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Terrestrial Carbon Sinks for the United States Predicted from MODIS Satellite Data and Ecosystem Modeling

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ABSTRACT: A simulation model based on satellite observations of monthly vegetation cover from the Moderate Resolution Imaging Spectroradiometer (MODIS) was used to estimate monthly carbon fluxes in terrestrial ecosystems of the conterminous United States over the period 2001–04. Predicted net

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ecosystem production (NEP) flux for atmospheric CO_2 in the United States was estimated as annual net sink of about +0.2 Pg C in 2004. Regional climate patterns were reflected in the predicted annual NEP flux from the model, which showed extensive carbon sinks in ecosystems of the southern and eastern regions in 2003–04, and major carbon source fluxes from ecosystems in the Rocky Mountain and Pacific Northwest regions in 2003–04. As demonstrated through tower site comparisons, net primary production (NPP) modeled with monthly MODIS enhanced vegetation index (EVI) inputs closely resembles both the measured high- and low-season carbon fluxes. Modeling results suggest that the capacity of the NASA Carnegie Ames Stanford Approach (CASA) model to use 8-km resolution MODIS EVI data to predict peak growing season uptake rates of CO_2 in irrigated croplands and moist temperate forests is strong.

KEYWORDS: Carbon dioxide; Ecosystems; Remote sensing; MODIS; EVI

1. Introduction

Carbon is important as the basis for food and fiber supplies that sustain and shelter human populations, and as the primary energy source that fuels economies. Carbon dioxide (CO_2) is a major contributor to the planetary greenhouse effect and potential climate change. Effective carbon management strategies will require new scientific information about flux processes of the carbon cycle and an understanding of long-term interactions with other components of the Earth system such as climate and the water and nitrogen cycles. Such management strategies also will require an ability to account for all carbon stocks, fluxes, and changes and to distinguish the effects of human actions from those of natural system variability (CCSP 2003).

Accurate estimates of how much carbon ecosystems can sequester will be fundamental to successful systems of national carbon accounting for the United States. Land areas that consistently add carbon by growth in ecosystem production are potentially important as future sinks for industrial CO_2 emissions. Conversely, land areas that do not consistently sequester carbon over time may be adding to already increasing atmospheric CO_2 from fossil fuel burning sources.

The launch of the National Aeronautics and Space Administration's (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, 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 1988; Goetz and Prince 1998).

Operational MODIS algorithms generate the enhanced vegetation index (EVI) (Huete et al. 2002) as global image coverages from 2000 to present. EVI represents an optimized vegetation index, whereby the vegetation index 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 and improved vegetation monitoring through a decoupling of the canopy background signal and a reduction in atmosphere influences. Houborg and Soegaard (Houborg and Soegaard 2004) found that MODIS EVI was able to accurately describe the variation in green biomass, in agriculture areas in Denmark, up to green leaf area index (LAI) of 5 ($R^2 = 0.91$). 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 this study, we present the results of the Carnegie Ames Stanford Approach (CASA) model predictions of terrestrial ecosystem fluxes using 2001–04 MODIS EVI inputs at 8-km spatial resolution to infer variability in nationwide carbon fluxes. Our NASA-CASA model (Potter et al. 1993; Potter et al. 1999; Potter et al. 2003) has been designed to estimate monthly patterns in carbon fixation, plant biomass increments, nutrient allocation, litter fall, soil carbon, CO_2 exchange, and soil nutrient mineralization. The model results from this NASA-CASA simulation study of annual net ecosystem exchange of CO_2 driven by nationwide MODIS observations imply that despite precipitation shortages and above-average temperatures in various sections of the country, there was an increasing trend in terrestrial ecosystem sinks for atmospheric CO_2 for the continental United States in 2003–04.

2. Modeling methods and global drivers

As documented in Potter (Potter 1999), the monthly NPP flux, defined as net fixation of CO_2 by vegetation, is computed in NASA-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 (S_r) and EVI from the MODIS satellite, plus a constant light utilization efficiency term ($e_{\max}$) that is modified by time-varying stress scalar terms for temperature (T) and moisture (W) effects [(Equation 1)]:

$$\mathrm{NPP} = S_r \mathrm{EVI} e_{\max} T W. \tag{1}$$

The $e_{\max}$ term is set uniformly at 0.39 g C MJ^{-1} PAR, a value that derives from the 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 (Figure 1a). Interannual NPP fluxes from the CASA model have been reported (Behrenfeld et al. 2001) and validated against multiyear 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 boreal forest sites in North America (Potter et al. 2001; Amthor et al. 2001; Hicke et al. 2002) and against atmospheric inverse model estimates of global NEP (Potter et al. 2003).

