City Lights, Spy Satellites, and Urban Sprawl

Marc Lee Imhoff NASA's Goddard Space Flight Center

Smithsonian, October 20, 2004

The Anthropocene

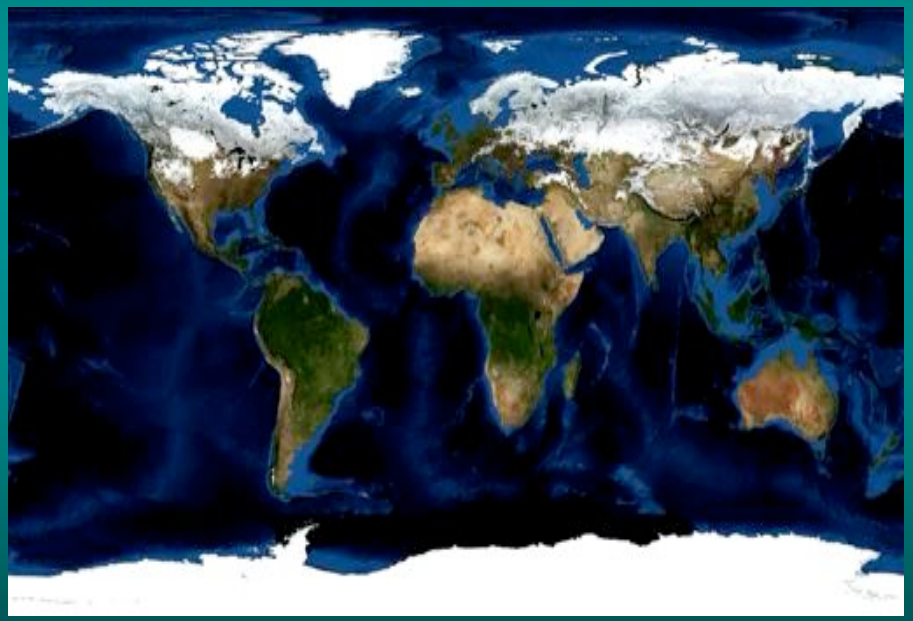
*"humans have become a geologic agent comparable to erosion and eruptions… it seems appropriate to emphasize the central role of mankind in geology and ecology by proposing to use the term '**anthropocene**' for the current geological epoch."*

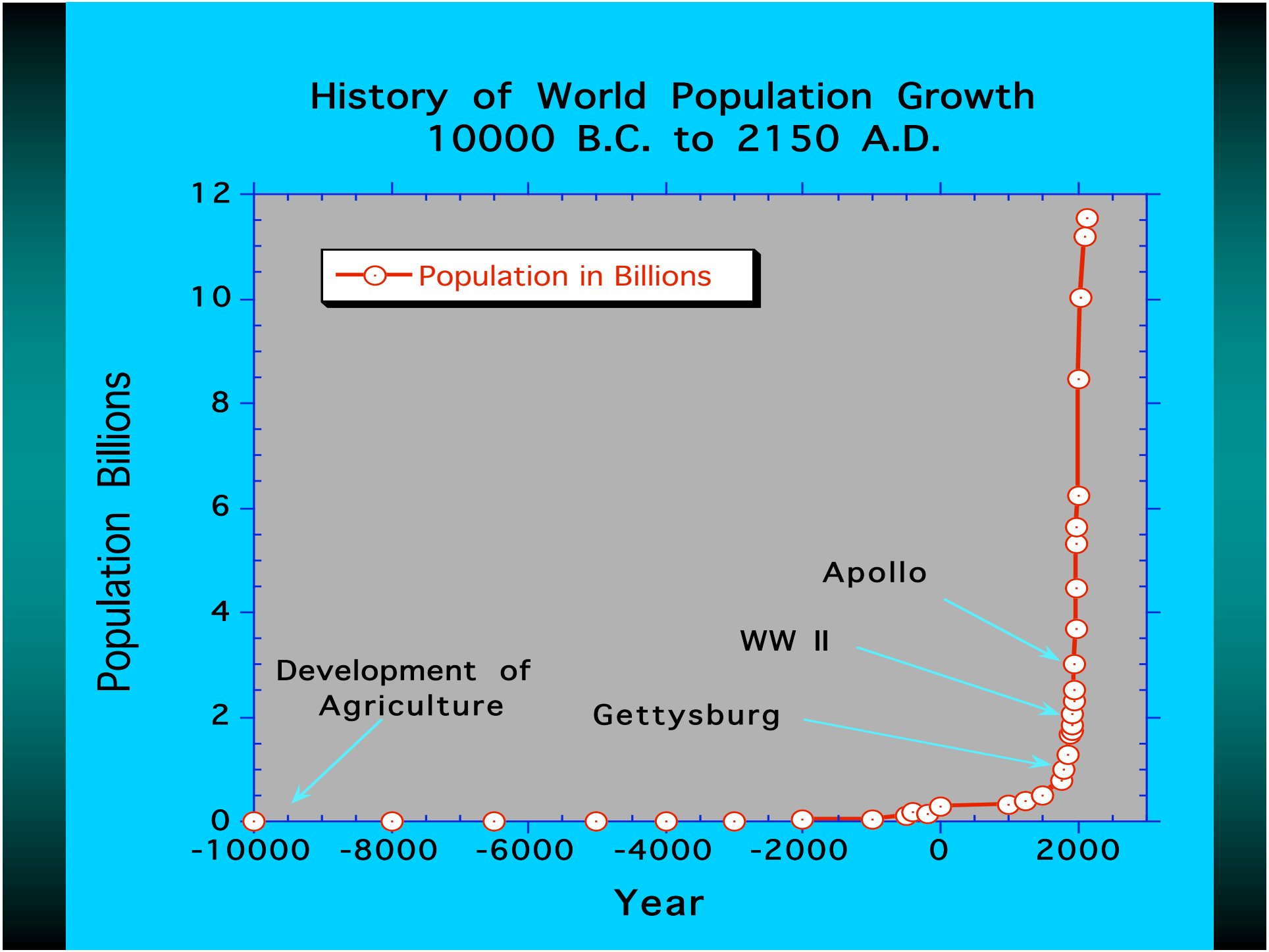
Paul J. Crutzen

Human Transformation of the Land Surface

The current land surface little resembles what existed 100,000 years or even 3,000 years ago

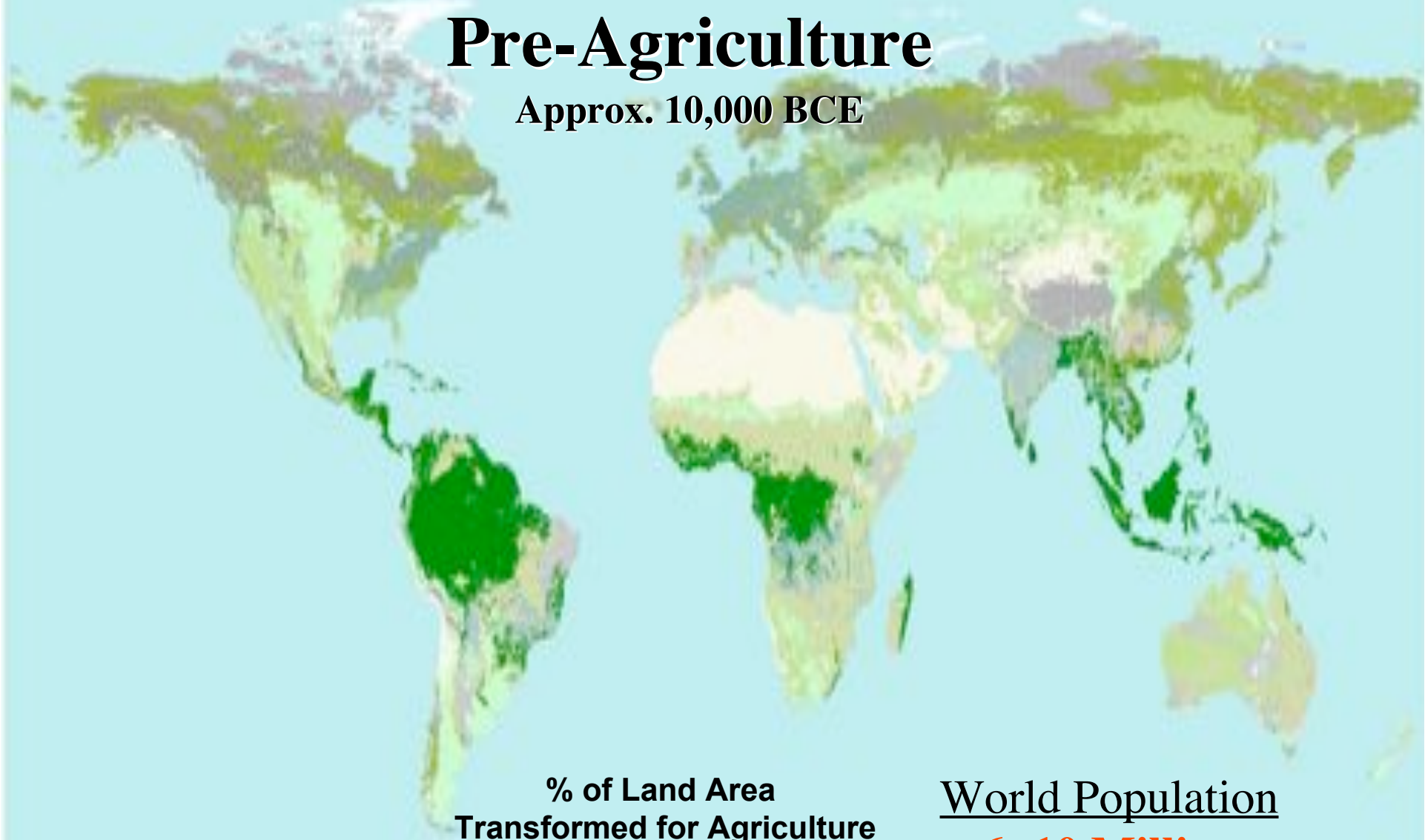
- Fire for ecosystem management
- Grazing
- Deforestation for metal smelting
- Agriculture
- Urbanization/infrastructure




History of World Population Growth
10000 B.C. to 2150 A.D.
Population in Billions
Population Billions
12
10
8
6
4
2
0
-10000
-8000
-6000
-4000
-2000
0
2000
Year
Development of Agriculture
Gettysburg
WW II
Apollo

