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# Exploring global patterns of net primary production carbon supply and demand using satellite observations and statistical data

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[1] A unique combination of satellite and socioeconomic data were used to explore the relationship between human consumption and the carbon cycle. The amount of Earth's net primary production (NPP) required to support human activities is a powerful measure of the aggregate impact on the biosphere and indicator of societal vulnerability to climate change. Biophysical models were applied to consumption data to estimate the annual amount of Earth's terrestrial net primary production humans require for food, fiber (including fabrication) and fuel using the same modeling architecture as satellite-supported NPP measurements. The amount of NPP required was calculated on a per capita basis and projected onto a global map of population to create a spatially explicit map of NPP-carbon "demand" in units of elemental carbon. NPP demand was compared to a map of Earth's average annual net primary production or "supply" created using 17 years (1982–1998) of AVHRR vegetation index to produce a geographically accurate balance sheet of NPP-carbon "supply" and "demand" for the globe. Globally, humans consume 20% of Earth's total net primary production on land. Regionally, the NPP-carbon balance percentage varies from 6% to over 70% and locally from near 0% to over 30,000% in major urban areas. Scenarios modeling the impact of per capita consumption, population growth, and technology suggest that NPP demand is likely to increase substantially in the next 40 years despite better harvesting and processing efficiencies.

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## 1. Introduction

[2] An important but relatively little studied part of the global carbon cycle is the fraction of the planet's net primary production (NPP) appropriated by human beings [*Vitousek et al.*, 1997; *Postel et al.*, 1996]. Human consumption of NPP in the form of food, fiber (including fabrication), and wood-based fuel products has significant implications both in terms of its proportion relative to total planetary NPP (up to 55% by some estimates) and its impact on a wide range of ecological and biophysical processes [*Wackernagel et al.*, 2002; *Vitousek et al.*, 1986; *Rojstaczer et al.*, 2001]. Human cooption of the products of photosynthesis alters the composition of the atmosphere [*Schimel et al.*, 2000], modulates the flow of important ecosystem services [*Daily et al.*, 1997], affects levels of biodiversity [*Pimm and Gittleman*, 1992; *Sala et al.*, 2000; *Haberl*, 1997] and diverts energy flows within food webs [*Field*, 2001; *Cardoch et al.*, 2002].

[3] The portion of Earth's NPP supporting human activity occupies a pivotal position in the carbon cycle through its dependence and feedback on socioeconomic conditions, ecosystem function, and climate. How it functions has immediate as well as long-term implications to human welfare and has been identified as an important focus area for scientific research and policy formulation [*Rosegrant and Cline*, 2003; *Hasselmann et al.*, 2003; *Smith*, 2003]. Of particular importance is how increasing human demands on Earth's ecosystems for producing food and fiber will affect the functioning of the biosphere and a sustainable future for the human enterprise within the context of global change.

## 2. NPP, the Biological Engine, and the Human Requirement

[4] From a biological perspective, NPP represents the primary energy source for Earth's ecosystems and complex food webs by supplying food energy to the planet's heterotrophic organisms (organisms that require preformed organic compounds for food, including human beings). Humans appear to exert a remarkable demand on this part of the carbon cycle for a species that represents roughly 0.5% of Earth's total heterotroph biomass [*Smil*, 1983]. An influential study by *Vitousek et al.* [1986], for example, estimated that humans appropriate 31% of global NPP (intermediate calculation) with "high" (39%) and "low" (3%) estimates, based on more or less inclusive definitions of human appropriation. *Rojstaczer et al.* [2001] in an approach similar to *Vitousek et al.* [1986] used improved data and robust statistical methods to estimate that humans use roughly 32% of global NPP, but they reported high uncertainty in this result (10% to 55% appropriation).

[5] Because these previous studies based their calculations on a mix of aggregated biome-wide averages and consump-

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tion information, they were unable to fully account for spatially heterogeneous processes (e.g., human caloric intake, agricultural productivity, NPP spatial distribution). As a result the spatial patterns of human NPP appropriation remained hidden and the methodologies did not lend themselves well to spatial comparisons with spatially explicit satellite-derived indices of biological productivity and global change [*Field*, 2001; *Haberl et al.*, 2002].

[6] In a previous work, we described an approach for estimating the fraction of NPP required to support human activities using biogeochemical relationships that match those used in satellite-based methods [*Imhoff et al.*, 2004]. This approach allowed a comparison of the rate of NPP required to support human consumption (NPP demand) with the rate of terrestrial production (NPP supply). Described here are new results from this approach showing the spatial characteristics of an NPP supply and demand relationship driven by population distribution and per capita consumption. Also included is an exploration of how changing population and socioeconomic conditions are reflected as potential forcings in NPP carbon demand under different consumption scenarios. In order to avoid confusion with the various published definitions of HANPP [*Haberl et al.*, 2002], quantities reported here for Human Appropriated NPP or HANPP represent the amount of total NPP required (as elemental carbon) to produce consumed products including; food, fiber, wood, and wood-based fuels (same as *Imhoff et al.* [2004]). NPP required, NPP demand, and HANPP are synonymous terms in this paper. Although humans also consume the products of primary production from aquatic and marine systems, this analysis is limited to terrestrial sources.

