volume,

chap. 8); and (3) state and transition-model-based estimates of carbon storage and flux under new configurations of biome and ecological condition (native dominated, mostly native, and mostly nonnative), where biome-specific and ecological-condition-specific carbon characteristics were carried forward and adjusted using map projections for the new distribution of biome type and ecological condition (Sleeter and others, this volume, chap. 8).

Several important caveats should be considered when interpreting projections from this assessment. Although current estimates are based on best available information required to quantify the carbon storage and flux, assessments of potential future carbon storage and flux under future climate and LULC are speculative as even the best projections for future climate and LULC in Hawai‘i are uncertain, particularly for future rainfall and LULC. Critically, this assessment does not construct global warming potential budgets that require a complete accounting of all GHGs and associated residence times in the atmosphere as well as cradle-to-grave (onsite and offsite sequestration) GHG analyses. Projected land-use changes are simply those projected by global-scale modeling of LULC, and so do not include careful local vetting. Further, projected future vegetation changes were derived entirely from dynamically downscaled climate data, which, as mentioned, carry important uncertainties, especially with respect to precipitation—an important driver of dry, mesic, and wet vegetation-type distributions. In addition, vegetation dynamics from succession or climate change were not modeled for the assessment. Nonetheless, this assessment represents a

sophisticated integration of ground-based observations, plane- and satellite-based remote sensing, and vegetation and climate numerical modeling, and so it provides an enormously improved carbon inventory compared to previous efforts for the region or compared to that which could be achieved relying solely on numerical modeling. We also examined the potential effects of fire on carbon emissions under current and projected future conditions for five of the seven main Hawaiian Islands (Hawbaker and others, this volume, chap. 5), and this work relied on (1) baseline carbon storage data (Selmants and others, this volume, chap. 6), and (2) inventoried and remotely sensed area burned (Trauernicht and others, 2015). Ecosystem disturbances considered by this report also included plant invasions. We do not consider, however, insect and disease outbreaks, hurricanes and other severe wind events, individual tree falls, or larger scale cohort senescence events of unknown cause.

The assessment is organized by biome (dry, mesic, and wet forest, shrubland, and grassland), by ecological condition (native dominated, mixed native and nonnative, mostly nonnative or heavily disturbed, and barren), and by major island. The terms stock or storage refer to the total amount of organic carbon contained by a reservoir of interest (for example, soil, living biomass, coarse woody debris), whereas flux refers both to CO_2 uptake by ecosystems of Hawai‘i and to CO_2 emissions to the atmosphere.

We relied on the following units of measurement for this report. Teragrams or petagrams of carbon (TgC or PgC) are used for estimates of storage at the scale of the State of Hawai‘i,
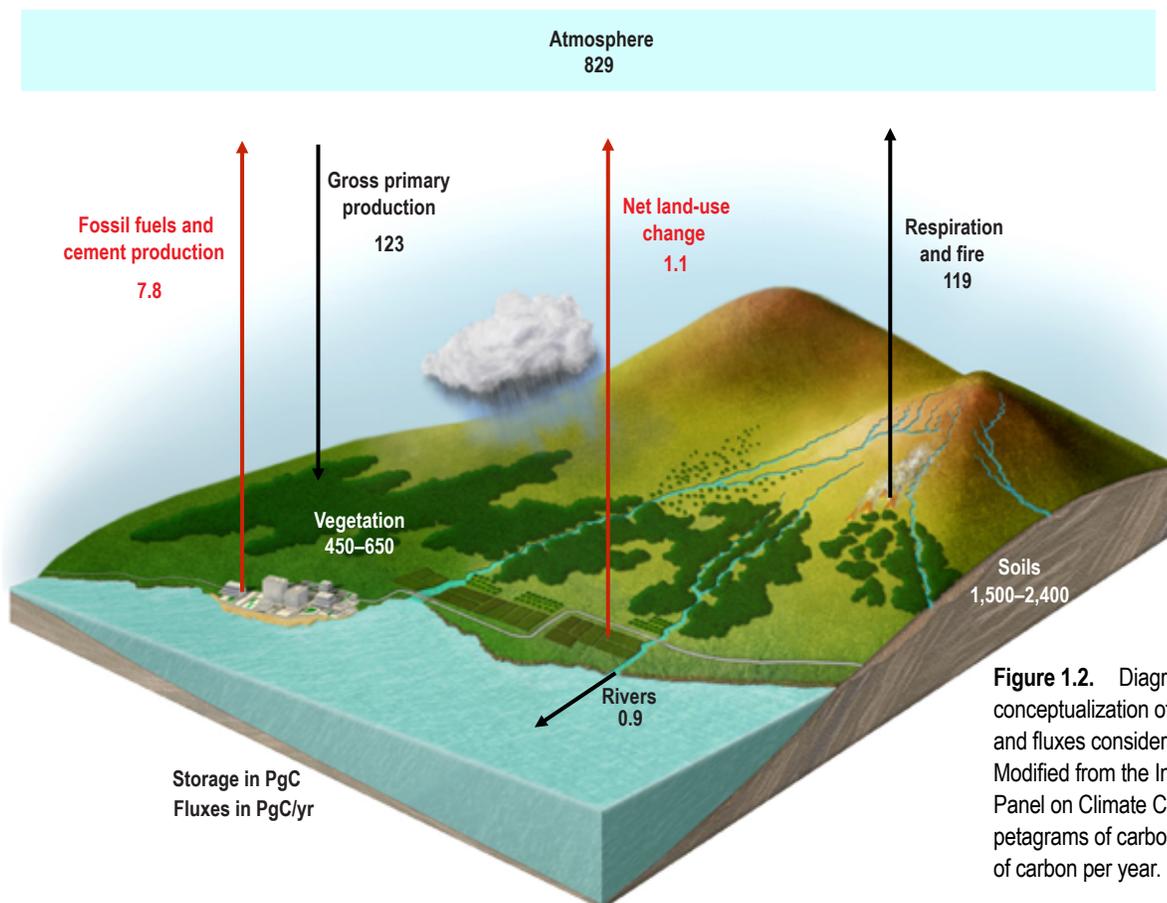