Global Land Cover
Pre-Agriculture

Approx. 10,000 BCE

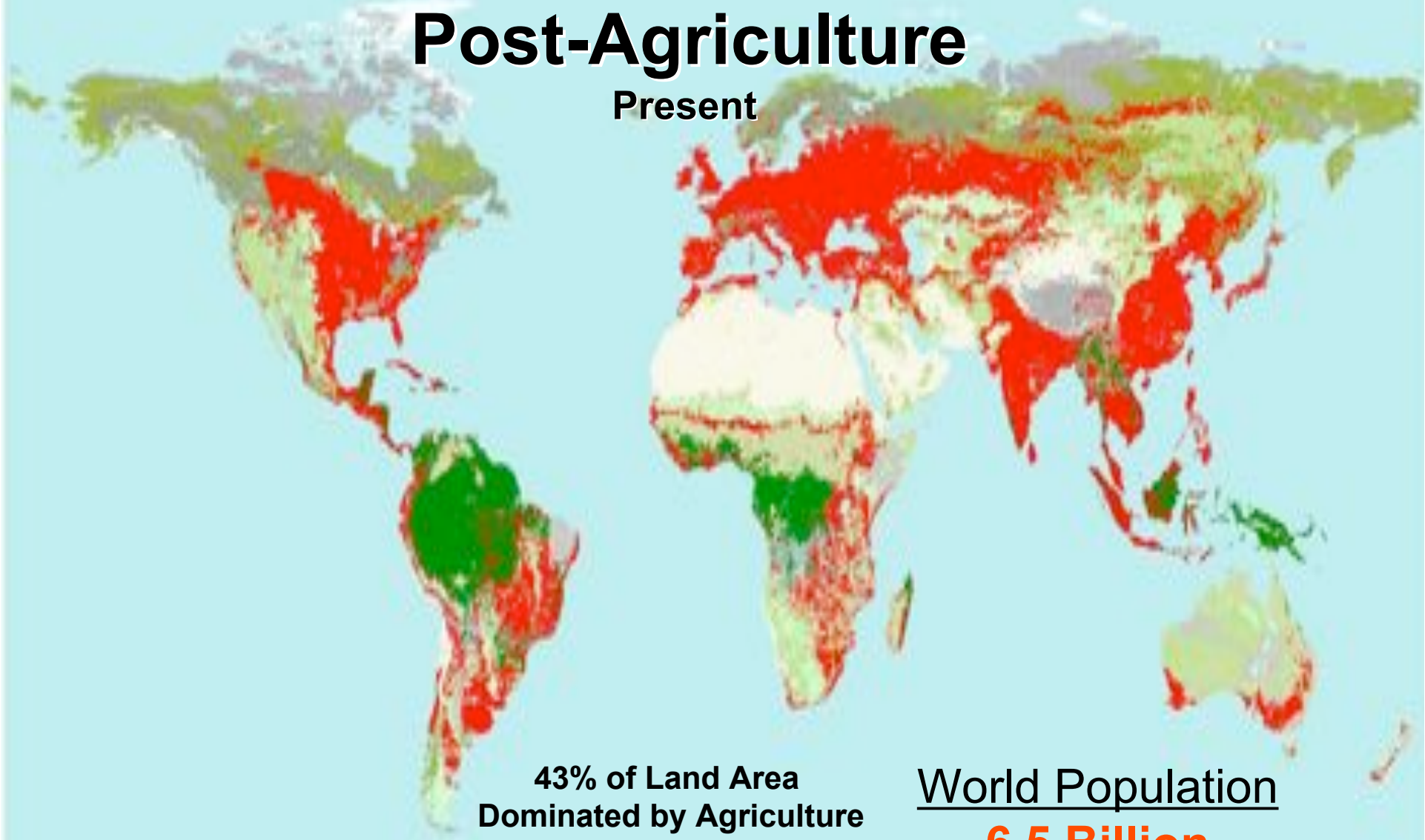


% of Land Area
Transformed for Agriculture
(Negligible)

World Population
6 -10 Million

Global Land Cover
Post-Agriculture

Present

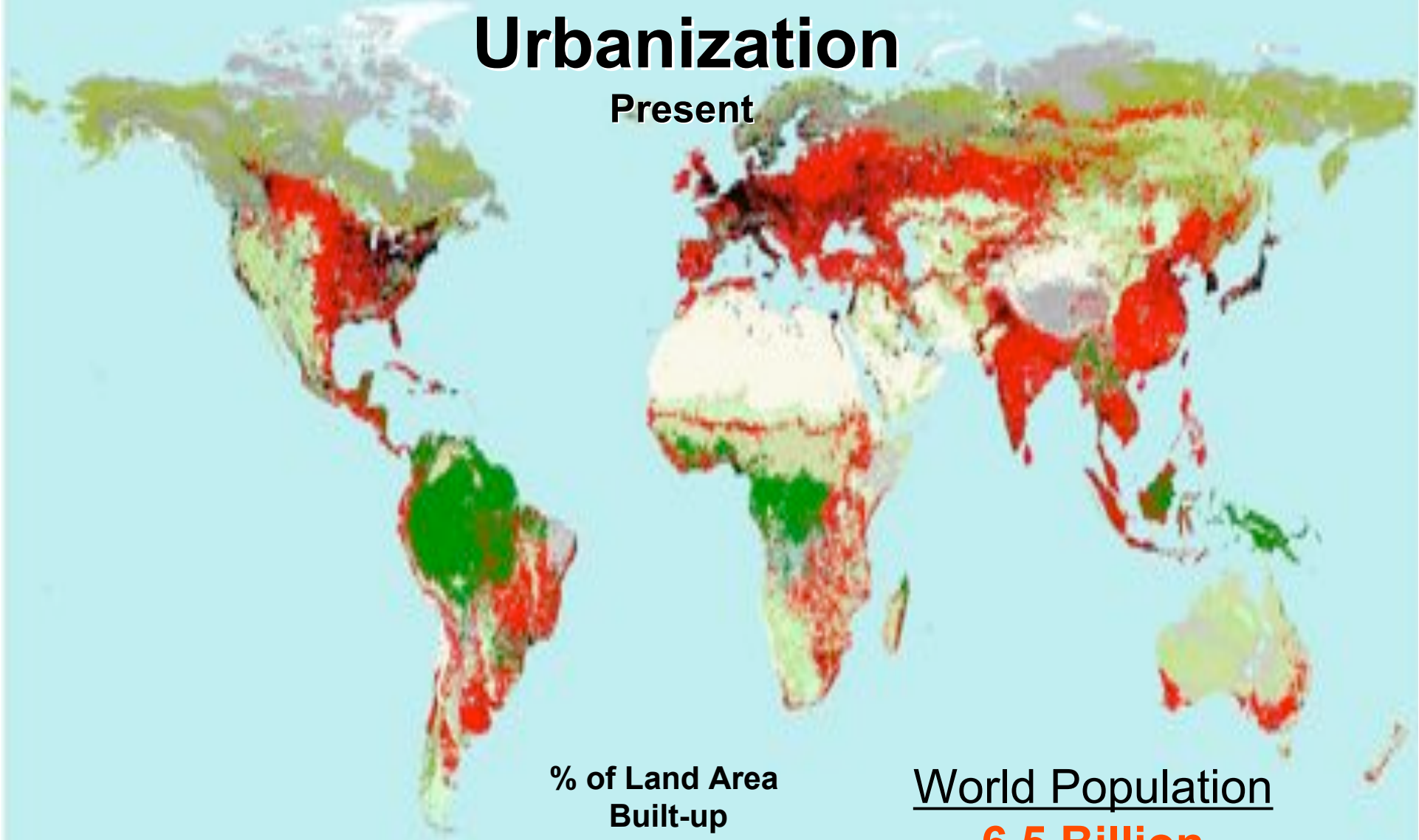


43% of Land Area
Dominated by Agriculture

World Population
6.5 Billion

Global Land Cover Urbanization

Present



% of Land Area Built-up
3 - 6%

World Population
6.5 Billion

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

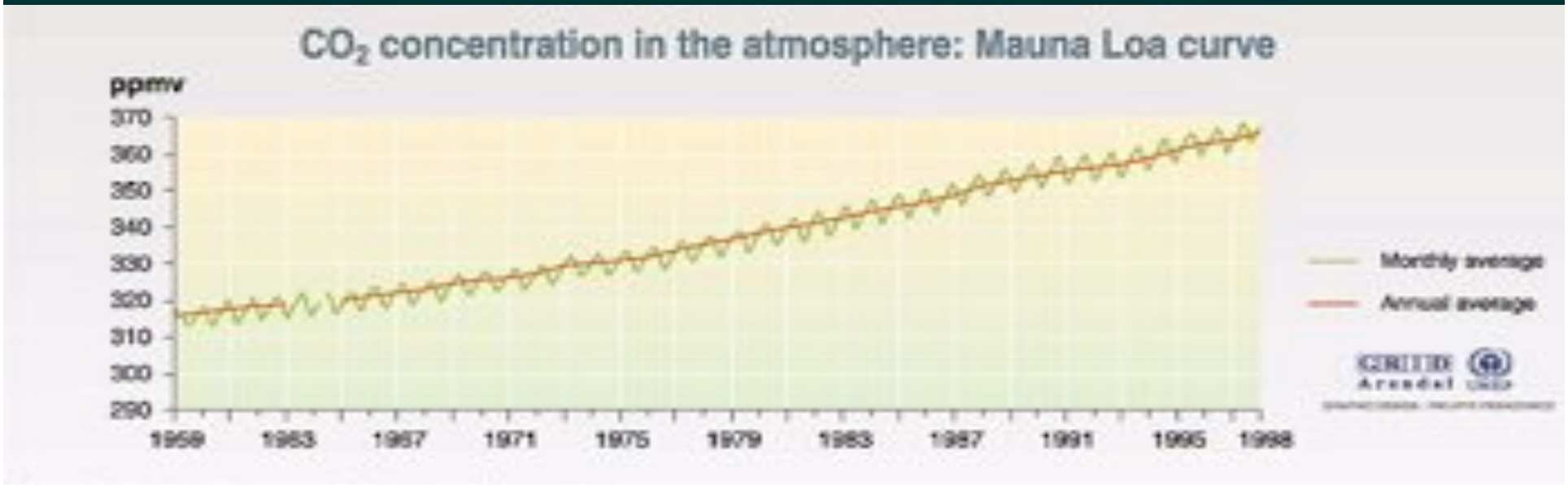
(photosynthesis - CO_2 exchange between atmosphere and biosphere (global climate change).

