Ecosystem carbon balance in the Hawaiian Islands under different scenarios of future climate and land use change

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Abstract

The State of Hawaiʻi passed legislation to be carbon neutral by 2045, a goal that will partly depend on carbon sequestration by terrestrial ecosystems. However, there is considerable uncertainty surrounding the future direction and magnitude of the land carbon sink in the Hawaiian Islands. We used simulation modeling to assess how projected future changes in climate and land use will influence ecosystem carbon balance in the Hawaiian Islands under all combinations of two radiative forcing scenarios (RCP 4.5 and RCP 8.5) and two land use scenarios (low and high) over a 90-year timespan from 2010-2100. Collectively, terrestrial ecosystems of the Hawaiian Islands acted as a net carbon sink under low radiative forcing (RCP 4.5) for the entire 90-year simulation period, with low land use change further enhancing carbon sink strength. In contrast, Hawaiian terrestrial ecosystems transitioned from a net sink to a net source of CO_2 to the atmosphere under high radiative forcing (RCP 8.5), with high land use accelerating this transition and exacerbating net carbon loss. A sensitivity test of the CO_2 fertilization effect on plant productivity revealed it to be a major source of uncertainty in projections of ecosystem carbon balance. Greater mechanistic understanding of plant productivity responses to rising atmospheric CO_2 will be essential to realistically constrain simulation models used to evaluate the effectiveness of ecosystem-based climate mitigation strategies.

1. Introduction

Terrestrial ecosystems are a major sink for atmospheric carbon dioxide (CO_2), removing ~30% of human emissions on an annual basis and reducing the rate of increase in atmospheric CO_2 (Keenan and Williams 2018, Friedlingstein *et al* 2019). There is increasing recognition among policymakers that natural and agricultural ecosystems can contribute to climate mitigation, which has given rise to the popularity of "natural climate solutions" (Cameron *et al* 2017). Defined as conservation and land management efforts aimed at enhancing ecosystem carbon storage (Griscom *et al* 2017), natural climate solutions are appealing because they are seen as cost-efficient and readily available (Galarraga *et al* 2017, Cameron *et al* 2017, Fargione *et al* 2018). However, effective implementation

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⁴³ is complicated by the uncertainty surrounding the future direction and magnitude of the land carbon

⁴⁴ sink, especially at the regional scale. Despite this uncertainty, evidence indicates that both interannual

⁴⁵ and long-term variability in carbon uptake by land ecosystems is driven primarily by fluctuations in

⁴⁶ climate, land use, and land cover change (Ahlström *et al* 2015, Prestele *et al* 2017, Friedlingstein *et*

⁴⁷ *al* 2019). Incorporating the interactive effects of land use and climate into spatially explicit future

⁴⁸ projections of ecosystem carbon balance could therefore provide a reference point to evaluate the

⁴⁹ effectiveness of land-based mitigation. Although a complex challenge, a growing number of

⁵⁰ sub-national jurisdictions plan to incorporate land-based mitigation strategies into their emissions

⁵¹ reduction efforts. These jurisdictions would benefit from understanding how future land use and

⁵² climate-biosphere feedbacks will affect ecosystem carbon balance in their respective regions (Sleeter

⁵³ *et al* 2019).

⁵⁴ The State of Hawai'i exemplifies the challenges associated with projecting the interactive effects of

⁵⁵ future climate and land use change on ecosystem carbon balance at a regional scale. Hawai'i was the

⁵⁶ first U.S. state to enact legislation committing to full carbon neutrality, requiring the state to account

⁵⁷ for and offset all of its greenhouse gas emissions by 2045 (State of Hawai'i Acts 15 and 16). This

⁵⁸ legislation emphasizes the mitigation potential of natural ecosystems as a key component to

⁵⁹ emissions reduction, necessitating baseline estimates and future projections of land carbon sink

⁶⁰ strength. However, Hawai'i's challenging terrain complicates these assessment efforts. The main

⁶¹ Hawaiian Islands are a complex mosaic of natural and human-dominated landscapes overlain by

⁶² steep climate gradients across relatively short distances, with mean annual temperature ranging from

⁶³ ~4-24° C (Giambelluca *et al* 2014) and mean annual rainfall ranging from ~200-10,200 mm

⁶⁴ (Giambelluca *et al* 2013). Temperatures have risen rapidly in the Hawaiian Islands since the mid

⁶⁵ 1970s (Giambelluca *et al* 2008, McKenzie *et al* 2019) and a long-term drying trend has persisted

⁶⁶ since the early 1920s (Frazier and Giambelluca 2017), resulting in reduced forest biomass and

⁶⁷ productivity (Barbosa and Asner 2017). These same drying and warming trends have increased the

⁶⁸ frequency and intensity of wildland fire (Trauernicht *et al* 2015, Trauernicht 2019) with predictable

⁶⁹ negative effects on ecosystem carbon balance (Selmants *et al* 2017). Ecosystem carbon stocks across

the main Hawaiian Islands have also been strongly influenced by the legacy of past land use change (Osher *et al* 2003, Asner *et al* 2011). Thousands of hectares were deforested beginning in the late 19th century to clear land for sugar plantations and cattle pasture (Cuddihy and Stone 1990). Since the mid-20th century, much of this agricultural land has been steadily converted to urban areas, commercial forestry plantations, or simply abandoned and colonized by non-native grass species (Suryanata 2009, Perroy *et al* 2016). Although these past trends surely inform the future impact of climate and land use change on ecosystem carbon balance, high spatial and temporal heterogeneity complicates realistic projection efforts. To date only one study has attempted to integrate land use, climate, and natural disturbances into future projections of Hawaiian ecosystem carbon balance, with projections limited to the mid-21st century under a single land use change scenario and moderate radiative forcing (SRES A1B, equivalent to RCP 6; Selmants *et al* 2017).

