Human Footprint Affects US Carbon Balance More Than Climate Change

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Glossary

A1B see SRES in the succeeding text
A2 see SRES in the succeeding text
B1 see SRES in the succeeding text
LandCarbon USGS biologic carbon sequestration assessment program (https://www2.usgs.gov/climate_landuse/land_carbon/)
MC2 second version (in C++) of the dynamic global vegetation model created by linking the CENTURY biogeochemistry model and the MAPSS biogeography model (http://bit.ly/2a9TrKD)
NFS no fire suppression, that is, potential vegetation without human intervention
RCP representative concentration pathways (RCP 8.5 causes an 8.5 W m^{-2} radiative forcing by 2100).
SRES Special Report on Emissions Scenarios (A1B for rapid economic growth, A2 for regionally oriented economic development, and B1 for global environmental stability)
LU land use and fire suppression

Abbreviations

C	Carbon
C3 or C4	Photosynthetic pathways
CMIP3 or CMIP5	Third and fifth Coupled Model Intercomparison Project
CONUS	Conterminous United States
DGVM	Dynamic global vegetation model
ESM	Earth system model
GCM	General circulation model
IPCC	Intergovernmental Panel on Climate Change
LU	Land use
NBP	Net biological production
NEP	Net ecosystem production
NPP	Net primary production

Introduction

Before the large-scale settlement of the North America by Europeans, ecosystems across the conterminous United States (CONUS) ranged from temperate rain forests in the Pacific Northwest to grasslands in the central Great Plains, with conifer and deciduous forests in the eastern mountains and plains (Kuchler, 1964; Bailey, 1995; Olson et al., 1983). Maintained by climate and disturbance regimes including Native Americans and lightning fires (Allen, 2002; Covington and Moore, 1994; Romme, 1982; Keane et al., 2007), vegetation characteristics (such as type, structure, rate of primary production, and successional stages) varied over space and time creating a diverse and resilient patchwork (Landres et al., 1999; Morgan et al., 1994; White and Walker, 1997).

Today, historical vegetation cover has been either replaced or modified by land use such as agriculture, urban development, and managed forestry and by fire suppression and the introduction of exotic invasives with effects on biodiversity, fire regimes, and carbon balance (e.g., Gitay et al., 2001; Neilson et al., 2005).

To mitigate these effects, policies and land management objectives for many of the US public lands, including lands managed by the Department of the Interior and Agriculture, have been proposed and put in place to protect, manage, and restore natural vegetation, habitats, and ecosystem conditions. Examples include the Endangered Species Act (28 Dec. 1973), the Wilderness Act (3 Sep. 1964), the Coastal Wetlands Planning, Protection, and Restoration Act (1990), and the sustainable forest management criteria and indicators (Montréal Process, 2009). Policies and practices in common have focused on the protection, management, and restoration of "natural" vegetation with reduced or removed human land use (Forest Stewardship Council, 2015; American Forest and Paper Association, 1993; Coulombe and Brown, 1999) generating a gradient of management objectives across national parks, national wildlife refuges, wilderness areas, and national forests.

In this paper, we report key results of a modeling exercise conducted to evaluate the potential effect of regional-scale differences between potential natural vegetation and contemporary land use on carbon balance across the CONUS (LandCarbon project, Zhu et al., 2010). This study was in partial fulfillment of the requirements by the Energy Independence and Security Act (EISA; US Congress, 2007) to evaluate policy-relevant carbon sequestration capacity and the potential for increasing sequestration in natural and managed ecosystems through management or restoration activities. By comparing simulated carbon stocks and balance of natural vegetation with that of land use scenarios, the potential carbon cost of contemporary and future land use and the potential carbon benefits of protecting, managing, and restoring natural vegetation may be evaluated. We also report more regional results for the state of California, this time using more recent climate change and land use scenarios but again evaluating the influence of humans versus climate on ecosystem processes.

To simulate the effects of land use on the carbon cycle, we used the MC2 model, which was developed and calibrated to take into account the role of fire in shaping US landscapes (Sheehan et al., 2015; Bachelet et al., 2015). The model was originally designed to simulate large domains such as the CONUS using a set of biogeography rules that would be general enough to allow reasonable simulations of vegetation distribution across the entire country. The CENTURY biogeochemistry core was used because its coarse temporal resolution (monthly) allows projections across centuries and because it balances equally above- and belowground processes without emphasizing aboveground physiology at the expense of the lesser-known belowground dynamics. The dynamic fire model developed for MC2 was the first of its kind to use process rather than correlations to determine when a fire occurred and how it might affect C cycle and vegetation dynamics. Land use and management were simulated for this project in a very simple way, but it followed a similar approach that earth system models (ESMs) used for the IPCC (2013). While well aware of the limitations of such oversimplification of complex agricultural land practices, we believe this was a valuable step in the direction of teasing out the role of human actions on C cycling from climate change direct and indirect (fire) effects.

Methods

MC2, the C++ version of its predecessor MC1, is a dynamic global vegetation model (DGVM) that simulates vegetation dynamics and produces monthly estimates of carbon, nitrogen, water pools and fluxes, as well as wildfire occurrence and effects (Bachelet et al., 2015; Sheehan et al., 2015). Because it was originally designed to run from continental to global scales, each grid cell is simulated independently with no cell-to-cell communication. However, drought conditions that trigger simulated wildfires often occur region-wide, resulting in similar fire effects across contiguous cells. The model always simulates competition between woody and herbaceous life-forms. For reasons of global scalability, MC2 does not simulate individual species, although crosswalk tables have been created to match species with MC2 plant functional types for regional/local studies (Creutzburg et al., 2015; Turner et al., 2015).

Biogeography Module

The biogeography module simulates vegetation types, each composed of a mixture of two life-forms, herbaceous and woody, the relative dominance of which varies as a function of climatic conditions. Woody life-forms include evergreen and deciduous needleleaf, evergreen and deciduous broadleaf trees and shrubs. Herbaceous life-forms include C3 (cool or temperate) and C4 (warm or subtropical) grasses (the term grass includes forbs and sedges).

The woody life-form is determined annually as a function of the minimum temperature of the coldest month and growing season precipitation smoothed over 15 years. The smoothing progressively enhances the legacy effect of existing vegetation and denotes the inertia of vegetation to short-term climate variability (Daly et al., 2000). Herbaceous life-forms are determined from the ratio of C3/C4 grass productivity, which depends on the temperature of the growing season, also smoothed over 15 years. Warmer temperatures favor C4 grasses. The balance between woody and herbaceous is determined by simulating competition for light, water, and nutrients, as mediated by fire. Vegetation types are defined by a combination of woody and herbaceous life-forms with biomass and climate thresholds (Tables A1–A3).

Biogeochemistry Module

The biogeochemistry model is a modified version of the CENTURY model (Metherell et al., 1993) that simulates carbon and nitrogen cycling between plant parts, multiple classes of litter, and three soil organic matter pools. Production rates vary between life-forms and are constrained by temperature, soil available water, and atmospheric CO_2 (Bachelet et al., 2001). Self-shading is simulated for woody and herbaceous life-forms; trees can also shade grasses. Soil temperature, which affects production and decomposition, is constrained by canopy shading (Parton et al., 1994). This module also simulates actual and potential evapotranspiration and soil water content in multiple soil layers, the number of which depends on total soil depth (input to the model).

