Satellite Views of Urbanization, Net Primary Production and the Human Demand for Food and Fiber: Can the Earth Keep Up?

M. L. Imhoff, L. Bounoua, Taylor Ricketts, and Colby Loucks
NASA’s GSFC, UMD ESSIC, WWF
“humans have become a geologic agent comparable to erosion and eruptions... it seems appropriate to emphasize the central role of mankind in geology and ecology by proposing to use the term 'anthropocene' for the current geological epoch.”

Paul J. Crutzen
The Carbon Cycle

Understanding the Carbon Cycle is one of the 7 primary focus areas in NASA’s Earth-Sun System Science.

Vegetation state has immediate impact on atmospheric CO2.
Earth’s “Bio-Engine”
Net Primary Production (NPP)

NPP is the amount plant material produced on Earth. It is the primary fuel for Earth’s food web. Represents all available food and fiber.

NPP can be measured in terms of Carbon (photosynthesis - CO2 exchange between atmosphere and biosphere (global climate change)).

Land use strongly impacts NPP
Humans require almost 20% of Earth’s NPP capacity on land

NPP is the “Common Currency” for Climate Change, Ecological, & Economic Assessment.
Terra MODIS Global Daily Coverage

QuickTime™ and a YUV420 codec decompressor are needed to see this picture.
Global NPP and CO₂

NPP MODIS

CO₂ concentration in the atmosphere: Mauna Loa curve
The current land surface little resembles what existed 100,000 years or even 3,000 years ago.

- Fire for ecosystem management
- Grazing
- Deforestation for metal smelting
- Agriculture
- Urbanization/infrastructure
History of World Population Growth
10000 B.C. to 2150 A.D.

Population in Billions

Year

-10000 -8000 -6000 -4000 -2000 0 2000

Development of Agriculture

Apollo

WW II

Gettysburg

Apollo

Population in Billions
Global Land Cover
Pre-Agriculture
Approx. 10,000 BCE

% of Land Area Transformed for Agriculture (Negligible)

World Population
6 -10 Million
Global Land Cover
Post-Agriculture

Present

43% of Land Area
Dominated by Agriculture

World Population
6.5 Billion
Urbanization

Global Land Cover

Urbanization

Present

World Population
6.5 Billion

% of Land Area
Built-up
3 - 6%
Malthus’s Dismal Theorem:

Thomas Malthus, a 19th Century economist, postulated that since human populations increase geometrically and food supplies grow arithmetically, human populations will undergo a cycle of growth and catastrophic decline.
1998-1999
“Malthus might be right, but probably not”

2001-2004
“Malthus is wrong”

2006
“Malthus might be relevant”
GLOBAL OBSERVATION OF URBANIZATION
We’ve Come A Long Way

Blue Marble
EOS Terra/Aqua 2000 -

TIROS
April 1, 1960
700 km Altitude

Apollo 17
Dec.7, 1972, 45,000 km from Earth,
70mm Hasselblad, 80mm lens
A BREAKTHROUGH IN URBAN MAPPING

Defense Meteorological Satellite
Operational Linescan System (OLS)

- 833 km, sun-synchronous, near circular, polar orbit.
- Nighttime data (PMT)
  - 0.47 - 0.95 um
  - $10^{-5}$ to $10^{-9}$ Watts per cm$^2$ per steradian.
- Pixel resolution:
  - 0.55 km at high resolution (fine mode)
  - 2.7 km at low resolution (smooth mode).
Nighttime Lights of the World
CREATING ACCURATE URBAN MAPS FROM RAW DATA

Raw Stable Lights DMSP

SPATIAL THRESHOLDING

Percent Occurance
- 8-88%
- 89 - 100%

SITUPS Urban Map
**PERIMETER MEASURES USED TO REDUCE BLOOMING AND DEFINE DENSE URBAN DEVELOPMENT**

**PERIMETER CHANGE IN MAJOR URBAN LIGHT POLYGONS AS A FUNCTION OF THRESHOLDING**

**THRESHOLDING TECHNIQUE IN GIS**

**ACCURATE AS U.S. CENSUS**

\[ Y = 96.845 + 0.97074X \]

\[ R = 0.96683 \]

Hyp.: No Significant Diff. between Methods (T test: DF=48, t-value=1.429, P-value=0.159)

\[ Y = 96.845 + 0.97074X \]

\[ R = 0.96683 \]
Consequences of Urbanization on NPP-Carbon in the United States

What is the overall impact in North America?
- Has the NPP-carbon sink been reduced?
- What are the consequences?