We used a stochastic, spatially explicit simulation model to estimate ecosystem carbon balance for Hawai'i's natural and agricultural lands on an annual basis for the period 2010–2100 under a range of assumptions about future climate, land use, land cover, disturbance, and global CO_2 emissions (Daniel *et al* 2016, 2018, Sleeter *et al* 2019). We explored four unique scenarios that represent all combinations of two land use change pathways (low and high) and two radiative forcing pathways (representative concentration pathway [RCP] 4.5 and RCP 8.5). In addition to these four scenarios, we conducted a separate series of simulations to examine how ecosystem carbon balance estimates vary in response to different levels of a CO_2 fertilization effect (CFE) on net primary productivity (NPP; Sleeter *et al* 2019). Our goals were to estimate changes in Hawaiian ecosystem carbon balance and their uncertainties under a range of plausible future scenarios, quantify the relative impact of major controlling processes such as land use change, disturbance, and climate change, and assess the sensitivity of model estimates to the introduction of a CFE on NPP.

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2. Methods

We used the Land Use and Carbon Scenario Simulator (LUCAS), an integrated landscape change and carbon gain-loss model, to project changes in ecosystem carbon balance for the seven main Hawaiian Islands. The landscape change portion of LUCAS is a state-and-transition model, where 'state' is the pre-defined land cover class assigned to each simulation cell and 'transition' is the change in state of each simulation cell over time (Daniel *et al* 2016). Landscape change occurs by applying a Monte Carlo approach to track the state type and age of each simulation cell in response to a pre-determined set of transition pathways (Daniel *et al* 2016). The carbon gain-loss portion tracks carbon stocks within each simulation cell over time as continuous state variables, along with a pre-defined set of continuous flows specifying rates of change in stock levels over time (Daniel *et al* 2018, Sleeter *et al* 2019). We parameterized the Hawai'i LUCAS model to estimate annual changes in carbon stocks and fluxes in response to land use, land use change, wildland fire, and long-term climate variability for the time period 2010-2100.

2.1 Study area

The spatial extent of this study was the terrestrial portion of the seven main Hawaiian Islands (figure 1), a total land area of 16,554 km^2. We subdivided this landscape into a grid of 264,870 simulation cells, each of which was 250 x 250 m in size. Each simulation cell was assigned to one of 210 possible state types based on the unique combination of three moisture zones (dry, mesic, and wet; supplemental figure 1), seven islands, and ten discrete land cover classes (figure 1).

2.2 States and transitions

We developed two land use scenarios (low and high) with transition pathways modified from Daniel *et al* (2016). Transition pathways between state types were pre-defined to represent urbanization, agricultural contraction, agricultural expansion, harvesting of tree plantations, and wildfire.
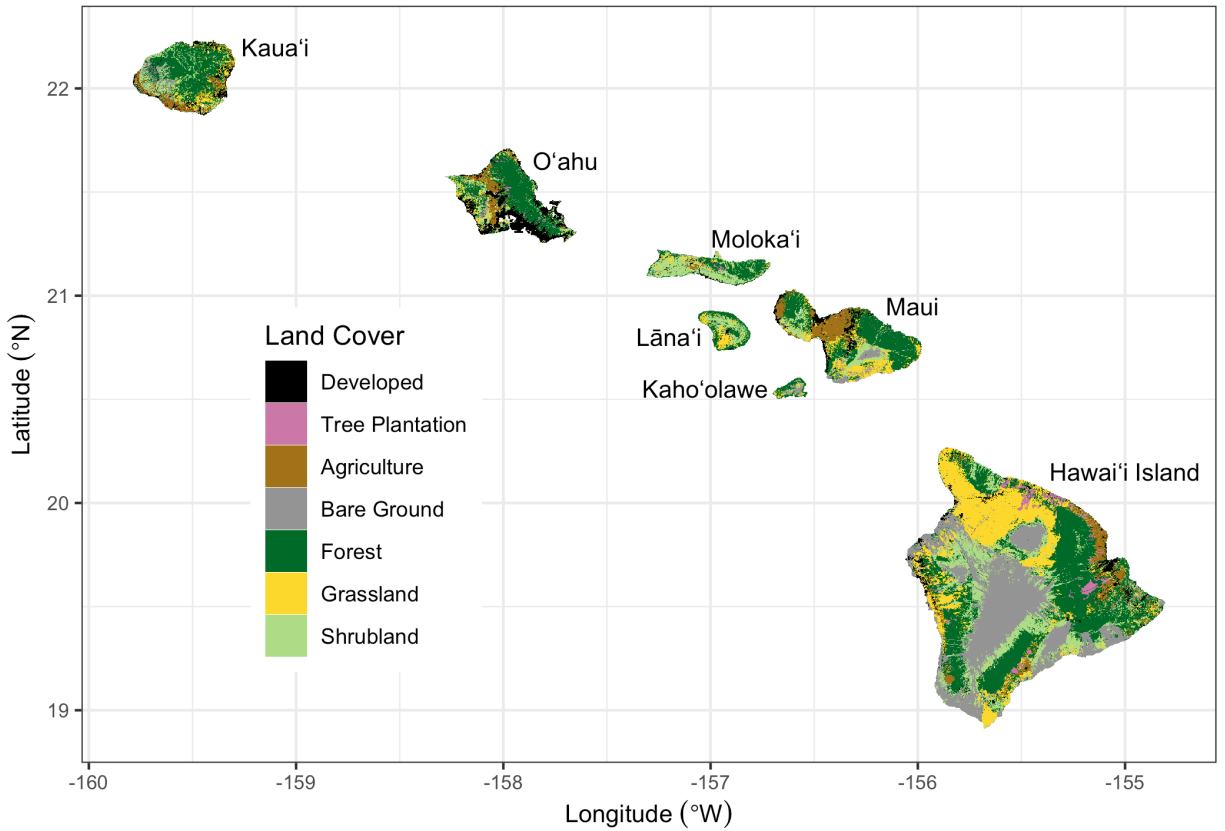
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Figure 1: Land cover classification of the seven main Hawaiian Islands, adapted from Jacobi *et al.* (2017). Agriculture in this map combines herbaceous and woody crops, but these two crop types are treated as separate land cover classes in the simulation model. Water and Wetland land cover classes are not shown.

