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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

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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 consumption 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.

### 3.2. Estimating NPP Carbon Demand

[10] NPP carbon demand is defined as the annual amount of terrestrial NPP required to derive the food and fiber products (construction material and fuel wood) consumed by humans as reported in the United Nations FAOSTATS database and the biomass lost in harvest and processing (e.g., crop residues).

[11] Starting with input data on food and fiber products consumed on an annual basis, models were developed estimating the amount of NPP required in the field (i.e., at the landscape level) to generate the various end products so that it can be compared on the same biophysical basis to satellite-supported estimates of NPP supply. The NPP-based products derived on land for 230 countries were compiled into seven categories: vegetal foods, meat, milk, eggs, wood (building and fuel), paper, and fiber. Harvest, processing, and efficiency multipliers and estimates of below-ground production were applied to successively add mass thereby reconstructing the total amount of NPP required, at-the-source, to derive the final products. Separate efficiency multipliers for industrialized and developing countries were

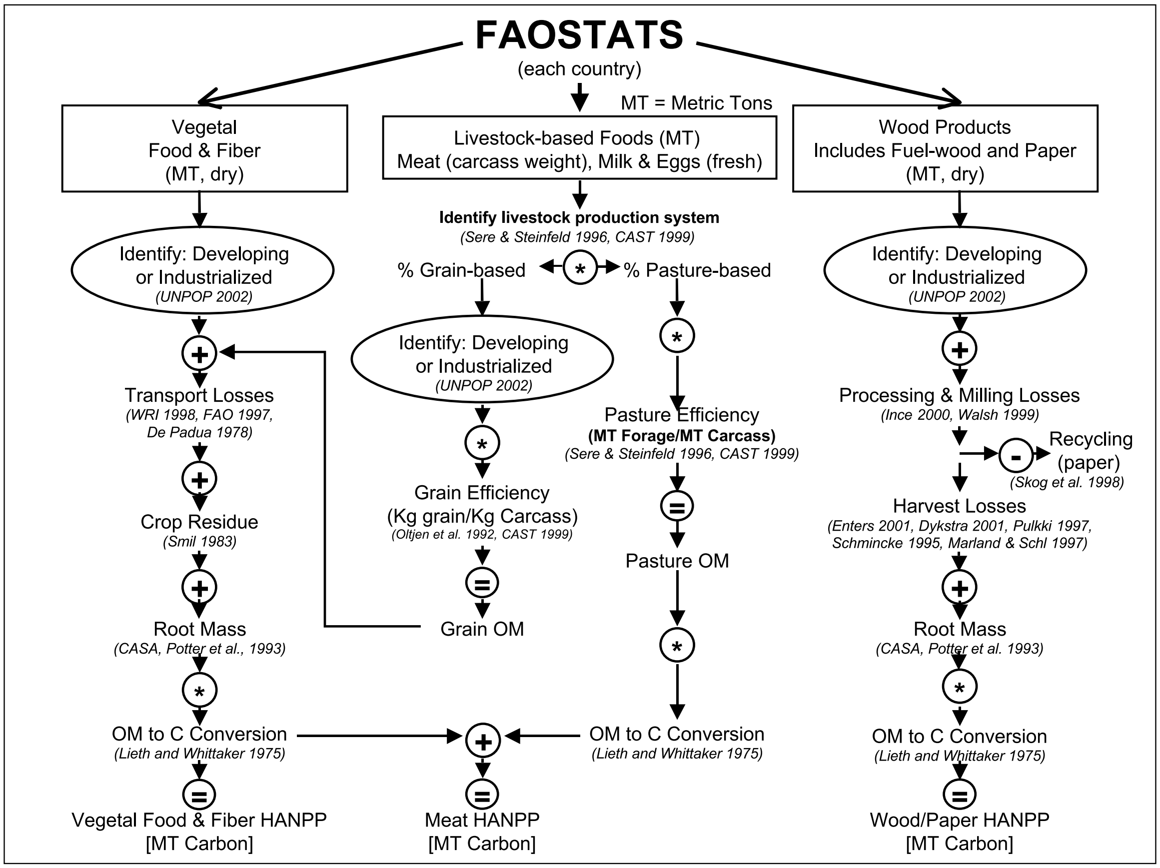


**Figure 1.** Logic chain (simplified) for estimating the amount of NPP required for food and fiber products. To constrain the calculation within country boundaries the FAOSTAT sums input to this process (top of graph) are the domestic supply (i.e., production + imports − exports).

derived from the literature based the UNFAO designated development status of the source countries (Figure 1).

