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The carbon budget of California

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ABSTRACT

The carbon budget of a region can be defined as the sum of annual fluxes of carbon dioxide (CO_2) and methane (CH_4) greenhouse gases (GHGs) into and out of the regional surface coverage area. According to the state government's recent inventory, California's carbon budget is presently dominated by 115 MMTCE per year in fossil fuel emissions of CO_2 (>85% of total annual GHG emissions) to meet energy and transportation requirements. Other notable (non-ecosystem) sources of carbon GHG emissions in 2004 were from cement- and lime-making industries (7%), livestock-based agriculture (5%), and waste treatment activities (2%). The NASA-CASA (Carnegie Ames Stanford Approach) simulation model based on satellite observations of monthly vegetation cover (including those from the Moderate Resolution Imaging Spectroradiometer, MODIS) was used to estimate net ecosystem fluxes and vegetation biomass production over the period 1990–2004. California's annual NPP for all ecosystems in the early 2000s (estimated by CASA at 120 MMTCE per year) was roughly equivalent to its annual fossil fuel emission rates for carbon. However, since natural ecosystems can accumulate only a small fraction of this annual NPP total in long-term storage pools, the net ecosystem sink flux for atmospheric carbon across the state was estimated at a maximum rate of about 24 MMTCE per year under favorable precipitation conditions. Under less favorable precipitation conditions, such as those experienced during the early 1990s, ecosystems statewide were estimated to have lost nearly 15 MMTCE per year to the atmosphere. Considering the large amounts of carbon estimated by CASA to be stored in forests, shrublands, and rangelands across the state, the importance of protection of the natural NPP capacity of California ecosystems cannot be overemphasized.

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1. Introduction

California is home to more than 10% of the population of the United States and is responsible for 13% of the U.S. gross domestic product (U.S. Census Bureau, 2000). The state's large population makes it a globally significant contributor to greenhouse gas (GHG) emissions. If California were a country, it would rank among the twenty highest national GHG emitters worldwide (Bemis, 2006), with annual fossil fuel emissions of CO_2 roughly equivalent to the national total of Canada and exceeding those (individually) of the nations of Australia, France, Italy, or Spain (UNFCCC, 2009).

The carbon budget of a region can be defined as the sum of annual fluxes of carbon dioxide (CO_2) and methane (CH_4) gases into and out of the regional surface coverage area. Fluxes for both of these trace gases are important to quantify, in part because they originate from a diverse set of processes, both natural and anthropogenic. The main sources of CO_2 emissions in California are energy consumption in commercial, residential, industrial, and transportation sectors, production of cement and lime, and waste treatment (both solid and water). The main sources of CH_4 emission in California are from landfills and agricultural (principally livestock-based) systems.

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California offers important examples and opportunities for refining the national carbon budget for the U.S., because it is a state with many different processes that contribute significantly to carbon fluxes, both natural and anthropogenic. California's carbon emission sources include a mix of fossil fuel emission and ecosystem fluxes that broadly represents the entire country, as does its mix of developed (urban) land, forests, shrubland, rangeland, cropland, and desert.

The objective of this study was to characterize the carbon budget of California for the time period 1990–2004 using a combination of inventory data and ecosystem modeling. In the process, three related questions were addressed:

1.1. How much carbon is emitted annually to the atmosphere in the state of California?

Statewide budget analysis in this study included major CO_2 and CH_4 emission sources (and sinks, in certain cases) associated with natural ecosystems (e.g., forests, shrublands, rangelands, wetlands), agricultural systems, industry, and fossil fuel combustion in all urban and transportation systems. Geographic analysis included the role of fossil fuel combustion versus CO_2 emissions from plant photosynthesis and soil microbial respiration across the state.

1.2. How much do carbon emissions vary from year-to-year in the state of California?

Analysis of emissions included the role of interannual variability in precipitation in determining net ecosystem emissions of CO_2 across the state.

1.3. How much carbon is stored in ecosystems in the state of California?

Estimates of the current size of carbon storage pools included standing wood in forests and shrublands, plus herbaceous vegetation carbon and surface soil pools of carbon in rangelands, wetlands, and agricultural systems.

Understanding where the largest ecosystem sources and sinks for carbon in vegetation land cover is a task well suited to a combination of satellite remote sensing and spatial simulation modeling. However, a combined observational-modeling approach must be applied at a spatial resolution on the ground that can capture important variations in plant growth rates, biomass yields, disturbance events, fertilizer demands, irrigation practices, soil carbon inputs, and multi-scale climate variations (Adler et al., 2007). We have summarized in this paper our approach to model all of these factors within a simulation framework that uses satellite remote sensing to scale-out carbon gas fluxes to large regions (Potter et al., 2007).

The launch of NASA's Terra satellite platform in 1999 with the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on-board initiated a new era in remote sensing of the Earth system with promising implications for carbon cycle research. Direct input of satellite vegetation index "greenness" data from the MODIS sensor into ecosystem simulation models is now used to estimate spatial variability in monthly net primary production (NPP), biomass accumulation in wood and herbaceous cover, and litter fall inputs to soil carbon pools. Global NPP of vegetation can be predicted using the relationship between leaf reflectance properties and the absorption of photosynthetically active radiation (PAR), assuming that net conversion efficiencies of PAR to plant carbon can be approximated for different ecosystems or are nearly constant across all ecosystems (Running and Nemani, 1998; Goetz and Prince, 1998).

Our ecosystem modeling framework has been designed to estimate historical as well as current monthly patterns in plant carbon fixation, living biomass increments, nutrient allocation, litter fall and decomposition, long-term decay of wood and crop residue pools, soil CO_2 respiration, and soil nutrient mineralization. To our knowledge, this is the first study to take full advantage of MODIS land surface products to compile annual net ecosystem production (NEP) estimates specifically for the state of California.