Agriculture, forest, grassland, shrubland, and tree plantation state types each had multiple transition pathways, while the barren state type could only transition to developed (i.e., urbanization). Although most state types had an urbanization transition pathway, there was no transition pathway out of an urbanized (developed) state. Water and wetland state types remained static throughout the simulation period.

Transition targets set the area to be transitioned over time. These targets were based on historical trends of land use change in the Hawaiian Islands from 1992-2011 (NOAA 2020) and on population projections for the State of Hawaiʻi (Kim and Bai 2018). For the high land use scenario, transition rates for each timestep and Monte Carlo realization were sampled from uniform distributions bounded by the median and maximum historical rates of agricultural contraction, agricultural expansion, and urbanization for each island. For the low land use scenario, rates of agricultural contraction and expansion were sampled from uniform distributions bounded by zero and the minimum historical rates for each island. Urbanization rates in the low land use scenario were based on island-level population estimates and projections at five year intervals from 2010-2045 (Kim and Bai 2018). We converted population projections into urbanization transition targets following Sleeter *et al* (2017) by calculating population density for each island and then projecting future developed area based on the five-year incremental change in island population. The spatial extent of agricultural contraction, agricultural expansion, and urbanization was constrained in both land use scenarios based on existing zoning maps (Daniel *et al* 2016). Transition targets for tree plantation harvest were set at ~75% of recent historical rates in the high land use scenario and ~40% of recent historical rates in the low land use scenario (Daniel *et al* 2016). In both land use scenarios, approximately 60% of tree plantation harvests were replacement harvests resulting in conversion to agriculture. The remaining 40% were rotation harvests replanted to *Eucalyptus* spp.

The wildfire transition sub-model was modified from Daniel *et al* (2016) by incorporating a new 21-year historical wildfire spatial database of the Hawaiian Islands (supplemental figure 2). We used this new spatial database to calculate historical wildfire size distribution and ignition probabilities for

each unique combination of moisture zone (supplemental figure 1), island, and state type (figure 1) for the years 1999-2019. Starting in 2020, the number and size of fires was randomly drawn from one of these historical year-sets for each timestep and Monte Carlo realization, using burn severity probabilities from Selmants *et al* (2017). Wildfire in the low land use scenario was sampled from the subset of historical fire years at or below the median area burned statewide from 1999-2019. The high land use scenario sampled from historical fire years above the median area burned over the same 21-year period (supplemental figure 2a).

2.3 Carbon stocks and flows

The fate of carbon stocks was tracked for each simulation cell based on a suite of carbon flows (i.e., carbon fluxes) specifying the rates of change in these carbon stocks over time (Daniel *et al* 2018, Sleeter *et al* 2019). We defined carbon stocks as continuous state variables for each simulation cell, including live biomass, standing dead wood, down dead wood, litter, and soil organic carbon. We also included and tracked carbon in atmospheric, aquatic, and harvest product pools to enforce carbon mass balance (Daniel *et al* 2018). To transfer carbon between stocks, we defined baseline carbon flows as continuous variables resulting from growth, mortality, deadfall, woody decay, litter decomposition, and leaching (which includes runoff). We also defined carbon flows resulting from land use, land use change, and wildfire (Selmants *et al* 2017, Daniel *et al* 2018).

Initial carbon stocks and baseline carbon flows were estimated based on the moisture zone (supplemental figure 1), state type, and age of each simulation cell using a lookup table derived from the Integrated Biosphere Simulator (IBIS; Foley *et al* 1996, Liu *et al* 2020), a process-based dynamic global vegetation model. We initiated IBIS with minimal vegetation and simulated forward for 110 years using 30-year climate normals for the Hawaiian Islands (Giambelluca *et al* 2013, 2014). We calibrated IBIS carbon stocks with statewide gridded datasets of soil organic carbon (Soil Survey Staff 2016) and forest aboveground live biomass (Asner *et al* 2016). We also calibrated gross photosynthesis in IBIS using a Hawai'i-specific gridded dataset derived from MODIS satellite

imagery (Kimball *et al* 2017).

Net primary production for each simulation cell was calculated as the mean IBIS-derived value for each combination of moisture zone and state type adjusted with a spatially explicit stationary growth multiplier to reflect local variation driven by microclimate (Sleeter *et al* 2019). We calculated this spatial growth multiplier as the NPP anomaly for each simulation cell relative to mean NPP values for each combination of moisture zone and state type based on empirical relationships between total annual NPP and mean annual rainfall or temperature (Schuur 2003, Del Grosso *et al* 2008) using Hawaiʻi-specific climate data (Giambelluca *et al* 2013, 2014). Soil carbon flux to the atmosphere (R_h) and aquatic soil carbon losses (leaching and overland flow) were estimated as the ratio of the IBIS-derived flux for each combination of moisture zone and state type to the microclimate-adjusted NPP value for each simulation cell. All other carbon flow rates were estimated as the ratio of the mean IBIS-derived flux for each combination of moisture zone and state type to the size of the originating carbon stock at each age (Sleeter *et al* 2018, Daniel *et al* 2018).

