Baseline and Projected Future Carbon Storage and Carbon Fluxes in Ecosystems of Hawaiʻi
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Chapter 9. Hawaiʻi Carbon Balance

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9.1. Highlights

- Ecosystem carbon balance of the seven main Hawaiian Islands (as outlined in Giardina and others, this volume, chap. 1) was estimated for two periods, a current baseline period (2004–2013) and a projected period (2012–2061), by synthesizing results for baseline carbon emissions from wildfire (Hawbaker and others, this volume, chap. 5), baseline carbon stocks and fluxes (Selmants and others, this volume, chap. 6), baseline and projected future aquatic carbon fluxes to nearshore waters (MacKenzie and others, this volume, chap. 7), and projected future carbon stocks and fluxes (Sleeter and others, this volume, chap. 8).
- Terrestrial ecosystems of the seven main Hawaiian Islands sequestered an average of 0.34 TgC/yr during the baseline period, which was about 4 percent of statewide terrestrial net primary production (NPP). Hawaiʻi Island represented the largest carbon sink, sequestering 0.24 TgC/yr or 70 percent of total statewide carbon sequestration.
- The combined carbon-leaching losses to nearshore waters through stream-water flux and submarine groundwater discharge was estimated as about 0.31 TgC/yr, or about 4 percent of statewide terrestrial NPP.
- During the projected period (2012–2061), carbon sequestration of terrestrial ecosystems of the State of Hawaiʻi was predicted to decrease by more than 30 percent (0.34 to 0.22 TgC/yr) primarily because of a decrease in NPP and increased carbon losses from land-use and land-cover change, as well as increased aquatic carbon-leaching losses to nearshore waters.
- Our analysis indicates that the State of Hawaiʻi would remain a net carbon sink overall, primarily because of carbon sequestration in terrestrial ecosystems on Hawaiʻi Island, but that predicted land-use changes on the islands of Kauaʻi and Oʻahu would convert these islands from net carbon sinks to net carbon sources to the atmosphere.

9.2. Introduction

Hawaiʻi is unique among the United States because of its isolation, tropical climate, discontinuous landmass, high degree of endemism, history of land-cover conversion, and dominance of some areas by invasive species. The year-round growing season, high rainfall on windward sides of islands and high fertility of volcanically derived soils all indicate that terrestrial ecosystems of Hawaiʻi have a high capacity to influence the exchange of carbon dioxide (CO_2) between ecosystems and the atmosphere and influence the overall ecosystem carbon balance of the state. However, much of Hawaiʻi has not previously been included in any major national carbon and greenhouse inventory reports. Thus, the current baseline carbon balance is poorly understood at a statewide level, and the potential for climate and land-use change to affect carbon dynamics in Hawaiʻi has not been formally assessed.

The main outcomes of the U.S. Geological Survey carbon assessment for Hawaiʻi include (1) estimates of the amount of carbon stored in ecosystems, (2) estimates of the capacity of ecosystems to sequester carbon, (3) estimates of the rate of carbon fluxes in and out of the ecosystems, and (4) evaluation of the effects of processes or driving forces that control ecosystem carbon balance. To support the outcomes of the assessment for the entire State of Hawaiʻi, the assessors sought to address the magnitude of carbon pools and fluxes in terrestrial ecosystems of the Hawaiian Islands and how the carbon balance of these ecosystems might be influenced by climate change, wildfire, leaching losses of carbon to nearshore waters and changes in land use and land cover. Chapters 2 through 8 of this assessment addressed these goals separately for different components and questions. In this chapter we focus on synthesizing results across terrestrial ecosystems of the Hawaiian Islands to summarize information at the statewide level on changes in carbon stocks, carbon fluxes, and ecosystem carbon balance for current baseline (2004–2013) and projected future (2012–2061) periods.