[12] The country level FAO data for 1995 were scanned to correct for missing data and reporting errors. Over reporting due to multiple entries for the same country was eliminated and national entities or territories reporting under another administrative country were identified (e.g., Guam reports under the United States). For calculations of per capita consumption at the national level, the population of these entities was added to that of the administrative country and a national per capita consumption was obtained by dividing the administrative country's consumption by the total population.

[13] Product sums for all plant products were rendered in terms of dry mass. For vegetal foods and fiber, mass was successively added to the reported value to account for post harvest processing, transport losses [*World Resources Institutes*, 1998; *United Nations Food and Agriculture Organization*, 1997; *De Padua*, 1978] and crop residue left in the fields [*Smil*, 1983]. For the intermediate case the weighted mean for major world crops was used while high and low estimates were ±1 standard deviation [see *Imhoff et al.*, 2004]. The large variation in residue among crop types yielded a high standard deviation.

[14] For wood and paper products, organic matter (OM) was added to account for milling [*Ince*, 2000; *Walsh et al.*, 1999] and harvest losses [*Enters*, 2001; *Dykstra*, 2001; *Pulkki*, 1997; *Schmincke*, 1995; *Marland and Schlamadinger*, 1997]. For paper, recycling was accounted for by subtracting the quantity recycled annually reported by *Skog et al.* [1998].

[15] In cases where the individual plant is killed in the process (all cases except pasture grasses), the mass of the root system was also included. Root organic matter was estimated using the same values employed in the NPP supply calculations (see below) with multipliers for short vegetation (2.0) applied to vegetal foods, fiber, and grain used in meat production, and woody vegetation (1.5) for wood and paper [*Potter et al.*, 1993]. No root OM was added to pasture grasses used for livestock.

[16] Meat production was reported as carcass weight (wet) including all meat types. The NPP required for meat was estimated by summing the NPP required for grain and pasture-based (forage) feed using a global average of 62% grain and 38% forage [*Sere and Steinfeld*, 1996]. The amount of feed as organic matter (OM) was estimated using feed use efficiency values (kg feed OM/kg carcass) for grain (2.3:1 average for all meat types) and pasture (21.46:1, ruminant [*Council for Agricultural Science and Technology*, 1999; *Oltjen et al.*, 1992]). The NPP required for total feed-grain was calculated in the same way as for vegetal foods, adding residue and loss factors appropriate to each country's development status and final conversion from organic matter to carbon. Since pasture grazing is in situ, no loss