Fire Module

The fire module simulates occurrence, behavior, and effects of fire by including a set of mechanistic fire behavior and effects functions (Rothermel, 1972; Peterson and Ryan, 1986; Van Wagner, 1993). Live and dead fuel loads in 1, 10, 100, and 1000 h fuel classes are estimated from carbon pools. Allometric functions relate woody carbon pool sizes to height, crown base height, and bark thickness to determine when crown or surface fires occur and to project mortality and/or biomass consumption by fire and resulting emissions.

Daily moisture content of fuel classes and potential fire behavior are calculated based on pseudodaily climate data interpolated from monthly inputs. Moisture content of plant parts determines live fuel moisture contents. A combination of the Canadian Fine Fuel Moisture Code (FFMC; Van Wagner and Pickett, 1985) and the National Fire Danger Rating System (Bradshaw et al., 1983) is used to estimate dead fuel moisture contents.

Potential fire behavior (including rate of spread) is calculated based on daily fuel loads, moisture contents, and weather, modulated by vegetation type for each grid cell, which affects fuel properties and realized wind speeds. Fire occurs once a year for each grid cell, when the calculated rate of spread is greater than zero and FFMC and buildup index (inverse functions of fine fuel and coarser fuel moisture contents, respectively) from the Canadian fire weather index system are exceeded.

Rogers et al. (2011) simulated intentional fire suppression by humans using thresholds for three fire intensity metrics (rate of spread, fireline intensity, and energy release component) that can be calibrated for each domain of interest (King et al., 2013).

Protocol to Run the Model (Tables A5.1 and A5.2)

The DGVM runs in three distinct phases. First, the static biogeography model MAPSS (Neilson, 1995) uses one year of average monthly mean climate (1895–1924) to generate a map of potential vegetation distribution. MAPSS assumes that steady state occurs when all the soil available water is used up during the driest month of the year. During the second part of the *MC2 equilibrium phase*, the DGVM biogeochemistry module uses iteratively the same average climate (1895–1924) to calculate the size of carbon and nitrogen pools associated with the vegetation types while allowing for prescribed vegetation-specific fire return intervals. The equilibrium phase ends when the resistant soil carbon pool size changes by $< 1\%$ annually. Consequently, the duration of this phase varies across the grid depending on the type of vegetation cover (from a few decades in the Great Plains grasslands up to 3000 years in the rain forests of the Pacific Northwest).

During the second, *MC2 spin-up phase*, the model is run iteratively using a detrended monthly historical climate time series (1895–2009) to capture the interannual variability and allow for readjustments of vegetation type and carbon pool sizes in response to dynamic wildfires. The time series is adjusted such that the climate variable means match the first 30 years of the historical period and allow for a smooth transition between spin-up and transient historical climate. The spin-up phase ends when the net biological production (NBP; net ecosystem production (NEP) minus carbon consumed by wildfire) oscillates near zero ($\sim$600–1500 years).

During the third, *MC2 transient phase*, the model is run with the time series of historical climate data and then with future climate projections from climate models.

Model Inputs

The MC2 model requires annual atmospheric CO_2 concentrations associated with both historical and future emission scenarios. It also requires soil depth, texture, fraction of rock fragments, and bulk density (Table A4). Climate inputs include monthly precipitation and vapor pressure or dew point temperature, daily maximum, and minimum temperatures averaged for each month. The model can also use land use data and projections combining MC2-generated potential vegetation categories for natural areas with categories including mining, developed (urban) areas, agriculture, and managed forests. Management practices are prescribed based on the land use type, and fire suppression is assumed (**Table 1**).

Table 1 Land use simulation to the vegetation model MC2

USGS land use categories	*MC2 protocol*
Water	Masked
Developed	Complete harvest monthly
Mechanically disturbed national forests	First year of the mechanical disturbance, complete harvest, then recovery (MC2 default conditions)[a]
Mechanically disturbed other public lands	First year of the mechanical disturbance, complete harvest, then recovery (MC2 default conditions)[a]
Mechanically disturbed private lands	First year of the mechanical disturbance, complete harvest, then recovery (MC2 default conditions)[a]
Mining	Complete harvest monthly
Barren	
Deciduous forest	MC2 potential vegetation dynamics
Evergreen forest	MC2 potential vegetation dynamics
Mixed forest	MC2 potential vegetation dynamics
Grassland	MC2 potential vegetation dynamics
Shrubland	MC2 potential vegetation dynamics
Agriculture	Annual harvest
Hay pasture	Annual harvest
Herbaceous wetland	Masked
Woody wetland	Masked
Perennial ice and snow transitions	MC2 potential vegetation dynamics

[a]If any cell was classified as mechanically disturbed in the first year of a future time period, harvest was implemented only if the cell was not mechanically disturbed in the final year of the historical time period.

Table 2 Brief description of the LandCarbon scenarios analyzed with the MC2 dynamic global vegetation model

Scenario	*Fire suppression thresholds*	*Vegetation types*
Potential vegetation only	No thresholds	36 potential vegetation types
Potential vegetation with land use scenarios and simulated fire suppression	Rate of spread = 0.51 m s^{-1} (100 ft min^{-1}) Fireline intensity = 3.1 MW m^{-1} (900 Btu ft^{-1} s^{-1}) Energy release component = 0.68 MW m^{-2} (60 Btu ft^{-2} s^{-1})	36 potential vegetation types plus agriculture and pasture (harvested annually), mechanically disturbed forests (fixed harvest rotation), mining and developed (all carbon removed monthly)

Other Definitions

We report on two management settings (**Table 2**): (1) simulating potential vegetation with no fire suppression (NFS) and (2) simulating potential vegetation with land use and fire suppression (LU). Potential vegetation refers to types of natural vegetation that would exist, given local climate conditions and fire disturbance regime, without a human footprint.

In the LandCarbon project for the CONUS (Zhu et al., 2010), the model uses historical and contemporary (1895–2010) monthly climate (Daly et al., 2008) and land use conditions (Sleeter et al., 2012; Sohl et al., 2014) as well as 21st century projections (2011–2100). We used three SRES greenhouse gas emission scenarios (A2, A1B, and B1; Nakićenović et al., 2000) and three climate models from the third Coupled Model Intercomparison Project (CMIP3; Meehl et al., 2007) are CSIRO Mk3.5 (Gordon et al., 2010), CGCM3 (Flato et al., 2000), and MIROC 3.5 medres (Hasumi and Emori, 2004) (Tables A6 and A7.1). Climate projections are bracketing the projected range of temperature increase across the United States. For California, we used four climate model [CanESM2 (Arora et al., 2011), CCSM4 (Gent et al., 2011), CNRM-CM5 (Voldoire et al., 2013), and HadGEM2-ES (Collins et al., 2011)] projections from the fifth Coupled Model Intercomparison Project (CMIP5; Taylor et al., 2012) under the representative concentration pathway 8.5 (RCP 8.5; Meinshausen et al., 2011; Van Vuuren et al., 2011) (Tables A6 and A7.2). Climate models were chosen as most representative regionally based on specific needs of California water resource planning (O'Daly et al., 2015). Land use projections were designed to match the various emission scenarios.

Model Testing

We compared our results to a variety of published estimates of forest area, carbon pools, and fluxes (Tables A8 and A9). Carbon stock estimates vary and are defined many different ways by the authors, who do or not include litter in their estimates, rendering comparisons difficult, but simulated NEP values agreed well with the published estimates.