9.3. Input Data and Methods

For the current baseline period, we synthesized estimates of net primary production (NPP) and heterotrophic respiration (R_h) from Selmants and others (this volume, chap. 6), aquatic fluxes to

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nearshore waters from MacKenzie and others (this volume, chap. 7), and fire emissions from Hawbaker and others (this volume, chap. 5) and compare these to the first 5 years (2012–2016) of modeled simulation estimates of carbon fluxes by the IBIS ecosystem carbon submodel from Sleeter and others (this volume, chap. 8). Estimates of NPP derived from statewide MODIS GPP (MOD17) were used to calibrate the IBIS annual NPP estimates, and baseline fire estimates from Hawbaker and others (this volume, chap. 5) were used to parameterize IBIS annual carbon emissions from wildfire. Estimates of baseline carbon fluxes to nearshore waters from stream- and groundwater discharge from MacKenzie and others (this volume, chap. 7) were not used to either parameterize or calibrate IBIS-submodel estimates of carbon-leaching losses, so these independent estimates can be used to cross-validate each other. Likewise, estimates of R_h were derived from regression-based estimates of ecosystem respiration (R_e) (Selmants and others, this volume, chap. 6) minus MODIS-based estimates of NPP and were not incorporated into IBIS estimates of R_h; these estimates can be cross validated with one another, as can estimates of net ecosystem production (NEP), the difference between NPP and R_h. For the current baseline period, mean annual carbon fluxes were calculated separately by island and expressed in TgC/yr.

For the projected future period (2012–2016), net ecosystem carbon balance (NECB) (see Chapin and others, 2006) for terrestrial ecosystems was calculated as follows:

$$\text{NECB} = \text{NPP} - R_h - \text{Fire C} - \text{C leaching loss} - \text{Land Use C flux}$$

for which the abbreviations for the fluxes are defined as above. Land Use C flux is a brief pulse of carbon lost to the atmosphere associated with land clearing and conversion, for example, urbanization and conversion to agriculture. We also compare independent estimates of projected future carbon losses from terrestrial ecosystems through stream- and groundwater discharge to nearshore marine waters from MacKenzie and others (this volume, chap. 7) and Sleeter and others (this volume, chap. 8), both of which are based on projected future changes in moisture zones induced by climate change as described in Fortini and others (this volume, chap. 3).

9.4. Results and Discussion

9.4.1. Synthesis of Carbon Dynamics in the Baseline Period (2004–2013)

Baseline estimates of terrestrial ecosystem carbon stocks and fluxes from Hawbaker and others (this volume, chap. 5), Selmants and others (this volume, chap. 6), and MacKenzie and others (this volume, chap. 7) are summarized in figure 9.1. We estimate that NEP of the State of Hawai‘i currently ranges from 0.9 to 2.4 TgC/yr (table 9.1) because estimates of NPP exceed estimates of R_h for all seven of the main Hawaiian Islands during this period. Although estimates of NPP derived from MODIS GPP described in Selmants and others (this volume, chap. 6) were used to calibrate NPP estimates from the IBIS submodel described in Sleeter and others (this volume, chap. 8), the statewide IBIS estimates of mean annual NPP for the first 5 years of the simulation were about 13 percent lower than the statewide estimates of mean annual NPP derived from MODIS data (table 9.1). This can be explained in part by land-use and land-cover changes during this initial simulation period. The independent estimates of R_h are much more similar, differing by only about 2 percent statewide (table 9.1.). However, R_h represented about 90 percent of NPP in the IBIS-submodel simulation, whereas the regression-based estimate of statewide R_h derived from the relationship between R_e and GPP from Selmants and others (this volume, chap. 6) represents only about 77 percent of NPP estimated from MODIS GPP data (table 9.1). The combination of lower NPP and higher R_h estimates in the IBIS submodel result in a statewide estimate of NEP that is less than half that of NEP estimated by the combined MODIS-regression approach (table 9.1). Mean annual carbon emission from wildfire for the years 2002–2011 was estimated to be 0.027 TgC/yr with a range of 0.002–0.06 TgC/yr (Hawbaker and others, this volume, chap. 5). Estimates from the first 5 years of the simulation were similar—statewide mean annual carbon emissions from wildfire were estimated to be 0.029 TgC/yr from 2012 to 2016, with a range of 0.002–0.12 TgC/yr, which is unsurprising given that wildfire area burned and carbon emissions from Hawbaker and others (this volume, chap. 5) were used to parameterize the Land Use and Carbon Scenario Simulator (LUCAS) model described in Sleeter and others (this volume, chap. 8).

