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Satellite-derived increases in net primary productivity across North America, 1982–1998

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[1] We used a new 17-year, high spatial resolution satellite record and a carbon cycle model to explore how changing net primary productivity (NPP) contributed to a proposed carbon (C) sink in North America. We found a small but significant increase in NPP, 0.03 Pg C yr^{-2} or 8% over 17 years, that could explain a substantial fraction of the C sink. The largest increases occurred in the central and southeastern United States, eastern Canada, and northwestern North America, and were consistent with NPP trends derived from forest inventories and crop yields. Interannual NPP variability was small, implying that the large interannual variability in the C sink found in previous studies were driven by changes in heterotrophic respiration. *INDEX TERMS:* 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 1615 Global Change: Biogeochemical processes (4805)

1. Introduction

[2] The existence and size of the terrestrial biosphere sink are major uncertainties in the global carbon (C) cycle. Atmospheric inverse modeling studies report that North America is a C sink of 0.7–1.7 Pg C yr^{-1} [*Bousquet et al.*, 1999; *Fan et al.*, 1998]. However, forest inventories and biogeochemical models estimate a North American C sink of less than 0.6 Pg C yr^{-1} [*Birdsey and Heath*, 1995; *Houghton et al.*, 1999; *Schimel et al.*, 2000]. A recent study by *Pacala et al.* [2001] attempted to reconcile these disparate approaches, finding that additional and revised estimates of component C cycle processes bring them closer into agreement. Identifying the persistence of and mechanisms responsible for a North American C sink requires that we explore variability in the separate fluxes of net primary productivity (NPP) and heterotrophic respiration. For this paper we computed NPP using the Carnegie-Ames-Stanford Approach (CASA) model driven by satellite observations [*Field et al.*, 1995; *Potter et al.*, 1993]. This study extends the time period of past efforts [*Goetz et al.*, 2000; *Malmström et al.*, 1997; *Myneni et al.*, 1997; *Potter et al.*, 1999] and analyzes changes in NPP instead of the more typical satellite normalized difference vegetation index (NDVI) [*Myneni et al.*, 1997], allowing direct comparison of our results with field, modeling, and atmospherically-based estimates of the C cycle.

2. NPP Calculation

[3] We used the NDVI 8 km satellite product (January 1982–December 1998) [*Tucker et al.*, in press; *Zhou et al.*, 2001]. *Tucker et al.* [in press] showed that this NDVI data set resulted in no NDVI trends over deserts. CASA calculates monthly NPP from fAPAR-the fraction of absorbed photosynthetically active radiation (PAR)-computed from the NDVI, PAR, and a light use efficiency:

$$NPP = fAPAR\ PAR\ \varepsilon^* T_\varepsilon\ W_\varepsilon, \quad (1)$$

where ε^* is the globally defined maximum light use efficiency; T_ε is the down-regulator associated with temperature; and W_ε is the down-regulator associated with precipitation [*Field et al.*, 1995; *Potter et al.*, 1993]. ε^* was set to 0.405 following the calibration and validation procedures described by *Potter et al.* [1993]; other CASA studies used higher values of ε^* [*Malmström et al.*, 1997]. Increasing ε^*, as might be the case with increasing atmospheric CO_2, has the effect of increasing the absolute value of NPP, although this has no impact on the relative temporal or spatial trends analyzed here. Temperature and precipitation data were used to determine T_ε and W_ε in CASA. These down-regulators reduce the light use efficiency by 9–47% depending on biome [*Field et al.*, 1995].

[4] We chose input data sets that do not have missing values for the time period and region of interest. National Centers for Environmental Prediction (NCEP) Reanalysis [*Kistler et al.*, 2001] surface temperatures and downwelling solar radiation were employed. Precipitation was taken from the Global Precipitation Climatology Project (GPCP) [*Huffman et al.*, 1997]. Both data sets are available at 2.5° resolution and were interpolated to the 8 km spatial resolution of the NDVI.