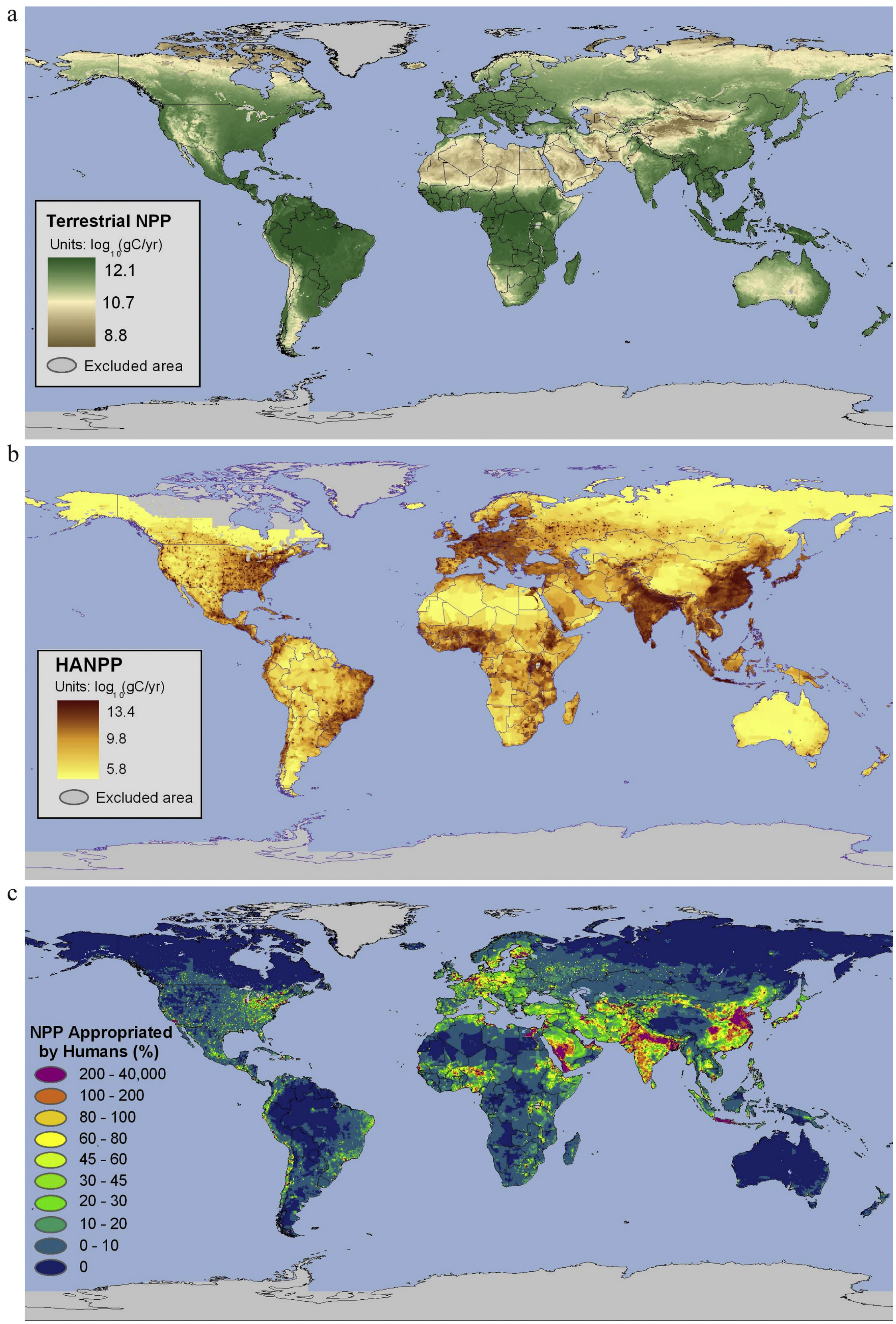


**Figure 2.** (a) Annual terrestrial NPP "supply" (56.8 PgC) estimated using a 17 year average of maximum monthly NDVI from AVHRR, the CASA model, and climate drivers. (b) Map showing the amount of NPP required (in $\log_{10}$ grams of carbon) to support the population in each grid cell on an annual basis. Statistics can be aggregated globally, regionally, subregionally, or by country. (c) Map comparing NPP supply versus demand at 0.25° resolution (NPP required as a % of NPP supply).

**Table 1.** Annual Estimates of NPP Required (PgC; 1Pg = $10^{15}$g) for a Population of 5.69 Billion in 1995

| Consumed Products | Low Estimate | Intermediate Estimate | High Estimate |
|---|---|---|---|
| Vegetal food | 0.89 | 1.73 | 2.96 |
| Meat | 1.69 | 1.92 | 2.21 |
| Milk | 0.15 | 0.27 | 0.43 |
| Eggs | 0.09 | 0.17 | 0.27 |
| Human food (subtotal) | 2.83 | 4.09 | 5.85 |
| Paper | 0.20 | 0.28 | 0.38 |
| Fiber | 0.32 | 0.37 | 0.42 |
| Wood products (construction and fuel) | 4.64 | 6.81 | 8.15 |
| Human commodities (subtotal) | 5.17 | 7.45 | 8.95 |
| Total NPP required | 8.00 | 11.54 | 14.80 |
| Total as % of NPP supply (56.8 Pg) | 14.10 | 20.32 | 26.07 |

or residue factors were applied to pasturage. Efficiency factors for milk and eggs are for grain component only. Final representation of NPP required was converted to elemental carbon using Carbon/OM ratios following *Lieth* [1975].

[17] For spatial representation, we calculated RNPP at the country level using domestic supply (i.e., production + imports – exports) to constrain the country totals to products consumed in situ.