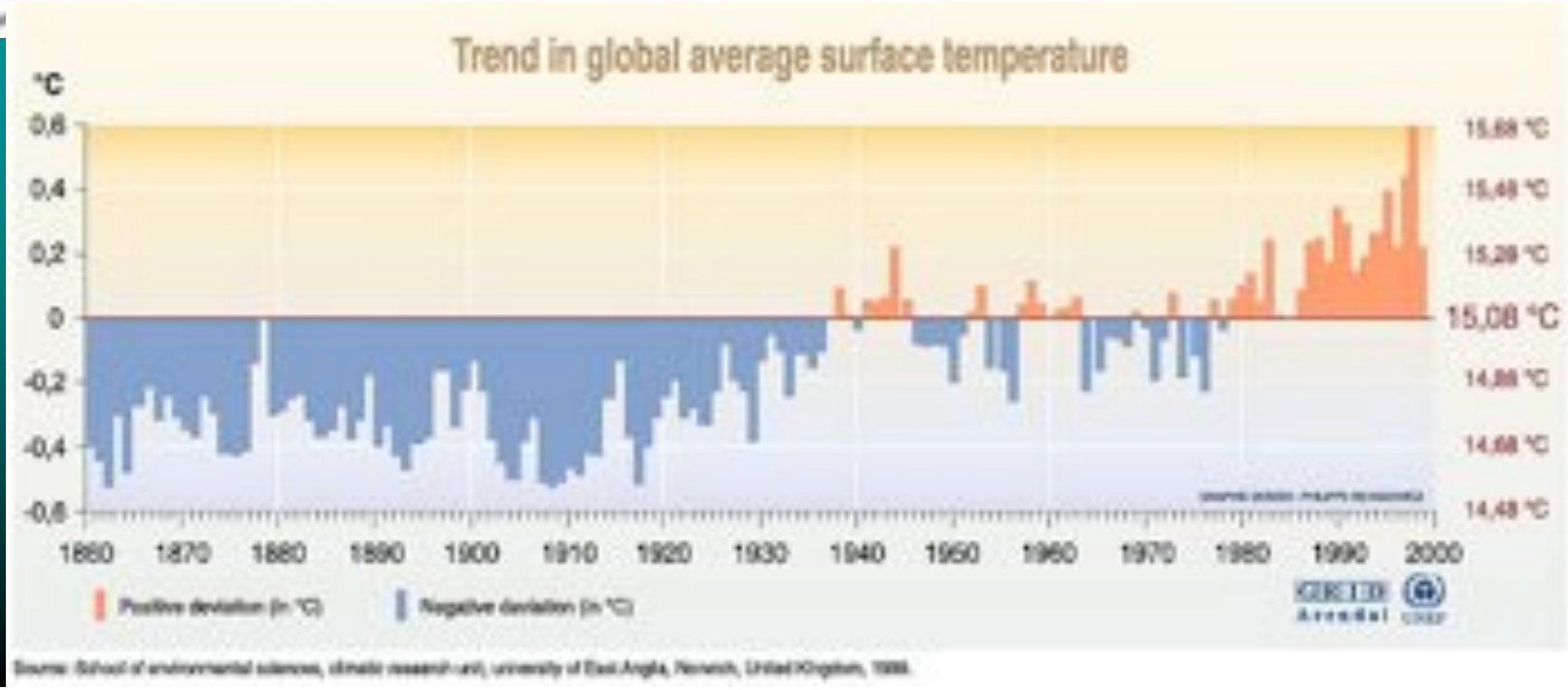
Land use strongly impacts NPP

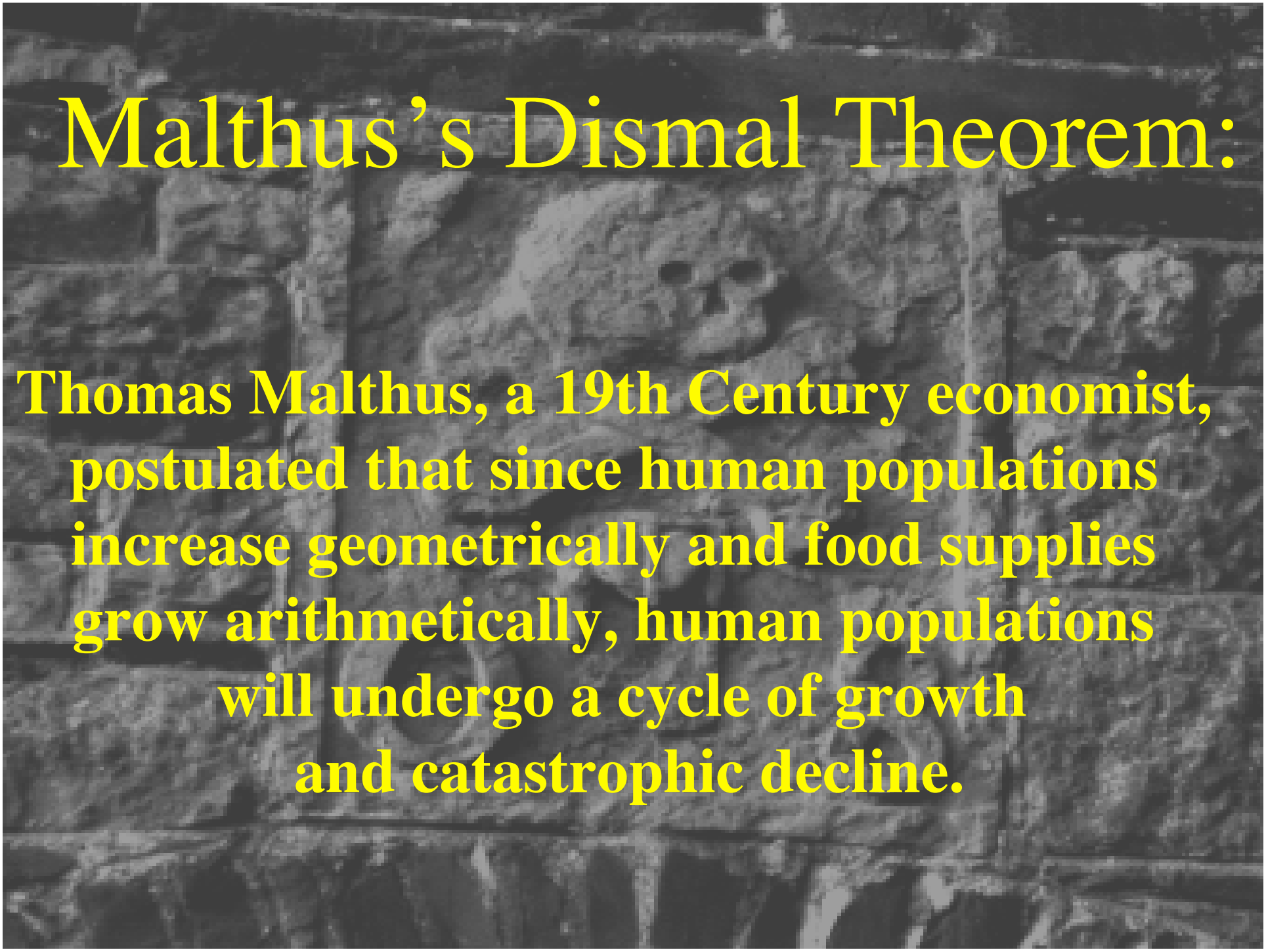
Humans require almost 20% of Earth's NPP capacity on land

NPP is the "Common Currency" for Climate Change, Ecological, & Economic Assessment.

The Link Between Vegetation and Climate







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."

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

The question, posed as the title of the symposium, was this: "Is the Human Species a Cancer on the Planet?"

Dr. Hern, the director of an abortion clinic in Boulder, Colo., noticed nearly a decade ago that aerial and satellite views of urban centers taken over a period of years bore a striking similarity to images of cancerous tissue (particularly melanoma) invading the healthy surrounding tissue.

In his presentation last week, Dr. Hern argued that in many parts of the world the increase in human numbers is rapid and uncontrolled, that it invades and destroys habitats, and that by killing off many species it reduces the differentiation of nature. All of these features are characteristic of cancerous tumors, he said.

This assessment was applauded by another member of the panel, Dr. Lynn Margulis of the University of Massachusetts, Boston, who is known for her coauthorship of another highly controversial theory known as the "Gaia Hypothesis."

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 the German philosopher Friedrich Nietzsche: "The Earth is a beautiful place, but it has a pox called man."

A different but complementary perspective was offered by Dr. Compton J. Tucker, a physical scientist at the National Aeronautics and Space Administration's Goddard Space Center. Dr. Tucker is an analyst of images of the Earth made by Landsat and other orbiting spacecraft. In particular, he keeps track of deforestation and other anthropogenic changes in the global habitat.

"In many regions, we've seen astonishingly rapid change since 1975," he said. "Vast tracts of both rain forest and dry tropical forest have disappeared in the Amazon Basin as human communities expand and clear the land for cattle ranching. This has led to a monoculture dominated by cattle breeding, with losses of immense numbers of the species deprived of forest habitat."

Several speakers cited United Nations statistics indicating that population growth rates in underdeveloped countries averaged only 1.77 percent a year between 1990 and 1995. The expectation for that period had been for a growth rate of 1.88 percent. This suggests that the increase in the population growth rate in underdeveloped countries declined somewhat during that five-year period.

The Rev. Thomas Robert Malthus said that population growth would lead to poverty and misery.

But since 1930, when the world population was about 2 billion, the population has nearly tripled, and each doubling has occurred in a much shorter time period than the previous doubling period. The United Nations report projected that the world population could reach 9.4 billion by the year 2050.

Demographers say that the population increase has leveled off in China (where the government limits family size) and that the rate of population increase has declined in Bangladesh and some other populous countries.

But recent United Nations statistics identified 28 countries (20 of them in Africa) where fertility rates increased during the past decade. Among these countries was the United States, which has the third largest population after China and India, and where the fertility rate increased 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 despite some errors in detail," said

REMEMBER THE NEEDIEST!

Time Magazine – Special Millennium Issue, November 8, 1999

So What do we do with Malthus?

1st - Don't Panic 

Avoid the extremes -Doomsday and Denial are poor choices

2nd - Use our best tools - address the issue.

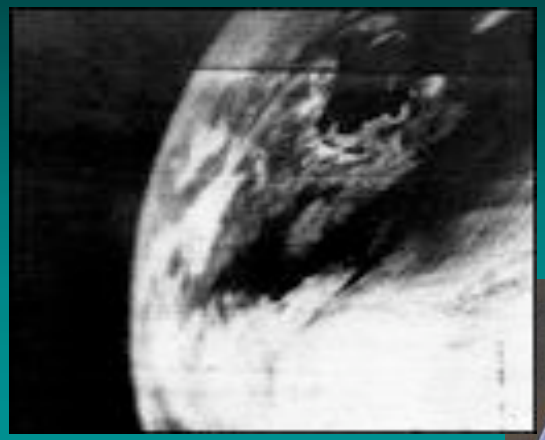
Past attempts failed because the system could not be "closed".

Treat Earth as a system.

Satellite technology enables this perspective for the 1st time in human history


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 -

Blue Marble 2002

- **True color satellite data visualization**
  - June-August 2001
  - MODIS (TERRA)
  - 1km (30") spatial resolution
  - Layers:
    - land
    - ocean
    - sea-ice
    - clouds
    - lights
    - topography

Credits:
Reto Stöckli, Rob Simmon and MODIS science team

Satellite Tools for Observing Land Cover Change and NPP

- Day time observations (daily, monthly composites)
  - Vegetation density
  - Climate (temperature, precipitation etc.)
- Nighttime observations "City Lights"

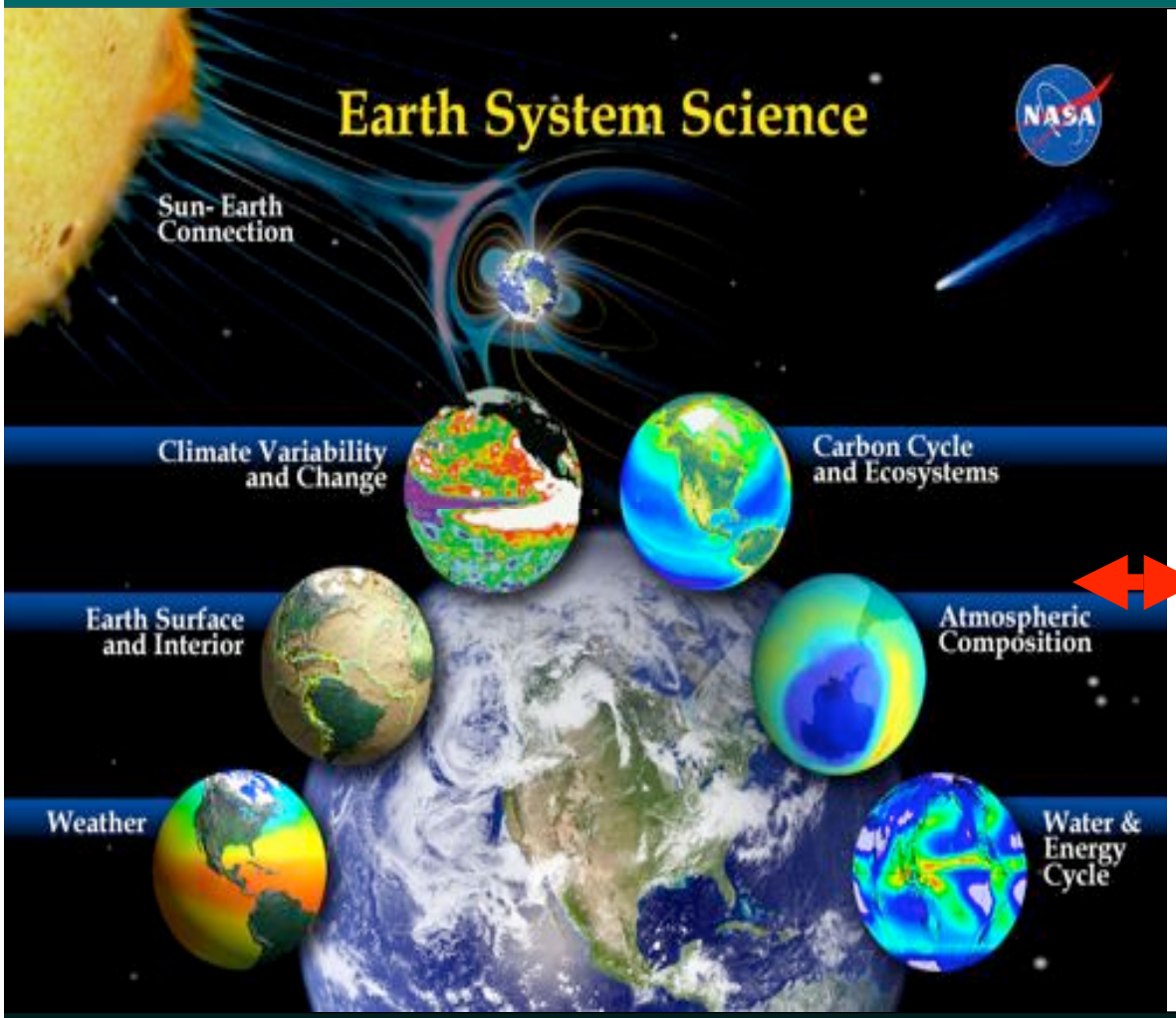
NPP "Supply"

