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

QuickTime™ and a
Cinepak decompressor
are needed to see this picture.

M. L. Imhoff, L. Bounoua, Taylor Ricketts, and Colby Loucks
NASA's GSFC, UMD ESSIC, WWF

NASA's Interests

Scale: Planetary
Focus: Biogeochemical Cycles and Climate

The Anthropocene

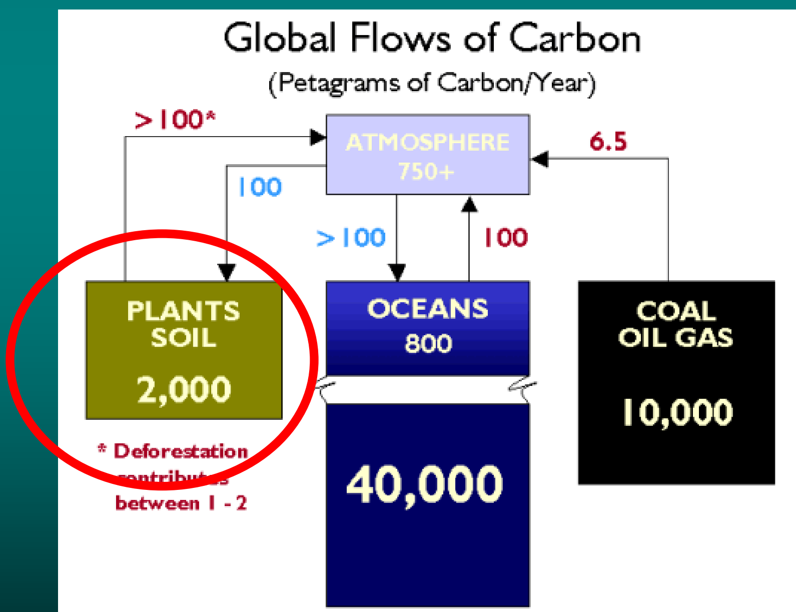
"humans have become a geologic agent comparable to erosion and eruptions… it seems appropriate to emphasize the central role of mankind in geology and ecology by proposing to use the term 'anthropocene' for the current geological epoch."

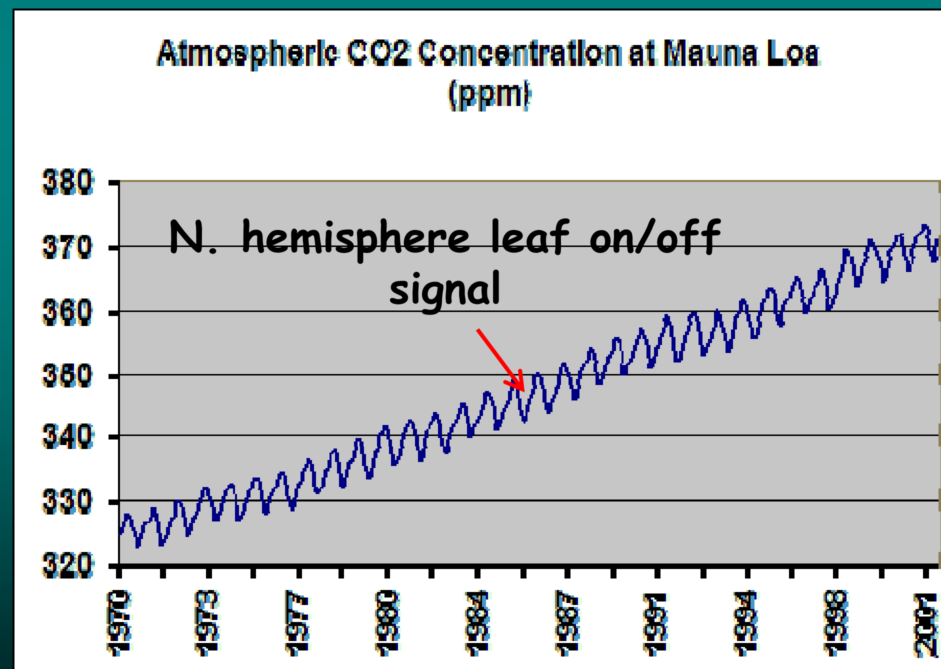
Paul J. Crutzen

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.

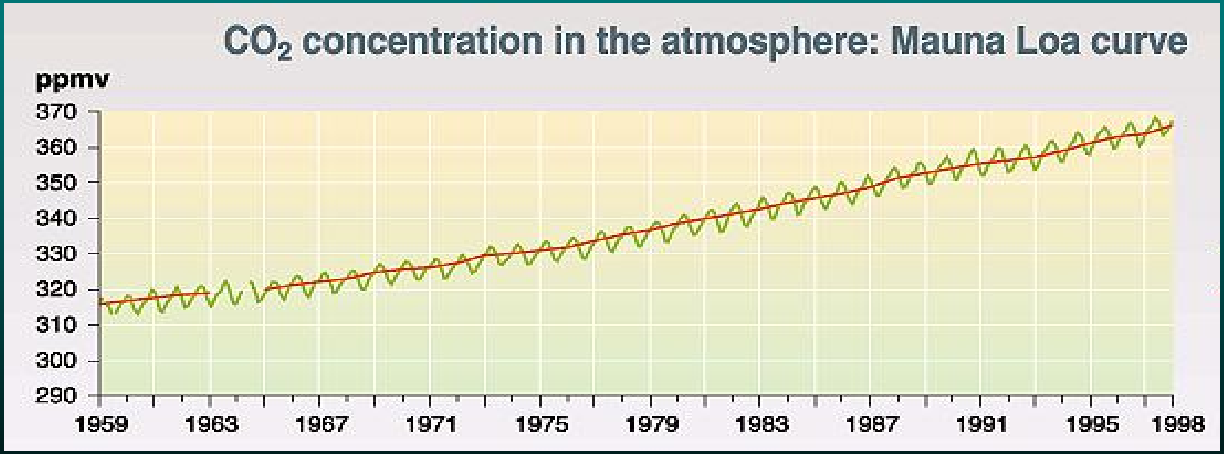
Terra MODIS Global Daily Coverage

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

Global NPP and CO_2

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

NPP MODIS



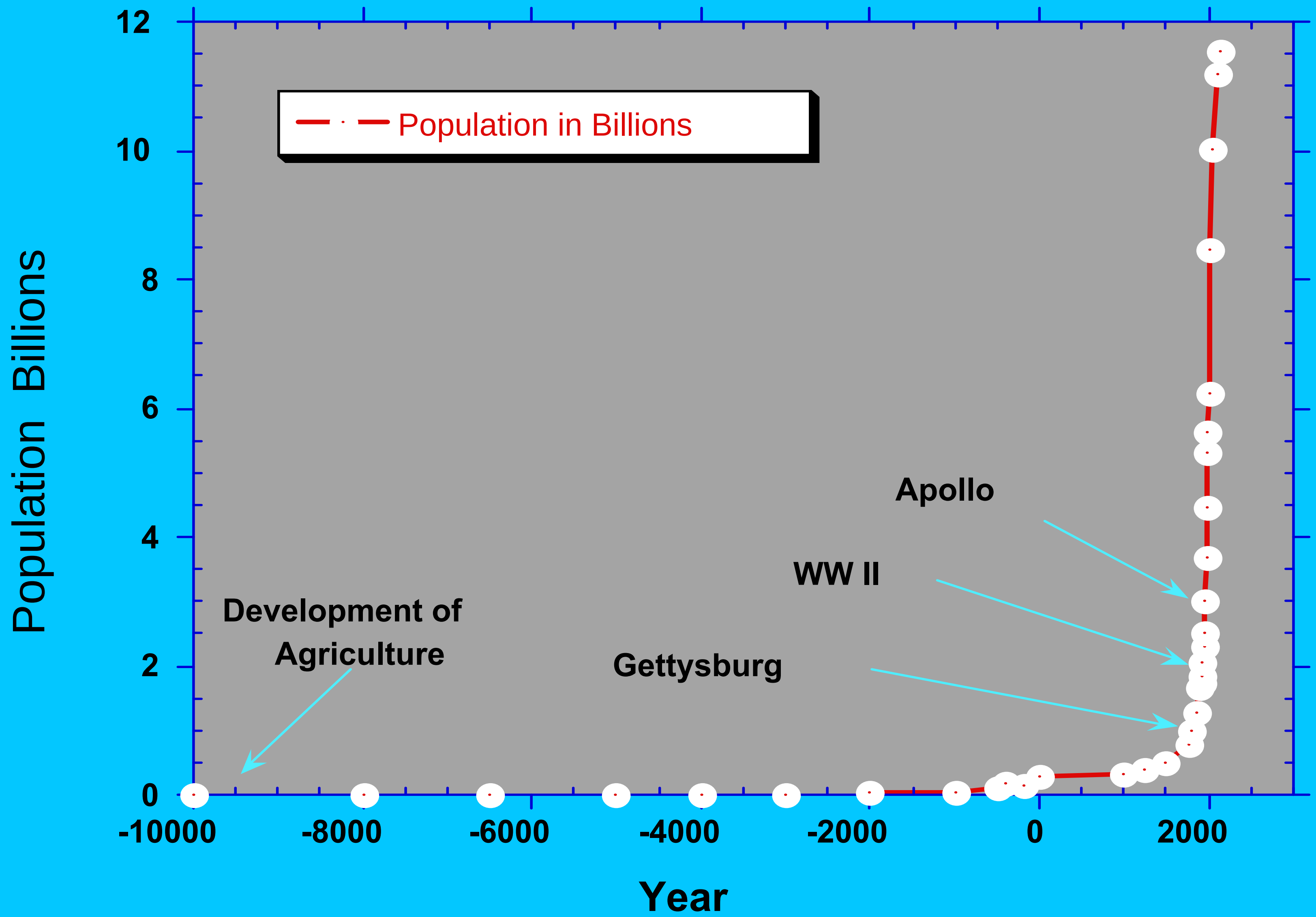
Human Transformation of the Land Surface

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

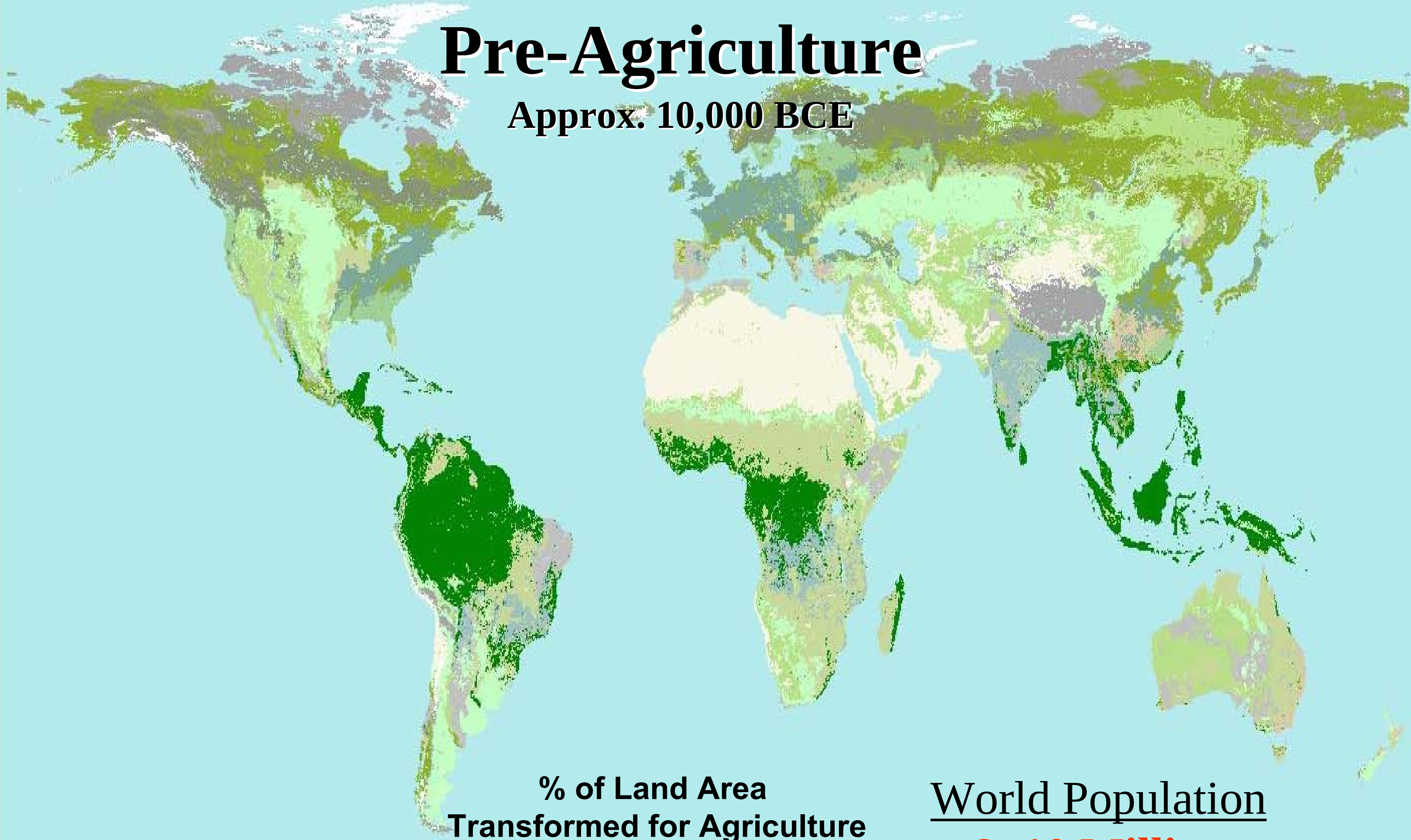
QuickTime™ and a
Sorenson Video decompressor
are needed to see this picture.

History of World Population Growth
10000 B.C. to 2150 A.D.