Results

Vegetation Dynamics

Over the CONUS, under all scenarios, increasing temperatures drive the replacement of most of the temperate (C3) grassland area by subtropical (C4) grasslands, which are characterized in the model by a warmer temperature optimum than C3, and alpine tundra disappears from mountain tops (not shown here). In the Interior West and the Great Plains, the model simulates tree and shrub expansion at the expense of the grasslands (Fig. 1A) as woody life-forms outcompete herbaceous life-forms when wildfires are suppressed and increased atmospheric CO_2 enhances water use efficiency of woody life-forms. Warmer-type forests are projected to expand in the southeast, including tropical forests at the southern end of the Florida peninsula (note that the model does not simulate sea-level rise). Along the Pacific coast, the model simulates the northward migration of warm mixed forests at the expense of cooler pure evergreen forests. When land use is imposed (Fig. 1B), climate-driven changes in vegetation distribution are a lot more limited, but the general trends toward woodier and warmer vegetation types are consistent across all scenarios. We find the exact same trends using the CMIP5 climate futures for the state of California (htttp://climateconsole.org).

Carbon Budget

Model results show regional increases and decreases in carbon stocks across the country (Fig. 1). Carbon stocks increase under warming conditions in all the areas where cold temperatures were the norm under historical conditions such as along mountain ranges and on high elevation plateaus. Decreases in live vegetation carbon appear in places such as Willamette Valley-Puget Trough ecoregion, the Rocky Mountains, the Great Lakes area, central Texas, and some eastern states particularly under the A2 scenario. Land use causes widespread declines in C stocks (Fig. 1B, Table 3), particularly in soils, on agricultural lands, and also on managed forestlands because harvests prevent soils to get the benefit of litter inclusion that occurs in natural systems.

We illustrate the importance of the climate model chosen to project future climate by showing carbon fluxes over the 21st century (Fig. 2). Terrestrial carbon fluxes result from differences between ecosystem productivity, soil respiration, fire effects, and harvest removals. Model results without land use do not show any significant trend in carbon fluxes but much year-to-year variability with large declines due to fire events. This variability in amplitude is much less pronounced with MIROC than with the two other climate models.

We summarized the simulated C budget for the state of California at the end of the 21st century for the three CMIP3 climate futures under the A2 emission scenario and the nine CMIP5 climate futures under the RCP 8.5 scenario with a series of simple cartoons (Fig. 3). With imposed land use, soil carbon is $\sim$10% lower than with potential vegetation. Even when fire suppression is imposed, the removal by harvest of material that, if left on-site, would have been incorporated in the litter and ultimately soil carbon pools causes an overall decrease in soil C stocks. Similarly, plant biomass is 10–20% lower when land use is imposed due to timber harvest and reduced woody expansion. Differences between a future under the A2 emission scenario and the RCP 8.5 emission scenario were minimal. In both cases, the carbon sequestration potential (NBP) is about 50% lower with land use.

Fire Occurrence and Effects

We simulated the area burned for the nine future scenarios in the LandCarbon project, and in almost all cases, it increased during the 21st century (Table 4). Under natural conditions (no land use), the model simulated a 27% increase between the second half of the 20th century and the first half of the 21st century but only a 15% increase in area burned between the second halves of the 20th and 21st century. With land use and fire suppression, the model simulated a 28% increase in area burned between the second half of the 20th century and the first half of the 21st century and an 88% increase in area burned between the second half of the 20th century and that of the 21st century. These counterintuitive results indicate that human actions on the landscape such as fire suppression can actually increase fire risk. This is particularly true in the western US where the proportion of federal land is large, while in the eastern US urbanization and agricultural expansion (plantations) restrict the impact of fire suppression on forest lands.

Model results show that regional differences are important. Fire in the model is limited by the amount of fuels available, their moisture content, and weather conditions. Rather than presenting a series of graphs showing how each climate model projections affects regional fire effects and consequently vegetation shifts and carbon stocks, we created a web tool where the user can toggle between different climate futures and see animated model results for the entire state of California over the 21st century (Fig. 4). As vegetation shifts from systems adapted to cooler environmental conditions to warmer types, the effects of fire may decrease. This is the case along the northwest coast of California where pure evergreen forests shift to a mixed type better adapted to drought. However, it is not the case in the Sierras where low-elevation forests move uphill replacing cooler types, but in this case, warmer conditions can cause more fires that facilitate the transition.

Discussion

The effect of land use on vegetation dynamics and resulting carbon cycle and fire regimes varies across the United States. Simulated northward shifts of eastern ecotones during the 21st century are driven by changes in climatic conditions but become almost invisible due to extensive land use. Simulated shifts in southwestern deserts between grass-dominated and shrub-dominated types