2. Non-ecosystem sources of carbon GHG emissions

The California Energy Commission (CEC, 2007) has compiled California's GHG emission inventory for the years 1990–2004. The principal method used to estimate industrial and fossil fuel sources of carbon GHGs has been based on emission factors (EFs) multiplied by activity data. An EF is a coefficient that translates reports of activity data (e.g., tons of solid material added to a landfill) into an estimate of GHG emission (e.g., million metric tons of carbon equivalent, MMTCE) per year. IPCC inventory methodology (IPCC, 2006) provides guidelines for many EF values used by the CEC.

The CEC has estimated that the major source of carbon dioxide emissions in California is fossil fuel combustion, at >85% of total annual GHG emissions. The majority of these fossil fuel GHGs were emitted (at a total of 115 MMTCE) to meet the requirements of the energy and transportation sectors (Fig. 1). In 2004, the breakdown of these energy combustion sources of annual carbon GHG emissions was 8 MMTCE from residential, 3 MMTCE from commercial, 45 MMTCE from industrial, and 50 MMTCE from transportation sectors. Other notable (non-ecosystem) sources of carbon GHG emissions in 2004 were 8 MMTCE from cement- and lime-making industries, 6 MMTCE from livestock-based agriculture, and 3 MMTCE from waste treatment activities. When broken down in terms of CO_2 and CH_4 contributions to total annual (non-ecosystem) GHG emissions in California, the CEC (2007) estimates a ratio of about 14:1 (CO_2:CH_4).

3. Methods—CASA ecosystem carbon modeling

The CEC's (2007) GHG inventory trend (shown in Fig. 1) includes what we consider to be a static "place-holder" entry for statewide ecosystem carbon exchange, which has been labeled in a generalized fashion as "forest sink" fluxes of CO_2 in previous CEC reports. Year-to-year variations in climate and land use combine to make actual ecosystem GHG exchange a dynamic item in any regional carbon budget (Potter et al.,

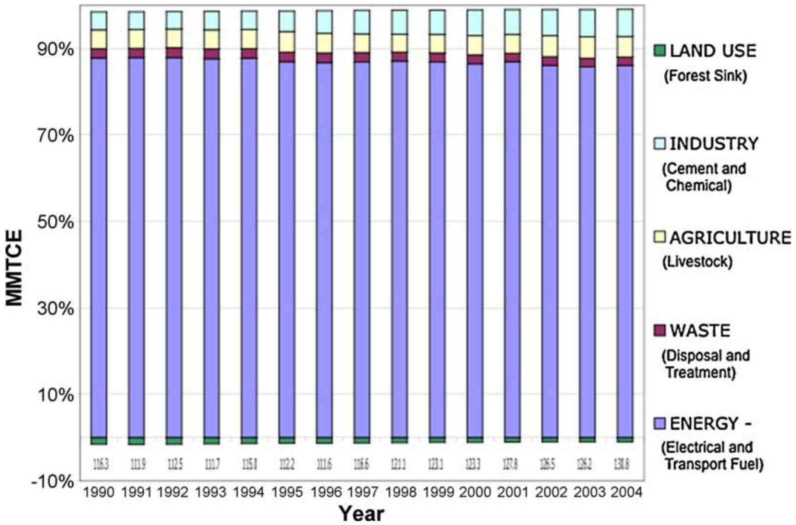

Fig. 1 – California GHG Inventory Summary 1990–2004 (from data compiled by the CEC, 2007). Estimated annual totals in MMTCE are provided at the bottom of each bar.

2007), and therefore a prime focus for revision in future versions of the state's GHG inventory reports.

The NASA-CASA model algorithms for both plant and soil carbon cycles in forests, shrublands, croplands and grasslands, as documented in Potter (1999), begin with monthly NPP flux. NPP is defined as net fixation of CO_2 by vegetation and is computed in CASA on the basis of light-use efficiency (Monteith, 1972). Monthly production of plant biomass is estimated as a product of time-varying surface solar irradiance, Sr, and the Enhanced Vegetation Index (EVI) from the MODIS satellite, plus a constant light utilization efficiency term (emax) that is modified by time-varying stress scalar terms for temperature (T) and moisture (W) effects (Eq. (1)):

$$NPP = S_r EVI e_{\max} TW \tag{1}$$

The $e_{\max}$ term is initially set uniformly at 0.39 g C MJ^{-1} PAR, a value that derives from calibration of predicted annual NPP to previous field estimates (Potter et al., 1993). This model calibration has been validated globally by comparing predicted annual NPP to more than 1900 field measurements of NPP (Zeng et al., 2008; Potter et al., 2007). Interannual NPP fluxes from the CASA model have been reported (Behrenfeld et al., 2001) and validated against multi-year estimates of NPP from field stations and tree rings (Malmström et al., 1997). Our NASA-CASA model has been validated against field-based measurements of NEP fluxes and carbon pool sizes at multiple northern forest sites (Amthor et al., 2001; Hicke et al., 2002) and against atmospheric inverse model estimates of global NEP (Potter et al., 2003).

The T stress scalar is computed with reference to derivation of optimal temperatures ($T_{\rm opt}$) for plant production. The $T_{\rm opt}$ setting will vary by latitude and longitude, ranging from near 0 °C in the Arctic to the middle thirties in low latitude deserts. The W stress scalar is estimated from monthly water deficits, based on a comparison of moisture supply (precipitation and stored soil water) to potential evapotranspiration (PET) demand using the method of Priestly and Taylor (1972).

Evapotranspiration in CASA is connected to water content in the soil profile layers (Fig. 2), as estimated using the CASA algorithms described by Potter (1999). The soil model design includes three-layer (M_1–M_3) heat and moisture content computations: surface organic matter, topsoil (0.3 m), and subsoil to rooting depth of 1 m for croplands and grasslands. These layers can differ in soil texture, moisture holding capacity, and carbon–nitrogen dynamics. Water balance in the soil is modeled as the difference between precipitation or volumetric percolation inputs, monthly estimates of PET, and the drainage output for each layer. Inputs from rainfall can recharge the soil layers to field capacity. Excess water percolates through to lower layers and may eventually leave the system as seepage and runoff.