Global Land Cover Pre-Agriculture

Approx. 10,000 BCE



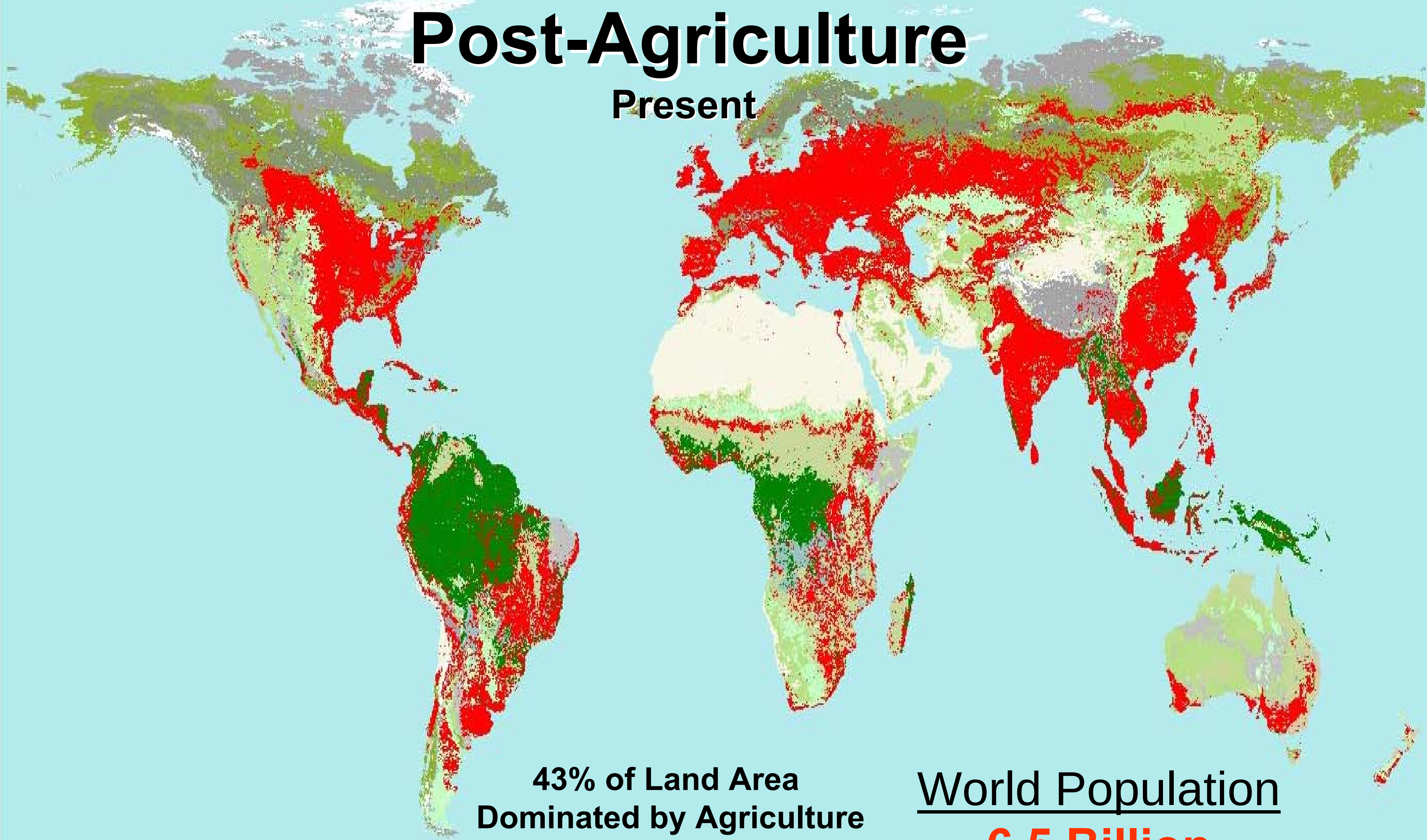
% of Land Area
Transformed for Agriculture
(Negligible)

<u>World Population</u>

6 -10 Million

Global Land Cover Post-Agriculture

Present



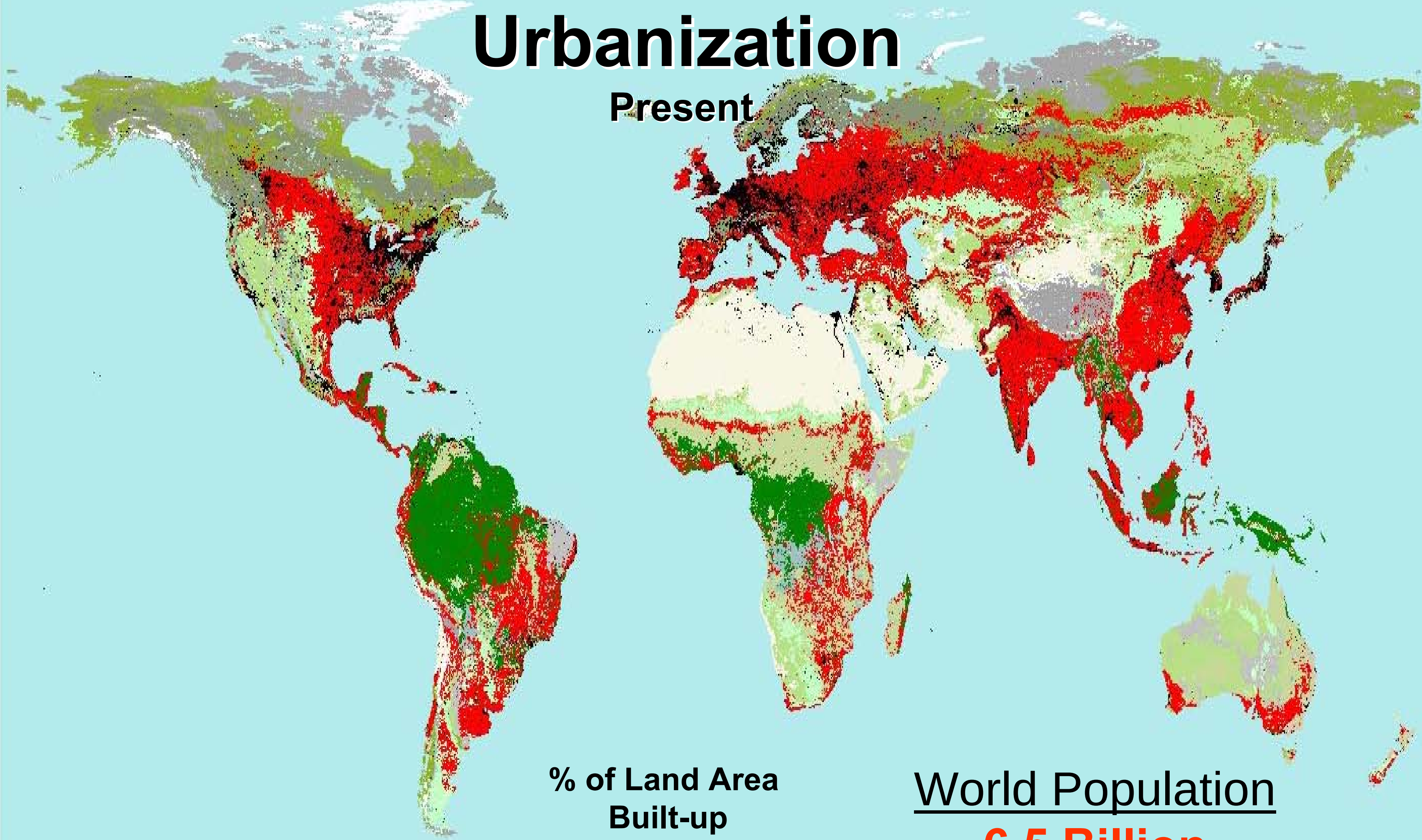
43% of Land Area Dominated by Agriculture

World Population

6.5 Billion

Global Land Cover Urbanization

Present



% of Land Area Built-up
3 - 6%

World Population
6.5 Billion

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.

NY Times/Science Times 12/8/98

Will Humans Overwhelm the Earth? The Debate Continues

By MALCOLM W. BROWNE

PHILADELPHIA, Dec. 4 — Two hundred years ago the Rev. Thomas Robert Malthus, an English economist and mathematician, anonymously published an essay predicting that the world's burgeoning human population would overwhelm the Earth's capacity to sustain it.

Malthus's gloomy forecast, called "An Essay on the Principle of Population As it Affects the Future Improvement of Society," was condemned by Karl Marx, Friedrich Engels and many other theorists, and it was still striking sparks last week at a meeting in Philadelphia of the American Anthropological Society. Despite continuing controversy, it was clear that Malthus's conjectures are far from dead.

Among the scores of special conferences organized for the 5,000 participating anthropologists, many touched directly or indirectly on the Malthusian dilemma: Although global food supplies increase arithmetically, the population increases geometrically — a vastly faster rate. The consequence, Malthus believed, was that poverty and the misery it imposes will inevitably increase unless the population increase is curbed.

This contention has prompted endless debate. Malthus's critics, especially the utopians of his time, have argued that man's ingenuity will always keep pace with population growth by finding improved ways to produce food.

Recent assaults on Malthusian pessimism have cited the success of the "Green Revolution" launched in the 1950's and 1960's by Dr. Norman Borlaug and his associates in developing high-yield strains of rice and wheat.

But the scientific descendants of Malthus argue that feeding the world's masses is only part of the problem. Just as dangerous, they contend, is the omnivorous consumption of nonrenewable resources, the irreversible destruction of habitats and species, the fouling of the air and seas and consequent changes in climate, and many other effects of the growing human horde.

One of the symposiums held at last week's meeting was so controversial that a conference with the same title had been banned from the 1994 meeting of the American Association for the Advancement of Science on the grounds (according to its organizer, Dr. Warren M. Hern, a Colorado physician and epidemiologist) that "You may not ask that question."

The question, posed as t[...] the symposium, was this[...] Human Species a Cance[...] Planet?"

Dr. Hern, the director of [...]tion clinic in Boulder, Colo[...] nearly a decade ago that [...] satellite views of urban ce[...]en over a period of year[...] striking similarity to imag[...] cerous tissue (particularly [...]ma) invading the healthy [...]ing tissue.

In his presentation last [...] Hern argued that in many [...] the world the increase i[...] numbers is rapid and unc[...] that it invades and destroys [...] and that by killing off man[...] it reduces the differentiati[...]ture. All of these features [...]acteristic of cancerous tu[...] said.

This assessment was a[...] by another member of the p[...] Lynn Margulis of the Univ[...] Massachusetts, Boston, [...] known for her coauthorshi[...] other highly controversial [...] known as the "Gaia Hypoth[...]

The Gaia idea, the brainchild of an English theorist, Dr. James E. Lovelock, and Dr. Margulis, who is a microbiologist, is that the entire Earth deploys feedback mechanisms to maintain an environment hospitable to life. In this it resembles a gigantic living organism, proponents of the idea believe.

Life on Earth has survived many crises, including mass extinctions caused by the impacts of asteroids and comets, Dr. Margulis said, and life will continue despite the threats created by humanity — but with reduced diversity.

She agreed with the notion that the human race is a kind of self-destructive cancer.

"For millions of years the Earth got along without human beings," she said, "and it will do so again. The only question is the nature of the human demise that has already begun."

Dr. Margulis quoted a line from [...]

Feeding the masses is just part of the problem, some say.

Bettman Archives

The Rev. Thomas Robert Malthus

from 1.9 to 2.1 percent, largely because of Hispanic immigration.

All the speakers at the symposium had expected vigorous criticism from the audience of anthropologists, but were surprised to encounter few strongly negative comments.

"Arguments over the accuracy of Malthus's views, future population trends and the Earth's carrying capacity are never-ending and never resolved," one speaker said. "Many people prefer to just forget about the big questions involved, and get on with their lives."

At another symposium held at last week's meeting participants were asked to address the question "Was Malthus Right?" None of the panelists called Malthus's assessment of the grim consequences of overpopulation wrong, although some argued that he had some details wrong.

"Most biologists would say that Darwin's work was mostly correct [...]

REMEMBER THE NEEDIEST!

Time Magazine Special Millennium Issue, Nov, 1999

visions 21

WILL MALTHUS BE RIGHT?

His forecast was ahead of its time, but nature may still put a lid on humanity

BY NILES ELDREDGE

MALTHUS WAS RIGHT, SO READ A CAR BUMPER sticker on a busy New Jersey highway the other day, and it got me thinking about the Rev. Thomas Malthus, the English political economist who gave the "dismal science" its nickname. His "Essay on the Principle of Population," published in 1798, predicted a gloomy future for humanity: our population would grow until it reached the limits of our food supply, ensuring that poverty and famine would persistently rear their ugly faces to the world.

1998-1999

"Malthus might be right, but probably not"

2001-2004

"Malthus is wrong"

2006

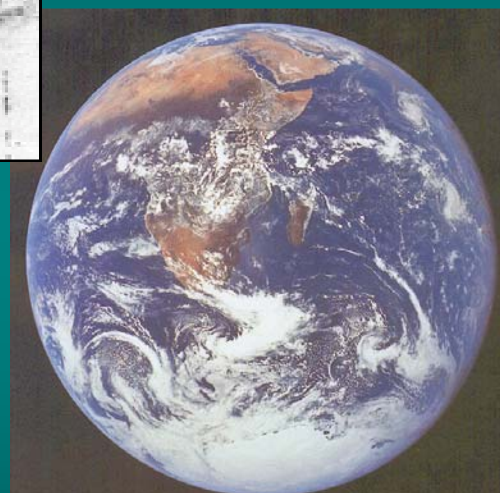
"Malthus might be relevant"

GLOBAL OBSERVATION OF URBANIZATION

ISS007E13860

We've Come A Long Way

TIROS
April 1, 1960
700 km Altitude



Apollo 17
Dec.7, 1972, 45,000 km from Earth,
70mm Hasselblad, 80mm lens

Blue Marble
EOS Terra/Aqua 2000 -

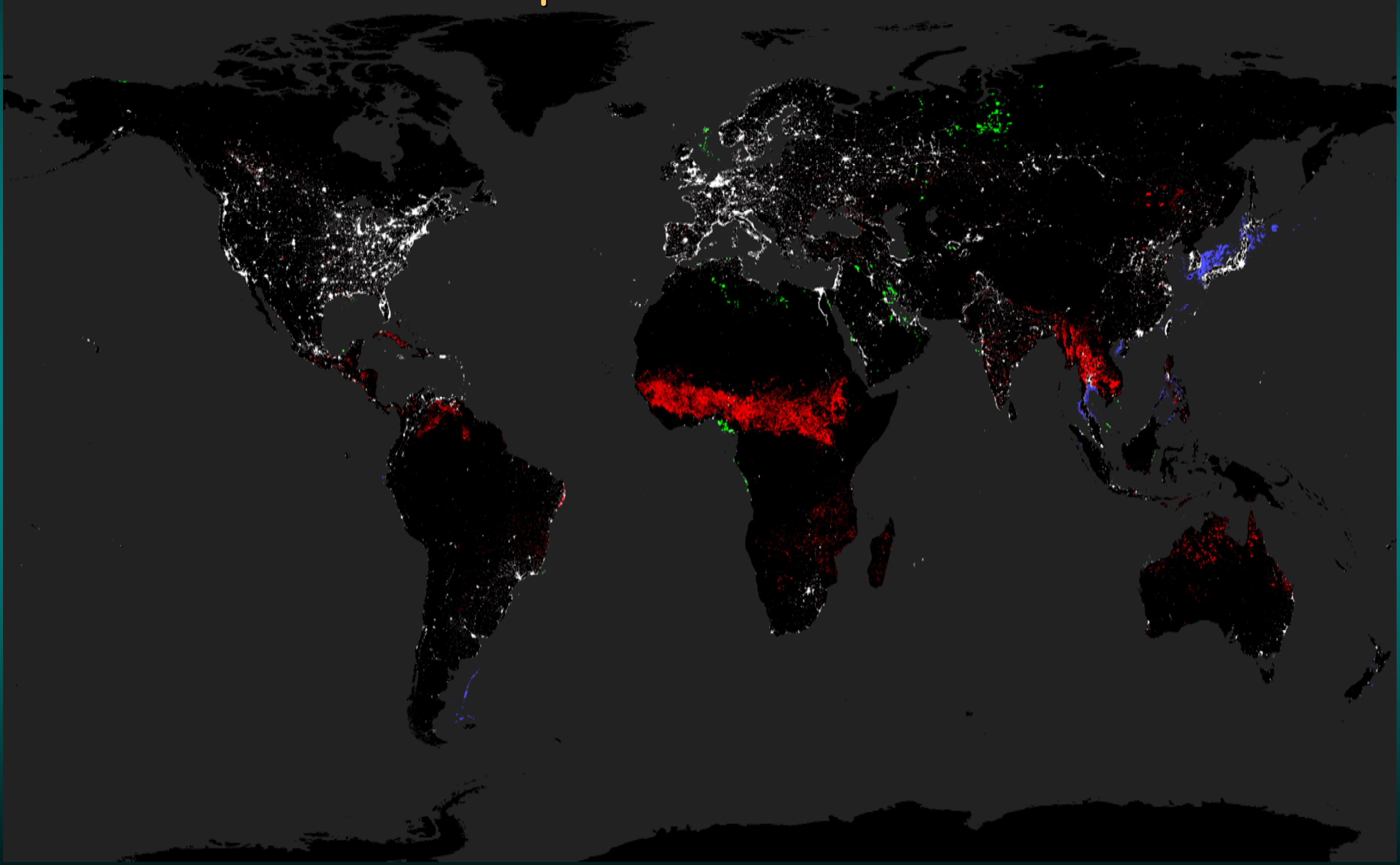
A BREAKTHROUGH IN URBAN MAPPING

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 sterradian.
- Pixel resolution:
  - 0.55 km at high resolution (fine mode)
  - 2.7 km at low resolution(smooth mode).