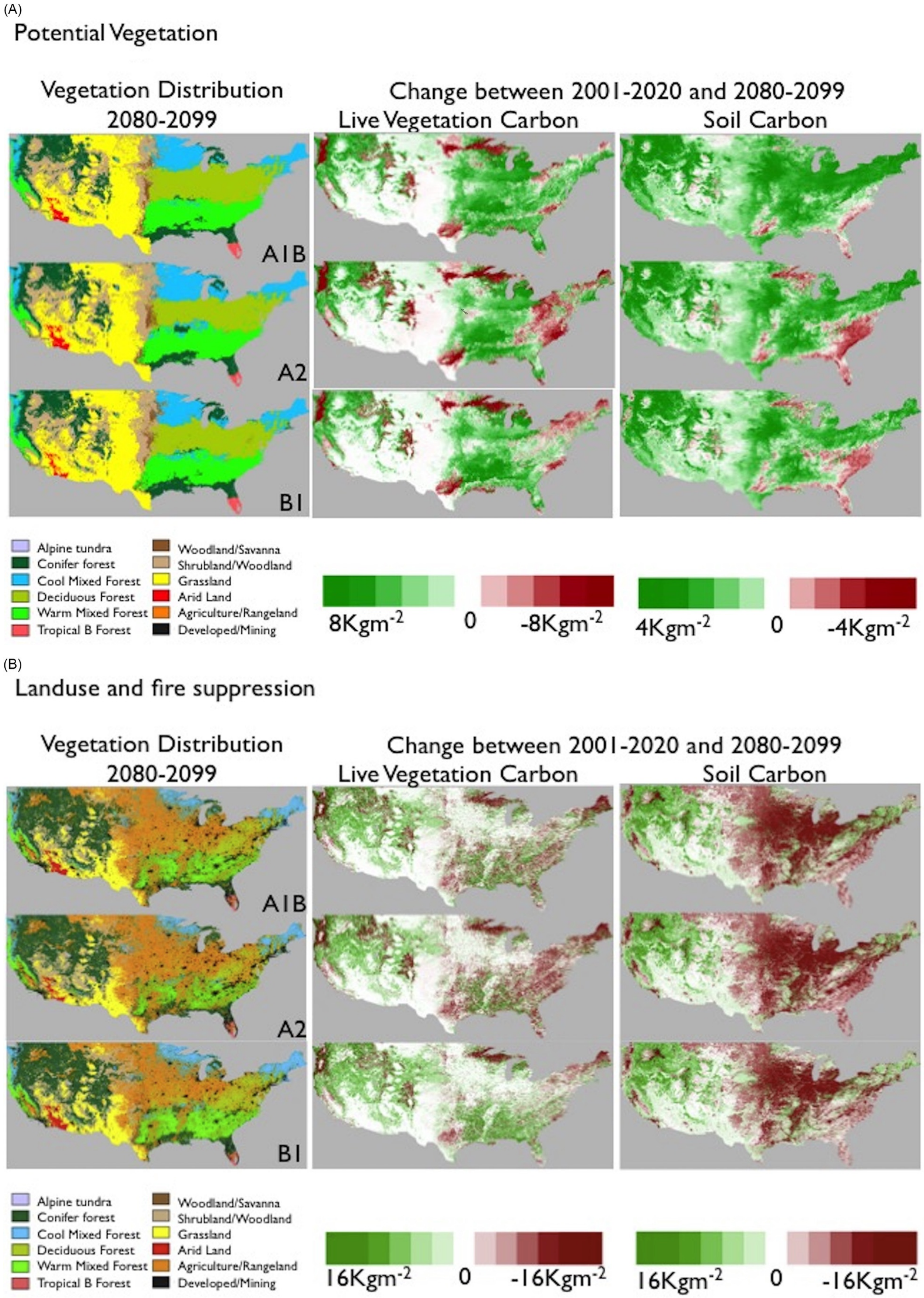

Fig. 1 Comparison of the change in vegetation distribution and carbon stocks in live vegetation and soil between potential vegetation (without fire suppression) and land use (with fire suppression) runs of the dynamic global vegetation model MC2 for the conterminous US averaged across 3 climate futures under the A2 emission scenario.

Table 3 Simulated soil carbon and live vegetation carbon stores for three emission scenarios used by three GCMs for the LandCarbon project

Potential vegetation with no fire suppression

		CONUS soil carbon (Pg C)			*CONUS vegetation carbon (Pg C)*		
1992–2005		82.1			37.5		
		CGCM3	CSIRO	MIROC	CGCM3	CSIRO	MIROC
2041–60	A1B	86.7	90.2	84.4	41.7	47.3	35.9
	A2	85.4	87.7	84.6	39.7	33.0	35.9
	B1	84.7	87.7	83.9	38.5	35.8	38.0
2081–2100	A1B	91.1	95.3	84.6	48.0	51.6	38.1
	A2	88.3	92.9	84.6	44.6	40.9	34.8
	B1	86.7	92.3	84.7	44.6	38.4	40.3

Potential vegetation with land-use and fire suppression

		CONUS soil carbon (Pg C)			*CONUS vegetation carbon (Pg C)*		
1992–2005		82.1			37.5		
		CGCM3	CSIRO	MIROC	CGCM3	CSIRO	MIROC
2041–60	A1B	86.7	90.2	84.4	41.7	47.3	35.9
	A2	85.4	87.7	84.6	39.7	33.0	35.9
	B1	84.7	87.7	83.9	38.5	35.8	38.0
2081–2100	A1B	91.1	95.3	84.6	48.0	51.6	38.1
	A2	88.3	92.9	84.6	44.6	40.9	34.8
	B1	86.7	92.3	84.7	44.6	38.4	40.3

are caused by precipitation variability. Whenever soil moisture availability becomes sufficient to promote productivity it causes biogeographic thresholds to be exceeded. Since because land use is minimal in those regions, it does not affect vegetation dynamics significantly. Because our model does not include any other disturbances than fire, in areas where pollution is important (eastern United States) or where large insect outbreaks have been observed (western United States), our results can only show potential changes under optimal conditions. Consequently, when the model simulates shifts, it indicates an underlying instability as environmental conditions change that could be exacerbated by local disturbances.

Our model shows that most ecosystems in western states, including the Great Plains grasslands, particularly along their eastern ecotone with the eastern deciduous forests, are maintained by wildfires with relatively short fire return intervals that prevent woody life-forms from expanding. When fire suppression is imposed, woody life-forms soon are projected to expand, increasing not only carbon stocks but also fuel loads. Because a large portion of the Great Plains has been transformed by land use, this expansion is greatly reduced, and carbon stocks that could be boosted by woody life-form invasion decrease due to harvest and grazing.

In the United States, land use history includes the frequent use of fires by Native Americans to maintain grasslands and open forests for agriculture, hunting, and ease of travel; the use of fires by European settlers for agricultural and urban expansion; the establishment of fire suppression rules early in the 20th century; and the use of prescribed burns to reduce fuel loads in the late 20th century. Such rich fire legacy that started well before 1895 is not included in the spin-up phase of model when natural fire return intervals are used (instead of the more frequent Native American fire regime). For regional projects in the Pacific Northwest, we have in the past calibrated the spin-up phase to include more frequent burning for areas such as the Willamette Valley that has a well-known history of land use (Yospin et al., 2015). But because we had limited knowledge of past legacies over the entire country, we decided to forego the frequent pre-20th century burning for areas the model simulates as forests but currently exist as woodlands or grass-dominated areas. Transition from frequent past burning to fire suppression would likely increase carbon sequestration above our projections.

Westerling et al. (2006) showed an increasing trend in observed area burned in the western United States over the last 30 years suggesting early signs of climate change impacts. Yue et al. (2013) used 15 climate futures with the A1B emission scenario and showed that wildfire activity in the West should increase significantly by midcentury and result in very large areas burned. MC2 simulates an increase in fire risk throughout the 21st century even when fire suppression is imposed. Fuel builds up above the model's thresholds of suppression, and dry conditions allow the occurrence of very large fires that may consume twice the historical average biomass (**Table 4**). In this case, land use reduces the risk of large fires by converting frequently burning grasslands to agriculture and reducing the expansion of flammable shrubs. In the model, because harvested material is removed entirely, never becoming potential fuel, forest harvests also reduce the accumulation of fuel that may cause large fires in western states with fire suppression.

However, imposing land use also causes a 15–40% decrease in C stocks in comparison with the potential vegetation simulations (**Table 3**). Soil C storage is an important part of the national carbon budget and an index of ecosystem stability. Forest management, particularly timber harvests, can significantly (30%) reduce soil C storage in forests (e.g., Nave et al., 2010) by altering the timing and quality of litter inputs, thereby affecting decomposition processes (Chen et al., 1995; Covington, 1981;