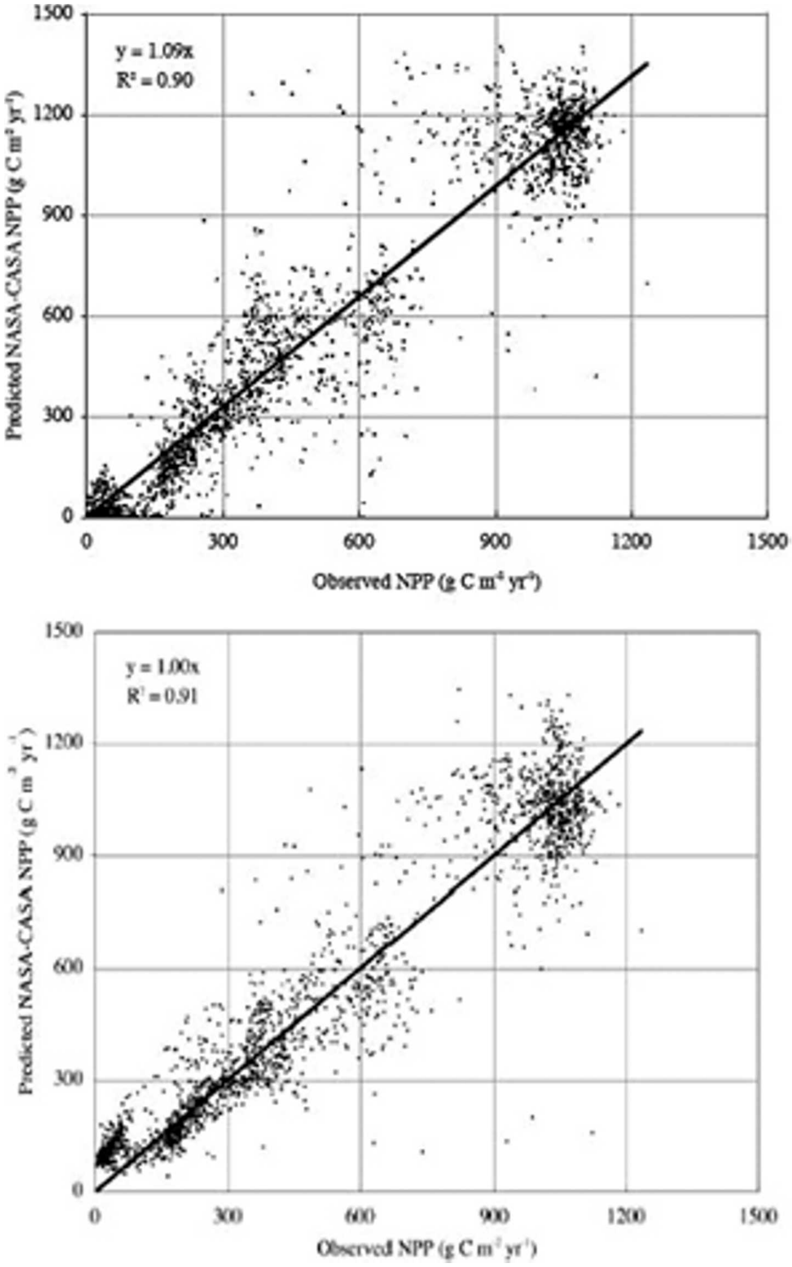

Figure 1. Comparison of annual observed NPP to predicted values from the NASA-CASA model (driven by 0.5° data inputs). (a) Inputs from AVHRR-FPAR 1982 and climate means from New et al. (New et al. 2000). (b) Inputs from MODIS-EVI 2001 and climate from NCEP–NCAR reanalysis products for 2001. Both figures include the 1:1 regression line. The dataset of more than 1900 observed NPP points was compiled for the Ecosystem Model–Data Intercomparison (EMDI) activity by the Global Primary Productivity Data Initiative (GPPDI) working groups of the International Geosphere Biosphere Program Data and Information System (IGBP-DIS; Olson et al. 1997).

For the first time in our NPP model, the $e_{\max}$ term has been adjusted for different cropland types to account for the effects of fertilizer nutrient additions on crop yield and biomass production. Following the synthesis results of Stewart et al. (Stewart et al. 2005), who summarized a total of 362 seasons of crop production, the average percentage of yield attributable to fertilizer generally ranged from about 40% to 60% in the United States. To capture these effects, the CASA $e_{\max}$ term included optional multipliers (in units of percent increase) for major U.S. commercial crops, including corn (*Zea mays* L.) at 41%–57%, sorghum (*Sorghum bicolor,* L.) at 19%, wheat (*Triticum aestivum* L.) at 16%–62%, barley (*Hordeum vulgare* L.) at 19%, rice (*Oryza sativa* L.) at 27%, and cotton (Gossypium *spp* L.) at 37%. Soybean [*Glycine max* (L.) Merr.], cowpea [*Vigna unguiculata* (L.) Walp.], and peanut (*Arachis hypogaea* L.) were assumed to receive negligible fertilizer amendments in U.S. cropping systems (Stewart et al. 2005). As previously noted by Lobell et al. (Lobell et al. 2002), field studies of corn production have shown that the $e_{\max}$ term for C_4 crops should be higher than for most C_3 plants, owing to greater water use efficiency of the C_4 assimilation pathway.

The T stress scalar is computed with reference to derivation of optimal temperatures (T_{opt}) for plant production. The T_{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 (Priestly and Taylor 1972). The MODIS 1-km land cover map (Friedl et al. 2002) aggregated to 8-km pixel resolution was used to specify the predominant land cover class for the W term in each pixel as either forest, crop, rangeland, or other classes such as water or urban area.

Evapotranspiration is connected to water content in the soil profile layers (Figure 2), as estimated using the NASA-CASA algorithms described by Potter (Potter 1999). The soil model design includes three-layer (M_1–M_3) heat and moisture content computations: surface organic matter (SOM), topsoil (0.3 m), and subsoil to rooting depth (1–2 m). 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. Freeze–thaw dynamics with soil depth operate according to the empirical degree-day accumulation method (Jumikis 1966), as described by Bonan (Bonan 1989).

For the first time in our model, the W water stress term has been set equal to unity (no water stress) for cropland types where irrigation water additions are used to sustain crop yield and biomass production. Döll and Siebert (Döll and Siebert 2000) developed the first global map of irrigated areas that described the fraction of each 0.5° cell area that was equipped for irrigation around 1995. The currently available global map of irrigated areas (version 3.0, April 2005) is a version of the Döll and Siebert (Döll and Siebert 2000) map that has been updated in cooperation with the Food and Agriculture Organization of the United Nations (FAO) for all countries worldwide by using a new mapping methodology and improved source

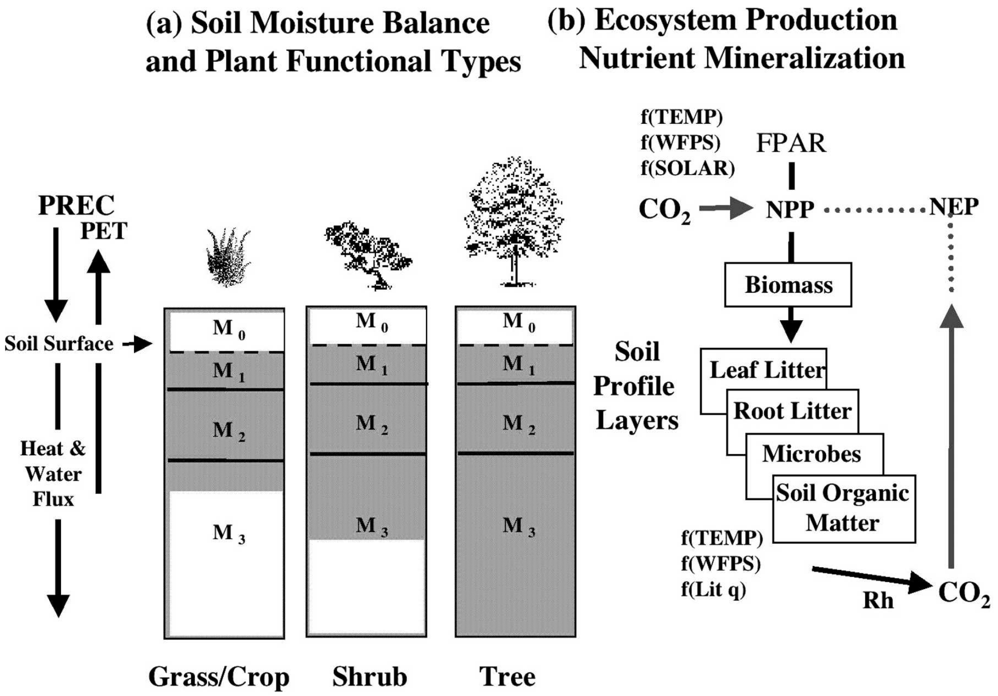

Figure 2. Schematic representation of components in the NASA-CASA model. (a) The soil profile component (I) is layered with depth into a surface ponded layer (M_0), a surface organic layer (M_1), a surface organic-mineral layer (M_2), and a subsurface mineral layer (M_3), showing typical levels of soil water content (shaded) in three general vegetation types (DeFries et al. 1995). (b) The production and decomposition component 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*).

data. It shows the area within each 5-min cell (area 9.25 km by 9.25 km at the equator) that was equipped for irrigation in the 1990s.