The baseline estimates of aquatic carbon fluxes to nearshore waters from MacKenzie and others (this volume, chap. 7) are the sum of estimates of organic and inorganic carbon fluxes in stream water and submarine groundwater discharge, and were calculated independently from estimates of carbon-leaching losses estimated for the first 5 years of the simulation by the LUCAS model (Sleeter and others, this volume, chap. 8); in other words, estimates from MacKenzie and others (this volume, chap. 7) were not used to either parameterize or calibrate the IBIS-submodel estimates of leaching losses described in Sleeter and others (this volume, chap. 8). Nevertheless, these independent estimates of carbon lost from terrestrial ecosystems by leaching into streams and groundwater are strikingly similar, differing by less than 1 percent statewide (table 9.2).

9.4.2. Assessment of Projected Future Carbon Dynamics (2012–2061)

Our assessment of statewide projected future estimated carbon dynamics of Hawai‘i (2012–2061) are based almost entirely on the LUCAS model results from Sleeter and others (this volume, chap. 8). The only exception is a comparison of projected future aquatic carbon losses to nearshore waters

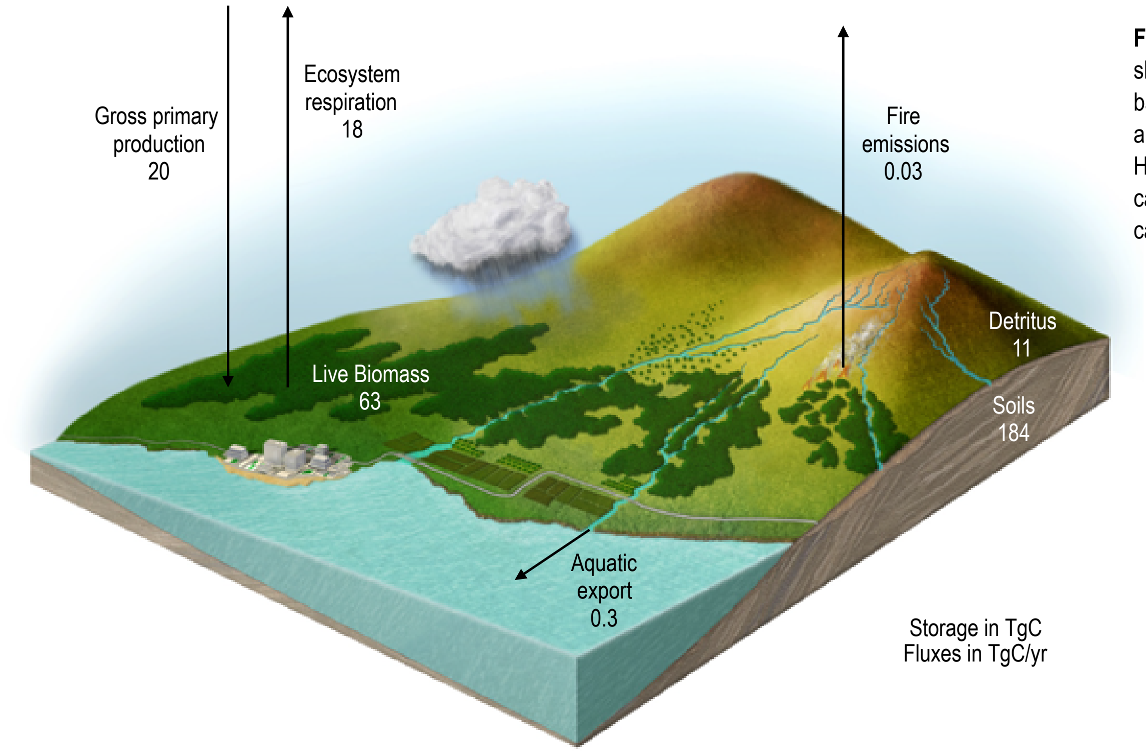

Figure 9.1. Diagram showing summary of current baseline carbon stocks and fluxes for the State of Hawai‘i. TgC, teragrams of carbon; TgC/yr, teragrams of carbon per year.

Table 9.1. Comparison of baseline estimates of net primary production, heterotrophic respiration, and net ecosystem production for the seven main Hawaiian Islands.