Nighttime Lights of the World

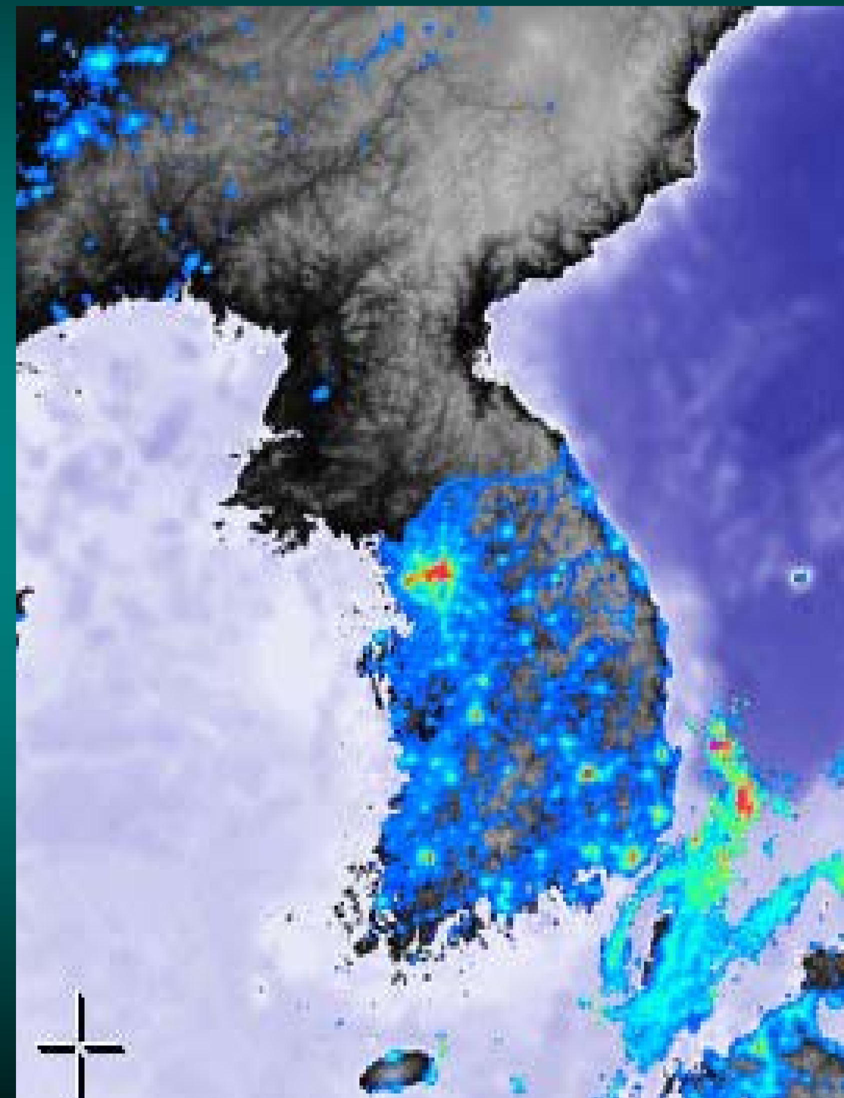
DMSP Global Composite Oct. 1994 - March 1995



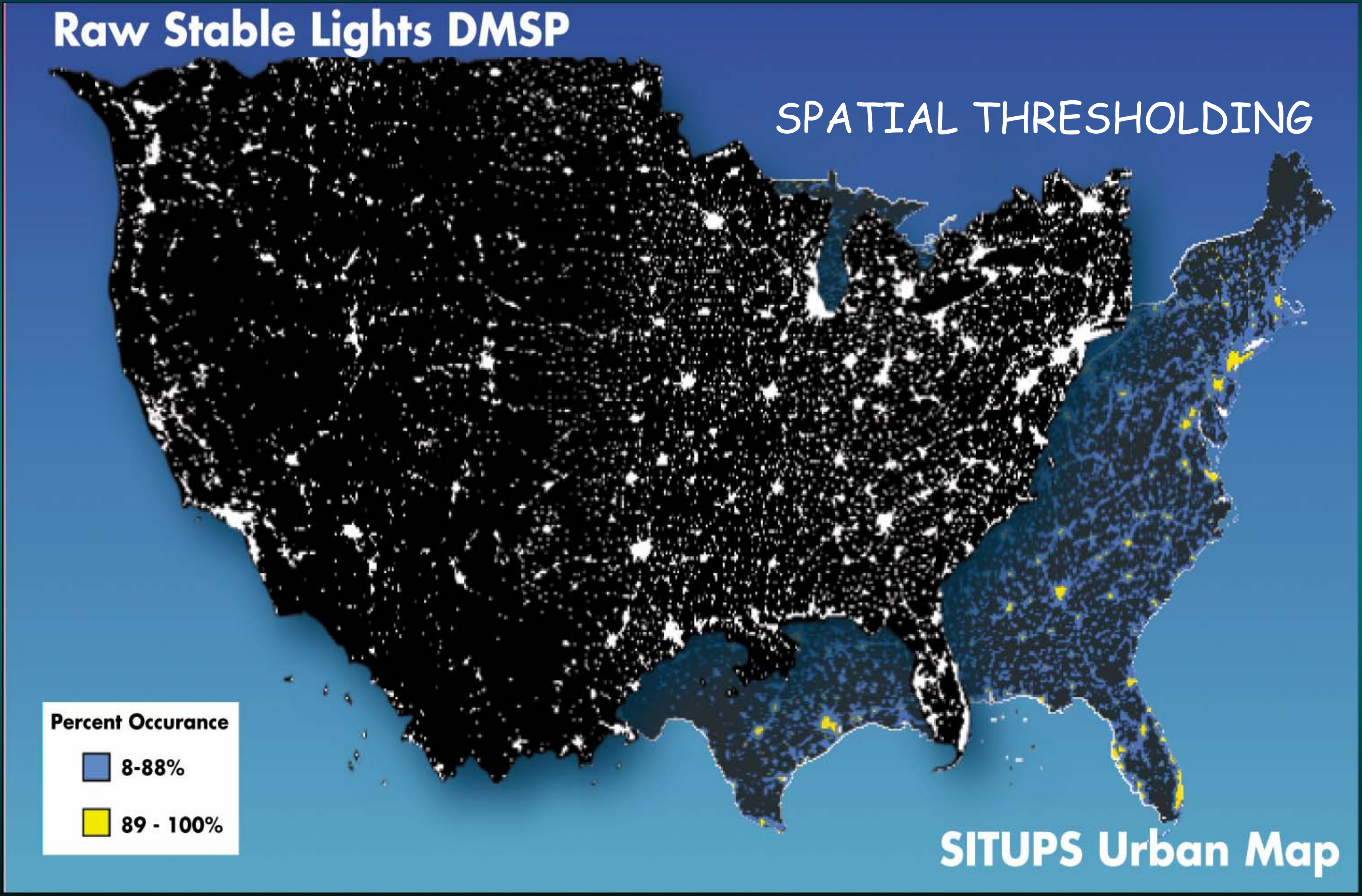
Korean Peninsula

Day - MODIS, April 6, 2000

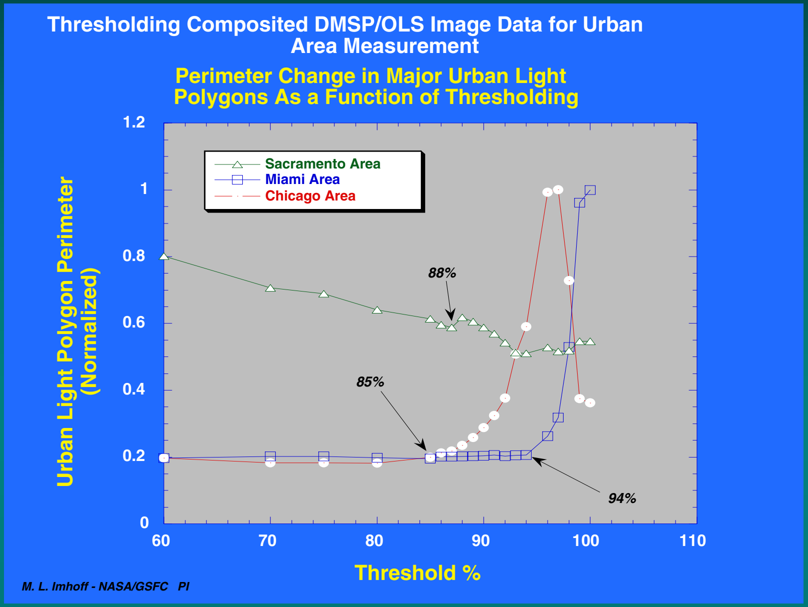
Night - DMSP, Oct., 2000

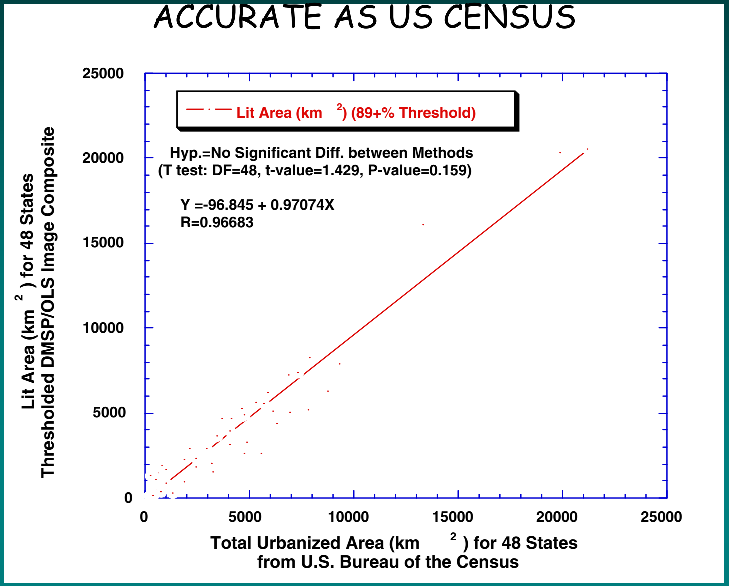


CREATING ACCURATE URBAN MAPS FROM RAW DATA



THRESHOLDING TECHNIQUE IN GIS

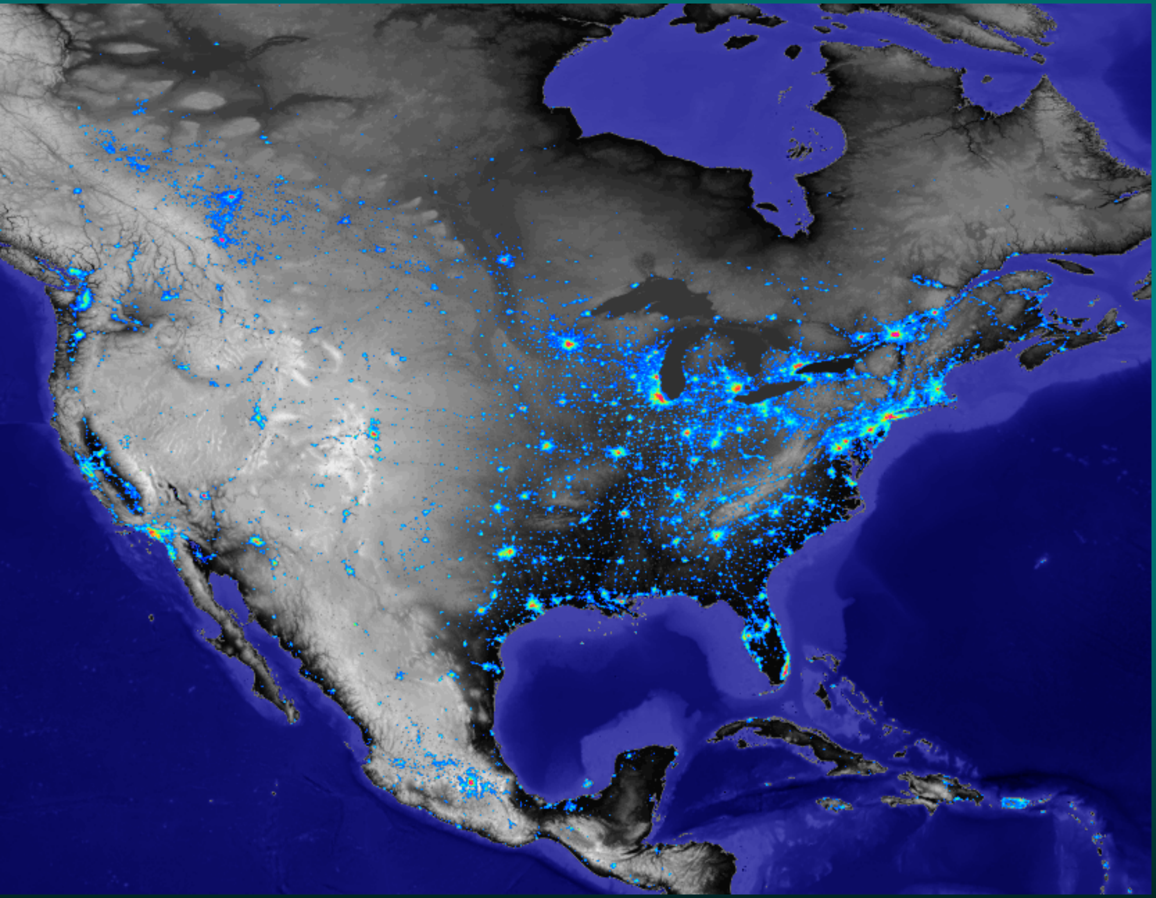




PERIMTER MEASURES USED TO REDUCE BLOOMING AND DEFINE DENSE URBAN DEVELOPMENT

QuickTime™ and a
Cinepak decompressor
are needed to see this picture.