For updating the continental U.S. irrigation map, no information was available on the area equipped for irrigation on a subnational level. Area equipped for irrigation was therefore estimated on a county level by first combining the inventories of the U.S. Department of Agriculture (USDA) and the U.S. Geological Survey (USGS) on irrigated area per county in years 1995, 1997, 2000, and 2002. The maximum value of irrigated area per county reported for these years was derived and assumed to represent the area equipped for irrigation. The National Land Cover Dataset on a 30-m resolution (USGS and USEPA 1999) grid was used to assign irrigated areas to specific cells within the subnational units of the conterminous United States. Irrigated area of subnational units was equally distributed over all National Land Cover Data (NLCD) cells classified as orchards and vineyards (value 61), row crops (value 82), small grains (value 83), or fallow (value 84). If the sum of these cropland areas was smaller than the total irrigated area per subnational unit, the remaining area was assigned to cells classified as pasture and hay (value 81). This appeared in the majority of the subnational units in the states of Arizona, California, Colorado, Idaho, Nevada, New Mexico, Oregon, Utah, Washington, and Wyoming and in some subnational units located in the states of Arkansas, Florida, Massachusetts, Missouri, Montana, Nebraska, and Texas.

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 worldwide. 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 NASA-CASA soil model uses a set of compartmentalized difference equations with a structure comparable to the CENTURY ecosystem model (Parton et al. 1992). First-order decay equations simulate exchanges of decomposing plant residue (metabolic and structural fractions) at the soil surface. The model also simulates 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.

In areas dominated by annual croplands, the NASA-CASA model returns all litter carbon to the soil decomposition pathways described above within the 8-km grid location where it has been produced as NPP. It is assumed that, while a portion of cropland NPP is harvested in yields that are not added directly and immediately back to the same cultivated soil, an equivalent portion of the plant biomass is consumed regionally for livestock and human needs within the same growing season cycle, and therefore must still make up a portion of the cropland soil respiration R_h flux of CO_2 back to the atmosphere on a regional basis. In other words, harvested carbon pools from commercial croplands are treated as a short-term recycling flux in the regional R_h flux of CO_2, unlike harvests of wood carbon products from forested areas that would not be returned to the atmospheric CO_2 pool for many years.

For NASA-CASA 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 the 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 2001–04 came from National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis products (Kistler et al. 2001).

The NASA-CASA 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 1979–81 (New et al. 2000). This 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, which were run on a monthly time step from January 1982 to December 2000. When this soil carbon initialization step is not properly included, we note that an ecosystem model will likely predict artificially large carbon sinks in the terrestrial biosphere that then diminish as an artifact feature over the actual simulation period of interest as the model eventually approaches steady state. 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. For instance, it is openly acknowledged that the NASA-CASA modeling approach using 8-km satellite data inputs cannot capture all the carbon sink effects of forest regrowth from recent wood harvest activities (Turner 2006), although impacts of major clear-cuts and wildfires are detectable (Potter et al. 2005). Higher-resolution (250 m) MODIS EVI datasets are currently in the evaluation phase for use in CASA model runs for intensively managed forest areas.

Whereas previous versions of the NASA-CASA model (Potter et al. 1993; Potter et al. 1999) used a normalized difference vegetation index (NDVI) to estimate fraction of photosynthetically active radiation (FPAR), the current model version instead has been calibrated to use MODIS EVI datasets as direct inputs to Equation (1) above. In long-term (1982–2004) simulations, continuity between Advanced Very High Resolution Radiometer (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. NASA-CASA model predictions with 2001 monthly MODIS EVI inputs have been adjusted using the same set of field measurements of NPP shown in Figure 1a, to which the model was previously calibrated for a best linear fit to AVHRR inputs (Potter et al. 2003). To best match predictions with previously measured NPP estimates at the global scale (Figure 1b), the model $e_{\max}$ term for 2001 MODIS EVI inputs was reset to 0.55 g C MJ^{-1} PAR, a value that is globally 42% higher than previously used in the model for AVHRR-driven NPP predictions from 1982 to 1998 (Potter et al. 2003). The regression coefficient (with line intercept forced through zero) of $R^2 = 0.91$ for this NPP recalibration to 2001 MODIS EVI inputs was statistically significant ($p < 0.01$).

3. Evaluation of NPP results at Ameriflux tower sites

Four tower measurement sites in the United States have been used in this study for model validation purposes. These four sites were evaluated by Turner et al. (Turner et al. 2005) as part of a network of sites representing the major biomes for carbon flux studies. Flux tower-based estimates of daily GPP estimates are now made routinely at the sites. Turner et al. (Turner et al. 2005) reviewed general uncertainties in tower-based GPP fluxes and described the methods used for scaling to a tower footprint prediction of monthly NPP from measured GPP data. Geographic coordinates and summary climate data for the four sites are listed in Table 1. Vegetation cover types and measured NPP fluxes (Turner et al. 2005) for the 5-km tower resolution are provided below in the descriptions of comparisons to NASA-CASA predictions of monthly NPP fluxes at the 8-km resolution.

An agricultural field site (AGRO) located near Bondville, Illinois, in the Midwest, is composed of no-till corn and soybean fields with small areas of urban development. Continuous measurements of flux data were made from 1997 through 2002 to evaluate the carbon budget for a no-till maize (*Zea mays* L.) and

Table 1. Site location and long-term average climate variables. MAT is the mean annual temperature.

Code	Vegetation	State	Lat (°N)	Lon (°W)	Precipitation (cm)	MAT (°C)
AGRO	Corn/soybean	IL	40.006 658	88.291 535	99	11.23
HARV	Hardwood forest	MA	42.528 513	72.172 907	111	8.31
METL	Conifer forest	OR	44.450 722	121.572 812	44	7.75
SEVI	Grassland	NM	34.350 858	106.689 897	35	13.57

soybean [*Glycine max* (L.) Merr.] rotation agricultural ecosystem (Hollinger et al. 2005; Bernacchi et al. 2005).

Monthly predicted NPP from the NASA-CASA model correlated closely ($R^2 = 0.85$) with monthly NPP carbon fluxes at this AGRO site (Figure 3a). Early and late growing season (March–May and September–October, respectively) NPP were overestimated slightly by the model, with a probable explanation being the greenness contribution of areas of noncropped land around the cultivated fields. Annual predicted NPP for this AGRO site was 475 g C m^{-2}, whereas measured NPP at the tower was 504 g C m^{-2}.

The temperate deciduous forest site (HARV) is predominantly (95%) closed hardwood conifer forest, with small areas of wetlands and urban development. The HARV tower is within the Harvard Forest Long-Term Ecological Research (LTER) site in Massachusetts. It is a forest stand approximately 70 yr old, dominated by red oak and red maple (Goulden et al. 1996). Bassow and Bazzaz (Bassow and Bazzaz 1998) observed an increase in leaf net photosynthetic rate in the dominant trees of the HARV forest from the early part of the growing season (June) to the middle of the growing season (July). In late summer, measured net photosynthesis rates declined again.

Monthly predicted NPP from the NASA-CASA model correlated almost exactly ($R^2 = 0.99$) with monthly NPP carbon fluxes at the HARV site (Figure 3b). Early growing season (March–May) NPP fluxes were overestimated slightly by the model. Annual predicted NPP for this HARV site was 543 g C m^{-2}, whereas measured NPP at the tower was 537 g C m^{-2}. We note that Xiao et al. (Xiao et al. 2004) similarly showed that MODIS EVI was a reliable predictor of forest GPP at the HARV site.