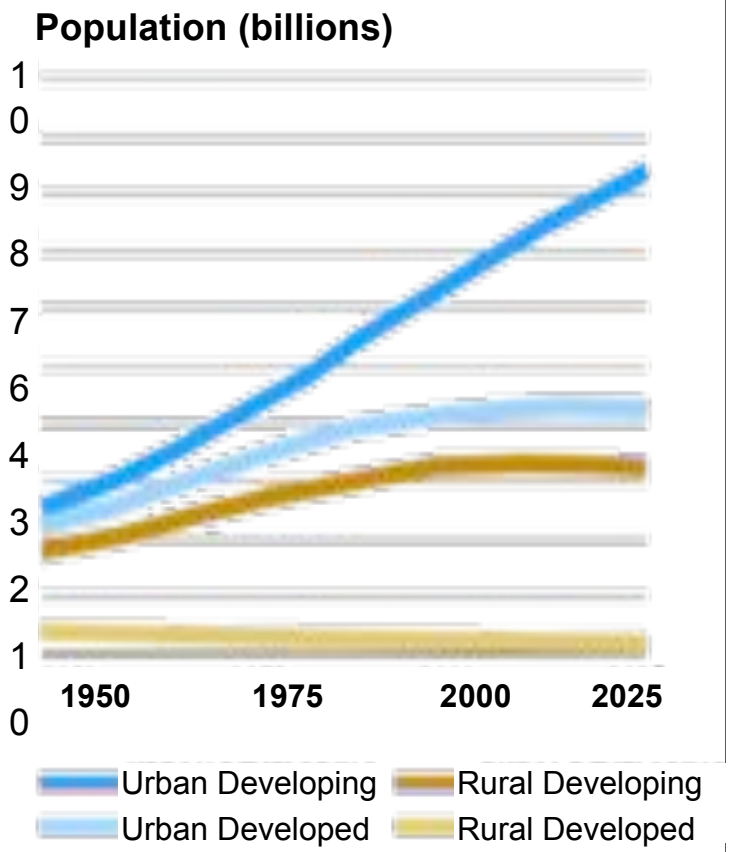
Earth's Current Terrestrial Production

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..)

How is the Urban Environment Affecting Earth's Weather, Climate, and Global Water Cycle?

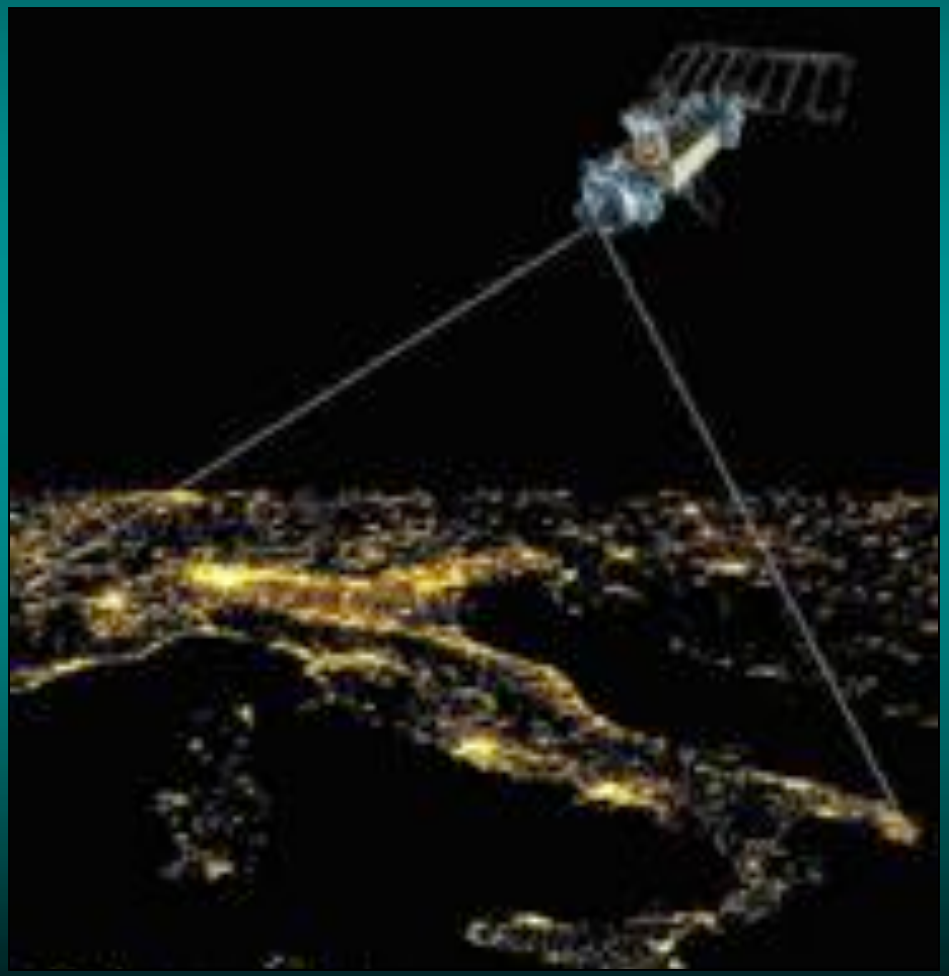




Source: United Nations Population Fund

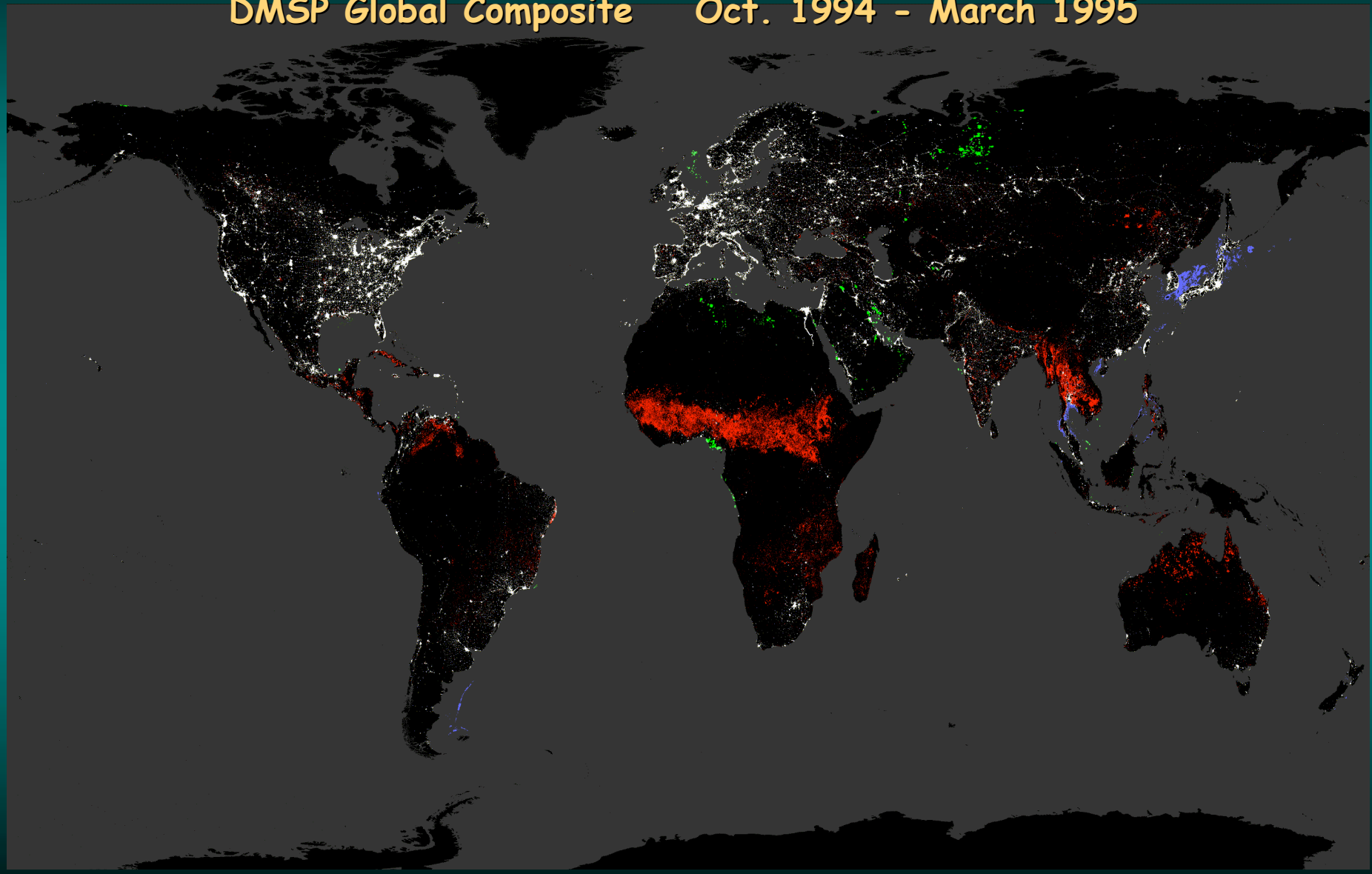
Defense Meteorological Satellite
Operational Linescan System (OLS)

- 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

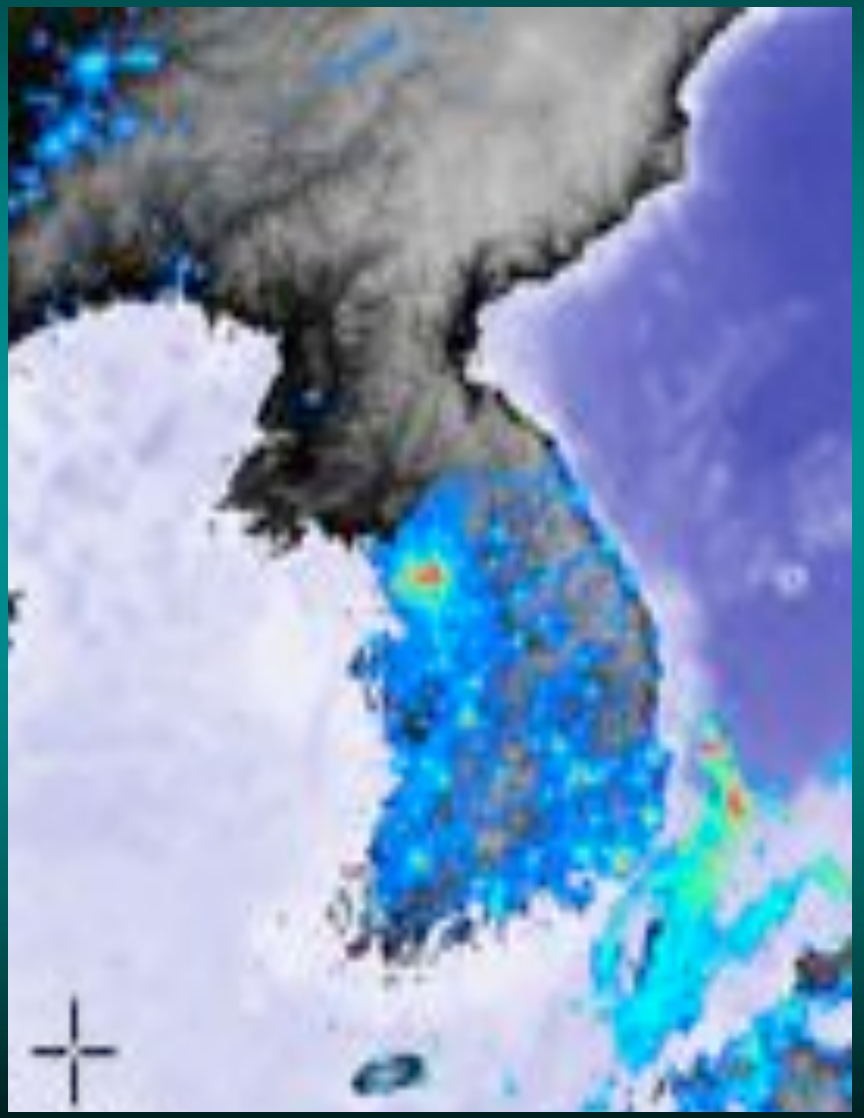
DMSP Global Composite Oct. 1994 - March 1995