Consequences of Urbanization on NPP-Carbon in the United States



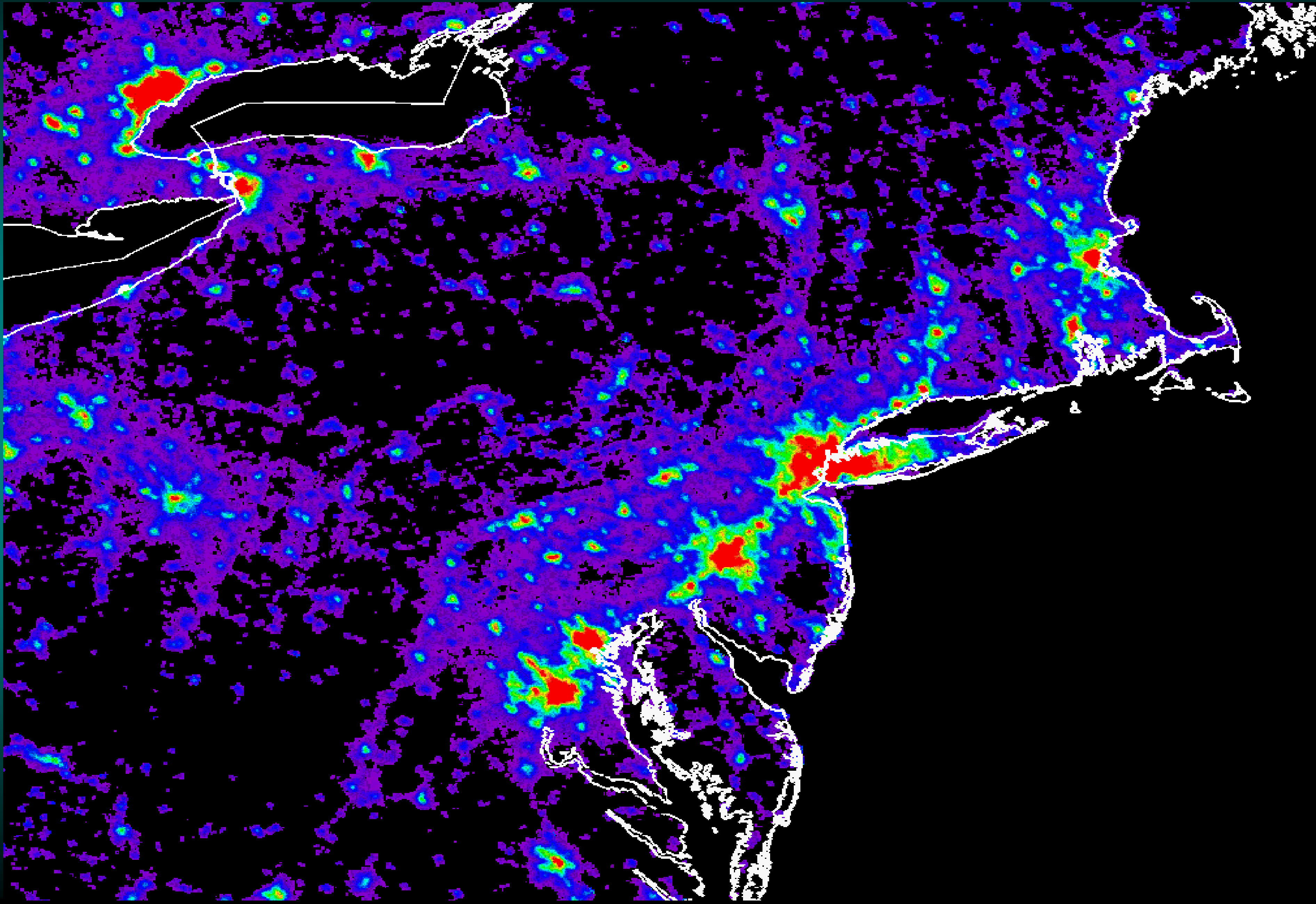
What is the overall impact in North America?

- –Has the NPP-carbon sink been reduced?
- –What are the consequences?

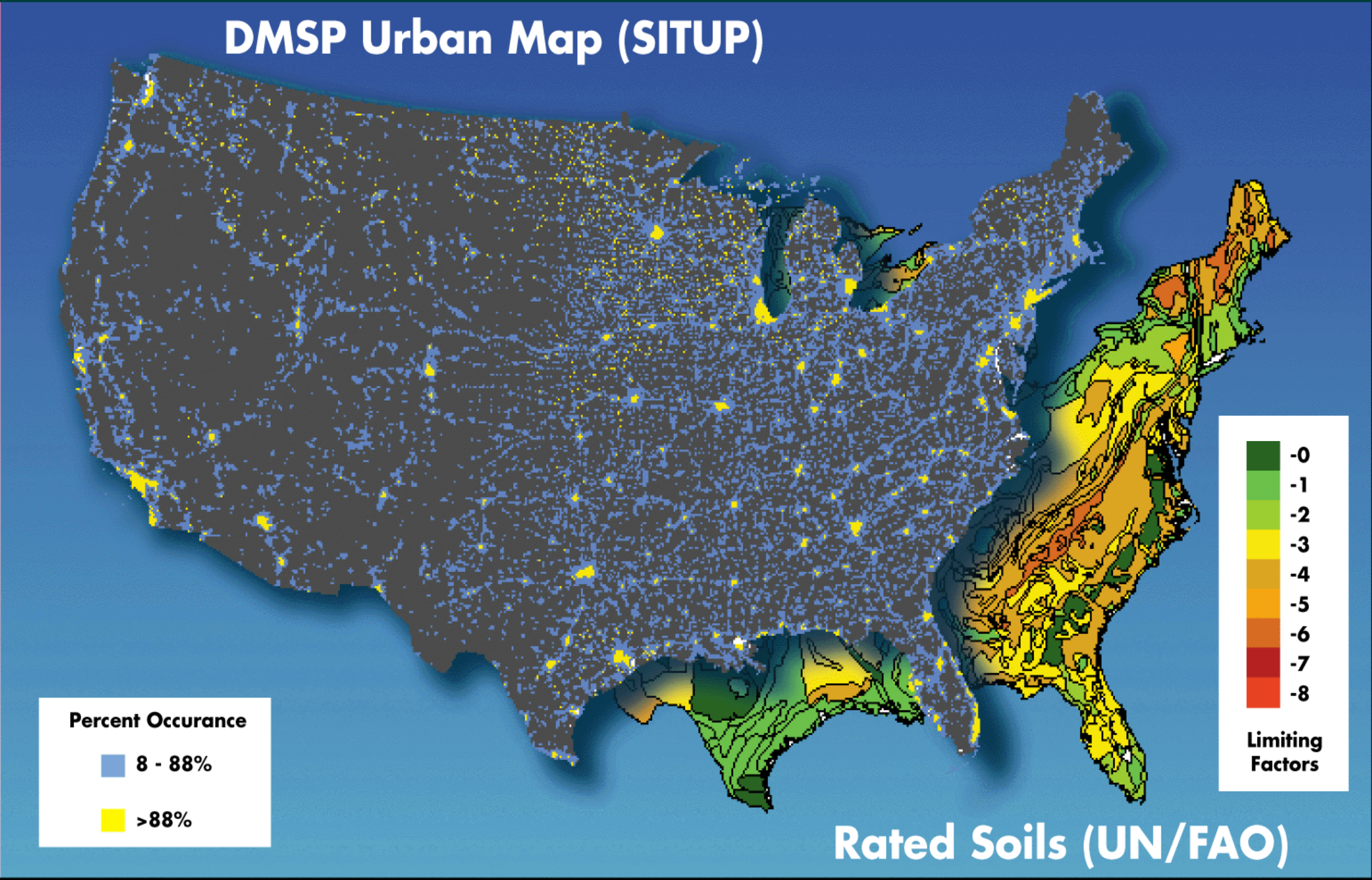
How does urbanization interact with climate locally?

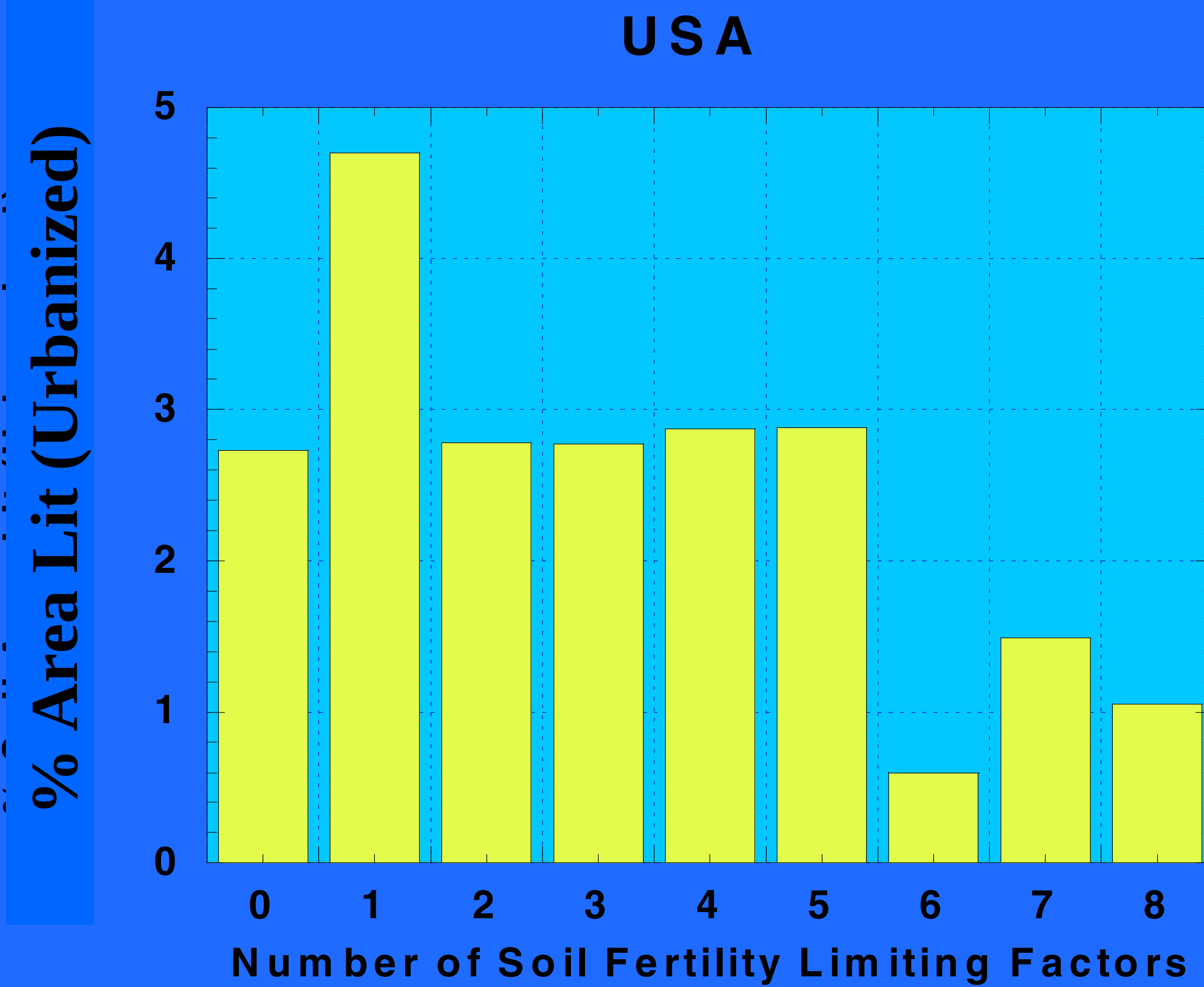
- –Is there a recognizable effect in the NDVI signal at 1km spatial resolution?
- –What are the seasonal dynamics?
- –Is urbanization's impact on NPP balance positive or negative?

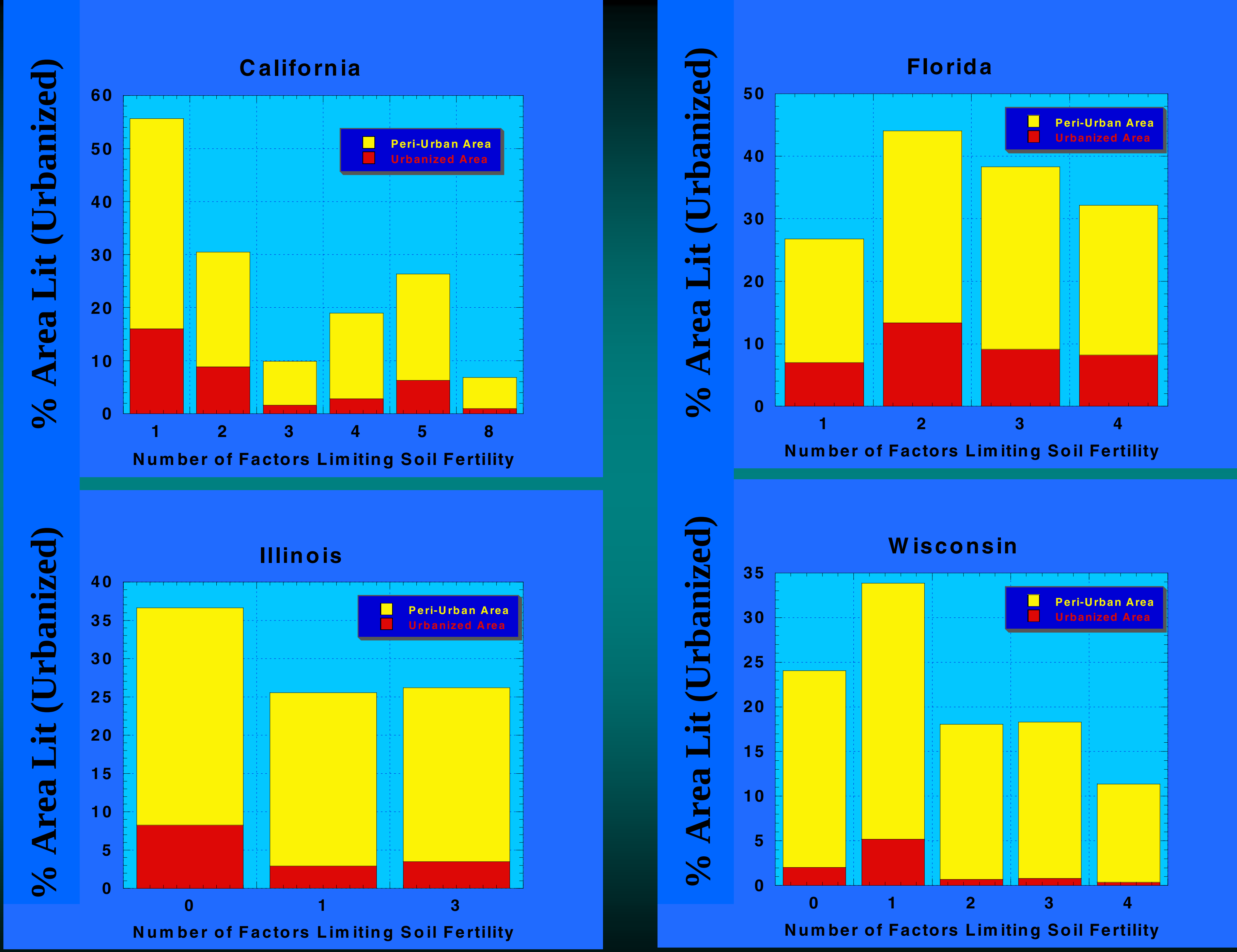
Gain Controlled DMSP Image of North Eastern USA