Based on plant production as the primary carbon and nitrogen cycling source, the NASA-CASA model is designed to couple daily and seasonal patterns in soil nutrient mineralization and soil heterotropic respiration (R_h) of CO_2 from soils. Net ecosystem production (NEP) can be computed as NPP minus R_h fluxes, excluding the effects of small-scale fires and other localized disturbances or vegetation regrowth patterns on carbon fluxes. The soil model uses a set of compartmentalized difference equations with a structure comparable to the CENTURY ecosystem model (Parton et al., 1992, 1994). First-order decay equations simulate exchanges of decomposing plant residue (metabolic and structural fractions) at the soil surface. The model also simulates surface soil organic matter (SOM) fractions that presumably vary in age and chemical composition. Turnover of active (microbial biomass and labile substrates), slow (chemically protected), and passive (physically protected) fractions of the SOM are represented. Along with moisture availability and litter quality, the predicted soil temperature in the M_1 layer controls SOM decomposition.

The soil carbon pools were initialized to represent storage and flux conditions in near steady state (i.e., an annual NEP flux less than 0.5% of annual NPP flux) with respect to mean land surface climate recorded for the period 1999–2000. This

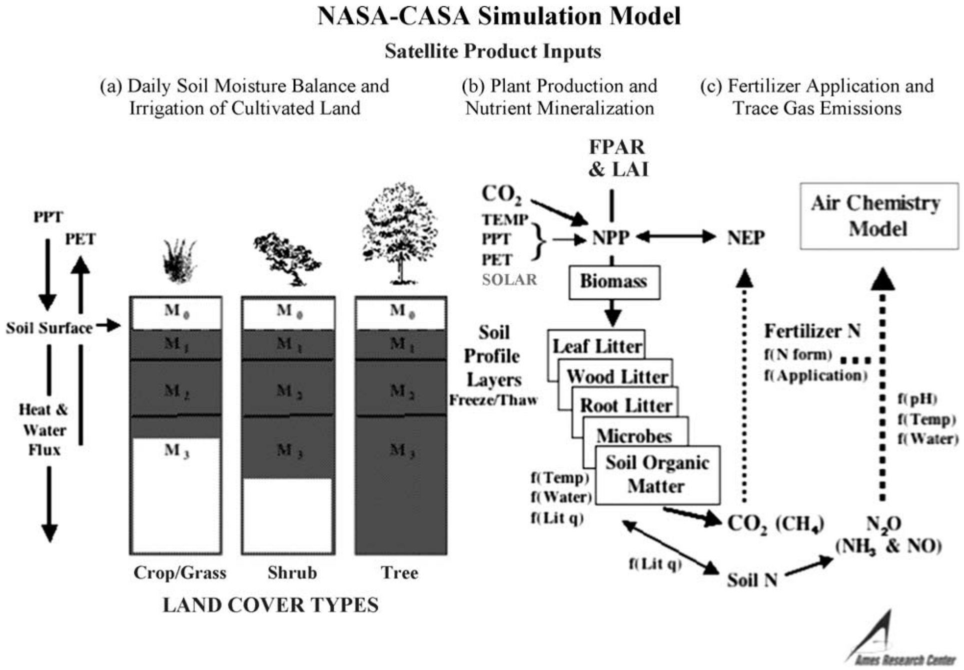

Fig. 2 – Schematic representation of components in the NASA-CASA model. The soil profile component (a) is divided by with depth into a surface ponded layer (M_0) above all other layers for wetlands only, a surface organic layer (M_1), a surface organic-mineral layer (M_2), and a subsurface mineral layer (M_3), showing typical levels of soil water content (shaded) in three general vegetation types. The production and decomposition component (b) shows separate pools for carbon cycling among pools of leaf litter, root litter, woody detritus, microbes, and soil organic matter, with dependence on litter quality (*q*).

initialization protocol was found to be necessary to eliminate any notable discontinuities in predicted NEP fluxes during the transition to our model simulation years of interest prior to MODIS EVI availability. Initializing to near steady state does not, however, address the issue that some ecosystems are not in equilibrium with respect to net annual carbon fluxes, especially when they are recovering from past disturbances.

Whereas previous versions of the CASA model (Potter et al., 1993, 1999) used a normalized difference vegetation index (NDVI) to estimate FPAR, the current model version (Potter et al., 2009) instead has been calibrated to use MODIS EVI datasets as direct inputs to Eq. (1) above. Operational MODIS algorithms generate the EVI (Huete et al., 2002) as global image coverages from 2000 to present. EVI represents an optimized vegetation index, whereby the isolines in red and near infrared spectral bands are designed to approximate vegetation biophysical isolines derived from canopy radiative transfer theory and/or measured biophysical–optical relationships. EVI was developed to optimize the greenness signal, or area-averaged canopy photosynthetic capacity, with improved sensitivity in high biomass regions. The EVI has been found useful in estimating absorbed PAR related to chlorophyll contents in vegetated canopies (Zhang et al., 2005), and has been shown to be highly correlated with processes that depend on absorbed light, such as gross primary productivity (GPP) (Xiao et al., 2004; Rahman et al., 2005).

In long-term (1982–2004) simulations, continuity between AVHRR and MODIS sensor data for inputs to NASA-CASA is an issue that must be addressed by recalibration of annual NPP results post 2000. Nonetheless, NASA-CASA model predictions with monthly MODIS EVI inputs have been adjusted using the same set of field measurements of NPP (Olson et al., 1997; Potter et al., 2003; Zeng et al., 2008; Potter et al., 2007). To best match of predictions with previously measured NPP estimates at the global scale ($R^2 = 0.91$), the model emax term for MODIS EVI inputs was reset to 0.55 g C MJ^{-1} PAR.