The temperate coniferous forest site (METL) is located on the eastern slope of the Cascade Mountains around the Metolius Research Natural Area of Oregon and is primarily open Ponderosa Pine (*Pinus ponderosa*) forests mixed with areas of grassland and shrubland (Law et al. 2004). Field data have showed that NPP and NEP at the METL were greater at the old pine site than the young site.

Monthly predicted NPP from the NASA-CASA model were closely matched with monthly NPP carbon fluxes at this METL site for the all months except July–August (Figure 3c). Predicted NPP fluxes were underestimated by the model during these months. Annual predicted NPP for this METL site was 119 g C m^{-2}, whereas measured NPP for the tower was 298 g C m^{-2}.

Primary production estimates by Turner et al. (Turner et al. 2005) were not well matched either with the tower observations at METL, a pattern most likely related to simulated water stress factors becoming strong in midsummer. Characterizing soil water availability is problematic at the areas around METL because some

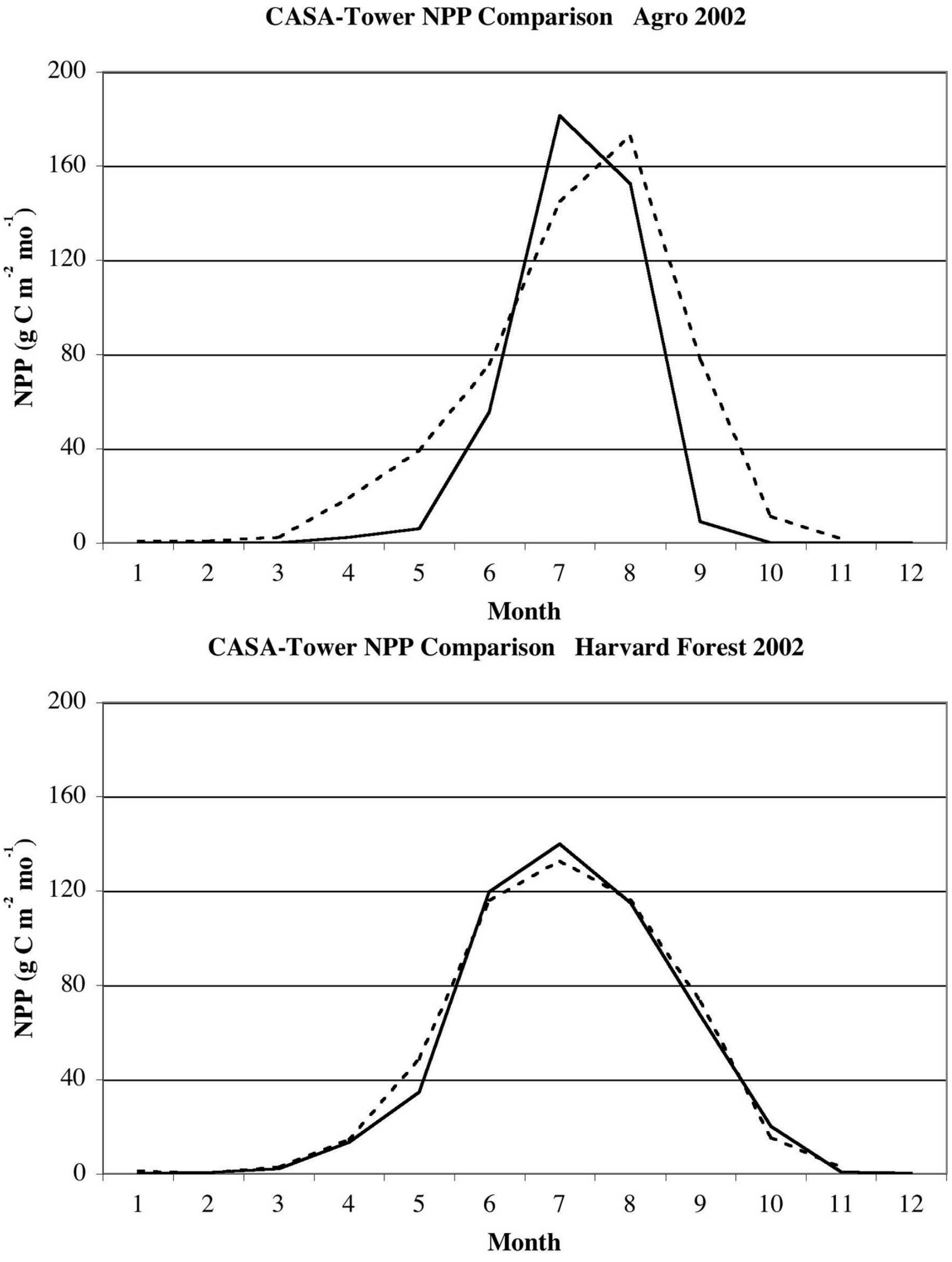

Figure 3. Comparison of predicted vs measured monthly NPP for four tower flux sites. Solid lines are the measured tower fluxes whereas dashed lines are the NASA-CASA model-predicted fluxes.

forest trees are accessing water deeper than 1 m, while grassland vegetation may be more constrained to upper soil water layers. There are also small-scale (<1 km) impacts of forest management (e.g., clear-cuts) at the METL site that are not accounted for in the NASA-CASA predictions.