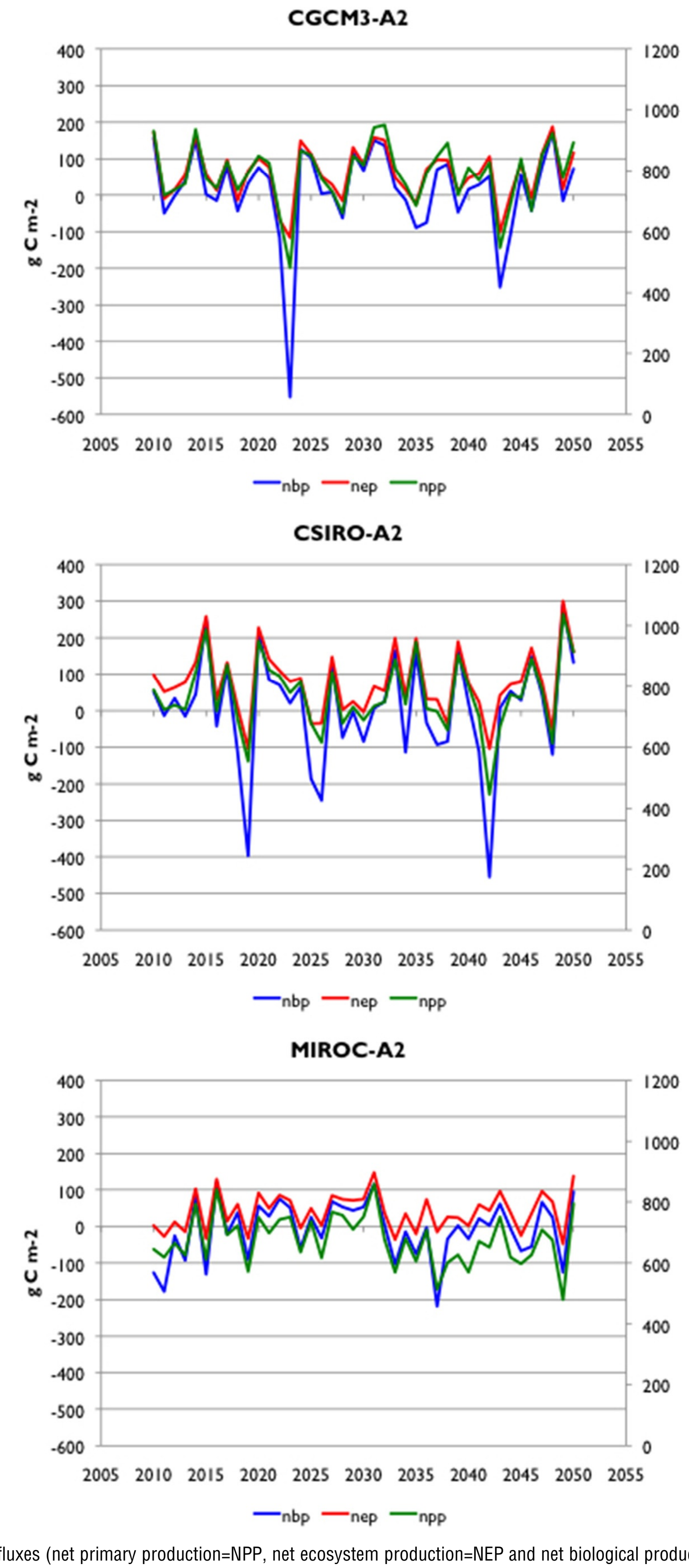

Fig. 2 Simulated carbon fluxes (net primary production=NPP, net ecosystem production=NEP and net biological production=NBP) for potential vegetation simulated by the dynamic global vegetation model MC2 with no fire suppression under the A2 emission scenario for three climate futures (CGCM3, MIROC, CSIRO).

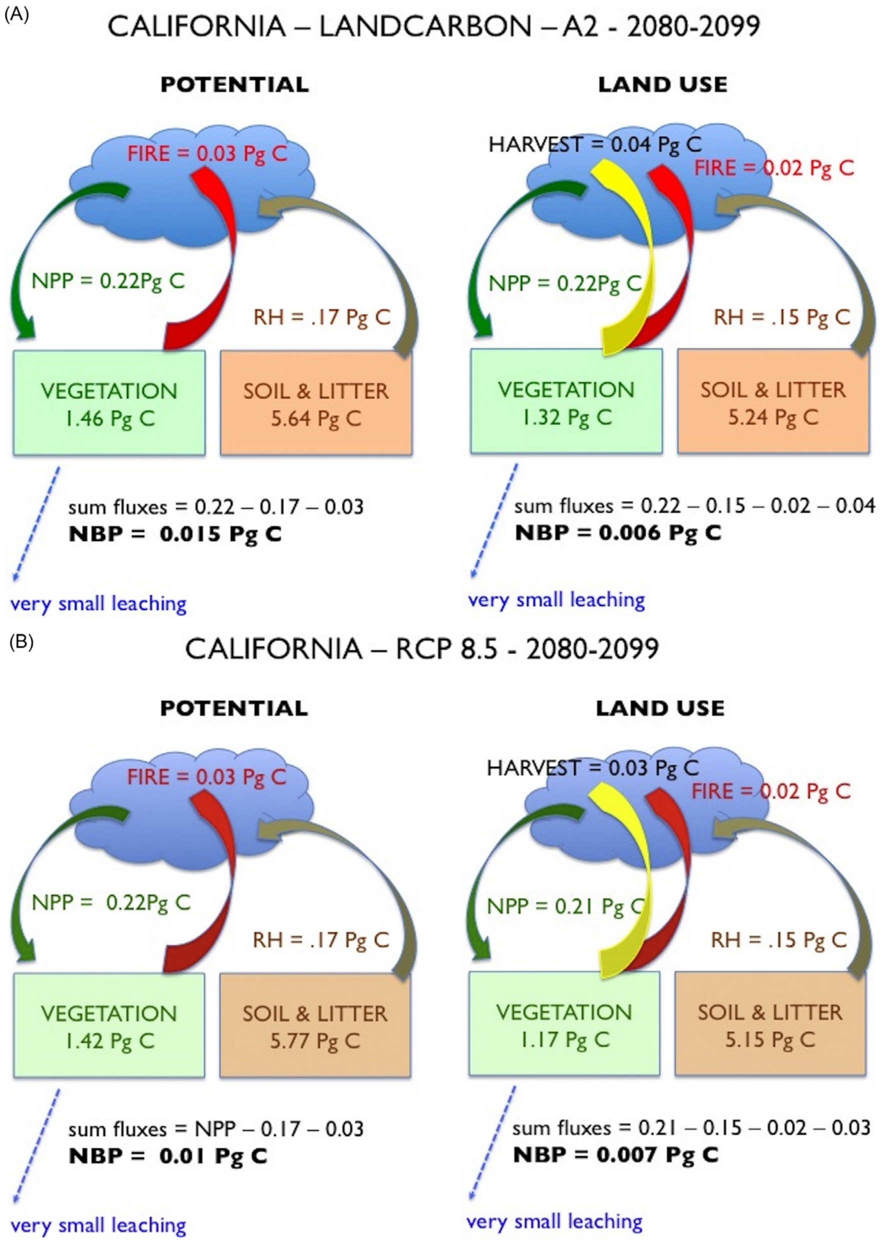

Fig. 3 Summary figures comparing the carbon budget for the state of California simulated by the dynamic global vegetation model MC2 averaged across three climate futures (CGCM3, MIROC, CSIRO) under the A2 emission scenario and averaged across 4 climate futures (CanESM2, CCSM4, CNRM-CM5, HadGEM2-ES) under RCP 8.5 for the 2081–2100 period.

Gray et al., 2002). Similarly, agriculture reduces inputs to soil because of regular harvests. While MC2 simulates an increase in C stocks with potential vegetation under all three emission scenarios, the model simulates a slight decline with land use except under the B1 scenario when harvest intensity is the lowest. Regional carbon sequestration potential varies across the country (Fig. 1), but we have shown for the state of California (with 47% of its area under protection - www.calands.org) that future land use can reduce the carbon sink by 10-20% (Fig. 3). Clearly, more work is needed to refine our estimates and more realistically represent regional human activities. Nonetheless, the striking differences between the potential vegetation and the land use run results confirm other reports on the importance of land use on ecosystem resilience to climate change.