For CASA model initialization, gridded monthly data from DAYMET (Thornton et al., 1997) were used as model inputs for surface air surface temperature (TEMP) and precipitation totals (PREC) for the years 1982–2000. Gridded model drivers for mean monthly solar radiation flux were derived from interpolated weather station records (New et al., 2000) distributed across all the continental masses. Monthly mean TEMP and PREC grids for model simulations over the years 2001–2004 came from NCEP reanalysis products (Kistler et al., 2001).

Soil texture attributes for the modeling were derived from the STATSGO digital soil association map developed by the National Cooperative Soil Survey (USDA, 1993). The continental U.S. STATSGO product consists of a broad based inventory of soils and non-soil areas that occur in a repeatable pattern on the landscape and that can be cartographically shown at the scale mapped.

4. Statewide carbon budget assessment

4.1. *Ecosystem carbon fluxes estimates*

According to CASA model predictions (and as first reported as part of the entire U.S. carbon budget in Potter et al. (2007) and

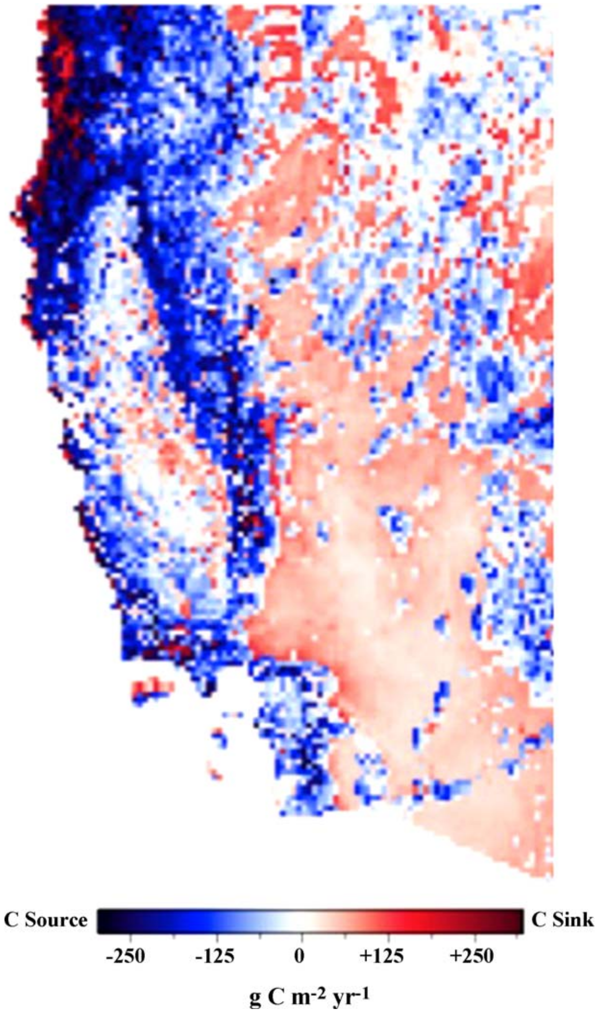

Fig. 3 – CASA model prediction of net ecosystem production for the year 2004.

Potter et al. (2005)), California's NPP for all ecosystems in the early 2000s was 120 MMTCE per year. This yearly flux of CO_2 into vegetation statewide was roughly equivalent to California's annual fossil fuel emission total for carbon. However, since natural ecosystems can accumulate only a small fraction of this annual NPP total in long-term storage pools such as standing wood and soil, the net sink flux for atmospheric carbon across ecosystems of the state (shown as NEP flux in Fig. 3) was estimated at a maximum rate of between 14 and 24 MMTCE per year under favorable annual precipitation conditions. The annual NEP storage amount is the same as the difference between carbon captured in NPP flux and that carbon going back into the atmosphere each year as CO_2 is due to respiration of litter decomposition and soil carbon losses (R_h fluxes) each year. Under less favorable precipitation conditions, such as those experienced during the early 1990s, ecosystems statewide were estimated to have lost about 15 MMTCE per year to the atmosphere as NEP flux.

A closer examination of annual precipitation variations in relation to ecosystem carbon sinks and sources revealed that during periods such as 1989–1992 when precipitation was 20–40% below the 50-year mean (1956–2005; DWR, 2009), CASA-predicted NPP in ecosystems of the state declined to the annual lowest levels and statewide NEP was the highest (as an annual emission source of CO_2) in the record since 1990. During relatively wet years such as 1993, 1995–1996, and 2000–2001 when annual precipitation was 5–60% above the 50-year mean, CASA-predicted NEP was the lowest (becoming a notable annual CO_2 sink) in the record since 1990.

Carbon flux estimates for ecosystems of California were broken down further in this study according to Major Land Resource Areas (MLRAs; Source: U.S. Geological Survey and the Natural Resources Conservation Service, USDA). MLRAs are characterized by overlapping patterns of soils, climate, water resources and land uses. The 16 MLRA regions of California are shown in Fig. 4.

The breakdown of the geographic patterns of NPP fluxes across the state from 2001 to 2004 revealed that vegetation of the Siskiyou-Trinity and Sierra Nevada MLRAs captured the most carbon annually as NPP at between 16 and 18 MMTCE total in each region. These areas were followed by the Central California Coast Range and the Sacramento and San Joaquin Valley MLRAs, which produced between 12 and 14 MMTCE total in each region in 2004.

Geographic patterns of yearly NEP fluxes across the state (Fig. 3) revealed that the area with the highest total sink fluxes of carbon annually from the atmosphere was the Sonoran Basin (at between 10 and 13 MMTC from 2001 to 2004), followed by Southern Nevada Basin and the Sacramento and San Joaquin Valley MLRAs (at between 2 and 3 MMTCE total in each region). These regions were not predicted to have unusually large annual NEP fluxes on a per unit area basis (in the range of 30–60 $g\,C\,m^{-2}\,year^{-1}$), but rather were predicted by MODIS inputs to the CASA model to be consistently productive at a relatively low level across the entire region. Moreover, the Sonoran Basin MLRA is two to three times larger in land area than most other MLRA regions of the state.