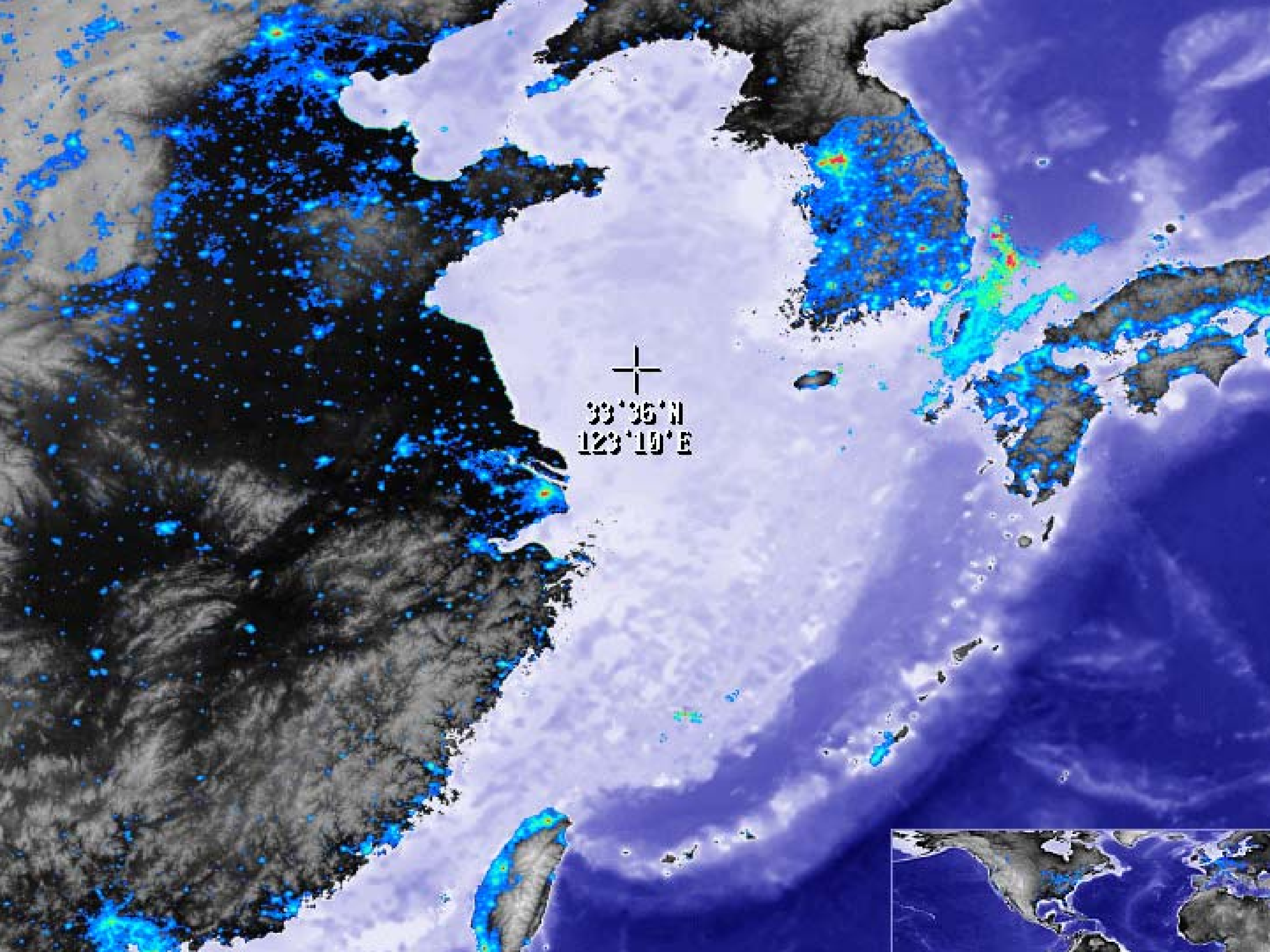


Urban Occupation of Soils in the USA



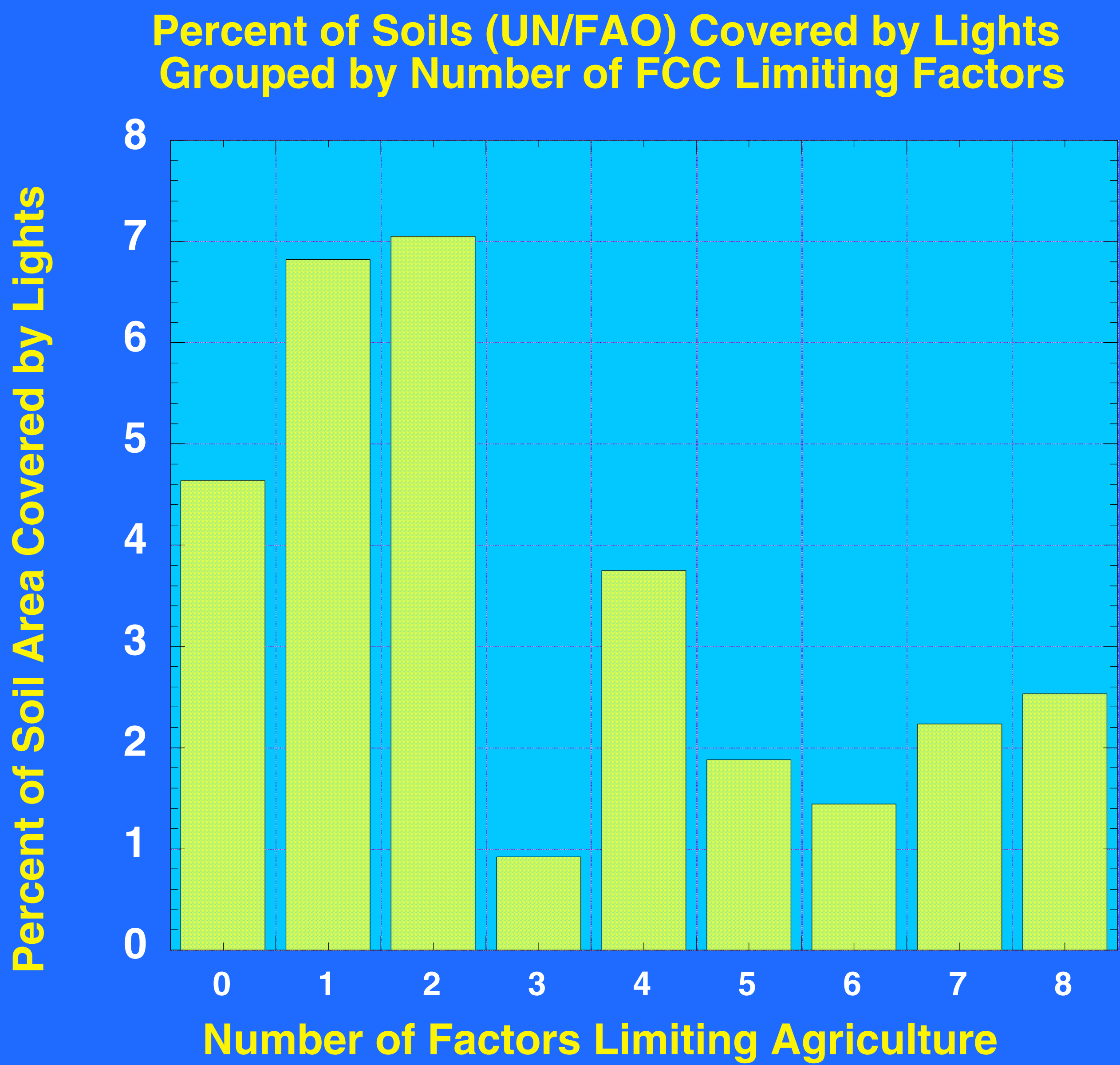

USA
% Area Lit (Urbanized)
0
1
2
3
4
5
0
1
2
3
4
5
6
7
8
Number of Soil Fertility Limiting Factors

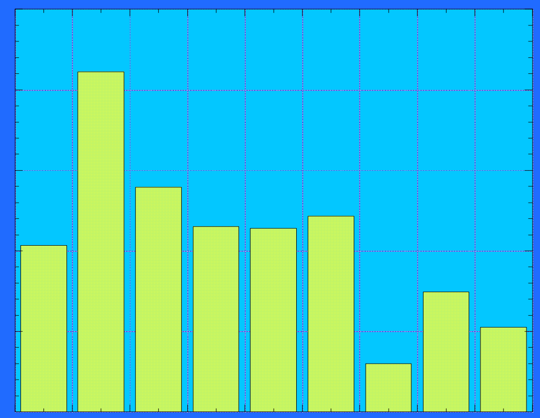

California
Florida
Illinois
Wisconsin
% Area Lit (Urbanized)
Peri-Urban Area
Urbanized Area
Number of Factors Limiting Soil Fertility
0
5
10
15
20
25
30
35
40
50
60
1
2
3
4
8

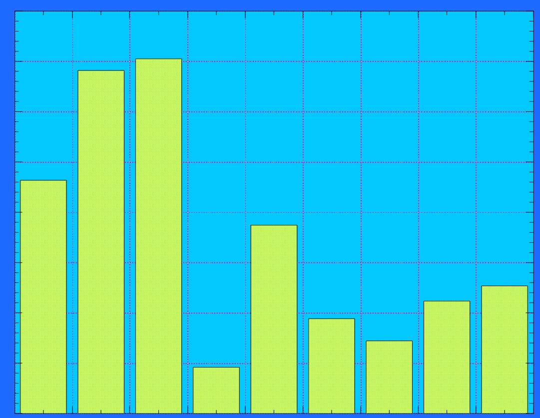

33°35'N
123°10'E

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

CHINA

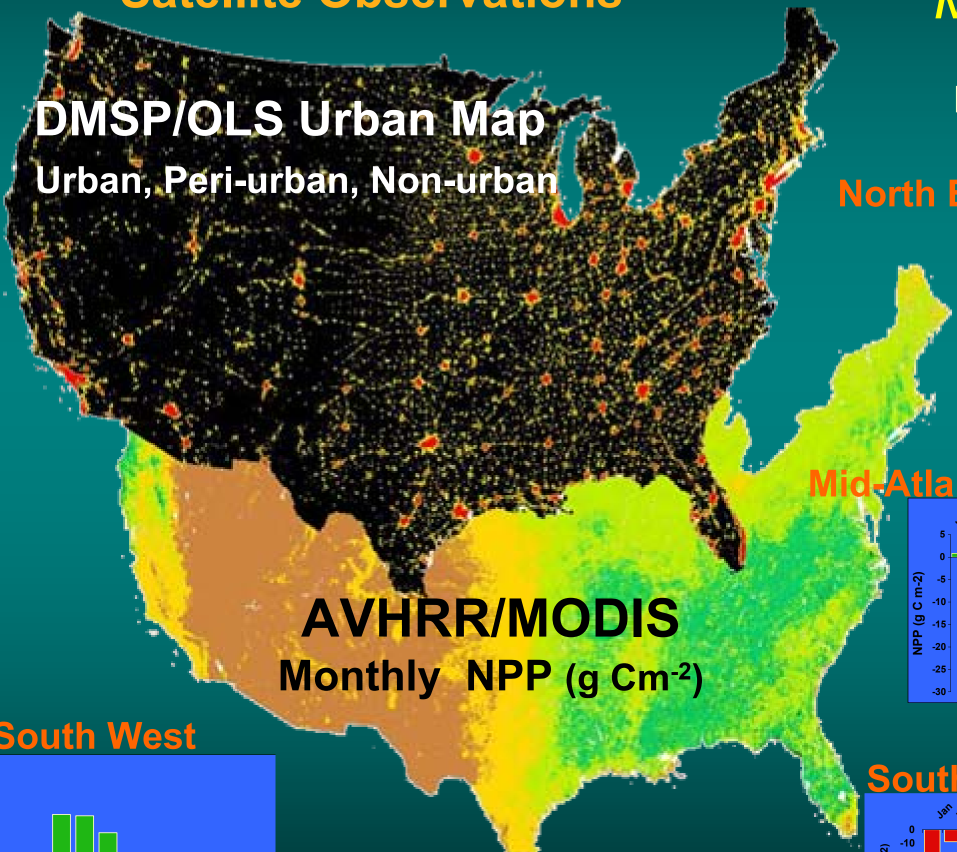

Percent of Soils (UN/FAO) Covered by Lights
Grouped by Number of FCC Limiting Factors
Percent of Soil Area Covered by Lights
0
1
2
3
4
5
6
7
8
Number of Factors Limiting Agriculture





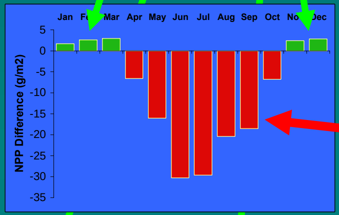
Consequences of Urbanization on NPP

Satellite Observations

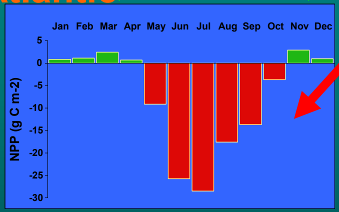


NPP and Local Climate:
Urban Heating Extends Length of growing season locally in cold climates.

North East

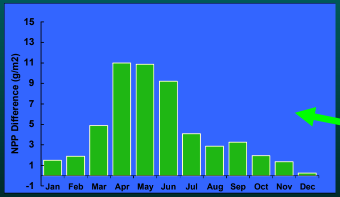


Mid-Atlantic



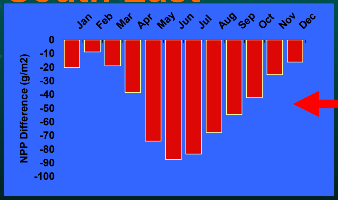
Winter NPP gain negated in peak season by reduced vegetation and heat stress.

South West



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

South East



Seasonal Offset diminishes in tropics

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%?

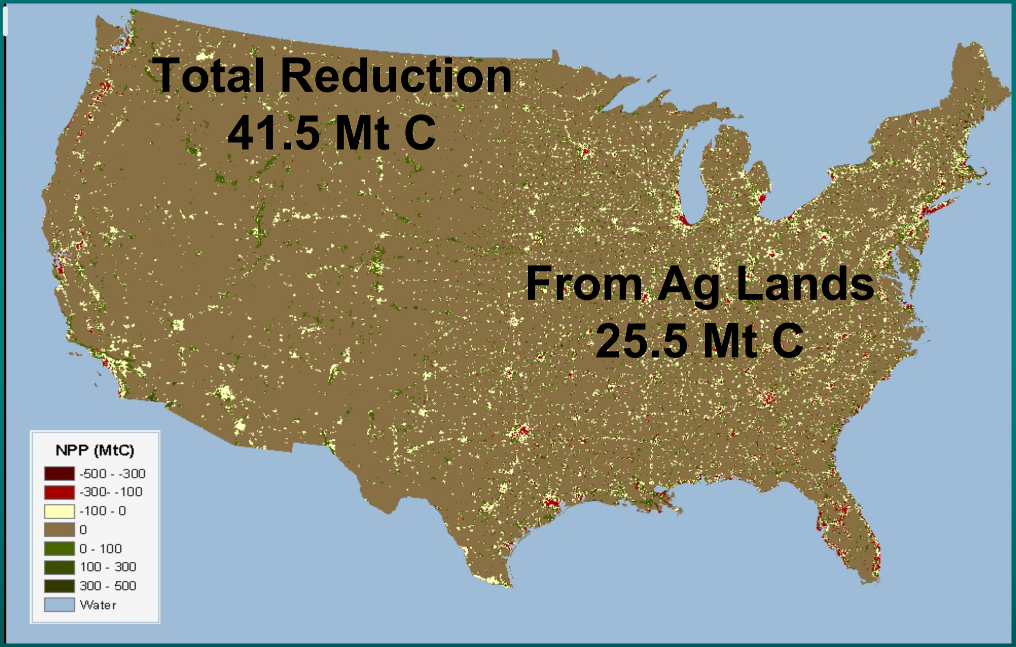
Location, Location, Location.
Urbanization is taking place on the most fertile lands

Reduction of NPP may have biological significance:

NPP Lost or Gained (annual)