## 4. Results and Discussion

### 4.1. NPP Supply

[18] We produced a global map of average annual terrestrial NPP for the 17 year time interval (Figure 2a). Summed across the land surface, we estimated the average total global NPP supply to be 56.8 Pg of elemental carbon (Pg, $10^{15}$ grams), a value within the range of other estimates using various models [*Cramer et al.*, 1999]. The averaging approach makes a good baseline estimate of NPP supply because using data collected over such a long time period reduces short-term variations in surface conditions while still incorporating decadal-scale effects of human influence on the land surface.

### 4.2. NPP Demand

[19] Summing the amount of NPP required for all products yielded an intermediate global NPP demand estimate of 11.5 Pg of elemental carbon, equivalent to 24.3 Pg of dry organic matter. To address uncertainty, we bracketed our intermediate calculation with low and high estimates using the range of reported efficiency, loss, and residue multipliers. Differences in these multipliers correspond to a country's technical proficiency linked to its development status (e.g., timber harvest and milling losses are typically lower in industrialized nations). For the intermediate estimate, we applied harvest and processing efficiencies to each country on the basis of its UNFAO-designated development status [*United Nations Food and Agriculture Organization*, 2001]. For high and low estimates, we applied to all countries the multipliers that produce maximum and minimum estimates, respectively. Our low and high calculations yield NPP demand estimates of 8.0 and 14.8 Pg C, respectively (Table 1).

[20] To produce a global map of NPP demand (Figure 2b), we applied the NPP required per capita (calculated at the country level) to a global database of human population produced by the Center for International Earth Science Information Network [*Center for International Earth Science Information Network*, 2000]. These data were gridded at 0.25° which equates to a spatial resolution of about 28 × 28 km at the equator.

### 4.3. Comparing Rates of NPP Supply and Demand

[21] Comparing our global total values for NPP supply and demand, we find that humans appropriate approximately 20% of terrestrial NPP globally, with low and high estimates of 14% and 26%, respectively (Table 1). We were also able to show spatial patterns revealing the regional balance between NPP supply and demand (Figure 2c). Since the NPP demand estimates are ultimately tied to population, the spatial comparisons show the direction toward which NPP carbon must flow. Specific sources for the NPP are not explicitly delineated in this representation. However, socioeconomically meaningful comparisons can be made constraining the analysis using regional or national boundaries. For example, some regions, such as western Europe and south central Asia, consume more than 70% of their regional NPP supply. Conversely, NPP demand in other regions is less than 15% of supply, with the lowest value of

**Table 2.** NPP Required for Selected Regions (Intermediate Estimate)

| Region[a] | Population, millions | Per Capita NPP Required, Mt | NPP Supply, Pg | Total NPP Required "Demand," Pg | NPP Required As % of Supply |
|---|---|---|---|---|---|
| Africa | 742 | 2.08 | 12.50 | 1.55 | 12.40 |
| East Asia | 1400 | 1.37 | 3.02 | 1.91 | 63.25 |
| South-central Asia | 1360 | 1.21 | 2.04 | 1.64 | 80.39 |
| Western Europe | 181 | 2.86 | 0.72 | 0.52 | 72.22 |
| North America | 293 | 5.40 | 6.67 | 1.58 | 23.69 |
| South America | 316 | 3.11 | 16.10 | 0.98 | 6.09 |

[a]Regions [*United Nations Population Division*, 2002].