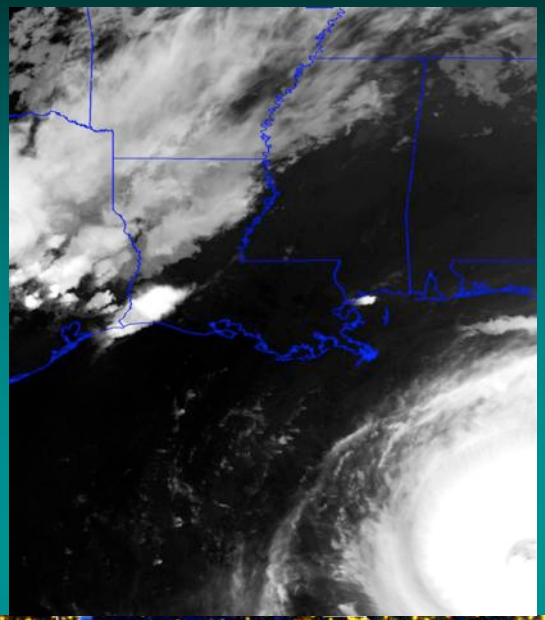
Korean Peninsula

Day - MODIS, April 6, 2000

Night - DMSP, Oct., 2000



DMSP Views Katrina



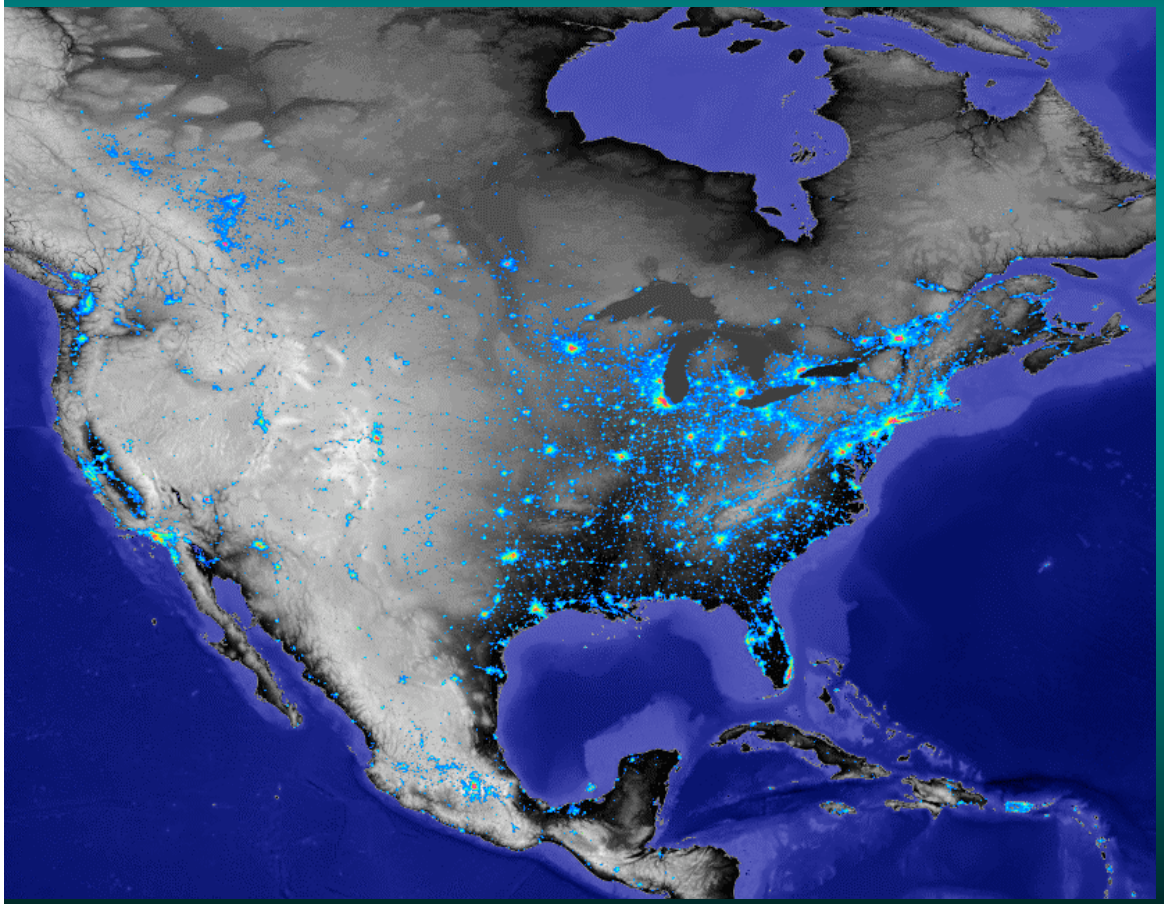
August 28, 2005

September 10, 2005

Before/After

Damaged area

Consequences of Urbanization on NPP-Carbon in the United States

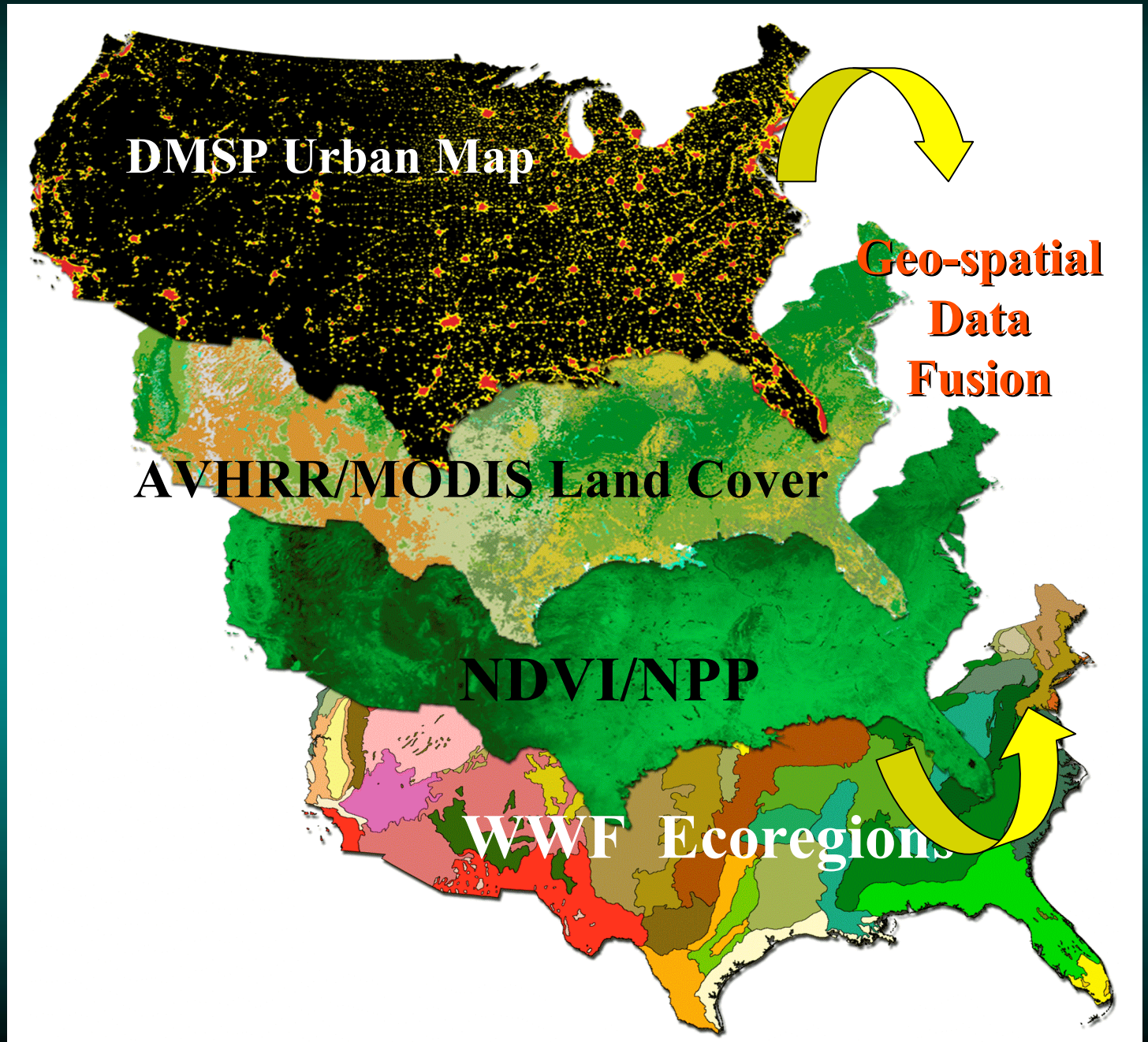


What is the overall impact in North America?

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

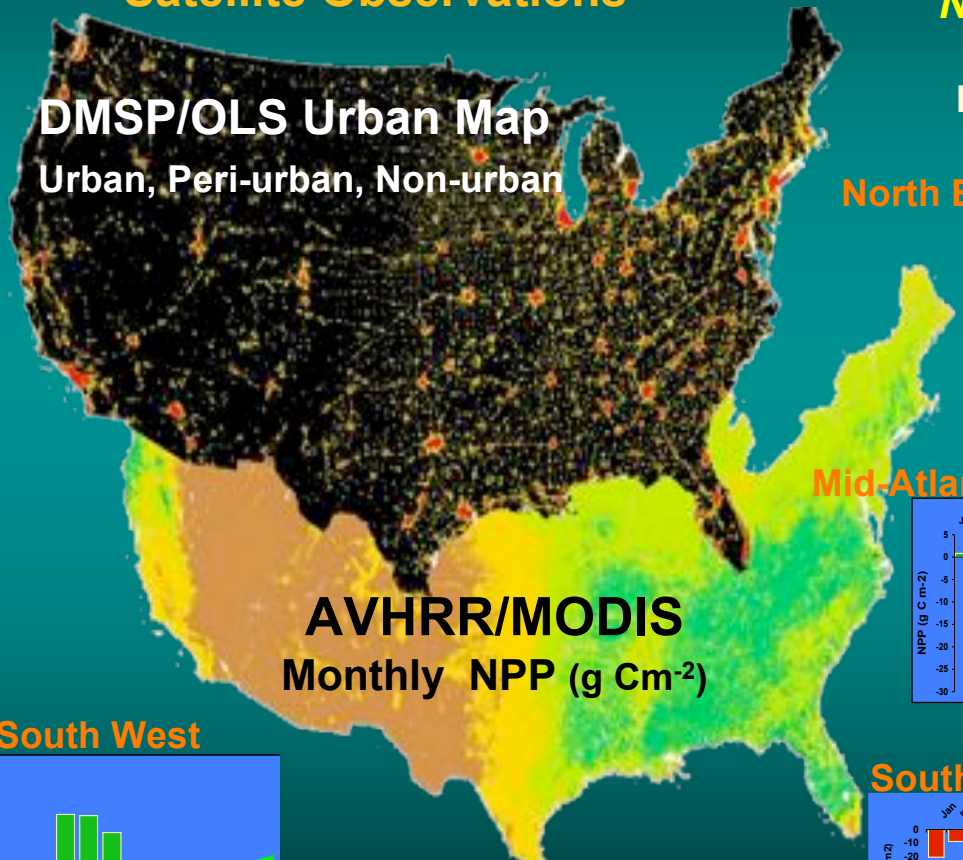
How does urbanization interact with climate locally?

- -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?