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[5] To investigate the sensitivity of the results to the input data sets, NPP was also computed with several other data sets. Solar radiation generated using satellite observations of clouds [*Bishop and Rossow*, 1991] was used in place of the NCEP solar radiation for 1984–1990. We also calculated NPP using the Vegetation/Ecosystem Modeling and Analysis Project (VEMAP) input drivers of temperature, precipitation, and solar radiation [*Kittel et al.*, 2000]. VEMAP Version 2 contains observations for the conterminous US up to 1993. The VEMAP data are at 0.5° resolution, and so better account for variations in topography that cannot be resolved at the spatial scale of 2.5°.

3. Results

[6] We calculated a mean annual NPP in North America (north of 22°N) of 6.2 Pg C yr^{-1} (Figure 1), increasing at 0.028 Pg C yr^{-2} (significant at the 99% level). The change over 17 years was equivalent to a 8% increase over the 1982 values. Replacing the NCEP solar radiation with that of *Bishop and Rossow* [1991] reduced the NPP by about 10%, though the interannual variation and trend are nearly equal. The reduction was due to the lower solar radiation and higher cloudiness in the *Bishop and Rossow* data set, affecting NPP through PAR. Similarly, using VEMAP drivers as input reduced NPP by 10% compared with NCEP and GPCP data, with little effect on the interannual variability and trend.

[7] Recent evidence from atmospheric inverse modeling suggests that the C sink in North America varies by 2 Pg yr^{-1} in a period of several years [*Bousquet et al.*, 2000]. This is one-third of the mean NPP computed in this study. Using CASA, we computed an interannual NPP variability of 0.5 Pg C yr^{-1}, or 8% of the mean NPP. The net C sink estimated from the inverse modeling study together with our modeled NPP implies that heterotrophic respiration varies by 1.5 Pg C yr^{-1}. In contrast to the inverse modeling study, biogeochemical models have estimated low interannual variability in the terrestrial C sink [*Schimel et al.*, 2000], though the spatial mismatch between the two may account for some of the difference (North America versus the conterminous US).

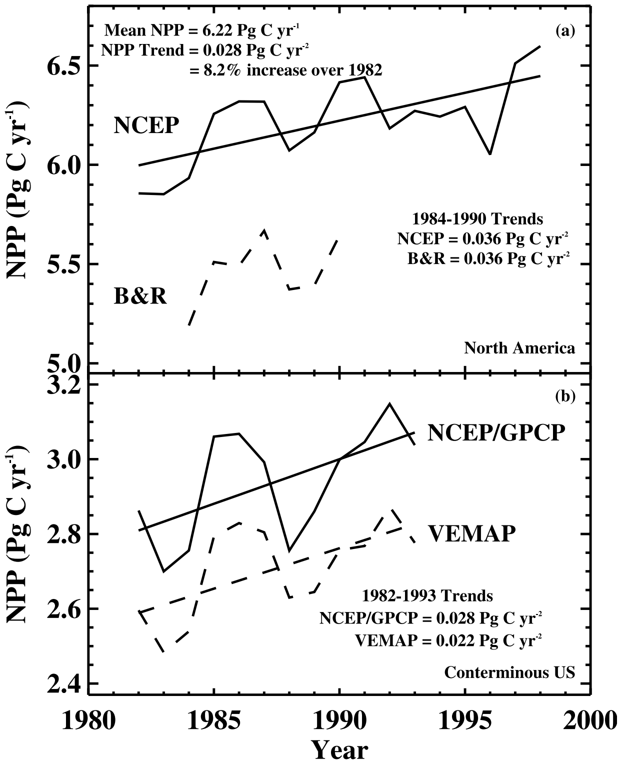

Figure 1. Annual net primary production (NPP; Pg C yr^{-1}) computed from a new 17-year time series of NDVI satellite data and the CASA carbon cycle model. (a) North American NPP using NCEP solar radiation (solid curve) and Bishop and Rossow (B&R) solar radiation (dashed curve). (b) NPP for conterminous US using NCEP temperature and solar radiation and GPCP precipitation (solid curve) and VEMAP inputs (dashed curve).