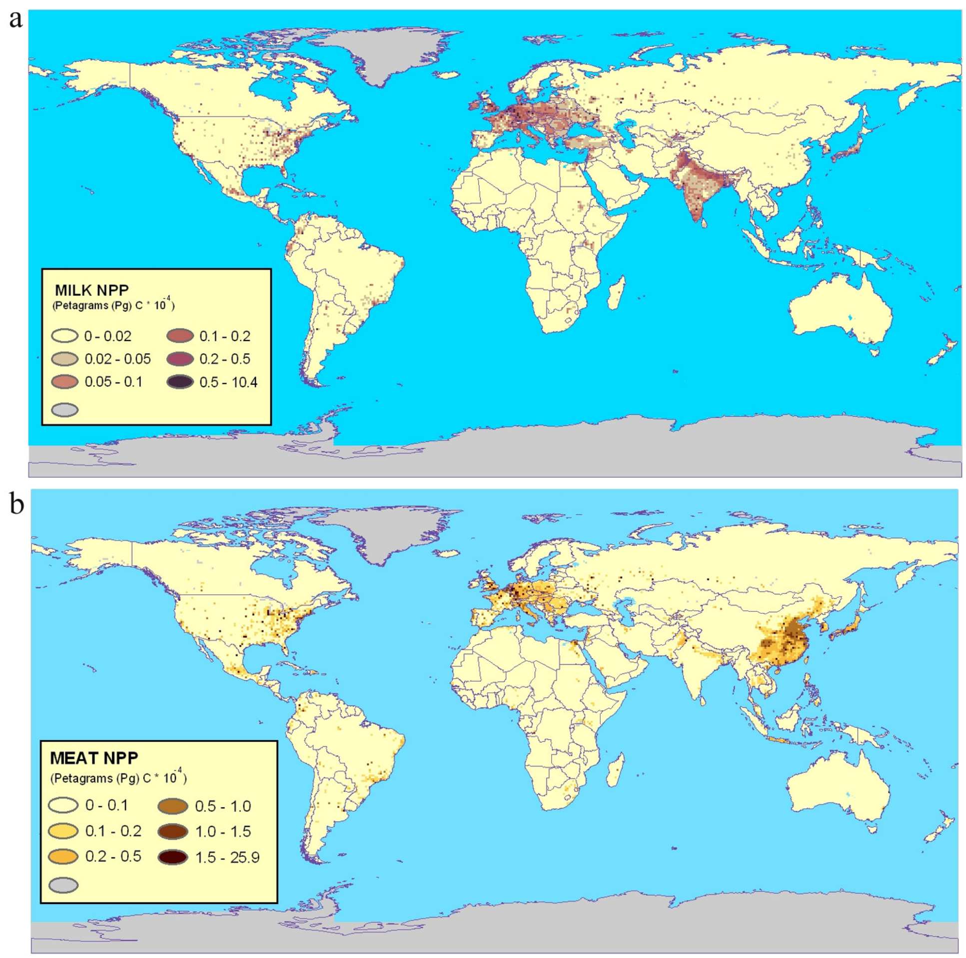


**Figure 3.** Maps of NPP required for (a) milk and (b meat products.

about 6% in South America (Table 2). At more local scales, these spatial differences in NPP balance are even more striking, varying from nearly 0% of local NPP in sparsely populated areas to over 30,000% in large urban centers.

[22] In addition to the basic drivers of population and consumption level, cultural differences in the amount of NPP required are also visible through product preferences as expressed within our categorization of the NPP-based products. This is clearly seen in the graphic representations of NPP required for meat versus milk products (most especially between south Asia and east Asia; see Figures 3a and 3b).

### 4.4. Drivers of Demand

[23] The population-consumption based approach for estimating NPP demand allows for some basic socioeconomic factors to be introduced as forcings to the NPP-carbon cycle. *Holdren and Ehrlich* [1974] introduced a simple relationship (I = PAT) describing the overall ecological impact (I) of human activities as product of population size (P), affluence (A) and technology (T). Our model reflects the influence of these three factors in the form of population numbers (P), per capita consumption level (A, affluence), and the different harvesting and milling efficiencies used for developing and industrialized countries (T). To explore this relationship in the context of NPP-carbon, we performed quantitative assessment of the impact of each of these factors under different combinations of P, A, and T using current conditions (1995) and estimates of future population.

[24] The role of population is obvious despite vast differences in consumption among nations. For example, Asia (east and south central Asia), with almost half the world's population (Table 2), appropriates 72% of its regional NPP supply despite having the lowest per capita consumption of any region (1.29 $Mt.yr^{-1}$). A model simulation assuming no appreciable change in global NPP and allowing the population to grow to 8.92 billion by 2050 shows that RNPP could rise to 17.4 PgC or nearly 31% of global NPP (combination 1, Table 3).