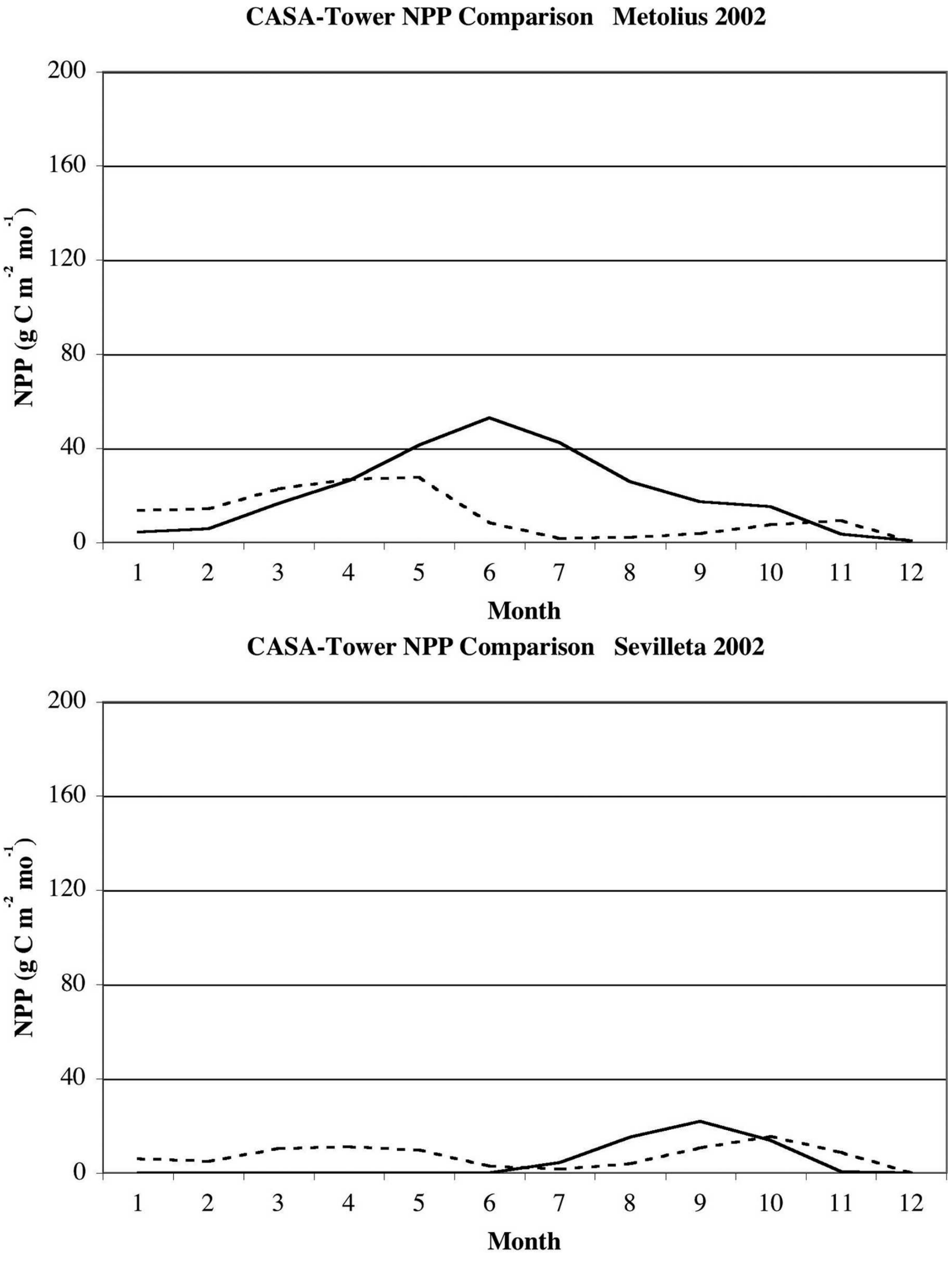

Figure 3. (*Continued*)

The desert grassland site (SEVI) is predominantly perennial bunchgrasses, dominated with Black Grama (*Bouteloua eriopoda*) and Blue Grama (*Bouteloua gracilis*). SEVI is in the Sevilleta LTER site in central New Mexico. Occasional cacti and shrubs are present. Cattle grazing is not permitted in the area of the tower measurements (Kurc and Small 2004).

Monthly predicted NPP from the NASA-CASA model was closely matched with monthly NPP carbon fluxes at the SEVI site for the all months except March–May (Figure 3d). Predicted NPP fluxes were overestimated by the model during these months. Annual predicted NPP for this SEVI site was 113 g C m^{-2}, whereas measured NPP for the tower was 53 g C m^{-2}. Similarly, the NPP model predictions reported by Turner et al. (Turner et al. 2005) overestimated annual NPP at the SEVI site. It is unclear from the published studies for SEVI why NPP is measured to be practically zero in the wet season months of March–May at this site, a period during which the MODIS EVI estimates are typically as high as during any other time of the year.

It is widely known that tower flux measurements of NEP can be used for model validation at the small site scale. Nevertheless, we have not included comparisons of tower-based NEP to NASA-CASA modeled NEP in this continental-scale study, because tower eddy flux estimates are not designed to represent large-scale (e.g., 8 km) NEP fluxes that we model with NASA-CASA. Specifically, 1) the typical eddy flux tower footprint is too small to capture large-scale variation in soil CO_2 fluxes and woody biomass pools undergoing decomposition in forested areas, 2) mortality-related tree fall of boles into large pools of dead wood carbon is a large-scale process that generally does not occur near the location and during the time span of tower flux measurements, and 3) monthly NEP fluxes are very small (relative to NPP fluxes) and highly variable in time and space, potentially due to heterogeneity in soil properties and litter pools that small tower footprints cannot adequately represent. Conversely, NPP flux estimates from towers can be considered more representative of large-scale model predictions, because plant CO_2 fluxes are controlled to a lesser degree by small-scale variations in soil properties and decomposing litter pools, and more by relatively uniform conditions of solar radiation fluxes and surface temperature.

4. National results for U.S. carbon fluxes

Annually summed NPP fluxes for the coterminous United States increased slightly over the period of 2000–04, from 2.67 Pg C yr^{-1} (1 Pg = 10^{15} g) in 2001 to a low of 2.59 Pg C yr^{-1} in 2002, up to 2.79 Pg C yr^{-1} in 2004 (Figure 4). Peak monthly NPP rates (typically for July) rose steadily for the country over the period from 2002 to 2004.

Annually summed NEP sink fluxes for the coterminous United States varied from year to year over the period of 2000–04, from 0.19 Pg C yr^{-1} C in 2001 to a low of 0.04 Pg C yr^{-1} in 2002, back up to around 0.2 Pg C yr^{-1} in 2003 and 2004 (Figure 5). Monthly NEP fluxes were largely influenced by monthly NPP predictions, which accounted for more that 95% of the variation in the predicted NEP sink fluxes nationwide (Figure 6). Monthly predicted R_h fluxes of CO_2 from soil microbial activity were not highly correlated with monthly predicted NEP fluxes but rather remained relatively consistent in seasonal magnitude from one year to the next.

Seasonal temperature patterns at different latitude zones explained much of the annual variability in predicted NPP and NEP fluxes of CO_2 in ecosystems of the coterminous United States. Compared to 2001 and 2002, the winter-to-spring

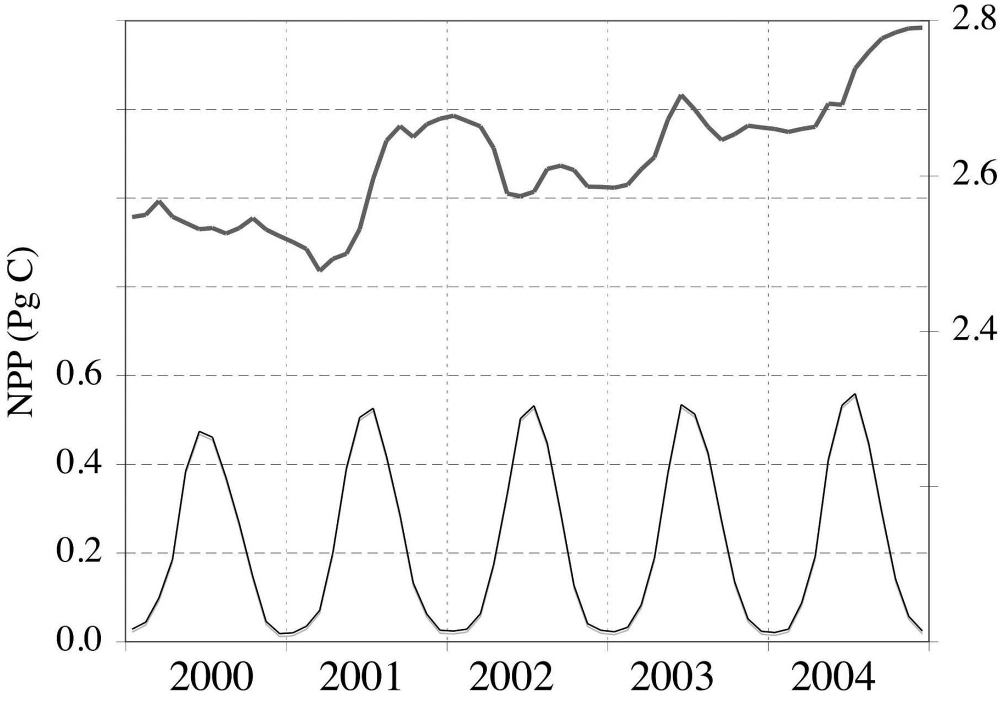

Figure 4. NPP in ecosystems of the coterminous United States from 2000 to 2004. The thin line is the monthly predicted NPP; the thick line is the 12-month running average NPP. Annual totals (Pg C) for 2000 = 2.52, 2001 = 2.67, 2002 = 2.59, 2003 = 2.66, and 2004 = 2.79.