In summary, we found an increasing trend in C stocks from the 20th to 21st century with both CMIP3 and CMIP5 future climate projections. Simulated forest area, which corresponds to the largest carbon stock, increases with fire suppression and is a major contributor to greater carbon sequestration. Such trend has been observed around the world where woody plant abundance has increased dramatically in the past 50–100 years. However, managed forest harvests reduce the carbon stock that they can hold. Human-driven factors such as fire suppression, reduced grazing, and increased atmospheric CO_2 concentrations have been proposed as likely explanations for the woody encroachment across grasslands (e.g., Archer et al., 1995). MC2 includes the assumption that as soil surface layers dry up under warmer conditions, trees can take advantage of deeper soil moisture that is

Table 4 Simulated area burned and biomass consumed by wildfires for three emission scenarios used by three GCMs for the LandCarbon project

Potential vegetation with no fire suppression

		CONUS area burned (M ha)			*CONUS biomass burned (Pg C)*		
1992–2005		18.6			0.2		
		CGCM3	CSIRO	MIROC	CGCM3	CSIRO	MIROC
2041–60	A1B	20.9	18.7	19.9	0.4	0.3	0.4
	A2	20.8	23.3	20.0	0.4	0.5	0.4
	B1	18.4	20.7	18.3	0.3	0.4	0.3
2081–2100	A1B	20.3	18.1	20.2	0.4	0.3	0.4
	A2	22.4	21.6	23.8	0.5	0.5	0.5
	B1	18.2	22.9	20.0	0.3	0.5	0.3

Potential vegetation with land-use

		CONUS area burned (M ha)			*CONUS biomass burned (Pg C)*		
1992–2005		18.6			0.2		
		CGCM3	CSIRO	MIROC	CGCM3	CSIRO	MIROC
2041–60	A1B	20.9	18.7	19.9	0.4	0.3	0.4
	A2	20.8	23.3	20.0	0.4	0.5	0.4
	B1	18.4	20.7	18.3	0.3	0.4	0.3
2081–2100	A1B	20.3	18.1	20.2	0.4	0.3	0.4
	A2	22.4	21.6	23.8	0.5	0.5	0.5
	B1	18.2	22.9	20.0	0.3	0.5	0.3

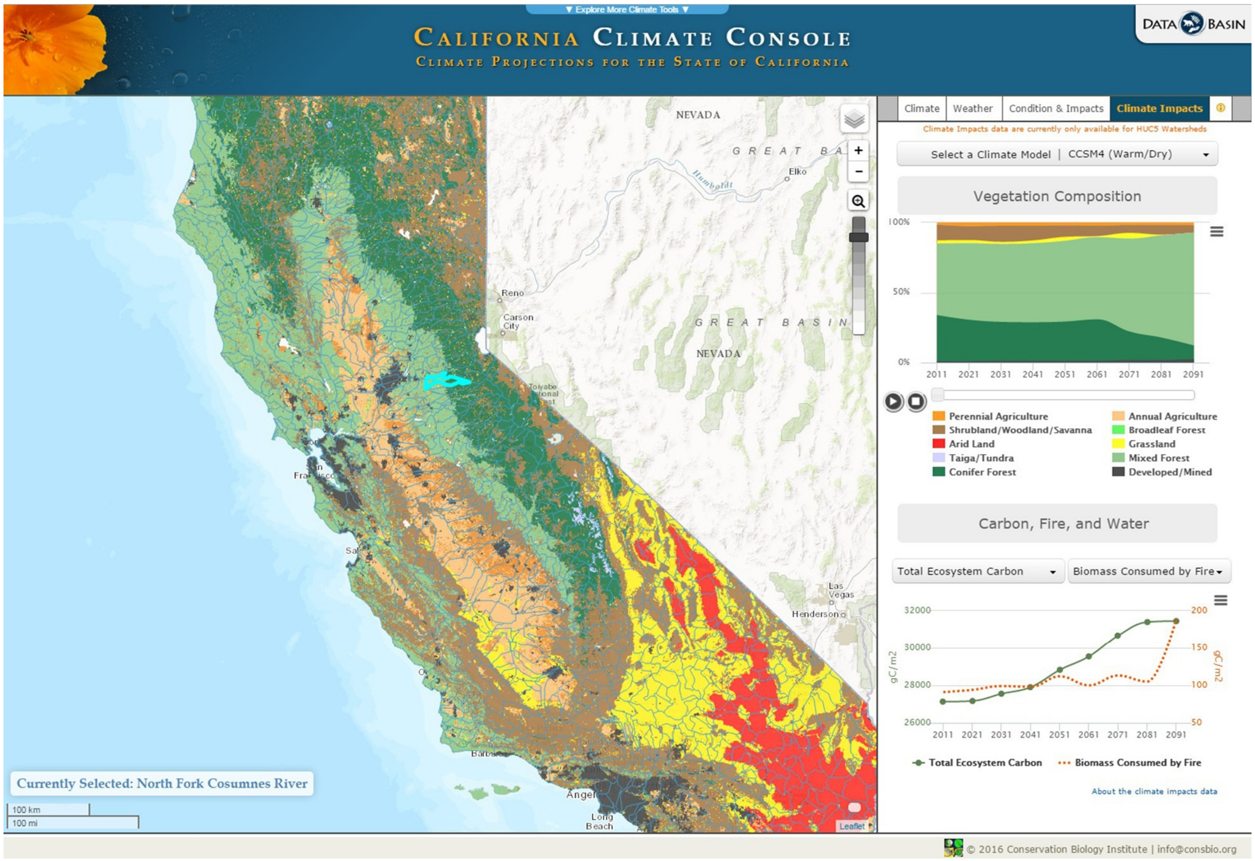

Fig. 4 Screenshot of the climate console for the state of California (climateconsole.org) displaying results from the dynamic global vegetation model MC2 under RCP 8.5 for four climate futures (CanESM2, CCSM4, CNRM-CM5, HadGEM2-ES).

inaccessible to grasses. Such competitive advantage in concert with fire suppression is enough to explain the woody expansion across western prairies even before high CO_2 concentrations cause a significant increase in their water use efficiency and promotes their growth. If this assumption is correct, it is likely that the trend in woody plant encroachment observed so far will continue in the future and contribute to further "woodification" of the West wherever land use allows it to happen. As human population continues to increase however, expanding land use is bound to reduce areas where natural vegetation dynamics would allow shifts to vegetation types better adapted to warmer and drier conditions. And while reducing losses of carbon through fire emissions, timber harvests and cultivation also reduce the potential for increased carbon sequestration across the country.

Appendix

Table A1 Woody-type determination rules

Leaf form	*Phenology*	*Growing season precipitation*	*Minimum* T_{min}	*Continentality (max*$T_{max}-$*min*T_{min}*)*	*Tree type*
N	D		$\leq -15^{\circ}C$	$\geq 60^{\circ}C$	DN
N	E		$\leq -15^{\circ}C$	$\leq 55^{\circ}C$	EN
	E	<55 mm	$> -15^{\circ}C$ and $<18^{\circ}C$		EN-EB
		>55 mm	$> -15^{\circ}C$ and $<1.5^{\circ}C$		EN-DB
B		>55 mm	$1.5^{\circ}C$		DB
B		>55 mm	$>1.5^{\circ}C$ and $<18^{\circ}C$		DB-EB
B	E		$\geq +18^{\circ}C$		EB

D, deciduous; *N*, needleleaf; *E*, evergreen; *B*, broadleaf. Temperatures and precipitation are smoothed over 15 years (T_{min} = minimum monthly temperature and T_{max} = maximum monthly temperature)

Table A2 Climate zone thresholds (temperatures are smoothed over 15 years)