[25] Affluence also plays a significant role. From our intermediate calculation, we find the average annual per capita NPP required for industrialized countries (3.2 Mt, Metric tons) is almost double that of the developing nations (1.8 Mt) which host 83% of the global population. If the per capita NPP required of developing nations is increased to match that of industrialized countries without increase in technological efficiency, NPP required increases to 20.2 PgC or 35% of current global NPP (combination 2). If we increase Technology and Affluence together (combination 3), the effect of rising consumption is considerably moderated by; better processing and harvest efficiencies and a reduction

**Table 3.** Changes in NPP Required With Shifts in Population, Affluence, and Technology[a]

| Combination | P[b] | A[c] | T[d] | NPP Required, PgC |
|---|---|---|---|---|
| 1 | ↑ | – | – | 17.42 |
| 2 | – | ↑ | – | 20.19 |
| 3 | – | ↑ | ↑ | 16.26[e] |
| 4 | ↑ | ↑ | – | 31.59 |
| 5 | ↑ | ↑ | ↑ | 25.5[e] |

[a]Dashes denote no change from baseline (i.e., 1995 intermediate estimate); up arrows denote an increase relative to baseline.

[b]Population increase from 5.69 billion (global population in 1995) to 8.92 billion (estimated global population in 2050 [*United Nations Population Division*, 2002]).

[c]Affluence increase applies average per capita consumption of industrialized countries (in 1995) for all countries.

[d]Technology increase applies technological efficiencies of industrialized countries (in 1995) to all countries.

[e]Per capita fuel wood use in developing countries reduced to average for industrialized countries in 1995.

in wood fuel use to levels comparable with industrialized countries. In this case, NPP required is 16.3 PgC. Even with better technology, however, increased consumption in the developing countries will have significant regional impacts compared to current NPP. In south central Asia, for example, regional NPP required would grow from 80% to a regionally unsustainable rate of 224% of supply. Without major changes to the productivity of the landscape, it would take more than 2 years for this region's ecosystems to produce the amount of food and fiber consumed by local populations in 1 year. A change of this magnitude, aside from signaling increasing ecological impoverishment in the region itself, would certainly require substantial imports of NPP, creating greater pressure on natural and agricultural systems worldwide.

[26] The positive influence of technology is best seen in the following example. If both population and affluence are increased without change in technology (combination 4), global NPP required increased to 31.6 PgC or nearly 56% of current supply. However, if technology is improved as well, the global NPP required increases to only 25.5 PgC (combination 5).

[27] These combinations help highlight potential changes in NPP demand that may result from different development trajectories. As the human population and per capita consumption increase, pressure will be exerted on global ecosystems to increase NPP supply to meet the growing demand.

## 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.

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## References

Bishop, J. K. B., and W. B. Rossow (1991), Spatial and temporal variability of global surface solar irradiance, *J. Geophys. Res.*, *96*, 16,839.

Cardoch, L. J., W. Day, and C. Ibanez (2002), Net primary productivity as an indicator of sustainability in the Ebro and Mississippi Deltas, *Ecol. Appl.*, *12*, 1044.

Center for International Earth Science Information Network (2000), Gridded population of the world (GPW), version 2, Columbia Univ., Palisades, N. Y.

Council for Agricultural Science and Technology (1999), Animal agriculture and global food supply, *Task Force Rep. R135*, Ames, Iowa. (Available at http://www.cast-science.org/cast/pub/anag_nr.htm)

Cramer, W., et al. (1999), Comparing global models of terrestrial net primary productivity (NPP): Overview and key results, *Global Change Biol.*, *5*, 1.

Daily, G. C., et al. (1997), Ecosystem services: Benefits supplied to human societies by natural ecosystems, *Issues Ecol.*, *2*, 1.

DePadua, D. B. (1978), Rice post-production and processing: Its significance to agricultural development, in *Accelerating Agricultural Development*, edited by J. D. Drilon and G. F. Sanguiguit, p. 135, SERCA Coll., Laguna, Philippines.

Dykstra, D. P. (2001), The old and new of reduced impact logging, *Trop. For. Update*, *11*, 3.

Enters, T. (2001), Trash or treasure? Logging and mill residues in Asia and the Pacific, *Rap Publ. 2001/16*, Asia-Pac. For. Comm., FAO Reg. Off. for Asia and the Pac., Bangkok, Thailand. (Available at http://www.fao.org/DOCREP/003/X6966E/X6966E00.htm)

Field, C. B. (2001), Sharing the garden, *Science*, *294*, 2490.

Haberl, H. (1997), Human appropriation of net primary production as an environmental indicator: Implications for sustainable development, *Ambio*, *26*, 143.

Haberl, H., F. Krausmann, K. H. Erb, and N. B. Schulz (2002), Human appropriation of net primary production, *Science*, *296*, 5575.