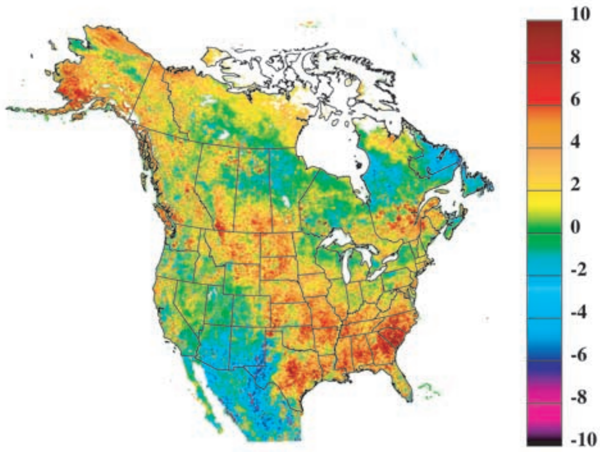

Figure 2. Trends in annual net primary productivity (g C m^{-2} yr^{-2}) from 1982 to 1998.

[8] Figure 2 shows the spatial pattern of the NPP trends. Large increases occurred in the central and southeastern United States as well as Alaska. Decreases can be seen in the southwestern United States and parts of eastern and northern Canada.

[9] To demonstrate the significance of the NPP trend, we used the single pool C model of *Thompson et al.* [1996]. The difficulty of initializing the soil C pools correctly for use within CASA to compute net ecosystem productivity (NEP) makes using this simple model attractive. We recognize that the soil C dynamics of this model are highly simplified, but we present this model to show the potential impact of our computed NPP trend. The model represents the carbon sink (NEP) as the sum of an NPP term, which linearly increases with time, and a respiration term, which is linearly dependent on the amount and turnover time of C in the system:

$$NPP(t) = NPP(t=0) + dNPP/dt\ t, \qquad (2)$$

$$R_h(t) = k\ C(t), \qquad (3)$$

t is time, C is the amount of C in the system, and k is the first-order rate constant for a single terrestrial C pool. The turnover time $\tau = 1/k$, and was set to 23 years by using CASA North American C pools and NPP. Solving for NEP(t), which equals dC/dt, results in

$$NEP(t) = dNPP/dt\ 1/k\left(1 - e^{-kt}\right). \qquad (4)$$

dNPP/dt was assumed to be constant and was the linear trend in NPP computed in this study.

[10] With the linear increase in NPP reported in this study (0.028 Pg C yr^{-2}), the model predicted a long-term NEP of 0.64 Pg C yr^{-1}, a substantial fraction of that reported by the atmospheric inverse models. This value was approached asymptotically; NEP was 90% of its maximum within 50 years.

[11] If we assumed C flux equilibrium in 1982 (NEP = 0), the simple model calculated a C sink of 0.34 Pg C yr^{-1} after only a few years, or one-third of that reported by the atmospheric inverse

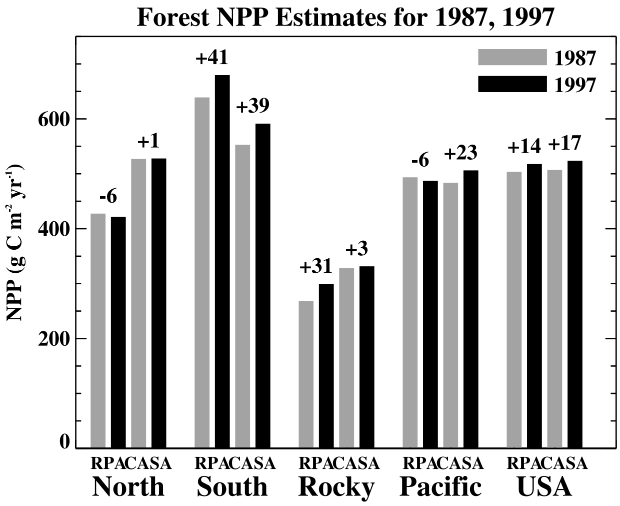

Figure 3. Regional estimates of NPP (g C m^{-2} yr^{-1}) from Resource Planning Act/Forest Inventory and Assessment (RPA/FIA) tree surveys and CASA for 1987 (gray bars) and 1997 (black bars). Numbers above the bars indicate the change from 1987 to 1997. For the RPA/FIA NPP values, dates for 1987 correspond to surveys in the 1970s and 1980s, and for 1997 to surveys in the 1990s and 1980s. For CASA, only forest biomes are used in the calculation, and 1987 represents the mean from 1982–1987 and 1997 the mean from 1988–1997. The Pacific region does not include Alaska or Hawaii.

modeling studies. It is highly unlikely that ecosystems were in equilibrium in 1982 since processes resulting in a C sink in the 1980s, such as regrowing forests, were occurring earlier. However, this demonstrates the speed with which a significant C sink can develop given the NPP trend reported here.