Figure 1.2. Diagram showing a detailed conceptualization of the carbon stocks and fluxes considered in this assessment. Modified from the Intergovernmental Panel on Climate Change (2014). PgC, petagrams of carbon; PgC/yr, petagrams of carbon per year.
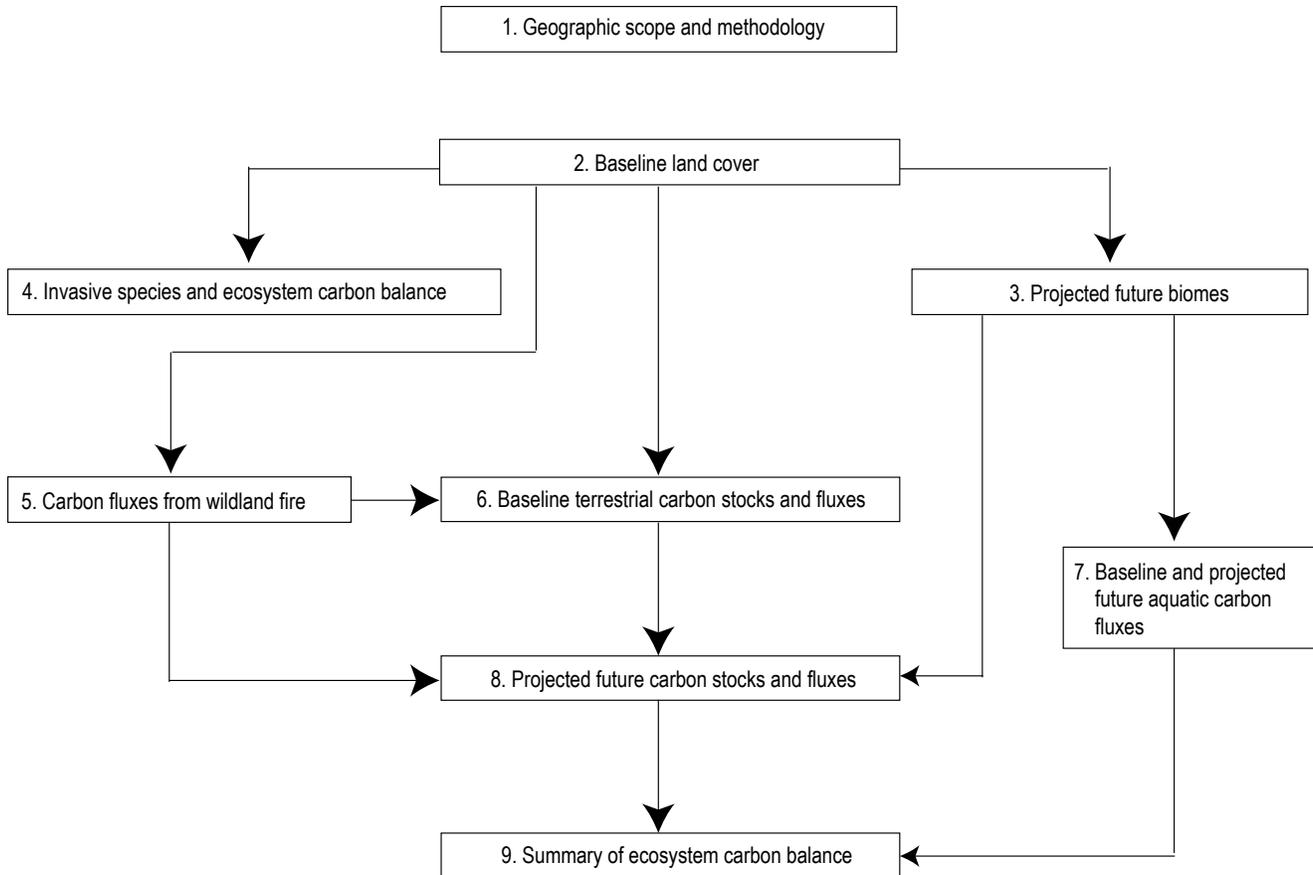
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Figure 1.3.   Diagram showing chapter flow of the Assessment.