warming rates were faster in 2003 and 2004 between the latitudes of 50° and 41°N (Figure 7). While the winter of 2002 was on average about 1°C warmer than in either 2003 or 2004 between the latitudes of 50° and 41°N, the average surface temperature in 2002 did not exceed 5°C until May of 2002, whereas by April of 2003 and 2004, average surface temperature had already reached 3°C. In the presence of adequate moisture supplies, a rapid warming trend early in the growing season generally promotes higher annual carbon gain in terrestrial ecosystems (Nemani et al. 2003).

Geographic patterns in annually summed NEP confirm that the year 2002 stood out from the other years 2000–04 with relatively large carbon source fluxes in ecosystems of the northeastern and north-central regions of the coterminous United States, as well as in parts of the Rocky Mountain and southern U.S. regions (Figure 8). Annual mean temperatures were above average in 2002 in the northeastern regions (NCDC 2004). Temperatures in the spring of 2002 were near normal nationally, compensating partially for a cooler than average March and May. Precipitation in the United States in 2002 was characterized by extreme dryness in the western and central United States, generally above-average wetness in the southern Mississippi Valley region, and dryness giving way to near-average conditions for the eastern regions. Colorado had its driest year on record during 2002 and Wyoming, Nevada, and Nebraska had their third driest year. Six states

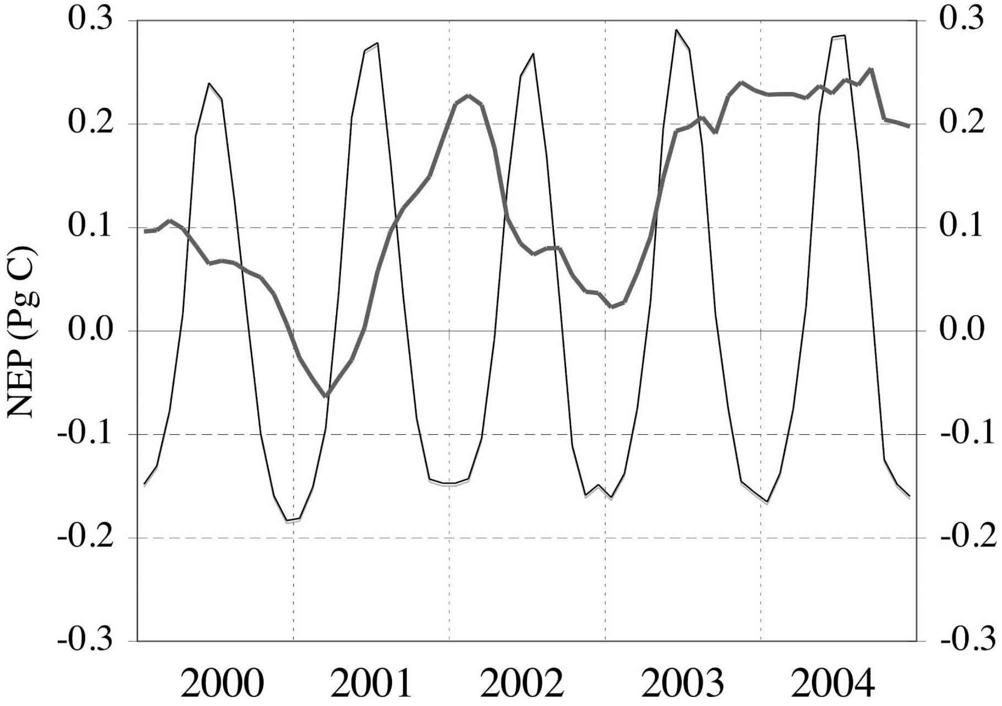

Figure 5. NEP of the coterminous United States from 2000 to 2004. The thin line is monthly predicted NEP; the thick line is the 12-month running average NEP. Annual totals (Pg C) for 2000 = 0.01, 2001 = 0.19, 2002 = 0.04, 2003 = 0.23, and 2004 = 0.20.

were much drier than normal in 2002 and the Southwest region as a whole was the fourth driest on record.

In contrast, annual mean temperatures were above average in 2003 and 2004 in the western U.S. regions, and below average in 2003 in the eastern U.S. regions. Precipitation in the United States was slightly above average in 2003 and 2004, with exceptions in the western and central U.S. regions in 2003 (where moderate to extreme drought covered more than 50% of 11 western states) and continuing into the northern Rocky Mountain and Pacific Northwest regions in 2004 (NCDC 2004). These regional climate patterns were reflected in the predicted annual NEP flux from the NASA-CASA model, which showed extensive carbon sinks in ecosystem of the southern and eastern regions in 2003–04, and major carbon source fluxes from ecosystems in the Rocky Mountain and Pacific Northwest regions in 2003–04 (Figure 8).

5. Carbon modeling focus on the midcontinental region

Atmospheric scientists working under the North American Carbon Program (NACP) have selected the midcontinental agricultural region of the central United States for intensive studies of sampling methods and models. The NACP will carry out this midcontinental intensive (MCI) study to help calibrate and validate remote

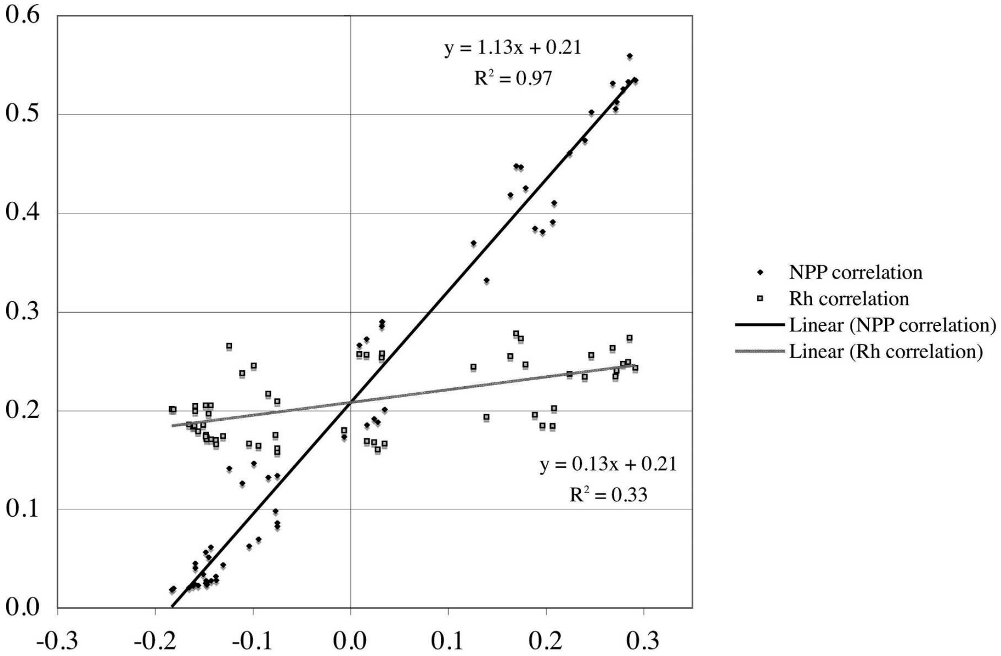

Figure 6. Correlations between predicted monthly NEP fluxes and predicted monthly NPP and R_h fluxes from the NASA-CASA model from 2000 to 2004.