Zone	*Rule (threshold)*	*Threshold definition*
Arctic–alpine	<1000 GDD	Upper GDD (above $0^{\circ}C$) limit for arctic/alpine zone
Taiga–tundra	>1000 GDD and <1330 GDD	Upper GDD (above $0^{\circ}C$) limit for taiga–tundra
Subalpine	1330 < GDD < 1900	Upper GDD (above $0^{\circ}C$) limit for subalpine zone
Boreal	$T_{min} < -13.0^{\circ}C$	Upper min temperature limit for boreal zone
Temperate	$-13^{\circ}C < T_{min} =< 7.75^{\circ}C$	Upper min temperature limit for temperate zone
Subtropical	$7.75^{\circ}C < T_{min} < 18^{\circ}C$	Upper min temperature limit for subtropical zone

GDD = sum of growing degree days above $0^{\circ}C$; T_{min} = minimum monthly temperature

Table A3 Thresholds defining the potential natural vegetation types used in MC2

	Zone	*GDD (degree days above* $0^{\circ}C$*)*	*Herbaceous C*	*Woody C*	*Herbaceous type*	*Woody type*	*Continentality*	*Other*
Barren	Arctic or alpine	≤0.			C3	EN		
Tundra	Arctic or alpine	>0.			C3	EN		
Taiga–tundra	Boreal	≤1330			C3	EN		
EN forest	Boreal			≥ 3000 g C m^{-2}	C3	EN		
Mixed woodland	Boreal			< 3000 g C m^{-2}	C3	EN		
Cool N forest	Temperate			≥ 3000 g C m^{-2}	C3	EN	≤18°C	>0°C
Maritime EN forest	Temperate			≥ 3000 g C m^{-2}	C3	EN	≤18°C	<0°C
Temperate EN forest	Temperate			≥ 3000 g C m^{-2}	C3	EN		
Temperate DB forest	Temperate			≥ 3000 g C m^{-2}	C3	DB		
Temperate cool mixed forest	Temperate			≥ 3000 g C m^{-2}	C3	EN-DB		
Temperate warm mixed forest	Temperate			≥ 3000 g C m^{-2}	C3	EB		
Subalpine forest	Temperate	≤1900			C3	EN		

(*Continued*)

Table A3 (Continued)

	Zone	*GDD (degree days above 0°C)*	*Herbaceous C*	*Woody C*	*Herbaceous type*	*Woody type*	*Continentality*	*Other*
Temperate EN woodland	Temperate			$\geq$1150 g C m^{-2}	C3	EN		
Temperate DB woodland	Temperate			$\geq$1150 g C m^{-2}	C3	DB		
Temperate cool mixed woodland	Temperate			$\geq$1150 g C m^{-2}	C3	EN-DB		
Temperate warm mixed woodland	Temperate			$\geq$1150 g C m^{-2}	C3	EB		
Temperate (C3) shrubland	Temperate			$\geq$1 g C m^{-2}	C3	EN-DB		
Temperate desert	Temperate			$<$1 g C m^{-2}	C3	EN-DB		
Temperate (C3) grassland	Temperate boreal or subtropical		$\geq$200 g C m^{-2}	$<$200 g C m^{-2}	C3	EN-DB		
Subtropical (C4) grassland	Subtropical or temperate		$\geq$200 g C m^{-2}	$<$200 g C m^{-2}	C4	EN-DB		
Subtropical EN forest	Subtropical			$\geq$3000 g C m^{-2}	C4	EN		
Subtropical DB forest	Subtropical			$\geq$3000 g C m^{-2}	C4	DB		
Subtropical cool mixed forest	Subtropical			$\geq$3000 g C m^{-2}	C4	EN-DB (EB)		
Subtropical EB forest	Subtropical			$\geq$3000 g C m^{-2}	C4	EB		
Subtropical EN woodland	Subtropical			$\geq$1150 g C m^{-2}	C4	EN		
Subtropical DB woodland	Subtropical			$\geq$1150 g C m^{-2}	C4	DB		
Subtropical mixed woodland	Subtropical			$\geq$1150 g C m^{-2}	C4	EN-DB (EB)		
Subtropical EB woodland	Subtropical			$\geq$1150 g C m^{-2}	C4	EB		
Subtropical shrubland	Subtropical			$\geq$1 g C m^{-2}	C4	EN-DB (EB)		
Subtropical desert	Subtropical			$<$1 g C m^{-2}	C4	EN-DB (EB)		
Tropical grassland	Tropical		$\geq$200 g C m^{-2}	$<$200 g C m^{-2}	C4	EB-DB		
Tropical EB forest	Tropical			$\geq$3000 g C m^{-2}	C4	EB		
Tropical D woodland	Tropical			$\geq$1150 g C m^{-2}	C4	DB		$\leq$0.45
Tropical savanna	Tropical			$\geq$1150 g C m^{-2}	C4	EB-DB		$>$0.45
Tropical shrubland	Tropical			$\geq$1 g C m^{-2}	C4	EB-DB		
Tropical desert	Tropical			$<$1 g C m^{-2}	C4	EB-DB		
Barren								No soil or npp $= < 0$

Note: "tree" refers to both tree and shrub, that is, woody life-forms; "grass" refers to herbaceous life-forms including sedges and forbs. Temperatures used to calculate growing degree days (GDD) are smoothed over 15 years.

E, evergreen; *D*, deciduous; *N*, needleleaf; *B*, broadleaf

forest_thres, biomass threshold above which the vegetation type is defined as forest; wood_thres, biomass threshold above which the vegetation type is defined as woodland; shrub_thres, biomass threshold above which the vegetation type is defined as shrubland; grass_thres, biomass threshold above which the vegetation type is defined as grassland; tt_thres, degree day threshold between the boral zone and the arctic zone; mari_threshold, mean annual temperature threshold below which the vegetation type qualifies as maritime; tmmin_thres, minimum monthly temperature threshold also used to define the maritime vegetation type (cool temperatures above freezing); ddecid_threshold, drought deciduous threshold; NPP, net primary production.

Table A4 Soils inputs to MC2

	% Sand	% Clay	% Rockiness	Bulk density	Mineral depth
Surface (0–50 cm)	x	x	x		
Intermediate (50–150 cm)	x	x	x		
Deep (greater than 150 cm)	x	x	x		
Entire profile				x	x

Table A5.1 Climate inputs to MC2 for the LandCarbon project (Zhu et al., 2010)

	Minimum and maximum monthly temperature	Monthly precipitation	Vapor pressure
Equilibrium	PRISM baseline (1895–1924 monthly averages)		
Spin-up	Detrended PRISM monthlies 30 arc sec (Daly et al., 2008), 1895–2005		
Historic	1895–2005 PRISM monthlies at 30 arc sec (Daly et al., 2008)		
Future (2000–2100)	MIROC 3.2 medres (Hasumi and Emori, 2004) CSIRO Mk3 (Gordon, 2010) CGCM3 (Flato et al., 2000)		