whereas teragrams or petagrams of carbon per year (TgC/yr or PgC/yr) are used for fluxes when reporting the total amount of carbon gained or released at this scale. The state-level balance of both losses and gains is called regional carbon balance (RCB). At the scale of a stand, carbon stock per unit of area is given in kilograms of carbon per square meter (kgC/m^2) and carbon flux per unit of area (GPP, NPP, ecosystem respiration) is given in kilograms of carbon per square meter per year ($kgC/m^2/yr$). We identify the balance of carbon gain and carbon losses at the stand level (NEP), commonly viewed as NPP minus heterotrophic respiration (R_h). The transport of DIC and DOC by stream discharge is reported in teragrams of carbon per year. Unless otherwise noted, and following convention from previous reports (Zhu and others, 2012), fluxes are all listed as positive numbers, except in balance calculations, where we use the terrestrial ecosystem science convention of listing uptake of CO_2 by ecosystems as positive and losses to the atmosphere as negative. Below is a chapter-by-chapter description of work encompassed in this assessment.

1.1.1. Chapter-by-Chapter Description

Chapter 2 addresses all land-cover components of the Hawai'i assessment. Jacobi and others created land-cover

maps for the Hawai'i assessment by building upon diverse existing land-use and land-cover map products for the main Hawaiian Islands. The required integration across map products necessarily involved an evaluation of individual mapped units with respect to both accuracy and relevance for the Hawai'i assessment. For the former, high-resolution imagery was used to improve accuracy of the mapped units including 2-m-resolution WorldView 2 and sub-meter-resolution Pictometry Online imagery. For the latter, previous delineations were collapsed into a hierarchical classification scheme that includes 48 detailed units, 27 general units, 13 biome units, and 7 land-cover units. An important modification associated with this effort included the refined delineation of ecological condition or status of the various vegetation-cover types into four broad classes: native dominated, mixed native and nonnative dominated, nonnative dominated or disturbed, and barren. Again, WorldView 2 and Pictometry Online imagery were used to improve delineations.

Chapter 3 examines potential climate-related major biome shifts during the current to end-of-century assessment period. To do this, Fortini and others mapped 500-m-resolution climatically determined wet (mean annual precipitation minus potential evapotranspiration [MAP–PET] >1,661 mm), mesic (MAP–PET between 0 and 1,661 mm), and dry (MAP–PET <0 mm) moisture zones under current and modeled future climate. For the former, MAT and seasonality of rainfall shape suitability of

all areas of the main Hawaiian Islands to a given moisture zone, whereas for the latter, dynamically downscaled climate data for the 2090–2100 period are used to project shifts in moisture zones. Current distributions are validated by randomly splitting baseline input data into training (80 percent) and evaluation (20 percent) sets. Finally, current and future moisture-zone projections were integrated into previous mapping of forest, shrubland, and grassland cover-type classifications (Jacobi and others, this volume, chap. 2) to delineate nine major biome classes (dry, mesic, and wet forest, shrubland, and grassland) and understand how these broad biome types change in response to a shift from current to projected future modeled climate.