Climate change impacts on carbon flows were represented by temporal growth and decay multipliers applied to each simulation cell based on mid-century (2049-2069) and end-of-century (2070-2099) statistically downscaled CMIP5 temperature and rainfall projections for the Hawaiian Islands under each of two radiative forcing scenarios (RCP 4.5 and RCP 8.5; Elison Timm *et al* 2015, Elison Timm 2017). The impact of future changes in rainfall and temperature on NPP were represented by annual growth multipliers calculated using empirical NPP models (Schuur 2003, Del Grosso *et al* 2008) and climate model projections of temperature and rainfall for each radiative forcing scenario. The effect of future warming on turnover rates of dead organic matter were represented by temporal decay multipliers calculated using Q_{10} temperature coefficients based on climate model temperature projections for each radiative forcing scenario. The Q_{10} temperature coefficients represented the proportional change in detrital carbon turnover due to a 10° C change in mean annual temperature. We applied a Q_{10} of 2.0 for wood and soil organic matter decay flows (Kurz *et al* 2009, Sleeter *et al* 2019) and a Q_{10} of 2.17 for litter decay flows (Bothwell *et al* 2014). Transition-triggered carbon

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193 flows resulting from disturbances associated with land use change, timber harvesting, and wildfire

194 were based on values from Don *et al* (2011), Selmants *et al* (2017), and Daniel *et al* (2018).

2.4 CO$_2$ fertilization effect

196 Increasing atmospheric CO_2 concentrations stimulate leaf-level photosynthesis, potentially increasing

197 NPP as well (Franks *et al* 2013). However, the magnitude and persistence of this effect is highly

198 uncertain, particularly across a range of climatic conditions and over long time spans (Walker *et al*

199 2020). Following Sleeter *et al* (2019), we developed a separate set of scenarios designed to test the

200 sensitivity of LUCAS model projections of ecosystem carbon balance to different rates of a CO_2

201 fertilization effect (CFE). We incorporated a CFE multiplier for NPP that represented the percent

202 increase in NPP for every 100 ppm increase in atmospheric CO_2 concentration under the high land

203 use and high radiative forcing (RCP 8.5) scenario. We tested five CFE levels ranging from 5% to

204 15%, which is within the range of CFEs observed in free air CO_2 enrichment (FACE) experiments.

205 For all levels, we assumed CFEs reached saturation at an atmospheric CO_2 concentration of 600 ppm,

206 with no further stimulation of NPP despite a continued increase in CO_2 concentration to 930 ppm by

207 2100. This 600 ppm threshold generally coincides with the upper limit from FACE experiments and

208 is reached by the year 2060 under RCP 8.5.

2.5 Scenario simulations and analysis

210 Each of the four unique scenarios were run for 90 years at an annual timestep and repeated for 30

211 Monte Carlo realizations, using initial conditions corresponding to the year 2010. All simulations

212 were performed within the SyncroSim (version 2.2.4) software framework with ST-Sim (version

213 3.2.13) and SF (version 3.2.10) add-on modules (Daniel *et al* 2016, 2018). Model inputs and outputs

214 were prepared with the R statistical computing platform (R Core Team 2019) using the tidyverse

215 (Wickham *et al* 2019), raster (Hijmans 2020), and rsyncrosim (Daniel *et al* 2020) packages. Carbon

216 stocks and fluxes for the seven main Hawaiian Islands were calculated for each scenario by summing

217 within each Monte Carlo realization on an annual basis and then calculating annual means as well as

218 the annual upper and lower limits of the 30 Monte Carlo realizations. Carbon balance for the seven

219 main Hawaiian Islands was calculated on annual basis for each scenario and Monte Carlo realization

220 as net biome productivity (NBP), which was equal to annual carbon input in the form of NPP minus

221 the annual sum of all carbon losses from terrestrial ecosystems, including heterotrophic respiration

222 (R_h) from litter and soil, carbon fluxes to the atmosphere triggered by land use and land use change,

223 wildfire emissions, and aquatic carbon losses through leaching and overland flow. Positive NBP

224 values indicated ecosystems of the seven main Hawaiian Islands were acting as a net sink for

225 atmospheric CO_2, while negative NBP values indicated that these ecosystems were acting as a net

226 carbon source to the atmosphere (Chapin *et al* 2006).

3. Results

3.1 Carbon stocks and fluxes

229 Terrestrial ecosystems of the seven main Hawaiian Islands stored an estimated 316 Tg of carbon at

230 the beginning of the simulation period in 2010 (figure 2a), with 58% in soil organic matter, 22% in

231 living biomass, and 20% in surface dead organic matter (litter and dead wood; figure 2b). Ecosystems

232 accumulated carbon in all scenarios but at different rates, with trajectories shaped primarily by

233 climate change and to a lesser extent by land use change. The highest and most consistent projected

234 accumulation of ecosystem carbon occured under the combination of low radiative forcing and low

235 land use change, yielding a ~15% increase in ecosystem carbon to an average of 363 Tg by 2100

236 (figure 2a). In contrast, high radiative forcing and high land use change resulted in the lowest

237 ecosystem carbon gain, reaching a peak of ~332 Tg in 2063 and a decline to 327 Tg in 2100, resulting

238 in a net increase of only 3% by the end of the simulation period (figure 2a). Ecosystem carbon

239 accumulation was driven exclusively by increasing soil organic carbon across all four scenarios, all