sensing observations relevant to NACP science objectives. The focus of the campaign will be centered on the adjacent areas of South Dakota, Nebraska, Kansas, Missouri, Iowa, Minnesota, Wisconsin, and Illinois. The MCI region covers a significant portion of the most intensively farmed area of the continent, with relatively low population density, but with several concentrated metropolitan centers. The difficulties of interpreting atmospheric measurements with transport models will be evaluated over the relatively flat terrain of the MCI region (NACP 2005).

Our MODIS-driven model predictions of monthly and seasonal NPP over the entire MCI state region show a high degree of year-to-year consistency from 2001 to 2004 (Figure 9a). The complete eight-state region of the MCI area (as delineated from the list of states above) was predicted with annual NPP carbon fluxes of between 0.50 and 0.55 Pg C yr^{-1} from 2001 and 2004 (Figure 9a). Predicted NPP in the western portions of the MCI region, namely, South Dakota, Nebraska, Kansas, and Missouri, were the most variable from one year to the next, compared to predicted NPP across Iowa and Illinois.

With the exception of 2002, predicted annual NEP sink fluxes of carbon ranged between +0.03 and +0.04 Pg C yr^{-1} from 2001 and 2004 (Figure 9b). Drought conditions in the western portions of the MCI region during 2002 reversed the aggregated NEP sink flux for this eight-state area to an ecosystem source flux of −0.02 Pg C yr^{-1}. On the whole, it appears that net CO_2 sinks for the MCI region are more sensitive to the growing season carbon gains in the westernmost states

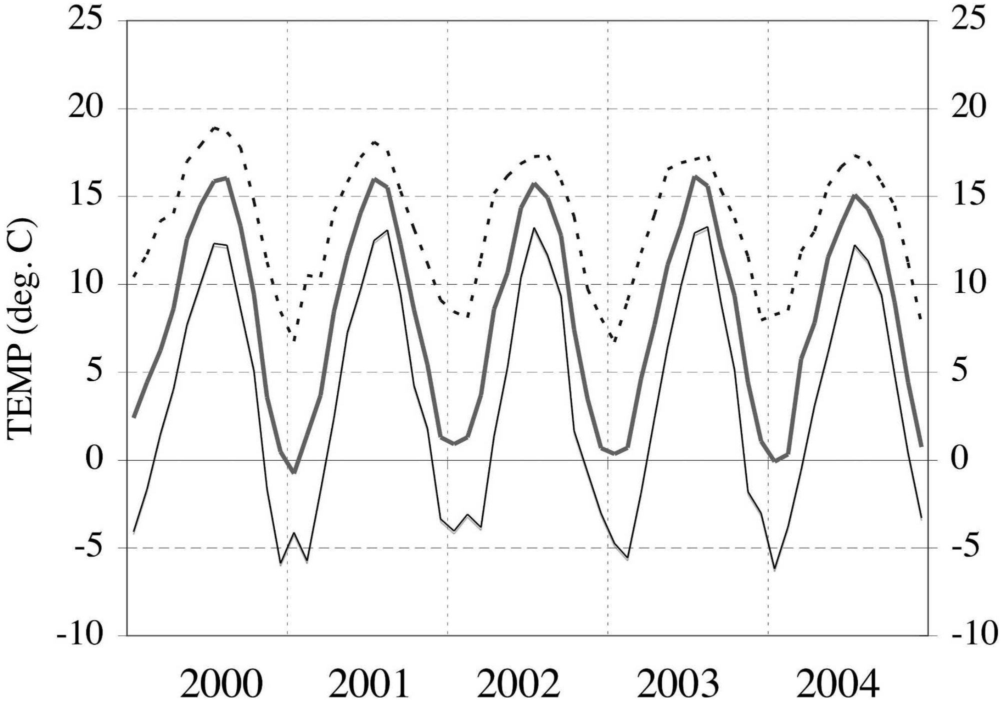

Figure 7. Average monthly temperature for three latitude zones of the coterminous United States from 2000 to 2004. The dashed line is mean over 30°–24°N, the thick line is mean over 40°–31°N, and the thin line is mean over 50°–41°N. Source: NCEP–NCAR (Kistler et al. 2001).

such as Nebraska and Kansas compared to carbon flux patterns across the easternmost state areas of Iowa and Illinois.

6. Discussion

Evidence from this modeling study indicates that the EVI is well suited as a variable to account for net carbon sinks in regional ecosystem budgets. As demonstrated particularly though the AGRO and HARV tower site comparisons, NPP modeled with monthly EVI inputs closely resembles both the measured high- and low-season carbon fluxes. The capacity of the NASA-CASA model using 8-km resolution MODIS EVI to accurately predict peak growing season uptake rates of CO_2 in irrigated croplands and relatively moist temperate forests means that the largest ecosystem carbon sinks across the country are not likely to be underestimated by the simulation approach presented above. A possible exception to that statement would be areas of small-scale forest harvesting or burning that are not well-represented at 8-km spatial resolution. Nevertheless, because MODIS EVI at 250-m resolution can be just as readily used to drive a model like NASA-CASA, there remains a major unexplored potential to capture in the MODIS data inputs more localized forest and rangeland management impacts on the nationwide carbon cycle.