How does urbanization interact with climate locally?
- Is there a recognizable effect in the NDVI signal at 1km spatial resolution?
- What are the seasonal dynamics?
- Is urbanization’s impact on NPP balance positive or negative?
Gain Controlled DMSP Image of North Eastern USA
Urban Occupation of Soils in the USA

DMSP Urban Map (SITUP)

Rated Soils (UN/FAO)
California

% Soil Area Lit

Number of Factors Limiting Soil Fertility

Florida

% Soil Area Lit

Number of Factors Limiting Soil Fertility

Illinois

% Soil Area Lit

Number of Factors Limiting Soil Fertility

Wisconsin

% Soil Area Lit

Number of Factors Limiting Soil Fertility
QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.
CHINA

Percent of Soils (UN/FAO) Covered by Lights Grouped by Number of FCC Limiting Factors

Number of Factors Limiting Agriculture

Percent of Soil Area Covered by Lights

CHINA
Consequences of Urbanization on NPP

Satellite Observations

DMSP/OLS Urban Map
Urban, Peri-urban, Non-urban

AVHRR/MODIS
Monthly NPP (g Cm⁻²)

NPP and Local Climate:
Urban Heating Extends Length of growing season locally in cold climates.

North East
Winter NPP gain negated in peak season by reduced vegetation and heat stress.

Mid-Atlantic
Seasonal Offset diminishes in tropics

South West
In semi-arid regions cities enhance NPP relative to surrounding areas

South East

Consequences of Urbanization on NPP-Carbon in the U.S.

**Urbanization and NPP**
- NPP decreased 41.5 M tons C / year.
- Roughly equivalent to the increase created by 300 years of agricultural development.

How can this happen when urban areas occupy only 3% of the land surface and agriculture occupies 29%?

*Location, Location, Location.*

Urbanization is taking place on the most fertile lands.

Reduction of NPP may have biological significance:
- Annual loss of food web energy 400 Trillion kilocalories (roughly equal to food energy requirement for 448 million people).
- Reduction of actual food products equivalent to needs of 16.5 million persons annually (about 6% of US population).

**NPP Lost or Gained (annual) Due to Urbanization**

Going from a pre-urban to a post urban world

Total Reduction

41.5 Mt C

From Ag Lands

25.5 Mt C
Human Consumption of NPP: Can the Earth Keep Up?

M. L. Imhoff, L. Bounoua, Taylor Ricketts, and Colby Loucks
NASA’s GSFC, UMD ESSIC, WWF
NPP Carbon Balance

NPP Supply

- 

NPP Demand

= 

NPP Balance
Satellite Observation using 17 Year Baseline
- NDVI-monthly composite (AVHRR) 1982-1993
  at (0.25x0.25 degree horizontal resolution)
  \(\text{NDVI} = \frac{\text{IR}+R}{\text{IR}-R}\)

Terrestrial Carbon Model - Carnegie Ames Stanford Approach - CASA
Calculates NPP in g/m² [above & below ground].
- NDVI + vegetation map \(\rightarrow\) FPAR (0.4-0.7mm)
- FPAR + solar surf. Irradiance \(\rightarrow\) IPAR
- IPAR + light use efficiency \(\rightarrow\) NPP rates (g m⁻²)
- Climate drivers (Temperature, Precipitation, etc..)
Average Annual NPP on Land
(1982-1998)

56.8 Pg Carbon
NPP Global “Demand”
Per capita Consumption

- Shows population pressure ‘laterally’ on NPP
  - NPP consumed *in situ* not produced *in situ.*
  - Indicates vulnerability (reliance on transport)

- **Product Specific**

- **Bio-agronomic modules**
  - Back-calculate the NPP required in *grams Carbon.*

- **Country level – spatially constrained**
  - Domestic Supply = Production + Imports - Exports
  - Separate parameterization for Developing and Industrialized countries.
Estimation of NPP Required for Food/Fiber Products [Vegetal Foods]

FAO Data
Food Product (dry OM)

Literature Sources
Transport, Storage, and Processing Losses
Residue Above and Below Ground
Industrialized vs Developing Countries

NPP Required
Total biomass Crop (dry OM)

Adding biomass from ‘grain’ to whole plant
NPP Required for Meat Products

[Below is a flowchart illustrating the process of calculating NPP required for meat products. The chart includes the following components:

- **FAO Data**
  - Industrialized vs Developing Country
  - Carcass (Fresh Wgt)

- **Literature Sources**
  - Livestock Production Type
  - % from Grain
  - % from Pasture
  - Organic Matter Calculated (dry)
  - Efficiency Model:
    - Carcass Wt. to Grain or Pasture