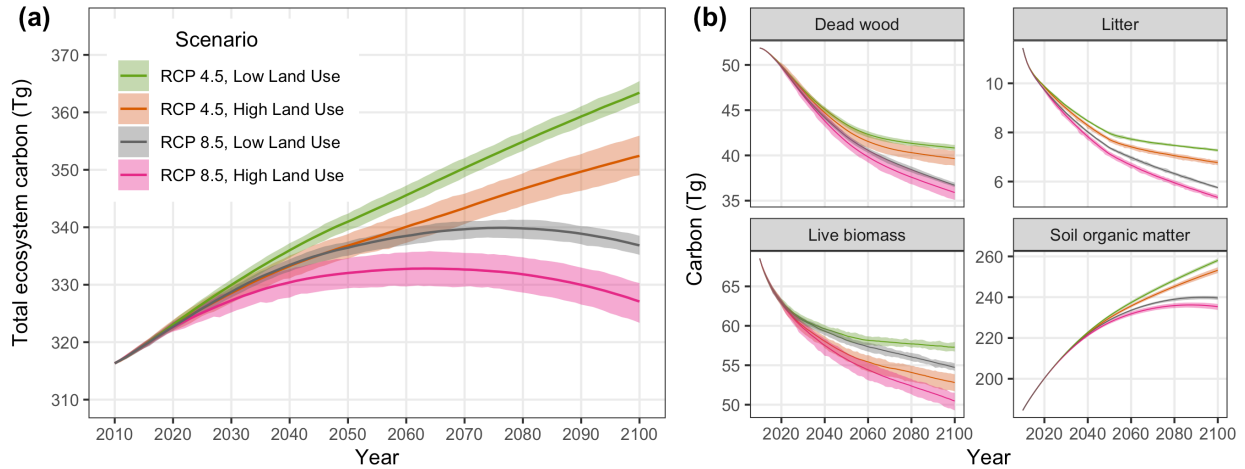240 other stocks declined over time (figure 2b).

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Figure 2: Projected changes in total ecosystem carbon storage (a) and individual carbon stocks (b) for the seven main Hawaiian Islands. Solid lines indicate the mean of 30 Monte Carlo realizations for each scenario, with shaded areas indicating the minimum and maximum range of Monte Carlo realizations.

Net primary production (NPP) for the seven main Hawaiian Islands declined across all four scenarios, driven primarily by climate change and to a lesser extent by land use change (Fig. 3). The combination of high radiative forcing (RCP 8.5) and high land use change led to the steepest decline in NPP over time, driven by intense long-term drying on the leeward sides of islands under RCP 8.5 (supplemental figure 4) and sustained losses of forest and shrubland land area in the high land use scenario (supplemental figure 5). In contrast, climate change led to increased heterotrophic respiration (R_h) over time, such that more intense warming under RCP 8.5 (supplemental figure 4) resulted in R_h being ~ 3% higher by 2100 than under RCP 4.5 (figure 3). Heterotrophic respiration declined substantially over time in the high land use scenario (figure 3) because of long-term reductions in forest and shrubland land area (supplemental figure 5), similar to trends in NPP. Transition-triggered carbon fluxes to the atmosphere from land use, land use change, and wildfire were largely independent of changes in climate, stabilizing by mid-century at an average of ~0.4 Tg y^{-1} in the high land use scenario and ~0.2 Tg y^{-1} in the low land use scenario (figure 3). Uncertainty around transition-triggered carbon fluxes were higher in the high land use scenario, driven primarily by greater variability in wildland fire probabilities.

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Figure 3: Projected changes in net primary production (NPP), heterotrophic respiration (Rh) and carbon fluxes induced by land use and land use change for the seven main Hawaiian Islands. Solid lines indicate the mean of 30 Monte Carlo realizations for each scenario, with shaded areas indicating the minimum and maximum range of Monte Carlo realizations.

3.2 Ecosystem carbon balance

Net biome productivity (NBP) averaged approximately 0.6 Tg C y^{-1} at the start of the simulation period and declined over time in all four scenarios (figure 4). On average, terrestrial ecosystems of the seven main Hawaiian Islands collectively acted as a net carbon sink throughout the simulation period under the RCP 4.5 radiative forcing scenario, but carbon sink strength was ~40% lower in the high land use scenario compared to the low land use scenario by the end of the simulation period (figure 4). In contrast, ecosystems of the Hawaiian Islands acted as a net carbon source to the atmosphere toward the latter half of the simulation period under RCP 8.5, with the transition from sink to source occuring 15 years earlier on average in the high land use scenario than in the low land use scenario (figure 4). The high land use scenario under RCP 8.5 represented a ~40% larger net source of carbon to the atmosphere by the year 2100 than the low-land use scenario under the same radiative forcing. Over the entire simulation period, both global emissions reductions and local avoided land conversion resulted in substantial increases in cumulative NBP (figure 5). However, switching from RCP 8.5 to RCP 4.5 increased cumulative NBP in the Hawaiian Islands more than twice as much as reducing emissions from local land use change and wildfire disturbance (figure 5). Switching from RCP 8.5 to RCP 4.5 under the low land use scenario yielded the greatest cumulative increase in NBP, resulting in a median gain of 26.5 Tg of carbon over the entire 90-year simulation period.

3.3 CO$_2$ fertilization effect

Projected estimates of both total ecosystem carbon storage and ecosystem carbon balance were highly sensitive to differing rates of a CFE on plant productivity. Under the high radiative forcing (RCP 8.5) and high land use scenario, the inclusion of a CFE ranging from 5-15% led to ~33-98 Tg of additional carbon storage in ecosystems by the end of the century, a ~10-30% increase (figure 6a). Compared to the reference scenario (0% CFE), a 5% CFE was sufficient to transform Hawaiian Island ecosystems from a net carbon source to the atmosphere during the latter half of the 21st century (figure 4b) to a net carbon sink for the entire simulation period (figure 6b), completely offsetting all other carbon

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Figure 4: Projected changes in net biome productivity (NBP) for the seven main Hawaiian Islands. Values above zero indicate terrestrial ecosystems are acting as a net carbon sink for atmospheric carbon and values below zero indicate ecosystems are acting as a net carbon source to the atmosphere. Solid lines indicate the mean of 30 Monte Carlo realizations for each scenario, with shaded areas indicating the minimum and maximum range of Monte Carlo realizations. The dashed horizontal line in each panel represents the boundary between ecosystems acting as a net carbon sink (positive NBP values) and a net carbon source (negative NBP values).