Table A5.2 Climate inputs to MC2 for the California project

	Minimum and maximum monthly temperature	Monthly precipitation	Vapor pressure
Equilibrium	PRISM baseline (1895–1924 monthly averages)		
Spin-up	Detrended PRISM monthlies at 30 arc sec (Daly et al., 2008), 1895–2010		
Historic	1895–2010 PRISM monthlies at 30 arc sec (Daly et al., 2008)		
Future (2000–2100)	ACCESS1.0 (Bi et al., 2013; Dix et al., 2013), CanESM2 (Arora et al., 2011; von Salzen et al., 2013), CCSM4 (Gent et al., 2011), CESM1-BGC (Long et al., 2013; Hurrell et al., 2013), CNRM.CM5 (Voldoire et al., 2013), GFDL-CM3 (Delworth et al., 2006; Donner et al., 2011), HadGEM2-CC (Collins et al., 2011; Martin et al., 2011), HadGEM2-ES (Collins et al., 2011; Martin et al., 2011), MIROC5 (Watanabe et al., 2010)		

Table A6 Brief description of the Special Report on Emissions Scenarios (SRES) (Nakićenović et al., 2000) used in the LandCarbon project (Zhu et al., 2010) and of the RCP 8.5 scenario used to simulate California

	Atmospheric CO_2 concentration in 2100 (ppm)	Temperature change (°C) *2090–99 relative to 1980–99 (SRES) *2081–2100 relative to 1986–2005 (RCP)	Sea-level rise (meters) *2090–99 relative to 1980–99 (SRES) *2081–2100 relative to 1986–2005 (RCP)
SRES A2	836	2.0–5.4 (3.4)	0.23–0.51
SRES A1B	703	1.7–4.4 (2.8)	0.21–0.48
SRES B1	540	1.1–2.9 (1.8)	0.18–0.38
RCP 8.5	936	2.6–4.8 (3.7)	0.45–0.82

Table A7.1 Brief description of the three climate models used in the LandCarbon project (Zhu et al., 2010)

General circulation model (GCM)	Vintage and institution	Atmosphere resolution grid cell size in degree lat × long L: # vertical levels	Ocean resolution grid cell size in degree lat × long L: # vertical levels
CGCM3.1 (T63)	2005 Canadian Center for Climate Modeling and Analysis (Canada)	2.8 × 2.8 L31	0.9 × 1.4 L29
CSIRO-MK3.0	2001 Commonwealth Scientific and Industrial Research Organization, Atmospheric Research (Australia)	1.9 × 1.9 L18	0.8 × 1.9 L31
MIROC3.2 (medres)	2004 Center for Climate System Research (U. Tokyo), National Institute of Environmental Studies, and Frontiers Research Center for Global Change (Japan)	2.8 × 2.8 L20	0.5–1.4 × 1.4 L43

Table A7.2 Brief description of the nine climate models used in the California project

General circulation model (GCM)	*Vintage and name*	*Atmosphere resolution grid cell size in degree lat × long L: # vertical levels*	*Ocean resolution grid cell size in degree lat × long L: # vertical levels*
ACCESS1.0	2011 Australian Community Climate and Earth-System Simulator, version 1.0	192 × 145 N96 L38	1 × 1 L50
CanESM2	2010 Second Generation Canadian Earth System Model	2.8 × 2.8 L35	256 × 292 L40
CCSM4	2010 Community Climate System Model version 4	1.25 × .94 L26	0.7–0.641 × 1.125L L60
CESM1-BGC	2010 Community Earth System Model, version 1-Biogeochemistry	1.25 × .9 L27	0.27–0.641 × 1.125L L60
CNRM.CM5	2010 Centre National de Recherches Météorologiques Coupled Global Climate Model, version 5.1	1.4 × 1.4 L31 TL127	0.7 × 0.7 L42
GFDL-CM3	2011 Geophysical Fluid Dynamics Laboratory Climate Model, version 3	2.5 × 2.0 L48	1° tripolar 360 × 200 L50
HadGEM2-CC	2010 Hadley Centre Global Environmental Model, version 2-Carbon Cycle	1.88 × 1.25N96 L60	1.875L × 1.251N96
HadGEM2-ES	2009 Hadley Centre Global Environmental Model, version 2-Earth System	1.88 × 1.25N96 L38	1 × 1 between 30 and poles; N180 L40
MIROC5	2010 Model for Interdisciplinary Research on Climate, version 5	1.4 × 1.4 L40	1.4 (zonally) × 0.5–1.4 (meridionally) L50

Table A8 Comparison of MC2-simulated C stocks for the LandCarbon project (Zhu et al., 2010) with published values

References	*Years of estimate*	*CONUS NEE (Tg C)*	*Forest area (M ha)*	*Forest C (Pg C)*	*Forest C/area (kg C m^{-2})*	*Soil C CONUS (Pg C)*
Turner et al. (1995)				12.6		
NBCD/Kellndorfer et al. (2012)				16.31		
Birdsey and Heath (1995)				16.75		
Blackard et al. (2008)				17.025[a]		
Potter (CASA) (1999)				37.65		
Vose et al. (2012) (p. 58)			281	20.5 (46)	7.3	25.5
Smith and Heath (2000)				24.9		
Heath and Smith (2000)						
GHG inventory for EPA (FIA-based) (EPA 2013)				20 ± 5		
Xiao et al. (2011)		630				
Butler et al. (2010) (inversion)		1200 ± 400				
Crevoisier et al. (2010)		500 ± 400				
SSURGO (from Sundquist)						80
MC2 NFS (2013)	1992–2005		516.8	40.0[b]	12.9	82.8
MC2 WLU (2013)	1992–2005		333.5	26.5[b]	12.58	80.0

[a]Assuming 25% above biomass = belowground so that total biomass carbon = aboveground biomass * 1.25 * 0.5.
[b]MC2 results include woody biomass in non-“forest” areas. NFS corresponds to MC2 runs without land use nor fire suppression while WLU corresponds to MC2 runs with land use.

Table A9 Comparison of MC2-simulated C fluxes for the LandCarbon project (Zhu et al., 2010) with published values

Reference	*Method*	*Period*	*CO_2 flux in Pg C year^{-1}*
Dixon et al. (1994)	Inventory Bookkeeping model	1980s	−0.1 to 0.25
IPCC–UNFCC (2000)	Emissions	1990s	−0.01
UN-ECE/FAO (2000)	(live) Inventory	1980–90s	−0.17

(*Continued*)

Table A9 (Continued)

Reference	*Method*	*Period*	*CO_2 flux in Pg C year^{-1}*
McGuire et al. (2001)	DGVMs	1980s	−0.03 to +0.03 (land use) −0.05 to +0.05 (climate) −0.24 to −0.05 (CO_2) −0.25 to −0.08 (total)
Pacala et al. (2001)	Inventory LUC	1980s	+0.37 to 0.71
Goodale et al. (2002)	Inventory Stand models	Late 1980s Early 1990s	−0.11 (live) −0.28 (live + dead)
Peylin et al. (2002)	Atm inversion models	1980s	−1.02 to +0.03
Hurtt et al. (2002)	ED model	1980s	+0.33 (45–90% total)
Houghton (2003)	Land use statistics Bookkeeping model	1980s	−0.12 (land use only)
MC2 (Bachelet et al., 2015)	NFS	1980–89	−0.03
MC2 (Bachelet et al., 2015)	WFS[a]	1980–89	+0.10

[a]WFS corresponds to MC2 runs without land use but with fire suppression while NFS corresponds to MC2 runs without fire suppression.

Adapted from House, J. I., Prentice, I. C., Ramankutty, N., Houghton, R. A. and Heinmann, M. (2003). Reconciling apparent inconsistencies in estimates of terrestrial CO2 sources and sinks. *Tellus* **55B**, 345–363.

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