[MODIS GPP data and regression estimates of ecosystem respiration [R_e] from Selmants and others (this volume, chap. 6) and IBIS model data from Sleeter and others (this volume, chapter 8). NPP, net primary production; R_h heterotrophic respiration; NEP, net ecosystem production (NPP – R_h); TgC/yr, teragrams of carbon per year]

Island	NPP (TgC/yr) MODIS	NPP (TgC/yr) IBIS	R_h (TgC/yr) MODIS regression	R_h (TgC/yr) IBIS	NEP (TgC/yr) MODIS-regression	NEP (TgC/yr) IBIS
Hawai‘i	5.58	5.51	4.41	4.93	1.17	0.586
Kaho‘olawe	0.03	0.02	0.02	0.02	0.01	0.001
Kaua‘i	1.34	1.00	0.99	0.90	0.35	0.100
Lāna‘i	0.19	0.09	0.14	0.08	0.05	0.005
Maui	1.29	1.01	1.00	0.91	0.29	0.108
Moloka‘i	0.57	0.34	0.37	0.31	0.20	0.026
O‘ahu	1.17	0.90	0.85	0.82	0.32	0.078
Total	10.17	8.87	7.78	7.96	2.39	0.903

Table 9.2. Comparison of baseline and projected future nearshore aquatic carbon fluxes to leaching losses of carbon.

[Baseline and projected future aquatic carbon fluxes to nearshore waters from MacKenzie and others (this volume, chap. 7) and leaching losses of carbon from Sleeter and others (this volume, chap. 8). Aquatic fluxes of nearshore waters are projected out to 2100, whereas leaching losses are projected out to 2061. TgC/yr, teragrams of carbon per year]

Island	Baseline aquatic flux (TgC/yr)	IBIS Baseline leaching loss (TgC/yr)	Projected future aquatic flux (TgC/yr)	IBIS projected future leaching loss (TgC/yr)
Hawai‘i	0.166	0.206	0.207	0.236
Kaho‘olawe	<0.001	<0.001	<0.001	<0.001
Kaua‘i	0.043	0.036	0.047	0.035
Lāna‘i	0.002	<0.001	0.002	<0.001
Maui	0.045	0.038	0.058	0.043
Moloka‘i	0.008	0.008	0.008	0.008
O‘ahu	0.047	0.025	0.047	0.023
Total	0.311	0.314	0.369	0.345

from MacKenzie and others (this volume, chap. 7) to those of the LUCAS model (Sleeter and others, this volume, chap. 8), both of which are based on projected moisture-zone changes described in Fortini and others (this volume, chap. 3). Overall carbon storage in terrestrial ecosystems was projected to increase by an average of about 0.29 TgC/yr during the 50-year course of the projected future period (fig. 9.2), almost entirely from increases in soil organic carbon storage (Sleeter and others, this volume, chap. 8). Carbon input from NPP is projected to average 8.69 TgC/yr from 2012 to 2061 (fig. 9.2), decreasing by an average of about 6 percent from the first 10 years of the simulation period (8.87 TgC/yr) to the final 10 years (8.36 TgC/yr). Projected estimates of R_h average 7.84 TgC/yr from 2012 to 2061 (fig. 9.2), with R_h projected to decrease by an average of about 4 percent from the first 10 years of the simulation period (7.96 TgC/yr) to the final 10 years (7.64 TgC/yr). The slightly more rapid statewide decrease in NPP compared to R_h results in about a 14 percent (0.13 TgC/yr) overall decrease in statewide NEP during the 50-year simulation period, contributing to a reduction in statewide carbon sequestration potential for the Hawaiian Islands (table 9.3).

Aquatic carbon-leaching losses to stream water and groundwater, and eventually to nearshore marine waters, represent the largest, non-respiratory loss of carbon from terrestrial ecosystems of Hawai‘i. The LUCAS model projects about a 10 percent increase in carbon loss from terrestrial ecosystems by leaching to nearshore waters during the 50-year simulation period, from an average of 0.314 TgC/yr during the first 5 years of the simulation period (2012–2016) to an average of 0.345 TgC/yr during the final 5 years of the simulation period (2051–2061; table 9.2). Independent projections (MacKenzie and others, this volume, chap. 7) of aquatic carbon flux to nearshore waters estimate an increase of about 19 percent from the current baseline period (0.311 TgC/yr) to the year 2100 (0.369 TgC/yr; table 9.2)—a similar rate of annual increase to the LUCAS model projections. Leaching losses of carbon from terrestrial ecosystems to nearshore marine waters are projected to average about 0.33 TgC/yr from 2012 to 2061 (fig. 9.2).