DMSP Urban Map
Geo-spatial
Data
Fusion
AVHRR/MODIS Land Cover
NDVI/NPP
WWF Ecoregions

Consequences of Urbanization on NPP

Satellite Observations



DMSP/OLS Urban Map

Urban, Peri-urban, Non-urban

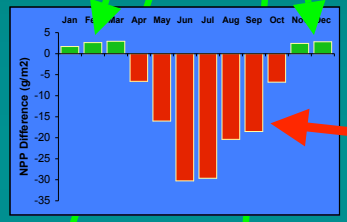
AVHRR/MODIS

Monthly NPP (g Cm^{-2})

NPP and Local Climate:

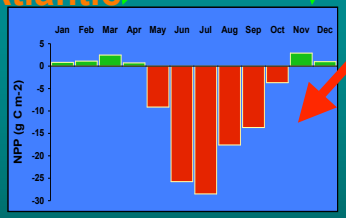
Urban Heating Extends Length of growing season locally in cold climates.

North East

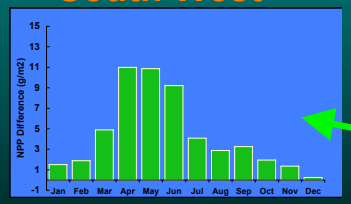


Winter NPP gain negated in peak season by reduced vegetation and heat stress.

Mid-Atlantic

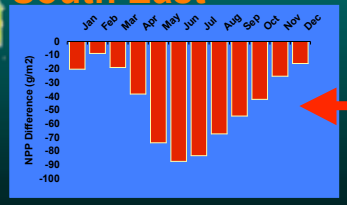


South West



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

South East



Seasonal Offset diminishes in tropics

Measuring Human Impacts on the Biodiversity and Carrying Capacity of Ecosystems [LCLUC99-0004-0016]

M. L. Imhoff, PI

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

Urbanization and NPP

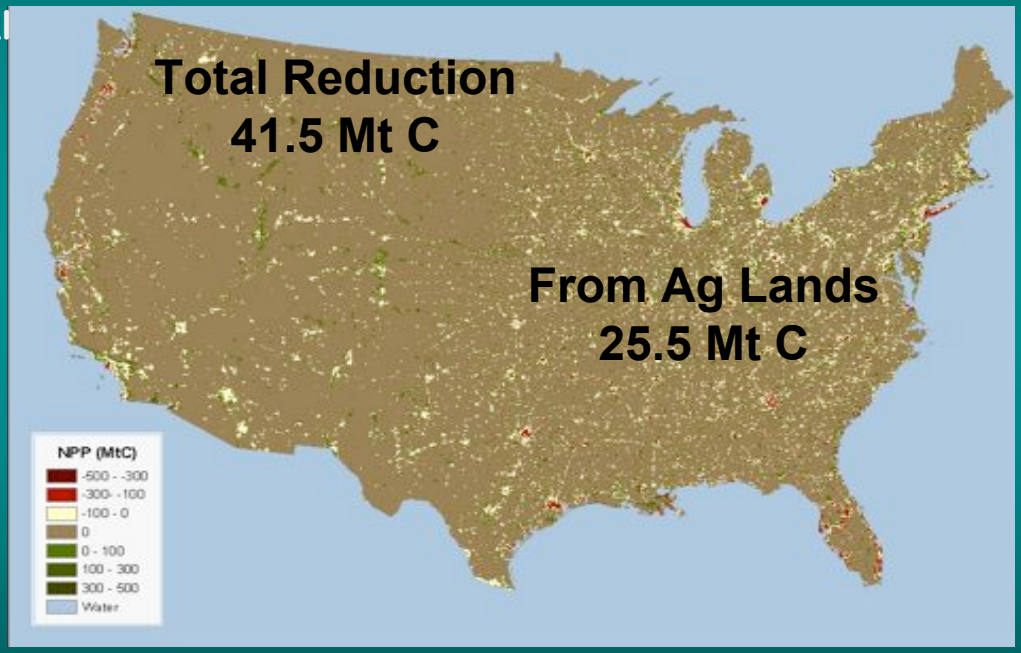
- NPP decreased 41.5 M tons C / year.
- Roughly equivalent to the increase created by 300 years of agricultural development.

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

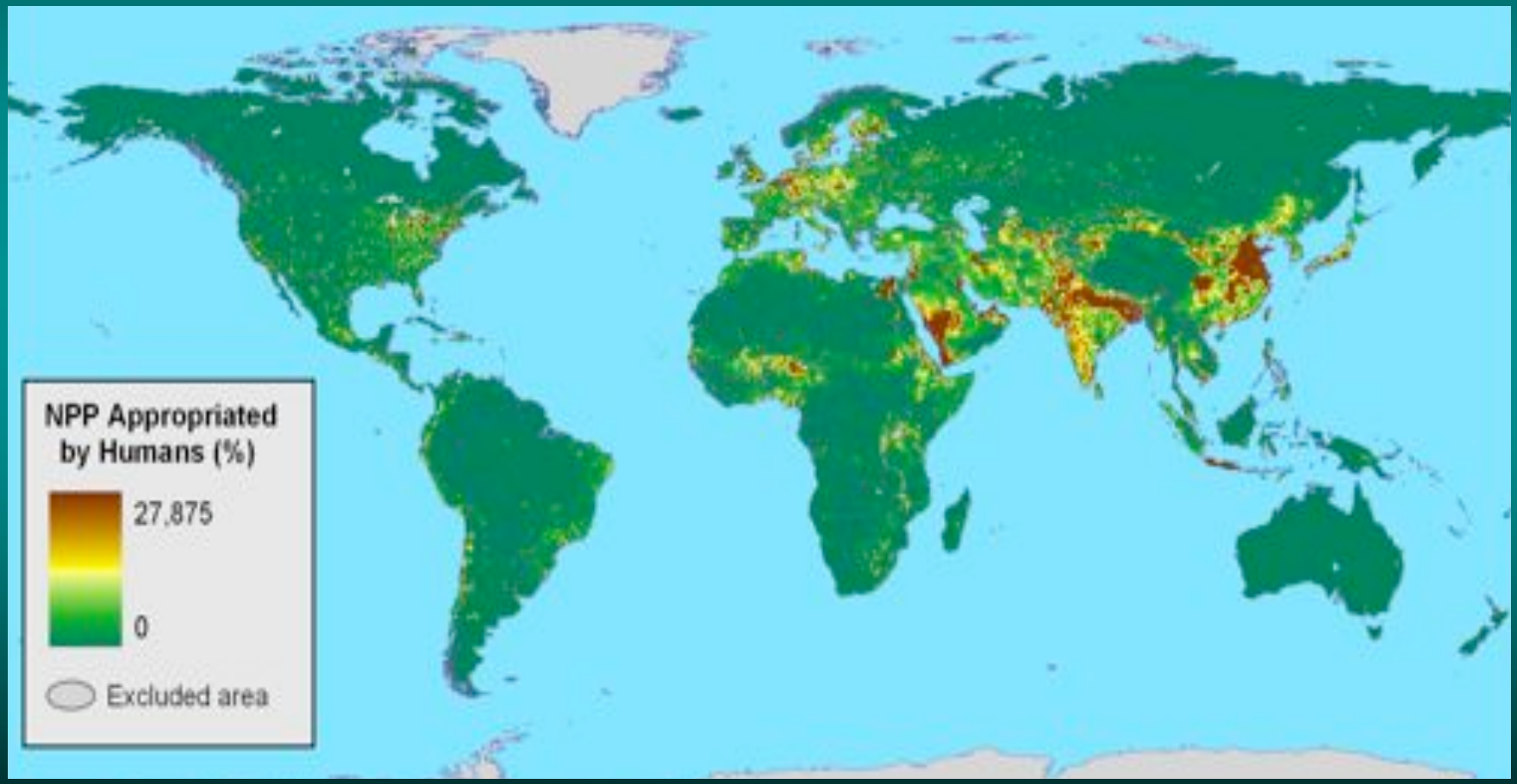
Reduction of NPP may have biological significance:

NPP Lost or Gained (annual)
Due to Urbanization
Going from a pre-urban to a post urban world



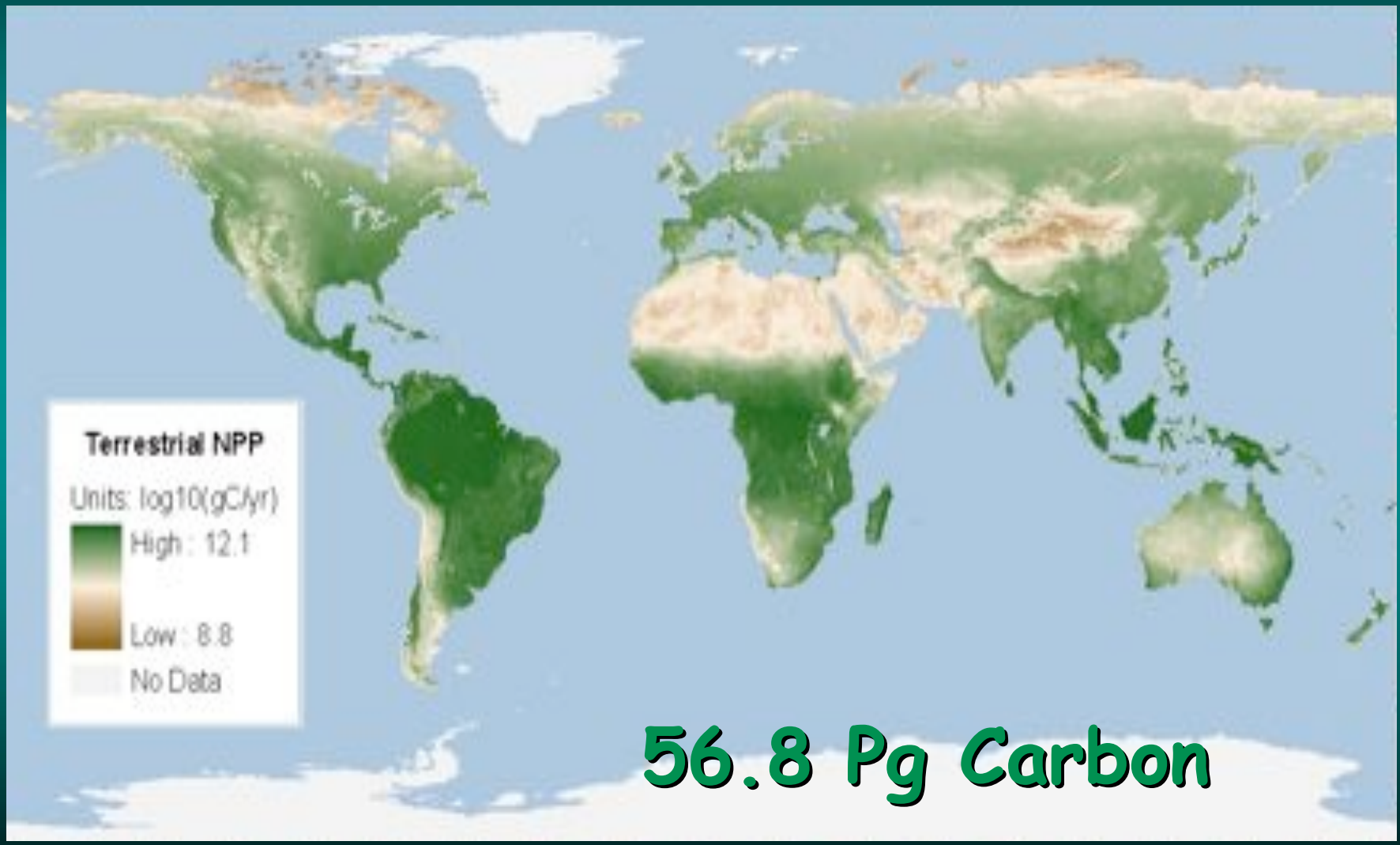
-Annual loss of food web energy 400 Trillion kilocalories (roughly equal to food energy requirement for 448 million people).
- Reduction of actual food products equivalent to needs of 16.5 million persons annually (about 6% of US population).