Hall, F. G., G. Collatz, S. Los, E. Brown de Colstoun, and D. Landis (Eds.) (2005), ISLSCP Initiative II [DVD/CD-ROM], NASA, Washington D. C.

Hansen, M., R. DeFries, J. R. G. Townshend, and R. Sohlberg (2000), Global land cover classification at 1 km spatial resolution using a classification tree approach, *Int. J. Remote Sens.*, *21*, 1331.

Hasselmann, K., et al. (2003), The challenge of long-term climate change, *Science*, *302*, 1923.

Hicke, J. A., G. P. Asner, J. T. Randerson, C. Tucker, S. Los, R. Birdsey, J. C. Jenkins, and C. Field (2002), Trends in North American net primary productivity derived from satellite observations, 1982–1998, *Global Biogeochem. Cycles*, *16*(2), 1018, doi:10.1029/2001GB001550.

Holdren, J. P., and P. R. Ehrlich (1974), Human population and the global environment, *Am. Sci.*, *62*, 282.

Imhoff, M. L., et al. (2004), Global patterns in human consumption of net primary production, *Nature*, *429*, 870.

Ince, P. J. (2000), Industrial wood productivity in the United States 1900–1998, *Res. Note FPL-RN-0272*, For. Prod. Lab., For. Serv., U.S. Dep. of Agric., Madison, Wis.

Kumar, M., and J. L. Monteith (1981), Remote sensing of crop growth, in *Plants and the Daylight Spectrum*, edited by H. Smith, p. 133, Elsevier, New York.

Lieth, L. (1975), The measurement of caloric values, in *Primary Productivity of the Biosphere*, edited by H. Lieth and R. H. Whittaker, p. 119, Springer, New York.

Los, S. O., G. J. Collatz, P. J. Sellers, C. M. Malmstrom, N. H. Pollack, R. S. DeFries, L. Bounoua, M. T. Parris, C. J. Tucker, and D. A. Dazlich (2000), A global 9-yr biophysical land surface dataset from NOAA AVHRR data, *J. Hydrometeorol.*, *1*, 183.

Marland, G., and B. Schlamadinger (1997), Forests for carbon sequestration or fossil fuel substitution? A sensitivity analysis, paper presented at XI World Forestry Congress, U. N. Food and Agric. Organ., Antalya, Turkey. (Available at http://www.fao.org/forestry/foda/wforcong/publi/v1/t4e/3.HTM)

Monteith, J. L. (1977), Climate and efficiency of crop production in Britain, *Philos. Trans. R. Soc. London, Ser. B*, *281*, 277.

Nemani, R. R., C. D. Keeling, H. Hashimoto, W. M. Jolly, S. C. Piper, C. J. Tucker, R. B. Myneni, and S. W. Running (2003), Climate-driven increases in global terrestrial net primary production from 1982 to 1999, *Science*, *300*, 1560.

Oltjen, J. W., M. R. George, and D. J. Drake (1992), Dynamic allocation of multiple forage sources for beef cattle herds, in *Computers in Agricultural Extension Programs*, edited by D. G. Watson, F. S. Zazuelta, and A. B. Bottcher, p. 58, Am. Soc. of Agric. Eng., St. Joseph, Mich.

Pimm, S., and J. Gittleman (1992), Biological diversity: Where is it?, *Science*, *255*, 940.

Postel, S. L., G. C. Daily, and P. R. Ehrlich (1996), Human appropriation of renewable fresh water, *Science*, *271*, 785.

Potter, C. S., J. T. Randerson, C. B. Field, P. A. Matson, P. M. Vitousek, H. A. Mooney, and S. A. Klooster (1993), Terrestrial ecosystem production: A process model based on global satellite and surface data, *Global Biogeochem. Cycles*, *7*(4), 811–842.

Pulkki, R. E. (1997), Literature synthesis on logging impacts in moist tropical forests, *Working Pap. GFSS/WP/06*, For. Prod. Div., U. N. Food and Agric. Organ., Rome.

Rojstaczer, S., S. M. Sterling, and N. J. Moore (2001), Human appropriation of photosynthesis products, *Science*, *294*, 2549.

Rosegrant, M. W., and S. A. Cline (2003), Global food security: Challenges and policies, *Science*, *302*, 1917.