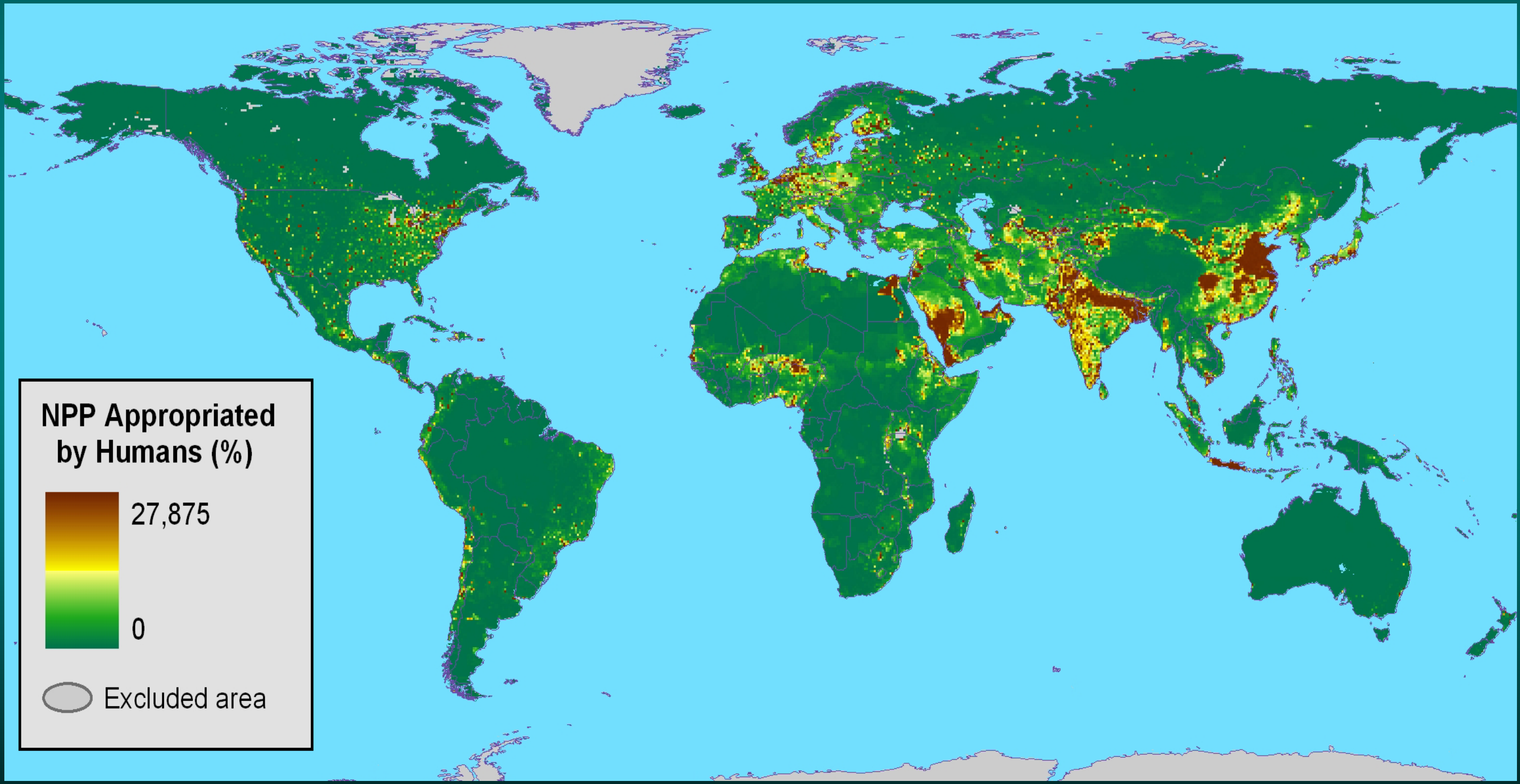
Due to Urbanization

Going from a pre-urban to a post urban world



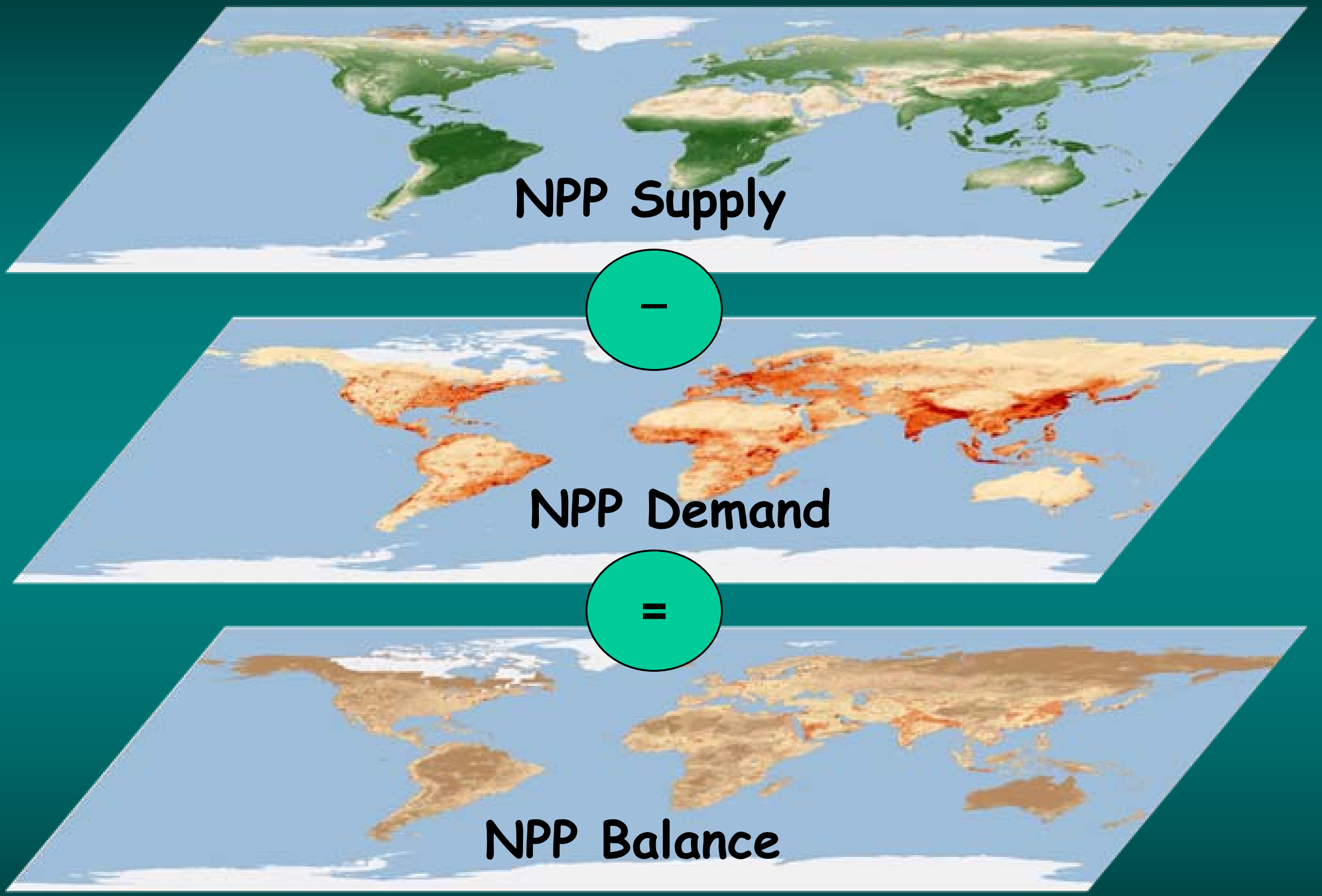
-Annual loss of food web energy 400 Trillion kilocalories (roughly equal to food energy requirement for 448 million people).
- Reduction of actual food products equivalent to needs of 16.5 million persons annually (about 6% of US population).

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



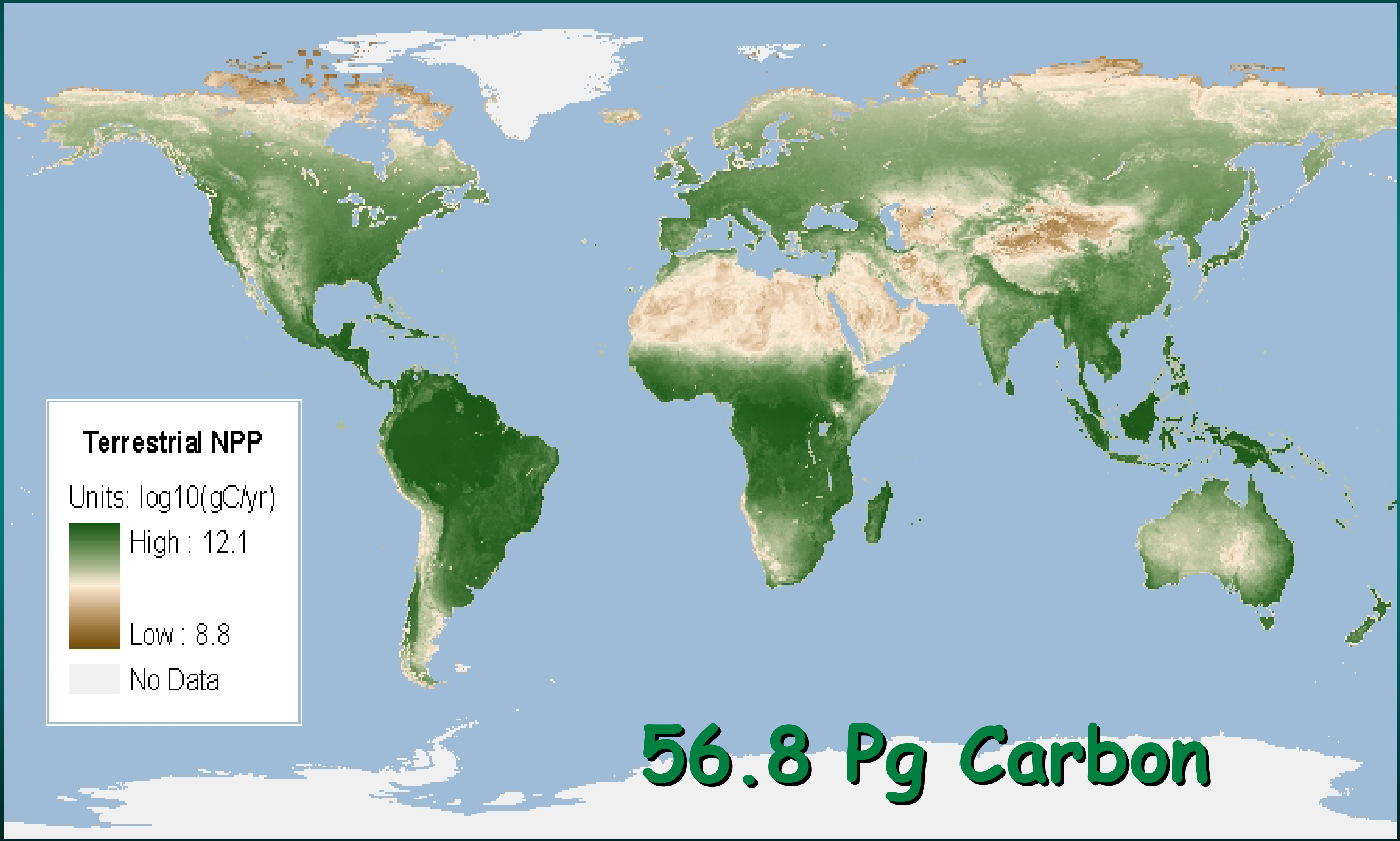
NPP “Supply”

Earth’s Current Terrestrial Production

Above and Below Ground

- Satellite Observation using 17 Year Baseline
  - NDVI-monthly composite (AVHRR) 1982-1993 at (0.25x0.25 degree horizontal resolution)
    - NDVI = IR+R/IR-R
- Terrestrial Carbon Model -Carnegie Ames Stanford Approach – *CASA*
- Calculates NPP in g/m2 [*above & below ground*].
    - NDVI + vegetation map → FPAR (0.4-0.7mm)
    - FPAR + solar surf. Irradiance → IPAR
    - IPAR + light use efficiency → NPP rates (g m^{-2})
    - Climate drivers (Temperature, Precipitation, etc..)

Average Annual NPP on Land
(1982-1998)



NPP Global "Demand"

Per capita Consumption

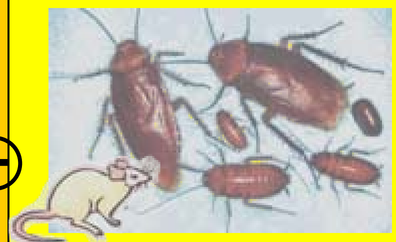
- Shows population pressure 'laterally' on NPP
  - NPP consumed *in situ* not produced *in situ*.
  - Indicates vulnerability (reliance on transport)
- Product Specific
  - Vegetal Foods, Livestock-based Products, Wood, Paper, and Fiber.
- Bio-agronomic modules
  - Back-calculate the NPP required in *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 | **Literature Sources** | **NPP Required**

Food Product (dry OM)

+



Transport, Storage, and Processing Losses

+

Residue Above and Below Ground

=

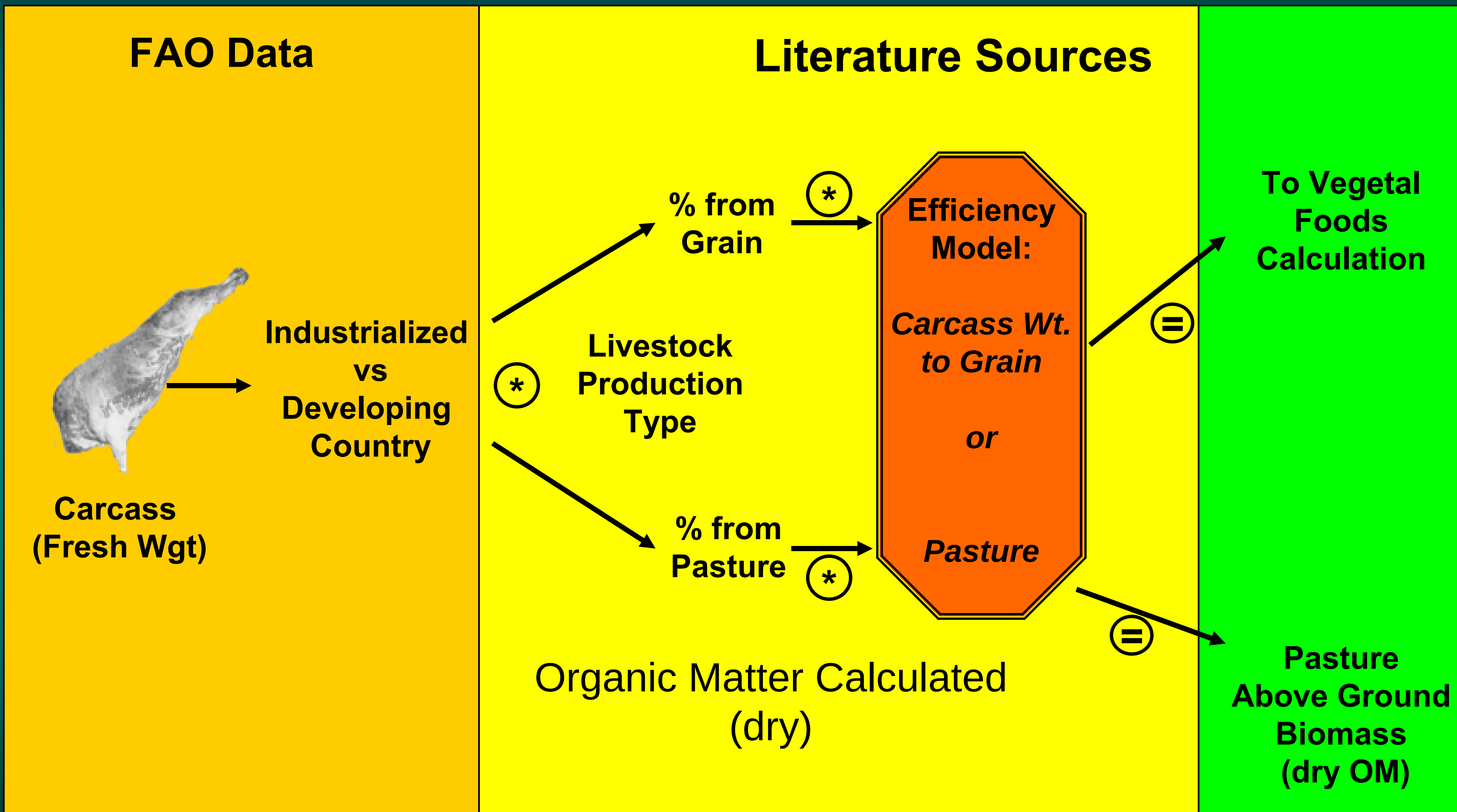
Total biomass Crop (dry OM)