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

Average Annual NPP on Land
(1982-1998)



NPP Global "Demand"

Amount of *total* NPP required for food and fiber products

- Sympathetic with AVHRR NPP supply
- Two approaches both using *United Nations Food and Agricultural Organization data (UNFAO-STATS)*
  - Per capita Consumption - 'Lateral'
  - Land area harvest index - 'Vertical'

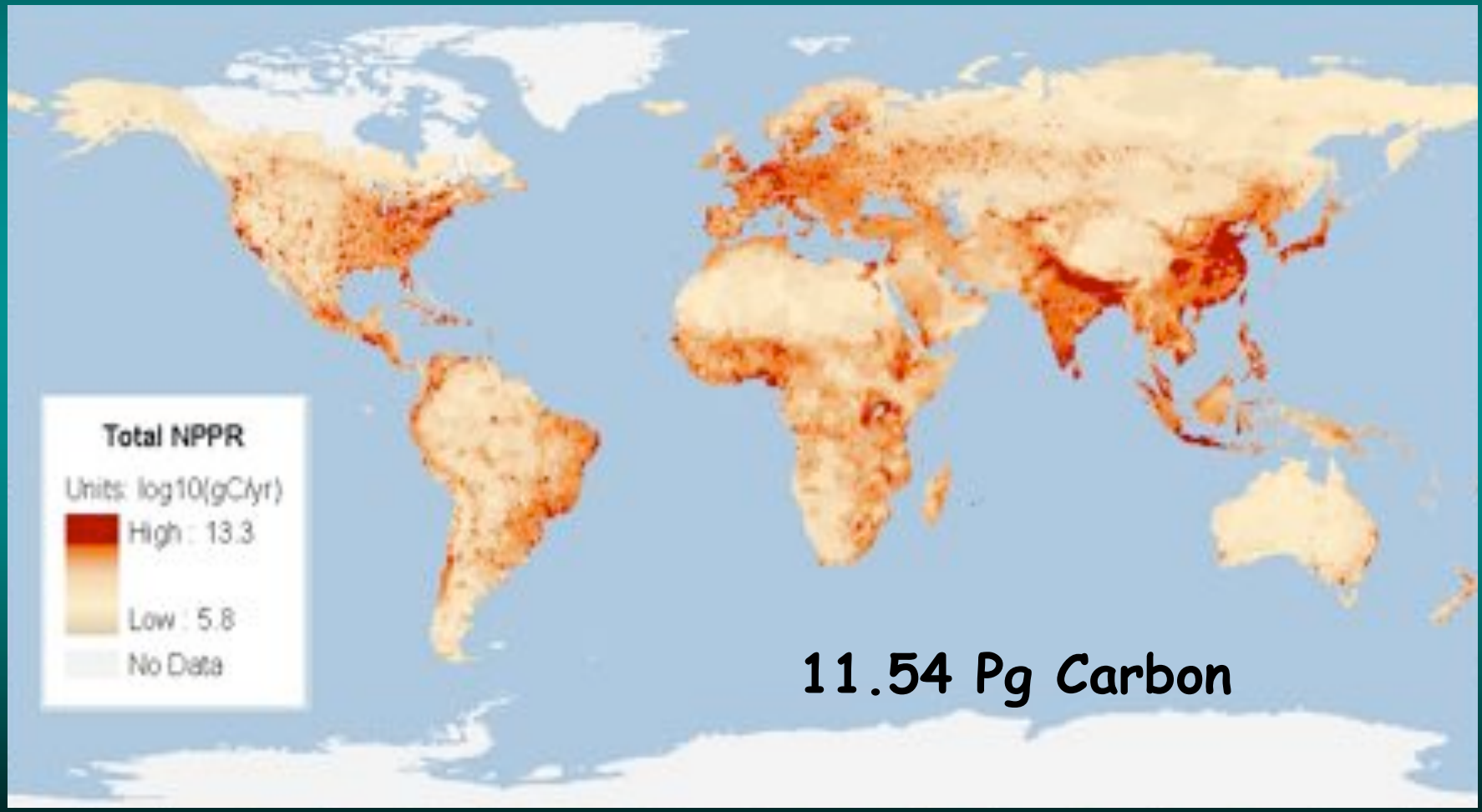
NPP Global "Demand"

Per capita Consumption

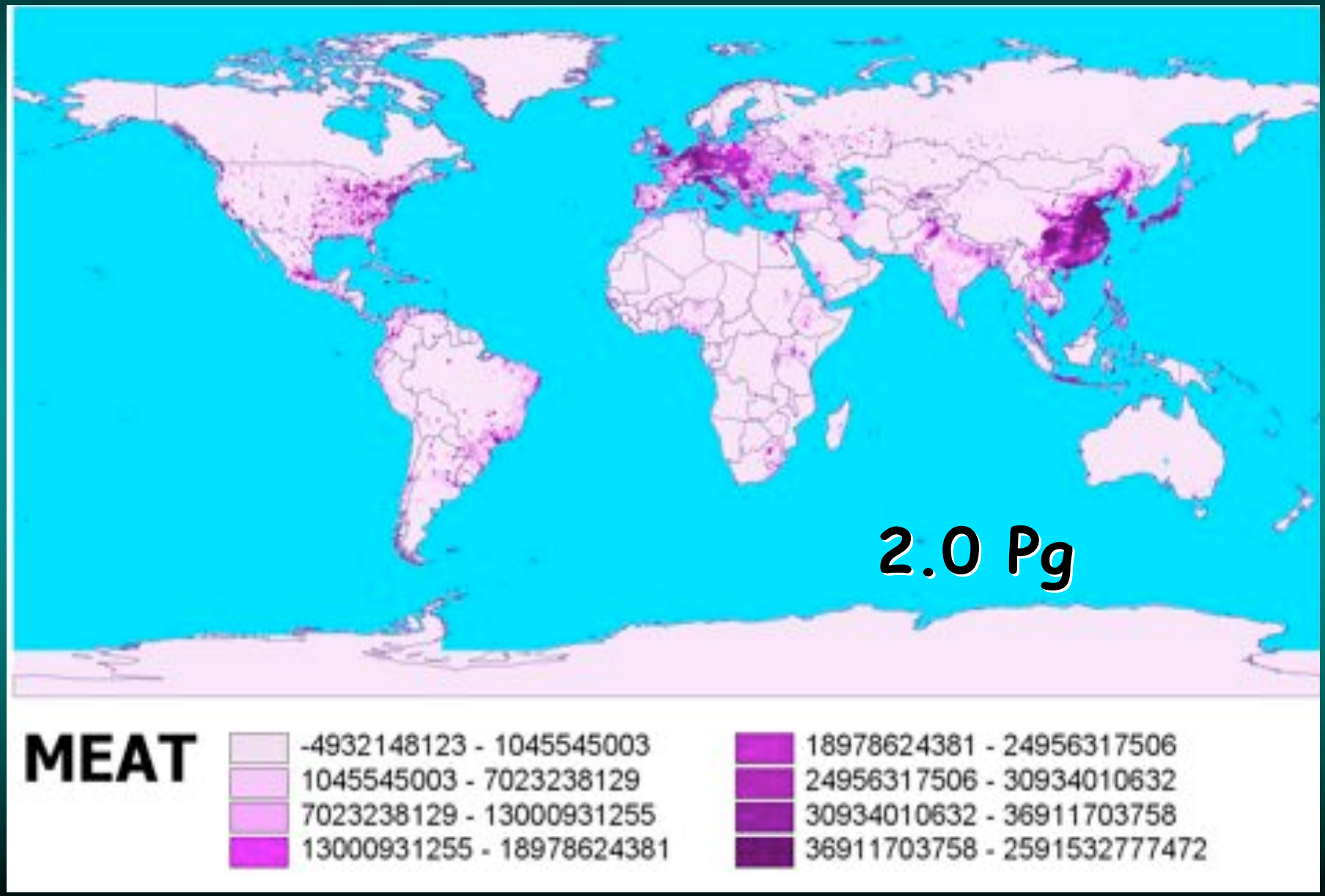
- Shows population pressure 'laterally' on NPP
  - NPP consumed *in situ* not produced *in situ*.
  - Indicates vulnerability (reliance on transport)
- Product Specific
  - Vegetal Foods, Livestock-based Products, Wood, Paper, and Fiber.
- Bio-agronomic modules
  - Back-calculate the NPP required in *grams Carbon*.
- Country level - spatially constrained
  - *Domestic Supply = Production + Imports – Exports*
  - Separate parameterization for Developing and Industrialized countries.

Annual Human NPP Carbon Demand

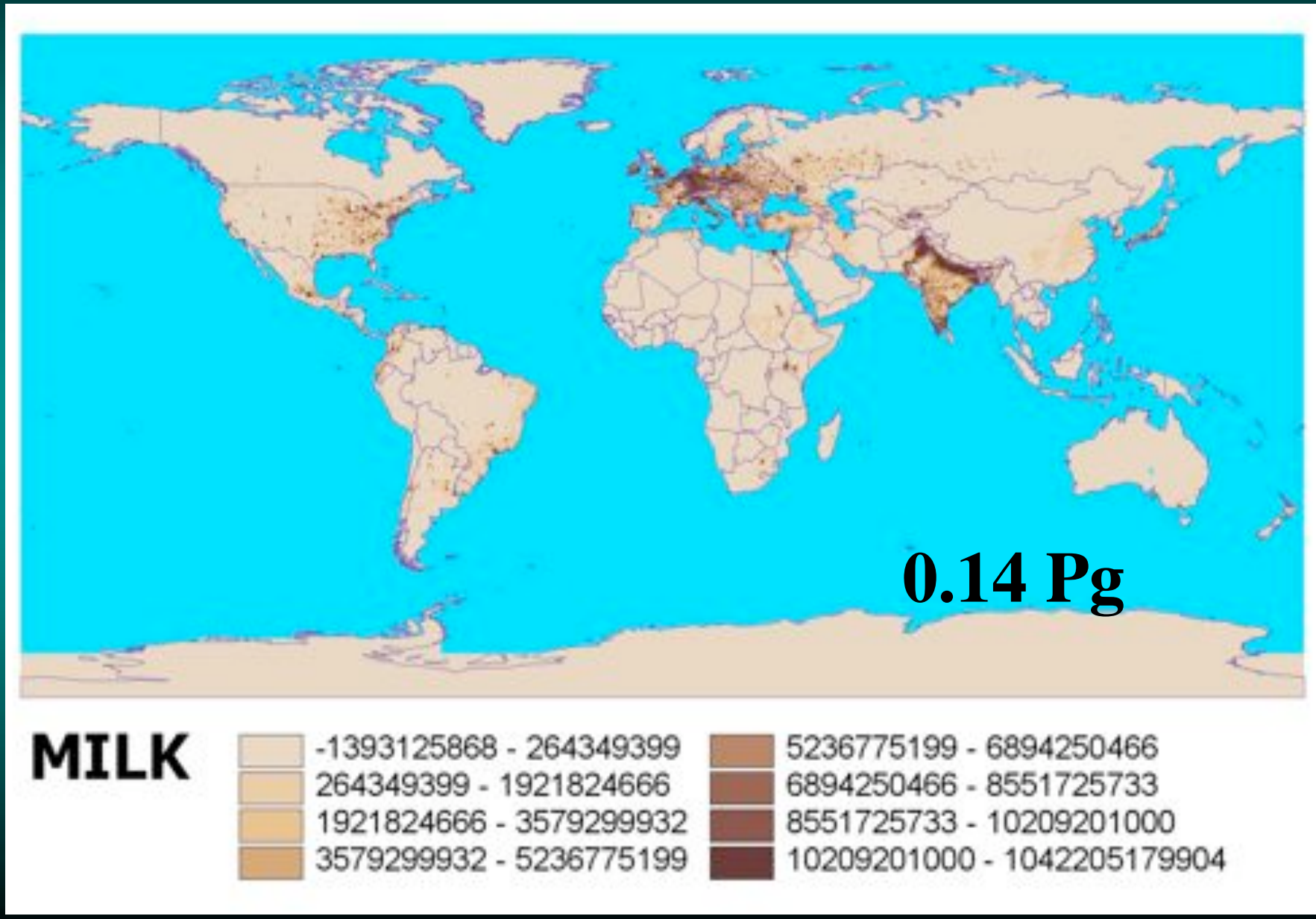
Terrestrial NPP Required for Food and Fiber (1995)