These predicted NEP patterns in the southern parts of the state were in contrast to that estimated for MLRAs such as the Siskiyou-Trinity and Sierra Nevada, where annual NEP fluxes were estimated as more variable across the region, due to higher year-to-year climate variations. Areas of highest source fluxes of carbon annually to the atmosphere from 2001 to 2004, at between 2 and 3 MMTCE total, were in the Sierra Nevada MLRA, with consistently high losses of carbon to the atmosphere, especially in the northern portion of the range.

It is worth summarizing several novel observations from the CASA estimates of NEP shown in Fig. 3. First, desert regions can be extensive low-level carbon sinks for the state, since decomposition of dead plant material should be very slow in such dry ecosystems. Second, croplands of the Central Valley have high NPP but practically no NEP storage capacity, because nearly all the crop biomass carbon is harvested and/or removed from the fields each year. Third, forested areas of the state have often been C sources to the atmosphere under warming climate conditions that are not favorable to maintain historical levels of NPP carbon inputs to the forest ecosystems.

4.2. *Ecosystem methane emissions*

Wetlands, floodplains, and irrigated fields can be important sources of methane to the atmosphere. Seasonal temperature,

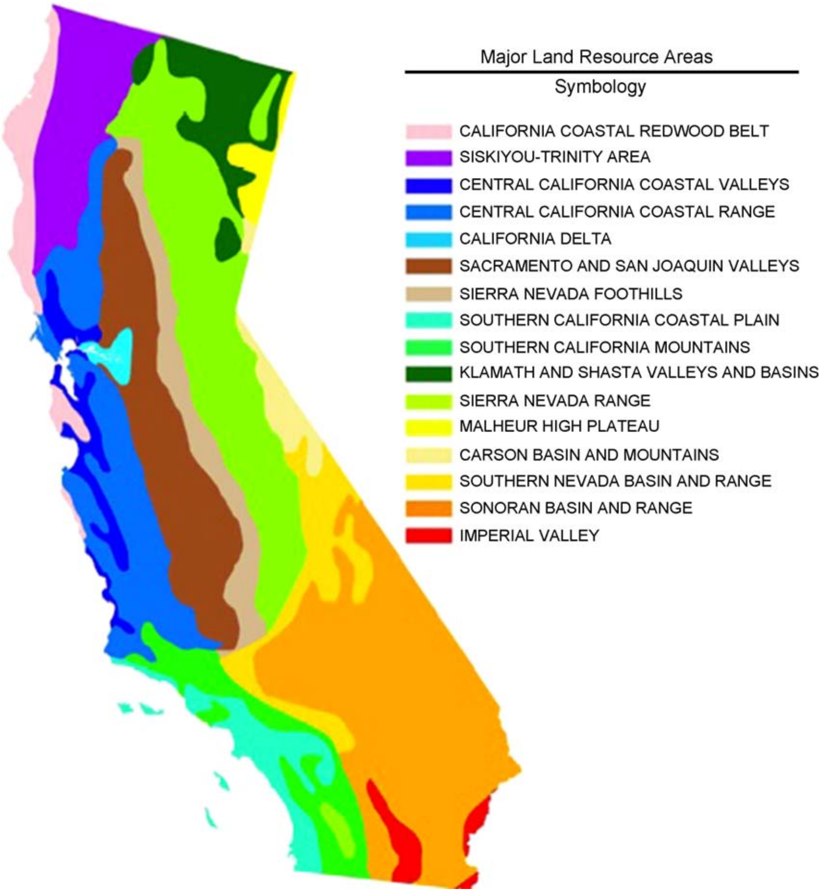

Fig. 4 – Major Land Resource Areas (MLRAs) of California. Source: U.S. Geological Survey and the Natural Resources Conservation Service, USDA.

water table dynamics, and carbon content of soils are the principal controlling factors for ecosystem methane emissions (Whiting and Chanton, 2001). Potter et al. (2006) combined satellite data sets for the coterminous U.S. with CASA ecosystem modeling to produce the first detailed national mapping of methane fluxes from natural wetlands on a monthly and annual basis.

The CASA models predicted mean emission flux of methane from wetlands of the California totaled to 0.43 MMTCE equivalent (based on an estimated global warming potential factor of 23 for methane; EIA, 2004). The MLRAs of the state estimated to make the highest percentage contributions to annual methane emission fluxes from wetlands (Fig. 5) were the Malheur High Plateau (32.5%), the Klamath and Shasta Valleys (24%), the Sacramento and San Joaquin Valleys (22.8%), the California Delta (5.9%), and the Central Coastal Valleys (5.3%). It is important to note that the CASA model was not designed to operate in human-engineered hydrologic zones such as reservoirs and canals where the growth of native wetland vegetation has been largely excluded.

4.3. *Ecosystem carbon pool estimates*

The CASA model predicts carbon storage in the major pools of four different 'strata' in any terrestrial ecosystem in California (Potter et al., 2008). These strata are live leaf, standing wood of trees and shrubs, dead woody litter, and surface mineral soil carbon. The live leaf pool is carbon stored in live (green) leaf tissues at the end of an annual vegetation growing season. The standing wood pool is carbon stored in live wood tissues, adjusted for forest stand age. Dead woody litter carbon stored in down wood litter pools at the soil surface. The surface soil pool is carbon stored in mineral soil layers to a depth of approximately 30 cm. CASA surface soil amounts do not include soil carbon pools measured in layers deeper than 30 cm, or soil carbon that has a mean residence time greater than approximately 25 years in the mineral soil fraction.

On a statewide basis, total carbon stored in all ecosystem strata was estimated at 4300 MMTCE. Nearly 50% of this statewide total was stored in standing wood pools. About 37% of the statewide ecosystem total was stored in soil carbon pools, followed by 11% in woody litter pools and 2% in live leaf pools.