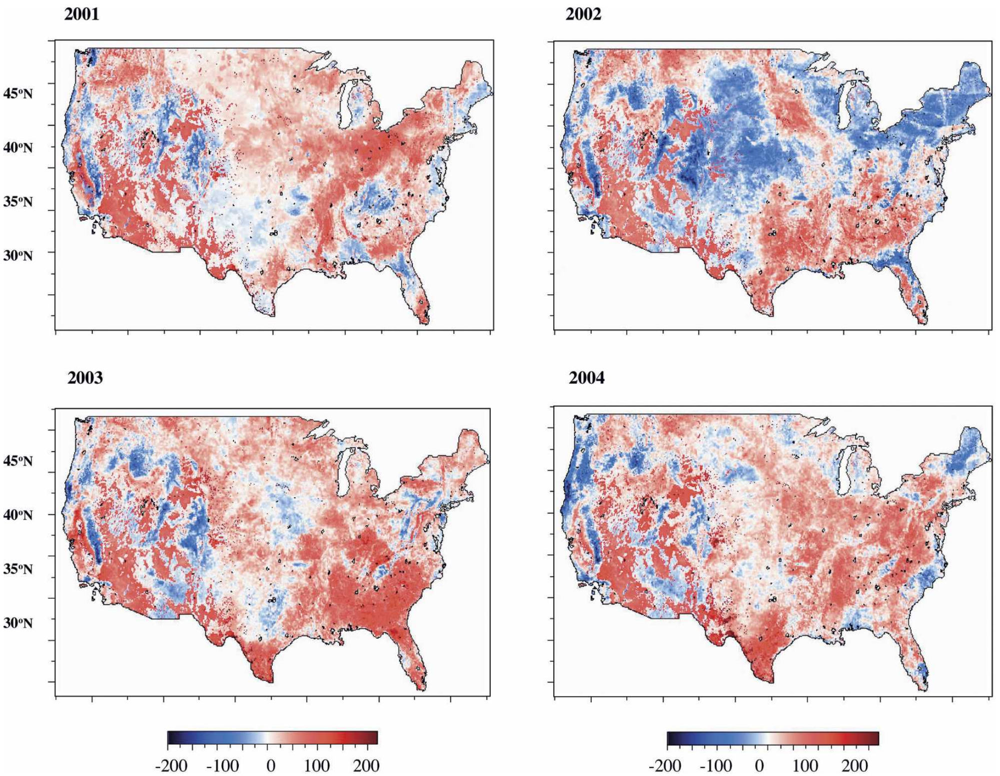

Figure 8. NEP maps for the coterminous United States from 2000 to 2004. Units are in Pg C per year, with red shading as annual C sinks and blue shading as annual C sources.

The results of NASA-CASA model simulations of NPP and NEP across the continental United States from 2001 to 2004 have several noteworthy implications for NACP assessment studies being planned for the years to come.

- Areas of the country that show consistently high carbon sink fluxes in terrestrial ecosystems on a yearly basis are the southern Appalachian Mountains, the western Gulf Coast states, the northern Rocky Mountains, and Sierra Nevada Mountains. Because seasonal climate and atmospheric circulation patterns are likely to differ substantially between these widespread areas of the country, new intensive study campaigns for NACP must be specifically tailored to each of these four priority regions with careful attention to the measurement network requirements for continuous atmospheric CO_2 monitoring.
- Areas of the country that show periodically high carbon source fluxes from terrestrial ecosystems on a yearly basis are the northeastern states, the eastern Gulf Coast, the southern Rocky Mountains, the western Great Basin, and the Pacific Northwest. Because the probability for climate-driven disturbances (ice storms, hurricanes, droughts, insect outbreaks, and wildfires) of forested lands in each of these regions of the country is high

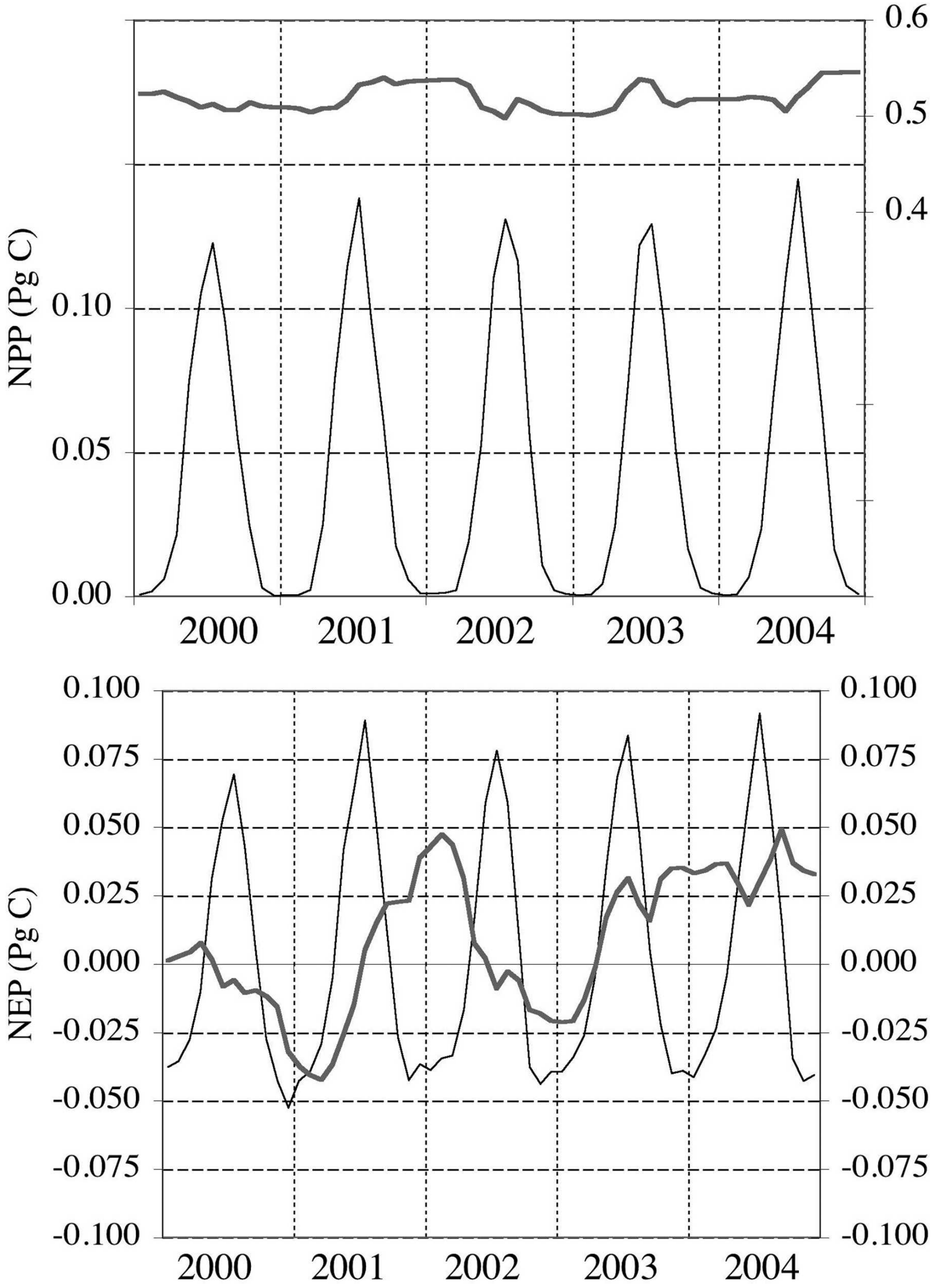

Figure 9. (top) NPP and (bottom) NEP in ecosystems of the midcontinental states of the United States from 2000 to 2004. The thin line is the monthly predicted NPP or NEP; the think line is the 12-month running average NPP or NEP.

(Potter et al. 2005), new types of integrated field and remote sensing study campaigns for NACP must be conceived.

We remark in closing that an advantage of combining ecosystem modeling with satellite observations for vegetation cover properties is to uniquely enhance the spatial resolution of source and sink patterns for CO_2 in the terrestrial biosphere. Using MODIS land products, carbon modelers have begun to identify numerous relatively small-scale patterns throughout the world where terrestrial carbon fluxes have varied in recent years between net annual sources and sinks. Predictions of NEP for these areas of high interannual variability will require further uncertainty analysis of carbon model estimates, with a focus on both flux algorithm mechanisms and potential scaling errors at the regional level.

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