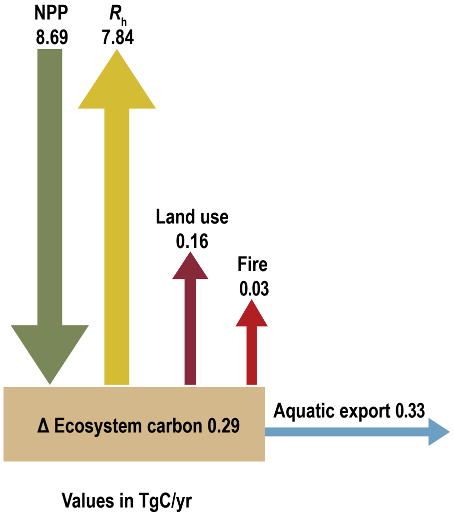

Figure 9.2. Diagram showing projected future mean annual carbon fluxes and change in ecosystem carbon storage for the State of Hawai‘i averaged across the 50-year future simulation period (2012–2061). NPP, net primary production; R_h, heterotrophic respiration; TgC/yr, teragrams of carbon per year.

The projected future decrease in NEP (table 9.3), combined with the projected increase in carbon losses from leaching and from emissions related to land-use and land-cover change (Sleeter and others, this volume, chap. 8), led to a more than 30 percent projected decrease in NECB during the 50-year simulation period (fig. 9.3), from a statewide average of 0.34 TgC/yr during the first 10 years of the simulation period (2012–2021) to an average of 0.22 TgC/yr during the final 10 years of the simulation period (2051–2061; table 9.4). This overall decrease in NECB represents a substantial weakening of statewide carbon-sink strength (fig. 9.3), and is projected to convert the islands of Kaua‘i and O‘ahu from net sinks to net sources of CO_2 to the atmosphere (9.4). The overall statewide decrease in NECB is due to reduced carbon sequestration potential related to land-use change—primarily urbanization (Sleeter and others, this volume, chap. 8).

Table 9.3. Projected changes in net ecosystem production during the 50-year future simulation period for the seven main Hawaiian Islands.

[Net ecosystem production (NEP) is net primary production minus heterotrophic respiration. ktC/yr, kilotons of carbon per year]

Island	Net ecosystem production (ktC/yr): 2011–2021			Net ecosystem production (ktC/yr): 2051–2061		
	Mean	Upper (97.5%)	Lower (2.5%)	Mean	Upper (97.5%)	Lower (2.5%)
Hawai‘i	586	665	508	535	619	454
Kaho‘olawe	1	2	1	1	1	0
Kaua‘i	100	117	83	73	88	58
Lāna‘i	5	6	3	4	5	3
Maui	108	124	92	94	110	78
Moloka‘i	26	31	20	19	24	14
O‘ahu	78	94	61	52	64	39
Total	903	1104	701	778	972	581

Table 9.4. Projected changes in net ecosystem carbon balance during the 50-year future simulation period for the seven main Hawaiian Islands.
[NECB, net ecosystem carbon balance (net ecosystem production minus carbon losses from fire, land use, and aquatic export to nearshore waters); ktC/yr, kilotons of carbon per year]

Island	NECB (ktC/yr): 2011–2021			NECB (ktC/yr): 2051–2061		
	Mean	Upper (97.5%)	Lower (2.5%)	Mean	Upper (97.5%)	Lower (2.5%)
Hawai‘i	236	323	153	208	290	129
Kaho‘olawe	1	2	0	0	1	-1
Kaua‘i	33	56	12	-11	18	-40
Lāna‘i	3	5	1	2	4	0
Maui	40	62	20	18	39	-2
Moloka‘i	14	20	7	8	14	2
O‘ahu	14	38	-9	-1	19	-22
Total	341	592	80	224	454	-6

9.5. Conclusions

Our synthesis of carbon dynamics in Hawai‘i indicates that the terrestrial ecosystems of the state currently sequester about 0.34 TgC/yr, which is almost 4 percent of statewide NPP. Terrestrial ecosystems of the seven main Hawaiian Islands offset about 7 percent of anthropogenic emissions, which were estimated at 4.9 TgC for 2013 and were primarily from energy and transportation. Hawai‘i Island represented the largest carbon sink at 263 TgC/yr during the baseline period, which was about 70 percent of the statewide carbon sink. Near the end of the simulation period (2051–2061) the statewide carbon sink was projected to decrease to about 2.7 percent of NPP. Terrestrial ecosystems would be projected to offset only 5 percent of anthropogenic emissions if they remained at 2013 levels. Hawai‘i Island was projected to represent more than 90 percent of the statewide carbon sink near the end of the simulation period, with the islands of Kaua‘i and O‘ahu projected to be converted from net sinks to net sources of CO_2 to the atmosphere.