Figure 5: Projected changes in cumulative net biome productivity (NBP) for the seven main Hawaiian Islands when switching from the high to low land use change scenario under each radiative forcing scenario (top panel) and when switching from the high (RCP 8.5) to low (RCP 4.5) radiative forcing scenario under each land use scenario (bottom panel). Box plots indicate the median (vertical black line), 25th and 75th percentiles (colored boxes), 10th and 90th percentiles (thin horizontal lines), and values outside of this range (black circles). Note the different x-axis scales in each panel.

281 losses induced by high radiative forcing and high land use. Net carbon sink strength was further

282 enhanced at higher CFE rates, with NBP increasing by an average of 0.07 Tg C y^{-1} for each 1%

283 increase in CFE (figure 6b). When compared to other scenarios, applying a 5% CFE to the high

284 radiative forcing and high land use scenario resulted in a mean annual NBP of 0.46 ± 0.3 Tg C y^{-1},

285 roughly equivalent to mean annual NBP in the low radiative forcing and low land use scenario with

286 no CFE (0.52 ± 0.12). A 15% CFE applied to the high radiative forcing and high land use scenario

287 resulted in a mean annual NBP of 1.18 ± 0.29 Tg C y^{-1}, more than double that of the low radiative

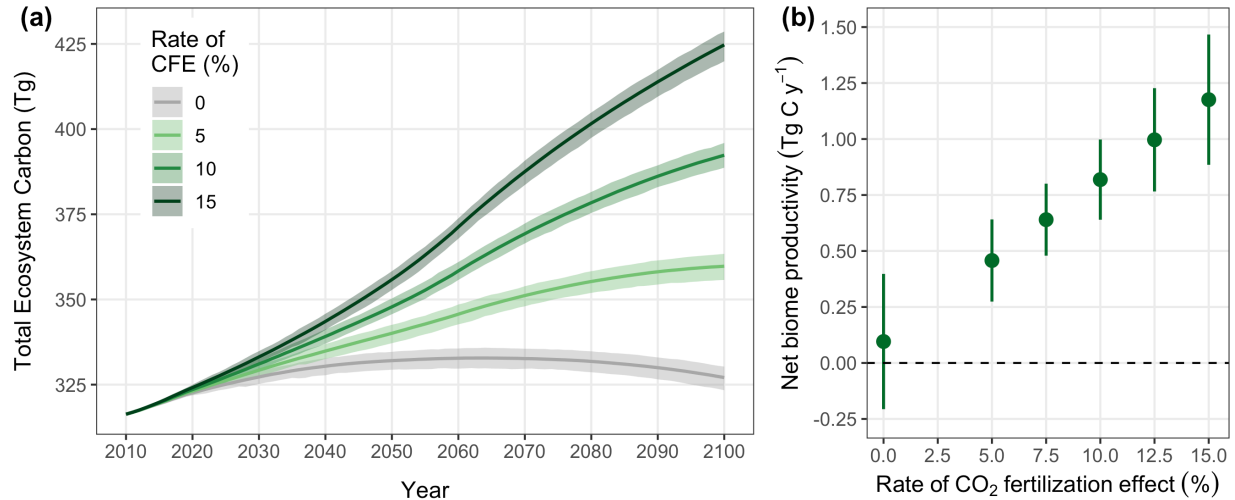288 forcing and low land use scenario with no CFE.

Figure 6: Sensitivity of projected changes in total ecosystem carbon storage (a) and mean annual net biome productivity (b) to different rates of carbon dioxide fertilization in the seven main Hawaiian Islands under the RCP 8.5 radiative forcing and high land use scenario. The carbon dioxide fertilization effect (CFE) is the percent change in net primary productivity (NPP) for every 100 ppm increase in atmospheric carbon dioxide. The CFE for all rates is capped at 600 ppm, which is achieved around the year 2060. Solid lines in (a) indicate the mean total ecosystem carbon storage across 30 Monte Carlo realizations for each CFE rate, with shaded areas indicating the minimum and maximum range of Monte Carlo realizations. Solid circles in (b) represent mean annual net biome productivity averaged across all years and Monte Carlo realizations for each CFE rate, with vertical lines indicating the standard deviation of the mean. The dashed horizontal line in (b) represents the boundary between ecosystems acting as a net carbon sink (positive NBP values) and a net carbon source (negative NBP values).