## 3. Methods

### 3.1. Estimate of NPP Supply Using ISLSCP Data

[7] Terrestrial NPP supply (here after designated as NPP) in the form of elemental carbon was estimated by applying the Carnegie-Ames-Stanford Approach (CASA) terrestrial carbon model [*Potter et al.*, 1993] to global fields of normalized difference vegetation index (NDVI) from the Advanced Very High Resolution Radiometer (AVHRR) and surface climatology data from ISLSCP II (International Satellite Land Surface Climatology Project *initiative II*) [*Hall et al.*, 2005] and the Global Inventory Monitoring and Modeling System (GIMMS). The data were composed of the maximum observed monthly NDVI spanning a 17 year time period from 1982 to 1998. The data processing for this time series included improved navigation, calibration of the four different sensors, corrections for sensor degradation, and atmospheric correction including Rayleigh absorption and scattering, and El Chichon and Pinatubo aerosols [*Los et al.*, 2000; *Tucker et al.*, 2001]. The correction of the satellite artifacts in this data set and the comparatively long period of coverage make it attractive for investigations of long-term trends in biological productivity [*Hicke et al.*, 2002].

[8] From the 17-year data series, we compiled a single set of monthly NDVI averages representing a composite annual cycle (the composite NDVI for January, for example, is the average of the observed monthly NDVI for all of the Januarys from 1982 through 1998).

[9] NPP was estimated by applying the CASA terrestrial carbon model to the satellite data and surface climatology. The CASA model characterized the fixation and release of carbon on the basis of a spatially and temporally resolved prediction of NPP in a steady state [*Potter et al.*, 1993]. NPP was estimated on a monthly timescale as the amount of intercepted photosynthetically active radiation (IPAR) modulated by a light use efficiency factor. IPAR was determined by the product of the total incident solar radiation and the fraction of the incoming PAR intercepted by the green fraction of the vegetation (FPAR) derived from the AVHRR data [*Sellers*, 1985; *Sellers et al.,* 1996a, 1996b]. The light efficiency factor was controlled by environmental stresses for temperature and water [*Monteith*, 1977; *Kumar and Monteith*, 1981]. The allocation of carbon to woods, leaves, and roots as well as the turnover times was determined by vegetation type from the vegetation classification map defining 12 classes of vegetation cover [*Hansen et al.*, 2000]. In addition to vegetation classification and its associated monthly biophysical fields derived from NDVI data, CASA also required monthly fields of temperature and precipitation [*Shea*, 1986], solar radiation [*Bishop and Rossow*, 1991] and soil texture [*Zobler*, 1986]. The climate drivers, temperature, precipitation and solar radiation were resampled from global $1^\circ \times 1^\circ$ resolution to $0.25^\circ \times 0.25^\circ$ resolution using a bilinear interpolation algorithm and averages generated from the historical data matching the satellite data. In a model intercomparison study including seventeen global models of terrestrial biogeochemistry, the annual NPP from CASA was close to the annual average value from the seventeen participating models including some that did not use satellite data [*Cramer et al.*, 1999]. The NPP calculation also compares well to other more recent satellite-supported estimates using the same AVHRR series [*Nemani et al.*, 2003] and MODIS [*Zhao et al.*, 2005]. In this analysis, only the vegetation existing on land was considered. Aquatic or marine systems were not included.

## 5. Conclusions

[28] Our results show one dimension of the human interaction with the NPP carbon cycle by comparing the rate of human NPP demand for products generated on land with the average rate of supply for the mid 1990s. The use of consumption data provides an independent estimate of NPP demand (eliminating circularity issues when comparing to satellite-based estimates of supply) and allows shifts in socioeconomic conditions to be readily incorporated. Because the FAO data reflect the influence of population, consumption level, and style (product preferences), and our model included the effect of technology through harvest and processing efficiencies on NPP demand, we were able to model current conditions as well as potential future trajectories. This approach does not explicitly portray the spatial aspect of the sources of NPP required by various populations of consumers. It shows an endpoint-oriented gradient of NPP carbon flow spatially oriented around population distribution. When constrained by physical or political boundaries, this viewpoint is useful for elucidating NPP supply and demand rate balance issues around conservation, policy, and food security. In order to fully account for impacts to particular ecosystems and land surface climatology, this approach needs to be augmented by identifying the specific source areas for NPP required as well as an accounting of the fate of the carbon with respect to relocation or transport.