The results of the current synthesis have implications for carbon management strategies that might be aimed at offsetting anthropogenic emissions in the State of Hawai‘i. However, several factors that could influence the carbon balance of terrestrial ecosystems of Hawai‘i were not considered in this assessment, these include increasing atmospheric CO_2 concentrations influencing CO_2 fertilization on NPP (carbon input) and increasing temperatures having direct and indirect effects on NPP and R_h (carbon loss) through plant physiological responses and changes in rates of decomposition and nutrient cycling. It is also important to recognize the uncertainties in the results reported here, primarily in the estimates of respiratory carbon losses. Incorporation of eddy flux data from Hawai‘i and an ensemble process-based simulation modeling approach

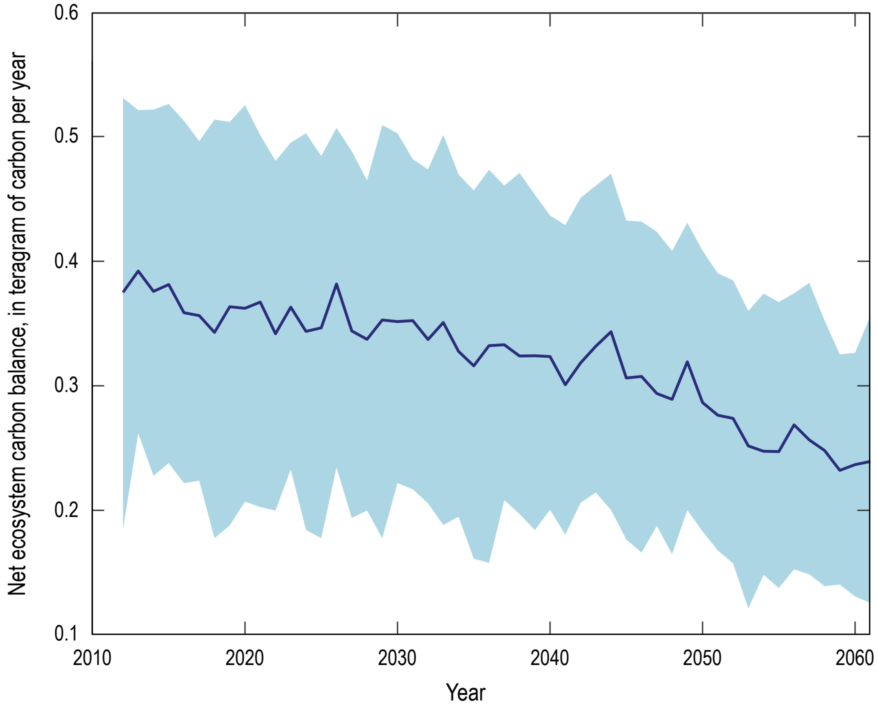

Figure 9.3. Plot showing projected future annual net ecosystem carbon balance (NECB) of the State of Hawai‘i for each year of the 50-year future simulation period (2012–2061). Each annual value for NECB is the mean of 100 Monte Carlo iterations from the Land Use and Carbon Scenario Simulator (LUCAS) model (see Sleeter and others, this volume, chap. 8).

would increase confidence in future estimates of carbon balance and sequestration potential of Hawaiian ecosystems. Reduction in these uncertainties will require enhancements in observation systems; research on landscape dynamics; process-based modeling research; and more detailed, realistic land-management and policy scenarios. Key enhancements in observation systems include increased biomass measurements in shrublands and grasslands of Hawaiʻi, estimates of NPP and crop biomass in agricultural areas, and stream-water carbon export from ephemeral streams. Increasing the detail of land-management and policy scenarios related to agricultural expansion, wildfire suppression and prevention, and restoration of ecosystems dominated by invasive species would provide a wider range of variables as inputs to the LUCAS state and transition model. Despite these limitations, the analyses presented here provide valuable information for setting research and policy priorities that should reduce uncertainties and improve future assessments.