4. Discussion

We estimated that terrestrial ecosystems of the Hawaiian Islands have been a consistent net sink for atmospheric carbon over the last decade (figure 4). For the time period 2011-2019, net biome productivity (NBP) averaged 0.64 TgC y^{-1} and ranged from 0.46 to 0.88 TgC y^{-1} across all scenarios. Based on this mean annual NBP estimate, Hawaiian terrestrial ecosystems offset approximately 13% of 2015 statewide CO_2 emissions from energy production and transportation (5.04 TgC), the State of Hawai'i's largest source of greenhouse gas emissions (State of Hawai'i 2019). Future projections indicate Hawaiian terrestrial ecosystems will continue to be a net sink for atmospheric carbon if global CO_2 emissions peak around 2040 and then decline (RCP 4.5), and that carbon sink strength can be further enhanced by reducing the intensity and extent of future land use change. If, however,

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global CO_2 emissions continue to rise throughout the 21st century (RCP 8.5), our projections indicate Hawaiian ecosystems will transition from a net sink to a net source of CO_2 to the atmosphere, with high levels of land use change accelerating this transition and exacerbating net carbon loss. Our model results also indicate that projections of ecosystem carbon balance are highly sensitive to the introduction of a CFE. Even a 5% increase in NPP for every 100ppm increase in atmospheric CO_2 was sufficient to completely offset all other carbon losses induced by the high radiative forcing and high land use scenario, maintaining Hawaiian Island ecosystems as a net carbon sink for the entire simulation period instead of transitioning to a net carbon source by mid-century. Reconciling the high uncertainty surrounding the response of net photosynthesis to rising atmospheric CO_2 is essential to more realistically constrain model projections of ecosystem carbon balance.

4.1 Impact of different climate and land use pathways

By comparing ecosystem carbon balance estimates under different scenario combinations, we were able to assess the relative impact of both global emissions reductions and regional actions to reduce emissions from land use, land use change, and wildland fire (figure 5). Global adherence to a lower emissions trajectory (i.e., switching from RCP 8.5 to RCP 4.5) had the largest impact, resulting in a median cumulative increase of 26 Tg C sequestered by Hawaiian ecosystems over the 90-year simulation period. Long-term reductions in the intensity of land use change also consistently led to an increase in ecosystem carbon sequestration, but to a lesser degree than global emissions reductions. Switching from the high to the low land use scenario resulted in a median cumulative retention of an additional 11.6 Tg C in Hawaiian ecosystems by 2100. The combination of global climate mitigation and local reductions in land use conversion had the largest potential benefit to ecosystem carbon sequestration, reducing cumulative net losses by over 400% (37.7 Tg C). Notably, the relative impact of reducing emissions from land use change was much greater under the high radiative forcing pathway (RCP 8.5). Cumulative NBP increased by 130% when switching from the high to low land use scenario under RCP 8.5, as opposed to a 37% cumulative increase in NBP when switching from high to low land use under RCP 4.5. These results demonstrate that reducing ecosystem carbon losses

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325 from land use change, harvest, and wildland fire can be an important component of greenhouse gas

326 reduction efforts by sub-national jurisdictions like the State of Hawaiʻi, regardless of the global

327 emissions trajectory. These results also highlight the utility of Hawaiʻi's multi-pronged approach of

328 participating in global climate mitigation efforts by reducing emissions from the energy and

329 transportation sectors while also reducing land use emissions to minimize positive feedbacks to the

330 climate system.

331 *4.2 Comparison to other studies*

332 There are few estimates of contemporary ecosystem carbon balance for the main Hawaiian Islands,

333 and even fewer model projections of future ecosystem carbon balance in response to climate and land

334 use change. Our mean annual NBP estimate of 0.64 TgC y^{-1} for the period 2011-2020 agrees well

335 with a recent State of Hawaiʻi Greenhouse Gas Inventory report, which estimated an annual net

336 carbon sink of 0.66 Tg C in 2015 from agriculture, forestry, and other land uses (State of Hawaiʻi

337 2019). In contrast, our NBP estimate for the past decade was ~ 88% higher than a previous statewide

338 LUCAS model estimate covering the same time period (0.341 Tg C y^{-1}; Selmants *et al* 2017). This

339 discrepancy was likely driven by modifications in how we calculated NPP, soil R_h, and soil aquatic

340 carbon loss compared to previous versions of the LUCAS model, as well our model's finer spatial

341 resolution (Selmants *et al* 2017, Daniel *et al* 2018). Previous versions of a Hawaiʻi LUCAS model

342 were run at 1-km spatial resolution and simulation cells within each unique combination of moisture

343 zone and state type all had the same mean IBIS-derived NPP value applied to them at the beginning

344 of the simulation period. In contrast, our NPP estimates at 250-m spatial resolution were adjusted on

345 a cell-by-cell basis using Hawaiʻi-specific climate data as described in section 2.3. As a result, our

346 statewide NPP estimates from 2011-2020 were 9.5% lower on average than previous LUCAS model

347 estimates for Hawaiʻi during the same time period (Selmants *et al* 2017), likely because of the greater

348 influence of more arid simulation cells. Soil carbon losses via R_h, leaching, and overland flow in

349 previous versions of the LUCAS model were calculated as the ratio of the IBIS-derived flux to the

350 size of the originating carbon stock, in this case soil organic carbon to 1-m depth (Daniel *et al* 2018).

Here we calculated soil R_h and aquatic carbon losses as the ratio of the mean IBIS-derived flux to the microclimate-adjusted NPP value of each simulation cell, which is a more realistic driver than stock size (Jackson *et al* 2017). Compared to previous Hawai'i LUCAS model estimates (Selmants *et al* 2017), soil R_h and aquatic carbon losses from 2011-2020 were reduced by an average of 15% and 21%, respectively, which widened the gap between between carbon gain (NPP) and carbon losses and accounted for the overall increase in NBP estimates for this time period.