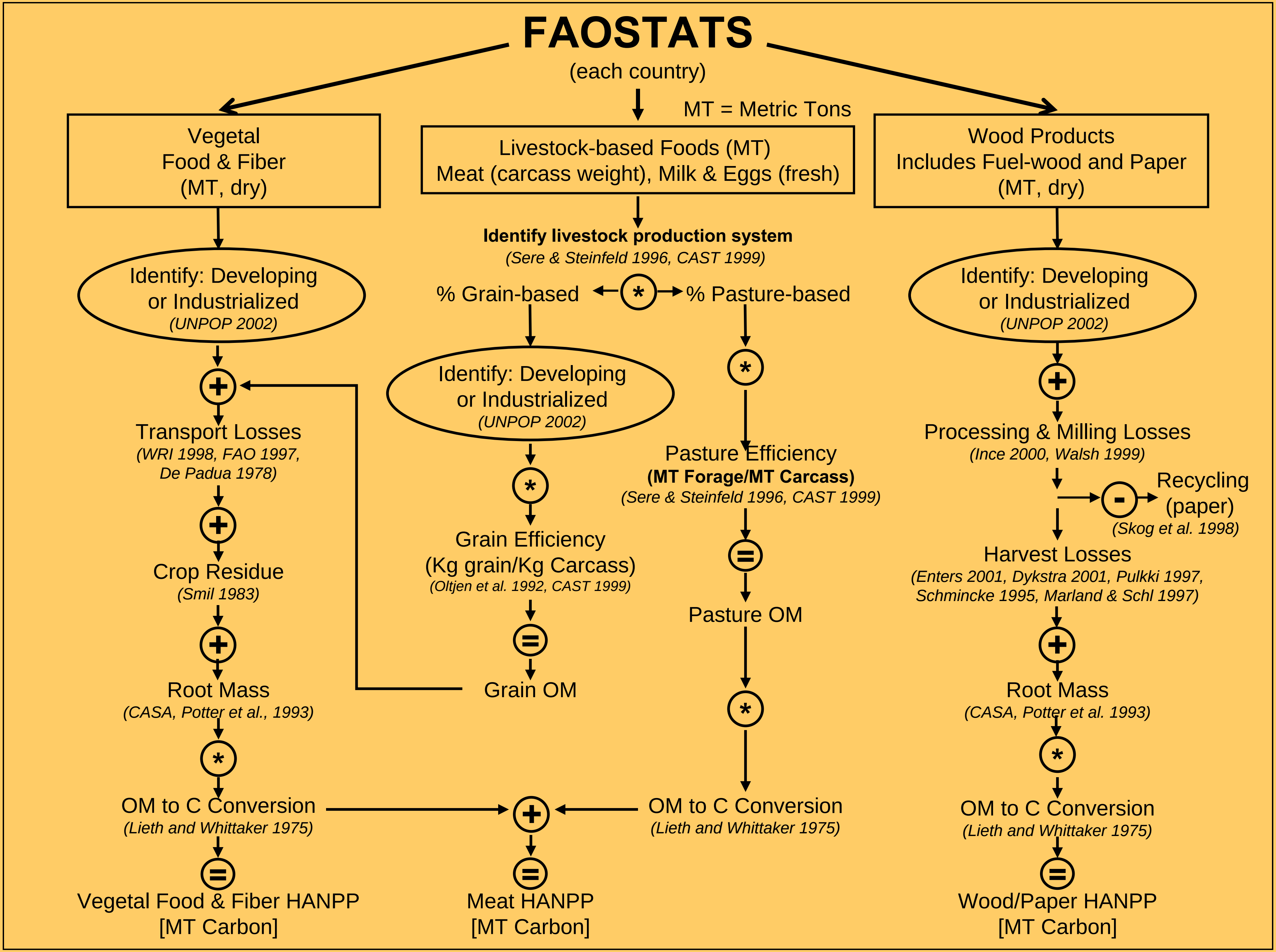
Industrialized vs Developing Countries

Adding biomass from 'grain' to whole plant

NPP Required for Meat Products

[Eggs and Milk Follow Similar Pathway]

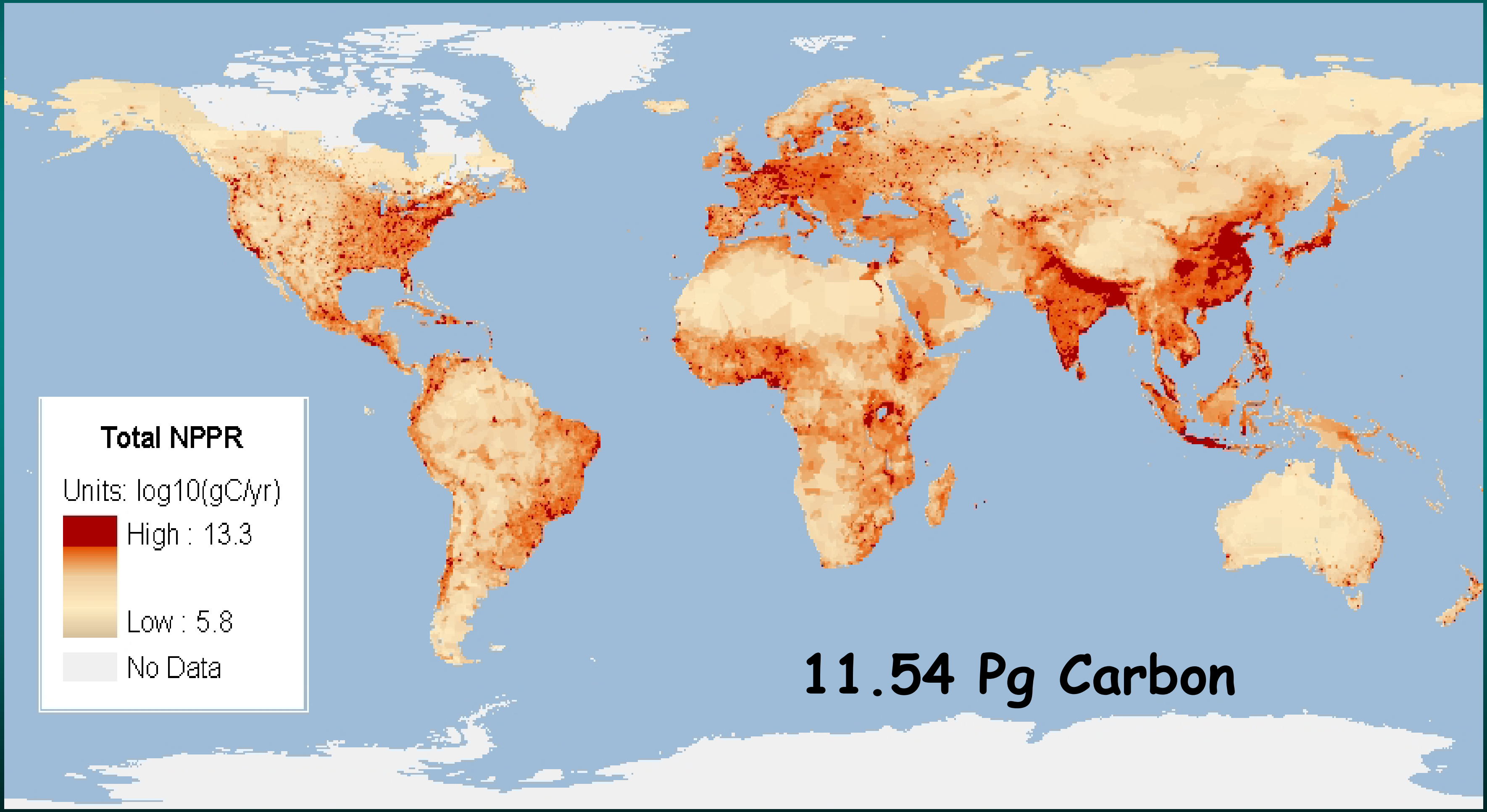




FAOSTATS
(each country)
MT = Metric Tons
Vegetal Food & Fiber (MT, dry)
Livestock-based Foods (MT) Meat (carcass weight), Milk & Eggs (fresh)
Wood Products Includes Fuel-wood and Paper (MT, dry)
Identify livestock production system
(Sere & Steinfeld 1996, CAST 1999)
% Grain-based
% Pasture-based
Identify: Developing or Industrialized
(UNPOP 2002)
Identify: Developing or Industrialized
(UNPOP 2002)
Identify: Developing or Industrialized
(UNPOP 2002)
Transport Losses
(WRI 1998, FAO 1997, De Padua 1978)
Processing & Milling Losses
(Ince 2000, Walsh 1999)
Pasture Efficiency
(MT Forage/MT Carcass)
(Sere & Steinfeld 1996, CAST 1999)
Recycling (paper)
(Skog et al. 1998)
Grain Efficiency
(Kg grain/Kg Carcass)
(Oltjen et al. 1992, CAST 1999)
Crop Residue
(Smil 1983)
Harvest Losses
(Enters 2001, Dykstra 2001, Pulkki 1997, Schmincke 1995, Marland & Schl 1997)
Pasture OM
Grain OM
Root Mass
(CASA, Potter et al., 1993)
Root Mass
(CASA, Potter et al. 1993)
OM to C Conversion
(Lieth and Whittaker 1975)
OM to C Conversion
(Lieth and Whittaker 1975)
OM to C Conversion
(Lieth and Whittaker 1975)
Vegetal Food & Fiber HANPP [MT Carbon]
Meat HANPP [MT Carbon]
Wood/Paper HANPP [MT Carbon]

Annual Human NPP Carbon Demand

Terrestrial NPP Required for Food and Fiber (1995)



Annual NPP Carbon Demand

Human Population 1995 (5.69 Billion people)

Consumed Products (Pg Carbon)	Low Estimate	Intermediate Estimate	High Estimate
Vegetal Food	0.89	1.73	2.95
Meat	1.69	1.92	2.21
Milk	0.15	0.27	0.43
Eggs	0.09	0.17	0.26
Food (subtotal)	2.83	4.09	5.85
Paper	0.20	0.28	0.38
Fiber	0.32	0.37	0.42
Wood Products (including fuel)	4.64	6.81	8.15
Commodities (subtotal)	5.17	7.45	8.95
Total ŅDemandÓ	8.00	11.54	14.81
Demand as % of Supply (56.8 Pg)	14%	20%	26%

NPP Supply and Demand

Methods:

Calculate NPP "supply" Map using satellite data.

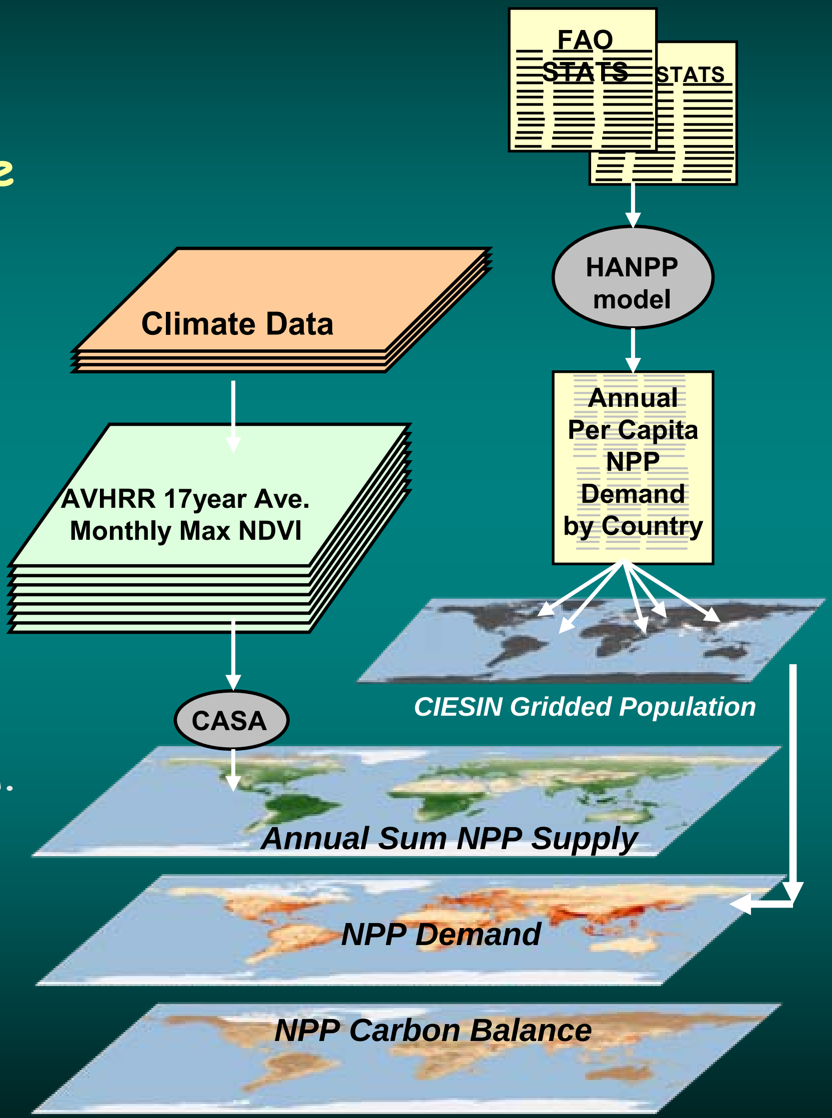
Develop Human Appropriation NPP (HANPP) consumption-based Model

- *NPP required* "in the field" for food and fiber products United Nations Food and Agriculture Organization database (UNFAO-STATS).
-Vegetal Foods, Livestock-based Products, Wood, Paper, and Fiber.

Make NPP "Demand" Map

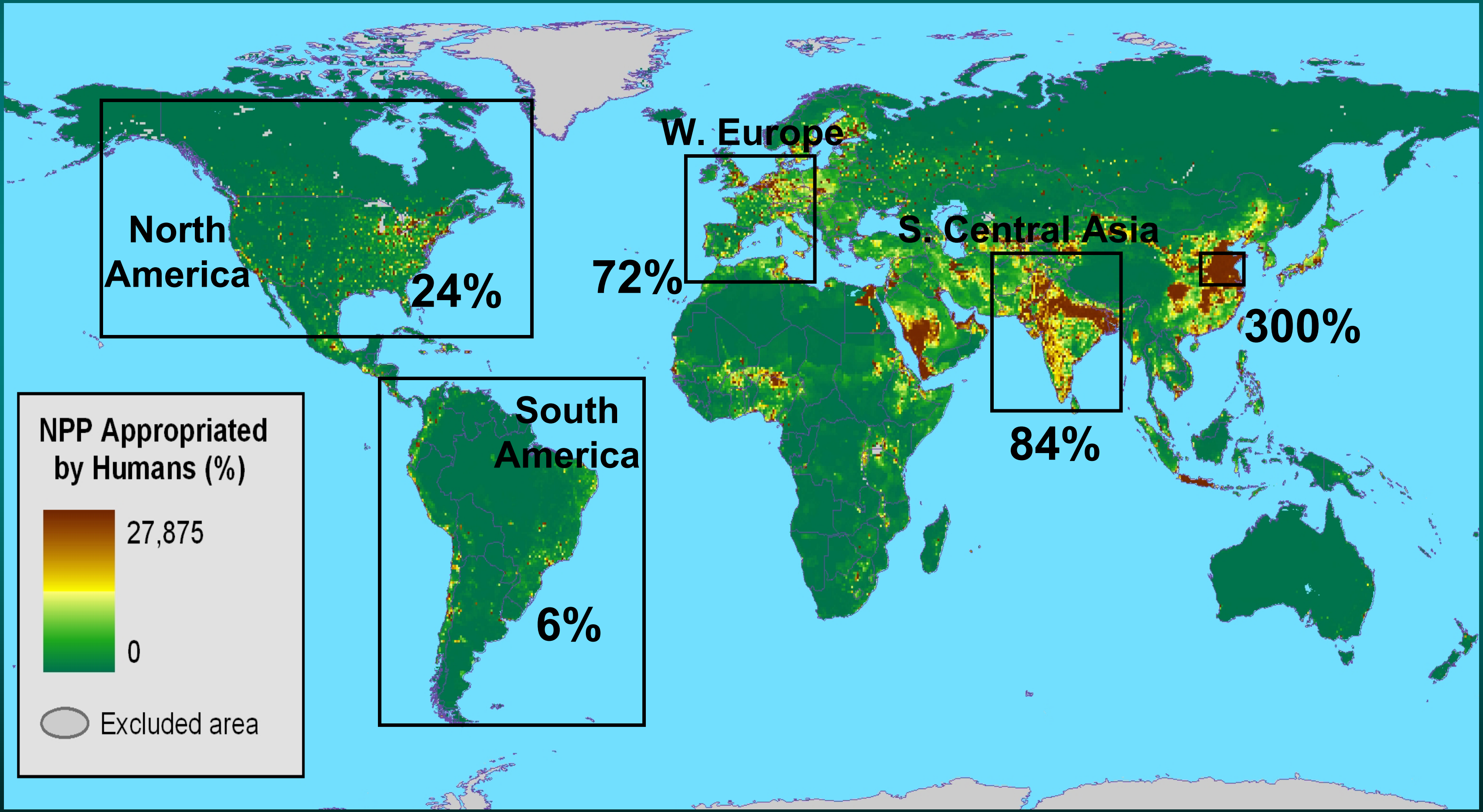
Apply HANPP of countries to population map from CIESIN using *per Capita* NPP consumption.