- **Calculation**
  - NPP Required for Meat Products
  - [Eggs and Milk Follow Similar Pathway]
  - Literature Sources: FAO Data
  - Organic Matter Calculated (dry)
  - To Vegetal Foods Calculation
  - Pasture Above Ground Biomass (dry OM)
Identify: Developing or Industrialized (UNPOP 2002)

Vegetal Food & Fiber (MT, dry)

Livestock-based Foods (MT)
Meat (carcass weight), Milk & Eggs (fresh)

Identify livestock production system
(Sere & Steinfeld 1996, CAST 1999)

% Grain-based $\rightarrow$ % Pasture-based

Identify: Developing or Industrialized (UNPOP 2002)

Wood Products
Includes Fuel-wood and Paper (MT, dry)

Wood/Paper HANPP [MT Carbon]

OM to C Conversion (Lieth and Whittaker 1975)

Root Mass (CASA, Potter et al., 1993)

Crop Residue (Smil 1983)


OM to C Conversion (Lieth and Whittaker 1975)

Vegetal Food & Fiber HANPP [MT Carbon]

Meat HANPP [MT Carbon]

Grain Efficiency (Kg grain/Kg Carcass)
(Oltjen et al. 1992, CAST 1999)

Pasture Efficiency (MT Forage/MT Carcass)
(Sere & Steinfeld 1996, CAST 1999)

Grain OM

OM to C Conversion (Lieth and Whittaker 1975)

Pasture OM

Grain Efficiency
(Oltjen et al. 1992, CAST 1999)

Harvest Losses

Root Mass (CASA, Potter et al. 1993)

Processing & Milling Losses
(Ince 2000, Walsh 1999)

Recycling (paper)
(Skog et al. 1998)

OM to C Conversion
(Lieth and Whittaker 1975)

OM to C Conversion
(Lieth and Whittaker 1975)

Wood/Paper HANPP [MT Carbon]
Annual Human NPP Carbon Demand
Terrestrial NPP Required for Food and Fiber (1995)

11.54 Pg Carbon
# Annual NPP Carbon Demand

**Human Population 1995** (5.69 Billion people)

<table>
<thead>
<tr>
<th>Consumed Products (Pg Carbon)</th>
<th>Low Estimate</th>
<th>Intermediate Estimate</th>
<th>High Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vegetal Food</td>
<td>0.89</td>
<td>1.73</td>
<td>2.95</td>
</tr>
<tr>
<td>Meat</td>
<td>1.69</td>
<td>1.92</td>
<td>2.21</td>
</tr>
<tr>
<td>Milk</td>
<td>0.15</td>
<td>0.27</td>
<td>0.43</td>
</tr>
<tr>
<td>Eggs</td>
<td>0.09</td>
<td>0.17</td>
<td>0.26</td>
</tr>
<tr>
<td><strong>Food (subtotal)</strong></td>
<td><strong>2.83</strong></td>
<td><strong>4.09</strong></td>
<td><strong>5.85</strong></td>
</tr>
<tr>
<td>Paper</td>
<td>0.20</td>
<td>0.28</td>
<td>0.38</td>
</tr>
<tr>
<td>Fiber</td>
<td>0.32</td>
<td>0.37</td>
<td>0.42</td>
</tr>
<tr>
<td>Wood Products (including fuel)</td>
<td>4.64</td>
<td>6.81</td>
<td>8.15</td>
</tr>
<tr>
<td><strong>Commodities (subtotal)</strong></td>
<td><strong>5.17</strong></td>
<td><strong>7.45</strong></td>
<td><strong>8.95</strong></td>
</tr>
<tr>
<td><strong>Total Demand</strong></td>
<td><strong>8.00</strong></td>
<td><strong>11.54</strong></td>
<td><strong>14.81</strong></td>
</tr>
</tbody>
</table>

Demand as % of Supply (56.8 Pg) 14% 20% 26%
Methods:
Calculate NPP “supply” Map using satellite data.

Develop Human Appropriation NPP (HANPP) consumption-based Model
- NPP required “in the field” for food and fiber products United Nations Food and Agriculture Organization database (UNFAO-STATS).

Make NPP “Demand” Map
Apply HANPP of countries to population map from CIESIN using per Capita NPP consumption.