Chapter 4 addresses the conceptual foundation for understanding how nonnative species invasion impacts carbon storage, flux, and sequestration. The assessment includes this chapter because invasive species exert a large influence on the composition, structure, function, and dynamics of Hawai'i's ecosystems, and so they influence the carbon storage, flux, and sequestration capacity of Hawai'i's ecosystems. Globally there is great uncertainty about the role of invasive species in the carbon balance of terrestrial ecosystems, with recent meta-analyses showing diverse responses depending on the functional type of the invader, the composition and functioning of the ecosystem being invaded, and the type of biome hosting these interactions (Qiu, 2015). In this chapter, Hughes and others address these questions by examining, in a case-study design, how primary groups of nonnative invasive species (nitrogen-fixing trees and shrubs, non-nitrogen-fixing trees and shrubs, and fire-prone grasses) enter into ecosystems and modify processes regulating carbon balance. Effects can be positive (as with some nitrogen-fixing trees on young geological substrates), negative (as with invasion of dry-to-mesic forests by fire-prone grasses and shrubs), or neutral or uncertain (as with understory invasions in wet forests). Overall, an effort is made to establish a framework for understanding these effects based on the structural and functional characteristics of the invader, the native communities being invaded, and the biome.

Chapter 5 addresses the role of fire-related disturbances on ecosystem carbon balance for the main Hawaiian Islands. Dry-to-mesic areas of Hawai'i, like many areas of the dry-to-mesic tropics, experienced extensive land clearing in the past century for ranching and agricultural land uses. In the second half of the last century, both agricultural and ranching industries declined, resulting in a buildup of fuels on undermanaged ranchlands and an invasion of fire-prone vegetation on former agricultural lands. As a result, large areas of Hawai'i were converted from forests characterized by low flammability vegetation to highly flammable shrub and grass vegetation, such that today more than 25 percent of total land area in Hawaii is threatened by wildfire, a disturbance that impacts vegetation composition, ecosystem function, and carbon storage and sequestration. Hawbaker and others estimated the effects of fire on carbon storage and sequestration for the main Hawaiian islands by (1) synthesizing annual-area-burned information from ground-based fire history databases (Trauernicht and others, 2015) and two remotely sensed data sources—the Monitoring Trends in Burn Severity

database and Landsat 7 (the latter being used to examine fire occurrences recorded in the Hawai'i fire history database but not in the MTBS database); (2) characterizing burn-severity patterns; (3) assembling biomass load data from 419 plots at 204 different sites examined in 19 studies and linking the associated plot- or site-level data to vegetation-cover types; (4) estimating the annual percentage of land in each cover type that burns; and finally (5) incorporating all of these data into the First-Order Wildland Fire Effects Model (FOFEM) to estimate biomass consumption and carbon-related fire emissions. Because of data gaps, Ni'ihau, Lāna'i, and Kaho'olawe were excluded from analyses in this chapter.

Chapter 6 examines ecosystem carbon stocks and fluxes at stand to whole-island scales. To examine stocks, Selmants and others assembled aboveground biomass carbon data for forests from Asner and others (2016), litter and downed woody debris data for all ecosystems from Hawbaker and others (this volume, chap. 5), and soil carbon to 1-m depth or bedrock from the NRCS gridded Soil Survey Geographic (gSSURGO) database. Selmants and others calculated belowground live biomass using a simple exponential equation describing the general relationship between root and shoot biomass for forest plants (Mokany and others, 2006) and aboveground-to-belowground ratios for grasslands (0.73) and shrublands (1.45). The main flux of carbon into ecosystems of Hawai'i is GPP, and this was determined from a Hawai'i-specific, 0.5-km-resolution MOD17 MODIS data product, refined from the global product by using the Jacobi and others (this volume, chap. 2) vegetation classification to assign carbon-use efficiencies to vegetation-cover types. Further, a local, high-resolution climate database (Fortini and others, this volume, chap. 3) was used to drive MOD17-modeled GPP estimates. Estimates of NPP were determined by applying Hawai'i-specific MOD17 assumed carbon-use efficiency coefficients to GPP estimates. Further, ecosystem respiration (heterotrophic plus autotrophic) was estimated from separate equations for forests, shrublands, and grasslands developed from published studies in order to estimate NEP for all islands.