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



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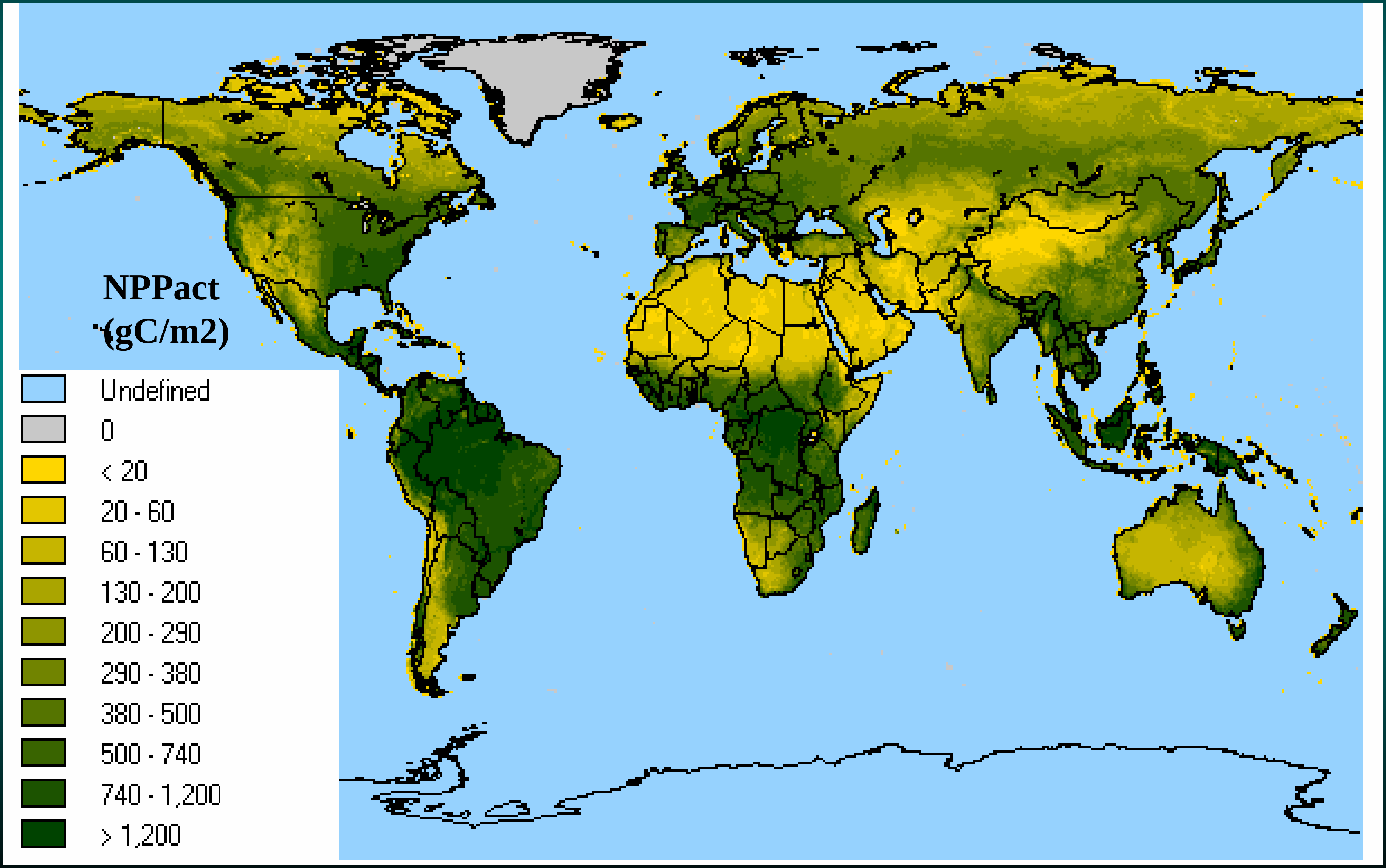
Regional NPP Carbon Supply versus Demand

(Intermediate Estimate of Demand)

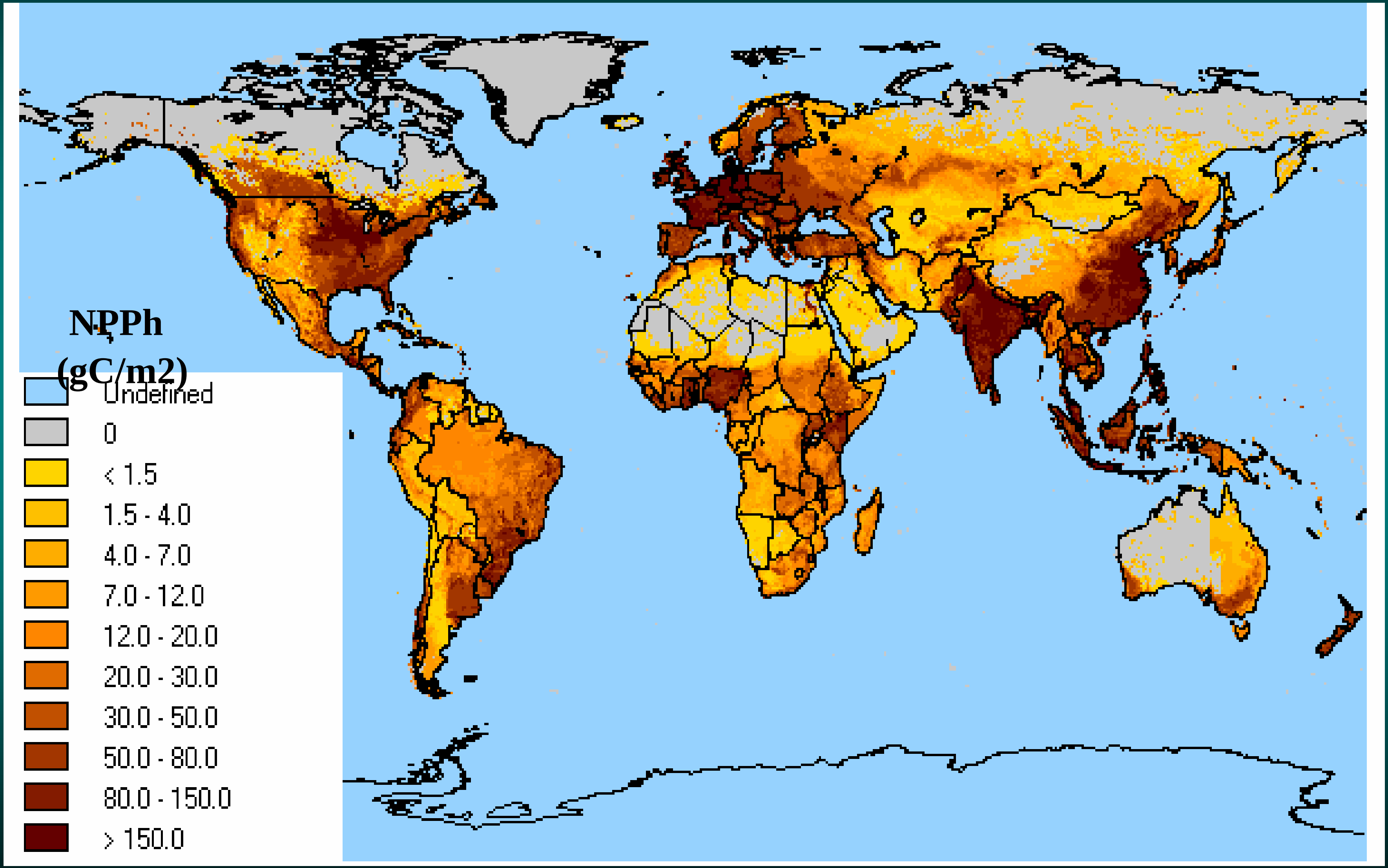
Region	Population (millions)	Per Capita NPP Demand (MT C)	Regional NPP Supply (Pg C)	Regional NPP Demand (Pg C)	Demand % Supply
Africa	742	2.08	12.50	1.55	12%
East Asia	1400	1.37	3.02	1.91	63%
South-Central Asia	1360	1.21	2.04	1.64	80%
Western Europe	181	2.86	0.72	0.52	72%
North America	293	5.40	6.67	1.58	24%
South America	316	3.11	16.10	0.98	6%

Terrestrial NPP 'Supply' in 1997

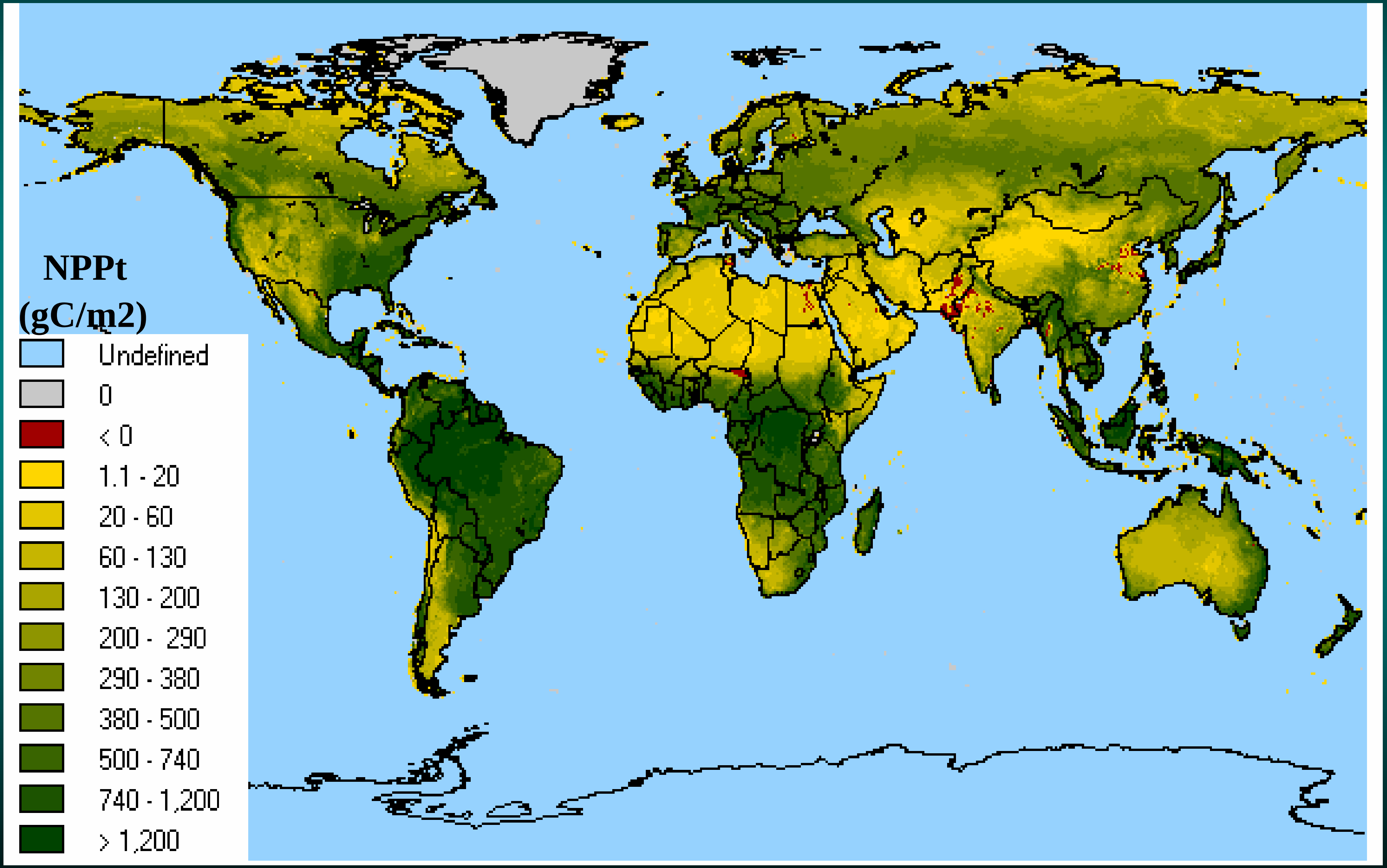
AVHRR/CASA



NPP Harvested by Humans in 1997



NPP Remaining After Human Harvest



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).

Scenario	P*	A**	T***	HANPP (PgC)	
1	↑	–	–	17.42	31%
2	–	↑	–	20.19	36%
3	–	↑	↑	16.26	29%
4	↑	↑	–	31.59	56%
5	↑	↑	↑	25.5	45%

↑(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.

Conclusions

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

- **"Exploring global patterns of net primary production carbon supply and demand using satellite observations and statistical data".** Imhoff, M. L., and L. Bounoua (2006), *J. Geophys. Res*., 111, D22S12, doi:10.1029/2006JD007377.
- **"Global patterns in human appropriation of net primary production",** Imhoff, M. L., L. Bounoua, T. Ricketts, C. Loucks, R. Harriss, W. Lawrence. 2004. *Nature*, vol. 429, June 24, 2004.
- "**The consequences of urban land transformation for net primary productivity in the United States",** Marc L. Imhoff , Lahouari Bounoua, Ruth DeFries, William T. Lawrence, David Stutzer, Compton J. Tucker, and Taylor Ricketts (2004).. *Remote Sensing of Environment, Vol. 89, Issue 4, pp. 434-443*.
- **"Assessing the impact of land conversion to urban use on soils with different productivity levels in the USA",** Nizeyimana EL, Petersen GW, Imhoff ML, Sinclair HR, Waltman SW, Reed-Margetan DS, Levine ER, Russo JM, Soil Science Society Of America Journal, 65: (2) 391-402 MAR-APR 2001.
- **"The Use of Multi-source Satellite and Geospatial Data to Study the Effect of Urbanization on Primary Productivity in the United States",** M. L. Imhoff, C. J. Tucker, W. T. Lawrence, D. Stutzer, and Robert Rusin, *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 38, No. 6, November 2000.
- **"A technique for using composite DMSP/OLS "city lights" satellite data to accurately map urban areas,"** Marc L. Imhoff et al., *Remote Sensing of Environment Journal* , Vol. 61:361-370 (1997).
- **"Using nighttime DMSP/OLS images of city lights to estimate the impact of urban land use on soil resources in the U.S."** Marc L. Imhoff, et al. *Remote Sensing of Environment Journal* , Vol. 59:105-117 (1997).