Estimated pools for all major ecosystem strata indicate that the MLRAs with highest carbon storage per unit area were in the California Coastal Redwood Belt and Siskiyou-Trinity (Tables 1 and 2). Average baseline carbon pools in standing biomass (Fig. 6) were in the range of 160–180 t C ha^{-1} for these MLRA regions. Average woody litter pools in these areas were 31 t C ha^{-1}, while surface soil pools were in the range of 103–105 t C ha^{-1}. The total carbon stored in all ecosystem strata of these two MLRAs combined was estimated at 1900 MMTCE.

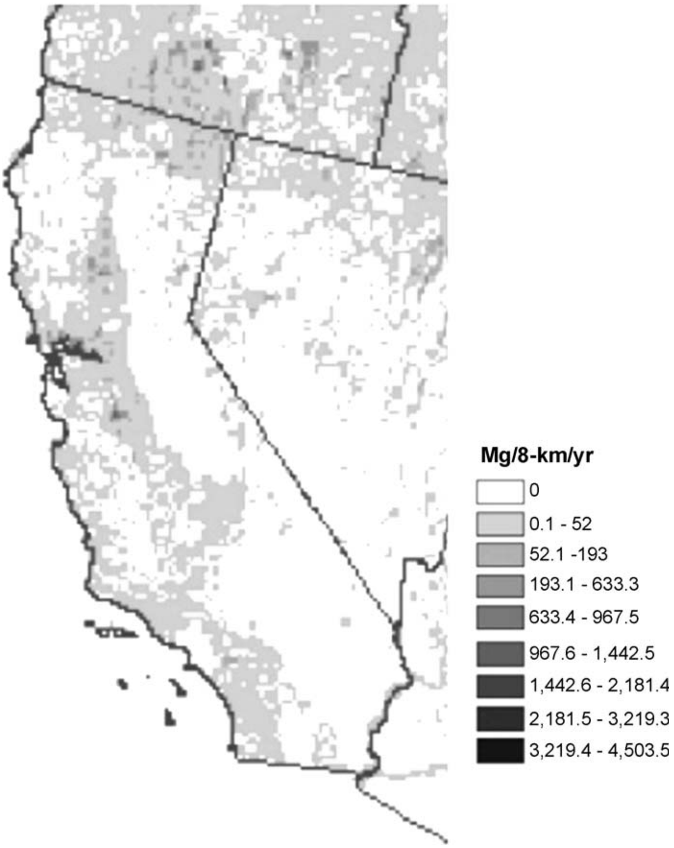

Fig. 5 – CASA model prediction of annual methane emission fluxes from wetlands of the state.

Carbon pools estimated for the Sierra Nevada mountains and the Central Coast Range and Valleys were the next highest in the state at 1300 MMTCE and 560 MMTCE (respectively) for total carbon stored in all ecosystem strata (Tables 1 and 2). Average baseline carbon pools in standing biomass (live leaf and wood) were in the range of 50–100 t C ha^{-1} for these MLRA regions. The Southern Coast, Malheur High Plateau, Carson Basin and Mountains areas were estimated with average

Table 1 – Estimated annual net ecosystem fluxes of carbon by MLRA in California.

MLRA name	Land area (km^2)	NEP 2002		NEP 2003		NEP 2004	
		MEAN (gC/m^2)	MMTCE	MEAN (gC/m^2)	MMTCE	MEAN (gC/m^2)	MMTCE
California Coastal Redwood Belt	13,952	−0.23	−0.28	−0.09	−0.11	−0.58	−0.72
Siskiyou-Trinity Area	28,544	−0.21	−0.85	−0.02	−0.10	−0.51	−2.02
Central California Coastal Valleys	10,304	0.34	0.35	0.69	0.70	0.27	0.27
Central California Coast Range	41,536	0.18	0.74	0.54	2.23	0.19	0.79
California Delta	2624	0.40	0.11	0.63	0.17	0.16	0.05
Sacramento and San Joaquin Valleys	46,592	0.49	2.25	0.66	3.00	0.40	1.81
Sierra Nevada Foothills	20,096	0.28	0.55	0.51	1.01	0.17	0.33
Southern California Coastal Plain	14,976	−0.23	−0.28	0.10	0.12	−0.15	−0.17
Southern California Mountains	19,008	−0.23	−0.41	0.07	0.12	−0.18	−0.33
Klamath and Shasta Valleys and Basins	19,968	0.02	0.05	0.06	0.18	−0.12	−0.35
Sierra Nevada Range	67,392	−0.47	−3.22	−0.35	−2.34	−0.38	−2.55
Malheur High Plateau	4608	0.28	1.96	0.32	2.26	0.33	2.30
Carson Basin and Mountains	7488	0.02	0.05	0.08	0.17	0.15	0.31
Southern Nevada Basin and Range	19,200	0.37	2.55	0.45	3.05	0.46	3.14
Sonoran Basin and Range	86,912	0.55	10.09	0.69	12.60	0.71	12.99
Imperial Valley	5504	0.63	0.49	0.51	0.40	0.47	0.37
Statewide Total	408,704		14.15		23.48		16.21

Mean fluxes of carbon as net ecosystem production (NEP) are shown as negative values for net source fluxes to the atmosphere from the ecosystem, and as positive values for net sink fluxes to the ecosystem from the atmosphere. Note on units: 1 g C m^{-2} = 0.01 t C ha^{-1} (for comparisons to values in Table 2). MMTCE is million metric tons carbon equivalent.

Table 2 – Estimated ecosystem pools of aboveground standing carbon by MLRA in California.