4.3 Limitations of this study

There is ample evidence that increasing atmospheric CO_2 concentrations can stimulate NPP (Norby *et al* 2005, Zhu *et al* 2016), but the magnitude and persistence of this effect remains highly uncertain (Franks *et al* 2013, Walker *et al* 2020). Our results demonstrate that long-term projections of ecosystem carbon balance are highly sensitive to uncertainty in CFE strength. With no CFE, Hawaiian ecosystems became a net source of CO_2 to the atmosphere beginning in the latter half of the 21st century under the high land use and high radiative forcing scenario. However, a CFE equivalent to a 5% increase in NPP for every 100 ppm increase in atmospheric CO_2 applied to the same scenario resulted in Hawaiian ecosystems remaining a net carbon sink throughout the entire simulation period. A 15% CFE applied to the high land use and high radiative forcing scenario resulted in a nearly 5-fold increase in mean annual NBP averaged across all years and Monte Carlo realizations. Despite this demonstrated sensitivity to a CFE, several potentially attenuating factors complicate the selection of a realistic CFE value with any degree of confidence (Walker *et al* 2020). Nitrogen and phosphorus limitation can reduce or eliminate a CFE (Reich *et al* 2006, Norby *et al* 2010, He *et al* 2017, Terrer *et al* 2019), as can water limitation and heat stress (Obermeier *et al* 2017, Birami *et al* 2020). Forest age may also be a factor, with young aggrading forests showing a strong positive growth response to CO_2 fertilization (Walker *et al* 2019), while old-growth forests show little to no response (Jiang *et al* 2020, Yang *et al* 2020). This evidence indicates that a CFE may be highly variable across space and time, suggesting it may be unrealistic to apply a single CFE rate value across an entire region over several decades. Until mechanistic understanding is improved, the most conservative approach when

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377 projecting future ecosystem balance in the context of climate mitigation planning may be to assume

378 no CFE, with the knowledge that any realized CFE will only enhance ecosystem carbon sequestration.

379 Our model does not currently differentiate between forests dominated by native versus non-native tree

380 species, which could influence estimates of ecosystem carbon balance. Native forests in the Hawaiian

381 Islands are dominated by ʻōhiʻa (*Metrosideros polymorpha* Gauditch), an endemic foundational tree

382 species found across a broad range of climatic and edaphic conditions (Ziegler 2002). Beginning in

383 2010, a fungal disease termed Rapid ʻŌhiʻa Death (ROD) caused by two *Ceratocystus* spp. has

384 emerged and caused widespread mortality to mature ʻōhiʻa trees across a range of size classes,

385 primarily on Hawaiʻi Island (Mortenson *et al* 2016, Fortini *et al* 2019). The distribution and potential

386 range of this emerging threat to Hawaiʻi's dominant native tree species have only recently been

387 mapped (Vaughn *et al* 2018, Fortini *et al* 2019), but the pulse of newly dead organic matter and

388 reduction in photosynthetic capacity induced by widespread tree mortality could significantly alter

389 ecosystem carbon balance over the long-term (Sleeter *et al* 2019). ROD-affected forests could also

390 undergo a replacement of canopy dominant stress-tolerating ʻōhiʻa trees by non-native tree species

391 with faster relative growth rates, lower wood density, and faster tissue turnover, potentially altering

392 the long-term trajectory of carbon cycling in Hawaiian forest ecosystems. New model projections for

393 Hawaiʻi that incorporate ROD spread rates and forest restoration scenarios will therefore require

394 differentiation among forest ecosystems dominated by native and non-native tree species.

395 Interannual climate variability is a primary factor influencing spatial and temporal patterns of global

396 wildland fire activity (Abatzoglou *et al* 2018), with climate warming expected to increase wildland

397 fire frequency and wildfire season length across a wide range of biomes (Sun *et al* 2019). Although

398 our model projections capture the spatial and temporal variation in ignition probability and fire extent

399 by sampling from previous fire years (1999-2019), we did not incorporate the effects of projected

400 future climate change on the frequency and extent of wildland fire. Recent fire probability modeling

401 for the northwest portion of Hawaiʻi Island indicated that projected drying and warming trends under

402 RCP 8.5 could increase maximum fire probability values more than three-fold and shift areas of peak

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flammability to higher elevation by mid-century (Trauernicht 2019). Extending this probability fire modeling approach statewide would provide a quantitative, spatially explicit assessment of wildland fire probability for the main Hawaiian Islands as predicted by climate, land cover, and ignition density, which is highly correlated with population density (Trauernicht *et al* 2015, Trauernicht 2019). This approach would provide future simulation model projections of Hawaiian ecosystem carbon balance with more realistic scenarios of expected annual area burned based on the integrated effects of future climate and land use change.

5. Conclusion

Although terrestrial ecosystems are currently an important sink for atmospheric CO_2, the future direction and magnitude of the land carbon sink are highly uncertain, especially at regional scales. Our simulation modeling results indicated that projected climate change, dictated by long-term trajectories in global greenhouse gas emissions, was the primary factor influencing terrestrial ecosystem carbon balance in the Hawaiian Islands. Long-term reductions in the intensity of land use change and wildland fire also consistently led to an increase in ecosystem carbon sequestration, but to a lesser degree than global emissions reductions. CO_2 fertilization of NPP was the largest source of uncertainty in long-term projections of ecosystem carbon balance in the Hawaiian Islands, highlighting the need for greater mechanistic understanding of the cascading effects of rising atmospheric CO_2 on ecosystem carbon sequestration. By incorporating the interactive effects of land use and climate change into future projections of ecosystem carbon balance, our model results could be used as a set of baseline projections for the State of Hawaiʻi to evaluate different ecosystem-based climate mitigation strategies. Studies like ours that incorporate stochasticity into spatially explicit simulation models could also provide a framework for the growing number of sub-national jurisdictions that plan to incorporate ecosystem carbon sequestration into their emissions reduction efforts. These long-term projections will be critical to understanding how future land use and climate-biosphere feedbacks could influence the achievement of climate mitigation goals.

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Data and code availability

Tabular model output data and metadata are available in machine readable format from the USGS ScienceBase data repository at https://doi.org/10.5066/P9AWLFKZ. Model input data and R code used to format input data, summarize output data, and compile this manuscript are available from a GitHub repository at https://github.com/selmants/HI_Model.

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