[12] Nationwide forest surveys repeated by the USDA Forest Service Forest Inventory and Analysis (FIA) Program at regular intervals provide a means of validating the satellite-derived (CASA) NPP trends [*USDA Forest Service*, 1992]. For this study, data from the most recent Resources Planning Act (RPA) report were aggregated to the regional level and converted from timber volume growth to units of mass. To develop estimates of wood C increment, net growth and mortality values for land classified as timberland from the FIA database for the period from 1987–1997 were added together and converted to biomass units using timber volume-to-carbon conversion factors developed specifically for each region. Aboveground foliar litterfall was computed by forest type and added to wood C increment to find aboveground NPP. Total NPP was calculated using the common assumption that fine root production equals fine litterfall, such that total NPP = wood C increment + 2*aboveground litterfall.

[13] Because we have data for two different time periods, we can calculate recent NPP trends using both methods. In the North, little trend was evident using either method, while the large increase observed in the South from the RPA data was matched by the CASA results. The large NPP increase in the Rockies and the slightly negative trend in the Pacific calculated using the RPA data were not seen in the CASA NPP. Instead, the Rockies increased only slightly while the Pacific region increased substantially. Due to the offsetting differences, the overall conterminous US trend evident in the RPA data was captured in the CASA results. Other forest inventory studies found shifts toward younger stand ages [*Brown et al.*, 1997; *Sheffield and Dickson*, 1998] in the southeastern United States, which, when combined with stand age studies of NPP [*Gower et al.*, 1996; *Ryan et al.*, 1997], are indirect evidence of increasing NPP.

[14] CASA NPP for forest biomes at similar time periods was used for comparison; however, temporal and spatial mismatches exist. Though surveys occurred nominally every decade, the exact year varied for each state, and some regions had better temporal resolution (e.g., the South) than others (e.g., the Rocky Mountains). Spatial mismatches occurred because we used the land cover classification of *Hansen et al.* [2000], for which forest biomes do not exactly match the timberland surveyed by the USFS. Because the regional total forest area from the land cover classification was generally less than the RPA timberland area, we also investigated including woodlands. This change brought the land cover areas well above RPA timberland areas, but did not have a serious impact on the NPP comparisons (maximum change in NPP trend was -5 g C m^{-2} yr^{-2} in the Pacific region). Additional research is required to reduce the uncertainty in these comparisons resulting from the temporal and spatial mismatches.

[15] Evidence for the large NPP trends calculated with CASA also exists from crop yields. The U.S. Department of Agriculture reports statistics on the annual yield of major crops, which indicate increasing yields during the past two decades. For example, U.S. total yields for corn, primarily grown in the central plains and Midwest, have grown by 30% from the early 1980s to the late 1990s [*USDA*, 2001]. *Lobell et al.* [submitted manuscript] showed that the trend for croplands across the United States computed using the CASA NPP described in this study matched the NPP trend computed using USDA yields.

4. Conclusions

[16] The NPP trends calculated here are in relatively close agreement with field-based information on forest growth and cropland production in the United States, suggesting that we have captured all regions where large NPP increases might occur. Since our approach is based on satellite observations, our results provide an additional constraint on an estimated North American C sink because we utilize direct evidence of NPP increases. Our estimate of an 8% increase in NPP in 17 years for North American ecosystems was large enough to generate a potential C sink of about 0.34 Pg C yr^{-1} using a simplistic model. This is close to the North American C storage estimates inferred from some atmospheric analyses [*Bousquet et al.*, 1999]. Although we show a large potential contribution to a North American C sink through an NPP increase, we note that satellite observations are unable to capture other processes that also may be responsible for the C sink such as changes in soil respiration.

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