MLRA name	Live leaf carbon		Standing wood carbon	
	Mean (t C ha^{-1})	MMTCE	Mean (t C ha^{-1})	MMTCE
California Coastal Redwood Belt	2.46	3.06	108.27	134.42
Siskiyou-Trinity Area	2.60	10.35	104.76	408.97
Central California Coastal Valleys	0.85	0.87	47.91	47.84
Central California Coast Range	0.92	3.79	48.01	185.59
California Delta	1.18	0.32	32.62	2.92
Sacramento and San Joaquin Valleys	1.04	4.74	37.71	92.18
Sierra Nevada Foothills	1.04	2.07	54.53	107.50
Southern California Coastal Plain	0.75	0.88	54.50	63.13
Southern California Mountains	0.74	1.34	52.13	94.43
Klamath and Shasta Valleys and Basins	1.03	3.13	57.49	145.32
Sierra Nevada Range	1.42	9.59	69.78	468.05
Malheur High Plateau	0.66	4.60	31.83	159.30
Carson Basin and Mountains	0.49	1.02	32.47	67.12
Southern Nevada Basin and Range	0.34	2.35	23.99	163.37
Sonoran Basin and Range	0.33	6.09	19.79	357.64
Imperial Valley	0.57	0.44	25.51	17.96
Statewide total		54.66		2515.76

baseline carbon pools in standing biomass (live leaf and wood) in the range of 34–36 t C ha^{-1}. Surface soil pools of stored carbon estimated for these areas (in the range of 46–48 t C ha^{-1}) were generally higher than aboveground carbon pools.

Soils of the heavily cultivated Sacramento, San Joaquin, and Imperial Valleys were estimated to be among the lowest in the state in terms of carbon storage. Surface soil baseline pools were in the range of 7–18 t C ha^{-1} (Table 2). There was, nonetheless, a trend of increasing soil carbon storage estimated moving from south to north, from the San Joaquin to the Sacramento Valley areas.

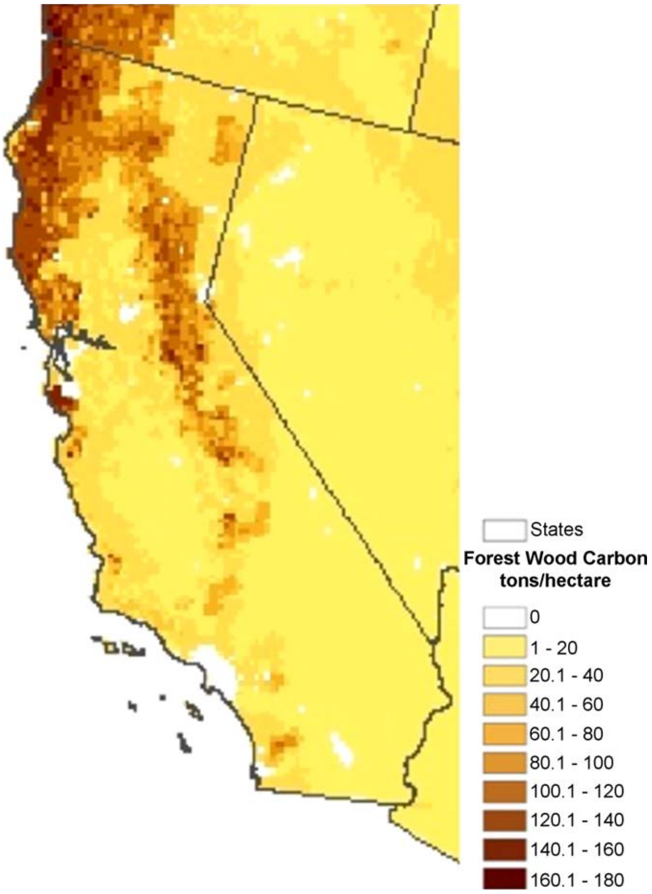

Fig. 6 – CASA model prediction of carbon pools in standing wood biomass.

4.4. Model comparisons to inventory-based estimates

In the following section, we briefly reviewed several inventory-based reports that provide baseline carbon pools for ecosystems of California. Since most inventory methods are based on measurements at the scale of a few meters, these plot-level estimates of single ecosystem types are not strictly comparable to the estimates from the CASA model. Unlike plot inventories, the CASA model takes into account minimum areas covering several square kilometers at a time. This means that the satellite data used as input to the CASA model includes the effects of some non-forest and many mixed-age forest areas in each estimate, i.e., not estimates for single ecosystem types represented in plot inventories. Nevertheless, the inventory-based methods can provide upper boundary estimates for the CASA model, particularly because inventories are commonly reported for forests managed for high potential production of biomass.

Two forest sites in northern California were recently surveyed by Winrock International (2004a) in a report to the California Energy Commission on biomass carbon storage potential. The two sites were Sierra mixed conifers at Blodgett Forest Research Station (BFRS) and the coastal redwoods at Jackson Demonstration State Forest (JDSF). At the BFRF, mature conifer stands were estimated with baseline pools in standing live biomass of about 225 t C ha^{-1}, whereas wood litter pools were estimated at 20 t C ha^{-1}. Younger conifer stands (20 years old) were measured with baseline pools in standing live biomass of about 50 t C ha^{-1}, whereas wood litter pools were estimated at 5 t C ha^{-1}. At the JDSF, mature conifer stands were estimated with baseline pools in standing live biomass of about 275 t C ha^{-1}, whereas wood litter pools were estimated at 13 t C ha^{-1}. Younger conifer stands (20 years old) were measured with baseline pools in standing live biomass of about 60 t C ha^{-1}, whereas litter pools were estimated at 5 t C ha^{-1}.

Based on our model results, mixed-age forest estimates from the CASA model fall easily within the range of these inventory-based carbon pools for both BFRS and JDSF. The averaged CASA estimate for BFRS was standing live biomass of 160 t C ha^{-1} and wood litter pools of 26 t C ha^{-1}. The averaged CASA estimate for JDSF was standing live biomass of 210 t C ha^{-1} and wood litter pools of 36 t C ha^{-1}. Because of the wide range of baseline carbon pools reported in the Winrock International (2004a) results, more detailed comparisons between model and inventory methods were not possible.