Compare NPP Supply with NPP Demand.
NPP Demand as % of Supply

Global NPP Demand is 20% of Supply (land)
There are large regional and local variations

[Map showing NPP Demand as % of Supply across different regions of the world, with percentages such as 24%, 72%, 300%, and 6% indicated for various regions like North America, South America, W. Europe, and S. Central Asia.]
<table>
<thead>
<tr>
<th>Region</th>
<th>Population (millions)</th>
<th>Per Capita NPP Demand (MT C)</th>
<th>Regional NPP Supply (Pg C)</th>
<th>Regional NPP Demand (Pg C)</th>
<th>Demand % Supply</th>
</tr>
</thead>
<tbody>
<tr>
<td>Africa</td>
<td>742</td>
<td>2.08</td>
<td>12.50</td>
<td>1.55</td>
<td>12%</td>
</tr>
<tr>
<td>East Asia</td>
<td>1400</td>
<td>1.37</td>
<td>3.02</td>
<td>1.91</td>
<td>63%</td>
</tr>
<tr>
<td>South-Central Asia</td>
<td>1360</td>
<td>1.21</td>
<td>2.04</td>
<td>1.64</td>
<td>80%</td>
</tr>
<tr>
<td>Western Europe</td>
<td>181</td>
<td>2.86</td>
<td>0.72</td>
<td>0.52</td>
<td>72%</td>
</tr>
<tr>
<td>North America</td>
<td>293</td>
<td>5.40</td>
<td>6.67</td>
<td>1.58</td>
<td>24%</td>
</tr>
<tr>
<td>South America</td>
<td>316</td>
<td>3.11</td>
<td>16.10</td>
<td>0.98</td>
<td>6%</td>
</tr>
</tbody>
</table>
Terrestrial NPP 'Supply' in 1997

AVHRR/CASA

NPPact (gC/m2)

- Undefined
- 0
- < 20
- 20 - 60
- 60 - 130
- 130 - 200
- 200 - 290
- 290 - 380
- 380 - 500
- 500 - 740
- 740 - 1,200
- > 1,200
NPP Harvested by Humans in 1997

NPPh
(gC/m²)

- Undefined
- 0
- < 1.5
- 1.5 - 4.0
- 4.0 - 7.0
- 7.0 - 12.0
- 12.0 - 20.0
- 20.0 - 30.0
- 30.0 - 50.0
- 50.0 - 80.0
- 80.0 - 150.0
- > 150.0
What Might the Future Hold?

“The future ain’t what it used to be” (Yogi Berra)

\[ I = PAT \]

- The overall ecological impact \[ I \] of human activities involves the tight interplay of population size \[ P \], consumption level or \[ A \], for “affluence”\] and the technologies employed \[ T \] (Holdren and Ehrlich, 1976).
How HANPP Changes as a Function of: Population, Affluence, and Technology

\[ I = PAT \]

- The ecological impact \([I]\) of human activities involves population size \([P]\), consumption levels \([A\), for “affluence”\], and the technologies employed \([T]\) (Holdren and Ehrlich, 1976).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>P*</th>
<th>A**</th>
<th>T***</th>
<th>HANPP (PgC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>↑</td>
<td>−</td>
<td>−</td>
<td>17.42</td>
</tr>
<tr>
<td>2</td>
<td>−</td>
<td>↑</td>
<td>−</td>
<td>20.19</td>
</tr>
<tr>
<td>3</td>
<td>−</td>
<td>↑</td>
<td>↑</td>
<td>16.26</td>
</tr>
<tr>
<td>4</td>
<td>↑</td>
<td>↑</td>
<td>−</td>
<td>31.59</td>
</tr>
<tr>
<td>5</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>25.5</td>
</tr>
</tbody>
</table>

↑ (increase), − (no change from the baseline 1995 intermediate estimate).

* Population increase from 5.69 Billion (global population in 1995) to 8.92 Billion (estimated global population in 2050; Ref 18).
** Affluence increase applies average per capita consumption of industrialized countries (in 1995) for all countries.
*** Technology increase applies technological efficiencies of industrialized countries (in 1995) to all countries.
† Per capita fuel wood use in developing countries reduced to average for industrialized countries in 1995.
The rate at which humans consume NPP-C is a powerful aggregate measure of human impact on biosphere function.

Human NPP-C Demand is between 10% and 20% of planetary supply with large regional and local variation.

Population-based ‘Lateral’ Supply and Demand approach illustrates the degree to which local populations depend upon NPP “imports”.

Results from our interaction with the late Roy Darwin (USDA/ERS)
Land area-based or ‘Vertical’ analysis illustrates in situ landscape NPP balance with direct implications for ecosystem function.

Human harvests of NPP substantially reduce the amount of actual NPP in many areas
On average, humans leave relatively less NPP in low-productivity ecosystems than in high-productivity ecosystems.
Published Documents