Chapter 7 evaluates the role of freshwater transport of carbon into oceans, including both stream transport and submarine groundwater discharge. For the former, MacKenzie and others estimated the flux of carbon transported in freshwater perennial streams to nearshore areas on Hawai'i, Maui, Moloka'i, O'ahu, and Kaua'i Islands. There are no perennial streams on Lāna'i and Kaho'olawe and so they were excluded from the analysis. Long-term data for discharge, pH, temperature, alkalinity, and carbon (total inorganic, total organic, and particulate) from 16 gaged perennial streams from across Hawai'i, as well as watershed characteristics such as drainage area, basin slope, soil permeability, and land-cover class distributions, were used to build the relationships needed to predict freshwater carbon inputs to the nearshore using the regression-based Load Estimator Model. These 16 streams were selected because for each stream, daily discharge data and a minimum of 12 sample collections over 3 years were available for water chemistry and quantity. The calibrated and validated model was used to estimate daily carbon flux for more

than 400 ungaged Hawai'i perennial streams with modeled mean flow data, estimated rainfall, and channel morphological measurements. Critically, this chapter did not examine ephemeral streams, which make up a large proportion of the total streams in Hawai'i. For the latter flux, MacKenzie and others used a hydrological budgeting approach to estimate submarine groundwater discharge for the main Hawaiian Islands and groundwater chemical data from wells to estimate inorganic and organic carbon fluxes.

Chapter 8 addresses how changing climate and land use or land cover will potentially impact future carbon storage and flux in the State of Hawai'i. To do this, Sleeter and others relied on the Land Use and Carbon Scenario Simulator (LUCAS), an integrated state-and-transition simulation stock-flow model that is linked to the Integrated Biosphere Simulator (IBIS), itself a carbon-flux simulator. The model structure allows for the entire state to be mapped to 1 of 189 condition states (3 moisture zones, 9 land-cover types, and 7 islands). LUCAS provides the ability to impose transitions on each cell, including rates of change to new condition states, with LUCAS tracking time since transition (defined as the set of changes that move a cell from one condition to another) or age of vegetation captured within a cell (the latter being important for understanding the effects of fire on carbon storage, for example). In theory, any cell type could transition into any other cell type, but transition probabilities are determined by regularly updated adjacency functions, protected area status, and the professional judgement of land managers and the coauthor team, which limits or even eliminates the likelihood of some transitions. Following initialization with data derived from the above chapters, these probabilities allow for changes in land use to be coupled to a stock-flow carbon submodel, which can track associated changes in ecosystem carbon storage under the selected IPCC "business as usual" scenario. To enhance the level of detail achieved by LUCAS, each cell was modeled using IBIS to secure the following outputs: living wood, standing and downed deadwood, litter, and soil. Inputs to the IBIS model were NPP and GPP values reported in Selmants and others (this volume, chap. 6), with rates constrained by targeted amounts of living biomass that could not be exceeded. From this initial startup, the IBIS model was used to simulate seven flow paths for each cell including growth, litterfall, humification, mortality, deadfall, emissions, and leaching, each of which varies according to the cell type, vegetation type, surrounding environmental conditions, and transitions.

Chapter 9 synthesizes estimates of NPP and R_h from Selmants and others (this volume, chap. 6), aquatic carbon fluxes to nearshore waters from MacKenzie and others (this volume, chap. 7), and carbon emissions from fire from Hawbaker and others (this volume, chap. 5) to calculate net ecosystem carbon balance (NECB) and carbon sequestration potential for the baseline period. These synthesized estimates of NECB and carbon sequestration potential were then compared to NECB and carbon sequestration potential calculated using the first 5 years (2012–2016) of modeled simulation estimates of carbon fluxes by the IBIS ecosystem carbon submodel of the LUCAS

model in Sleeter and others (this volume, chap. 8) to provide a range in baseline estimates. The overall trend in projected future ecosystem carbon balance and sequestration was examined by comparing islandwide and statewide estimates of mean annual NEP and NECB from the first 10 years of the modeled simulation (2011–2022) described in Sleeter and others (this volume, chap. 8) to islandwide and statewide estimates of mean annual NEP and NECB from the final 10 years of the modeled simulation (2051–2061). Implications, limitations, and uncertainties of the approach used to estimate statewide NECB and carbon sequestration are discussed, as are proposed mechanisms to improve future assessments in Hawai'i.

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