In another relevant report by Winrock International (2004b) to the California Energy Commission, the total carbon stock in agricultural lands for 1997 was estimated to be 20 MMTCE. This appears to be an underestimated baseline, compared to the CASA total carbon stock estimated at 119 MMTCE for the Sacramento and San Joaquin Valleys (Table 1). The Winrock report does state that potential errors in their estimates could be notable (e.g., >30%), mainly caused by uncertainty in the reported carbon densities of croplands.

5. Discussion

To minimize the risks associated with human-induced climate change, global GHG emissions must be significantly reduced over the 21st century (IPCC, 2007). One way to facilitate emission reductions is through the use of regional and national carbon budgets. These budgets compare the emission sources from industrial, residential, and transportation activities to those from agriculture, forestry, and other ecosystem fluxes and storage pools in the same units of GHG amounts over consistent geographic areas. As such, carbon budget calculations can support assessments of tradeoffs in emission reduction planning.

California offers an important example for developing a U.S. national carbon budget, in part because of its diversity of land cover types, use of natural resources, and urban lifestyles. California's carbon budget includes a mix of fossil fuel emissions, alternative energy sources, and ecosystem sinks that is broadly analogous to that of the entire country, as is its representation of developed land, forestland, rangeland, cropland, shrubland, grassland, and desert. For instance, annual NPP fluxes of CO_2 in California exceed the annual fossil fuel CO_2 emission budgets of the nations (individually) of Australia, Canada, France, Italy, or Spain (UNFCCC, 2009). Carbon stored in living biomass of forests, shrublands, and rangelands across the state exceed the totals of aboveground biomass carbon in the nations (individually) of Italy, Norway, or the Untied Kingdom (Potter, 1999).

Comparisons of the most recent GHG emissions data for the state indicates that fossil fuel contributions totaled 115 MMTCE in 2004, while statewide NPP from ecosystems was predicted at a comparable total of 120 MMTCE. During years when precipitation is received at above long-term average amounts, we estimate that California ecosystems may offset between 14 and 24 MMTCE through the sequestration of a fraction of the annual NPP uptake of atmospheric CO_2 in wood and soil carbon pools (Fig. 7). Considering the large amounts of CO_2 that can be (re)captured and stored in living biomass of forests, shrublands, and rangelands across the state (presently estimated at a total standing stock of 2570 MMTCE), the importance of protection and conservation of the natural NPP capacity of California ecosystems cannot be overemphasized.

Assuming that climate change has already begun to impact ecosystems in the western United States (Field et al., 1999), the carbon sink capacity of forests and rangelands must be closely monitored in the coming years. Warming trends off the Pacific coast can generate longer summer dry periods as well as earlier snow melt. As more winter precipitation falls as rain, forests have been reported to grow more sparsely and trees have been dying at rates that have more than doubled in old-growth forests across the western United States (van Mantgem et al., 2009). These rising forest mortality rates spanned a range of elevations, species, and tree sizes. Such persistent changes in tree mortality rates can alter forest structure and rapidly reduce carbon storage rates. Fellows and Goulden (2008) reported that unmanaged forests, especially in the Sierra Nevada Mountains, have lost carbon over the last 70 years largely as a result of the selective mortality of large trees. This mortality was likely caused by episodic insect outbreaks, which may have been exacerbated by stand thickening associated with fire suppression.

Despite efforts to control forest burning, according to Westerling et al. (2006), the frequency of large wildfires has increased in the western United States over the past 25 years, a trend strongly associated with increased spring and summer

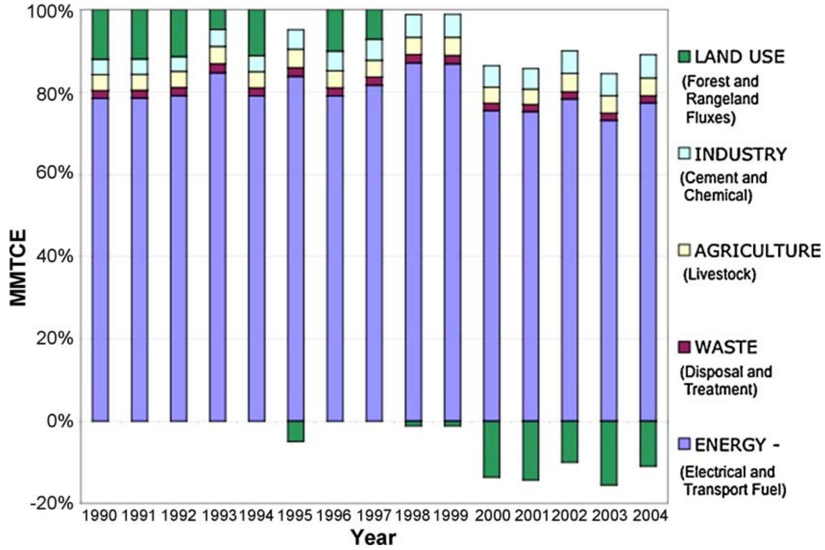

Fig. 7 – CASA model adjusted California GHG Inventory Summary 1990–2004.

temperatures and an earlier spring snowmelt. Global climate model predictions were used by Westerling and Bryant (2008) to predict future fire activity in California, with increasing temperatures promoting greater large fire frequency in wetter, forested areas, based mainly on fuel flammability effects.

In closing, it is worth noting that state legislation (Assembly Bill 32) requires California to reduce GHG emissions to 1990 levels by 2020 and by another 80% below the 1990 levels by 2050. California's growing population and the demand for all forms of energy will make meeting these targets a major challenge. To maintain an accurate and complete accounting of the state's total GHG emission inventory, the information presented in this paper suggests that changes in net ecosystem fluxes of CO_2 are just a critical to monitor as are fossil fuel sources of GHG emissions. The technology exists to monitor forest, rangeland, and cropland carbon cycles from Earth-observing satellites, but this capability must be maintained at current quality standards for decades to come if GHG reduction targets are to be fairly evaluated.

Potter et al. (2008).

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