Sala, O. E., et al. (2000), Global biodiversity scenarios for the year 2100, *Science*, *287*, 1770.

Schimel, D., et al. (2000), Contribution of increasing $CO_2$ and climate to carbon storage by ecosystems in the United States, *Science*, *287*, 2004.

Schmincke, K. H. (1995), Forest industries: Crucial for overall socio-economic development, *Unasylva*, *182*, 46.

Sellers, P. J. (1985), Canopy reflectance, photosynthesis and transpiration, *Int. J. Remote Sens.*, *8*, 1335.

Sellers, P. J., D. A. Randall, G. J. Collatz, J. A. Berry, C. B. Field, D. A. Dazlich, C. Zhang, and L. Bounoua (1996a), A revised land surface parameterization (SiB2) for atmospheric GCMs. Part I: Model formulation, *J. Clim.*, *9*, 676.

Sellers, P. J., S. O. Los, C. J. Tucker, C. O. Justice, D. A. Dazlich, G. J. Collatz, and D. A. Randall (1996b), A revised land surface parameterization (SiB2) for atmospheric GCMs. Part II: The generation of global fields of terrestrial biophysical parameters from satellite data, *J. Clim.*, *9*, 706.

Sere, C., and H. Steinfeld (1996), World livestock production systems, *FAO Animal Prod. Health Pap. 127*, U. N. Food and Agric. Organ., Rome. (Available at http://www.fao.org/WAICENT/FAOINFO/AGRICULT/AGA/LSPA/Paper127/cover1.htm)

Shea, D. (1986), Climatological atlas: 1950–1979, surface air temperature, precipitation, sea level pressure, and sea surface temperature, Natl. Cent. for Atmos. Res., Boulder, Colo.

Skog, K. E., P. J. Ince, and R. W. Haynes (1998), Wood fiber supply and demand in the United States, paper presented at Annual Meeting, Forest Products Study Group Workshop, N. Am. For. Comm., For. Prod. Soc., Merida, Mexico. (Available at http://www.fpl.fs.fed.us/documnts/pdf2000/skog00a.pdf)

Smil, V. (1983), *Biomass Energies: Resources, Links, Constraints*, Springer, New York.

Smith, H. J. (2003), Series introduction: The shape we're in, *Science*, *302*, 1171.

Tucker, C. J., D. A. Slayback, J. E. Pinzon, S. O. Los, R. B. Myneni, and M. G. Taylor (2001), Higher northern latitude NDVI and growing season trends from 1982 to 1999, *Int. J. Biometeorol.*, *45*, 184.

United Nations Food and Agriculture Organization (1997), Estimated post-harvest losses of rice in Southeast Asia, New York. (Available at http://www.fao.org/NEWS/FACTFILE/IMG/FF9712-e.pdf)

United Nations Food and Agiculture Organization (2001), *FAOSTAT 2001*, Rome, Italy.

United Nations Population Division (2002), UN-POP world population prospects: The 2000 revision, Dep. of Econ. and Soc. Affairs, New York.

Vitousek, P. M., P. Ehrlich, A. Ehrlich, and P. M. Matson (1986), Human appropriation of the products of photosynthesis, *Bioscience*, *36*, 368.

Vitousek, P. M., H. A. Mooney, J. Lubchenco, and J. M. Melillo (1997), Human domination of Earth's ecosystems, *Science*, *277*, 494.

Wackernagel, M., et al. (2002), Tracking the ecological overshoot of the human economy, *Proc. Natl. Acad. Sci. U. S. A.*, *99*, 9266.

Walsh, M. E., et al. (1999), Biomass feedstock availability in the United States: 1999 state level analysis, Bioenergy Inf. Network, Bioenergy Feedstock Dev. Program, Oak Ridge Natl. Lab., Oak Ridge, Tenn. (Available at http://bioenergy.ornl.gov/resourcedata/)

World Resources Institutes (1998), *Disappearing Food: How Big Are Post-harvest Losses?*, Washington, D. C. (Available at http://www.wri.org/trends/foodloss.html)

Zhao, M., F. Heinsch, R. R. Nemani, and S. W. Running (2005), Improvements of the MODIS terrestrial gross and net primary production global data set, *Remote Sens. Environ.*, *95*, 164.

Zobler, L. (1986), A world soil file for global climate modeling, *NASA Tech. Memo. 87802*.

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