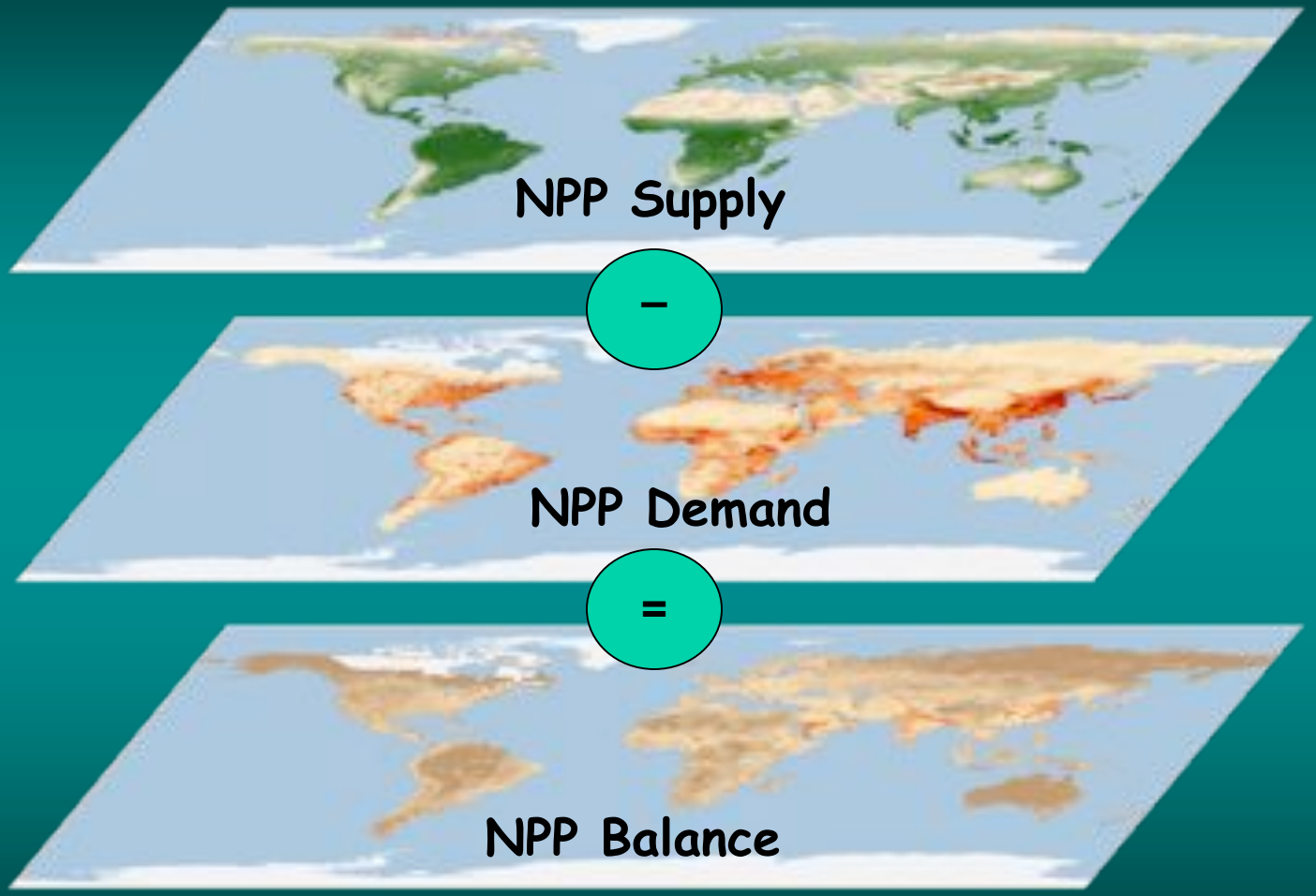
NPP Required (g C) - Meat Consumption (1995)



NPP Required (g) - Milk Consumption (1995)

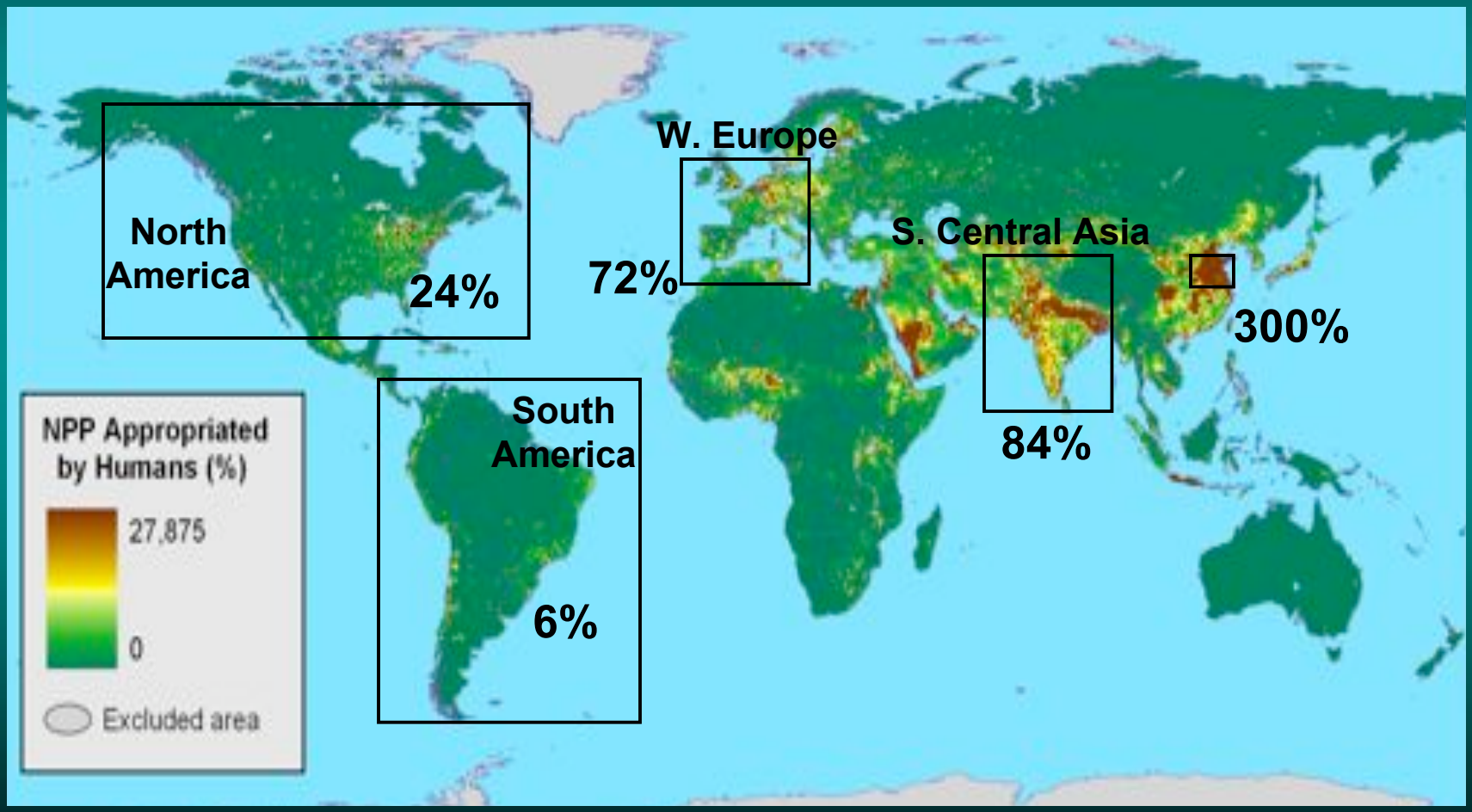


NPP Carbon Balance



NPP Demand as % of Supply

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



[Locating Risks to Biodiversity: A Carbon Balance Approach CARBON-0000-0009] M. L. Imhoff, PI

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 "Demand"	8.00	11.54	14.81
Demand as % of Supply (56.8 Pg)	14%	20%	26%

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%

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
2	–	↑	–	20.19
3	–	↑	↑	16.26 †
4	↑	↑	–	31.59
5	↑	↑	↑	25.5 †

↑(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".

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

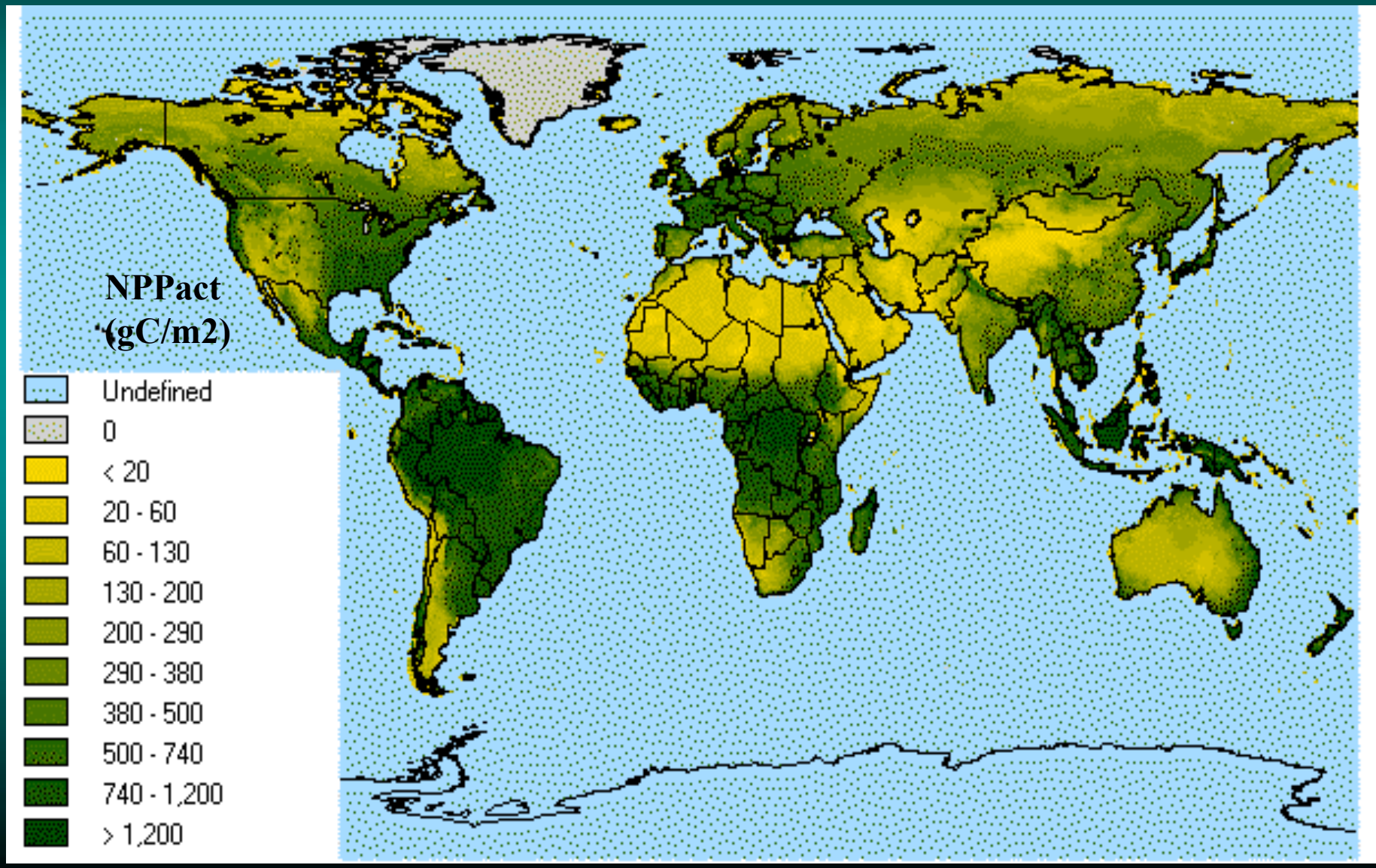
Reference: *M. L. Imhoff, L. Bounoua, T. Ricketts, C. Loucks, R. Harriss, and W. Lawrence. Global patterns in human consumption of primary production.* ***Nature****, 24 June 2004, pp. 870-873.*

Land Area Based Assessment
'Vertical'

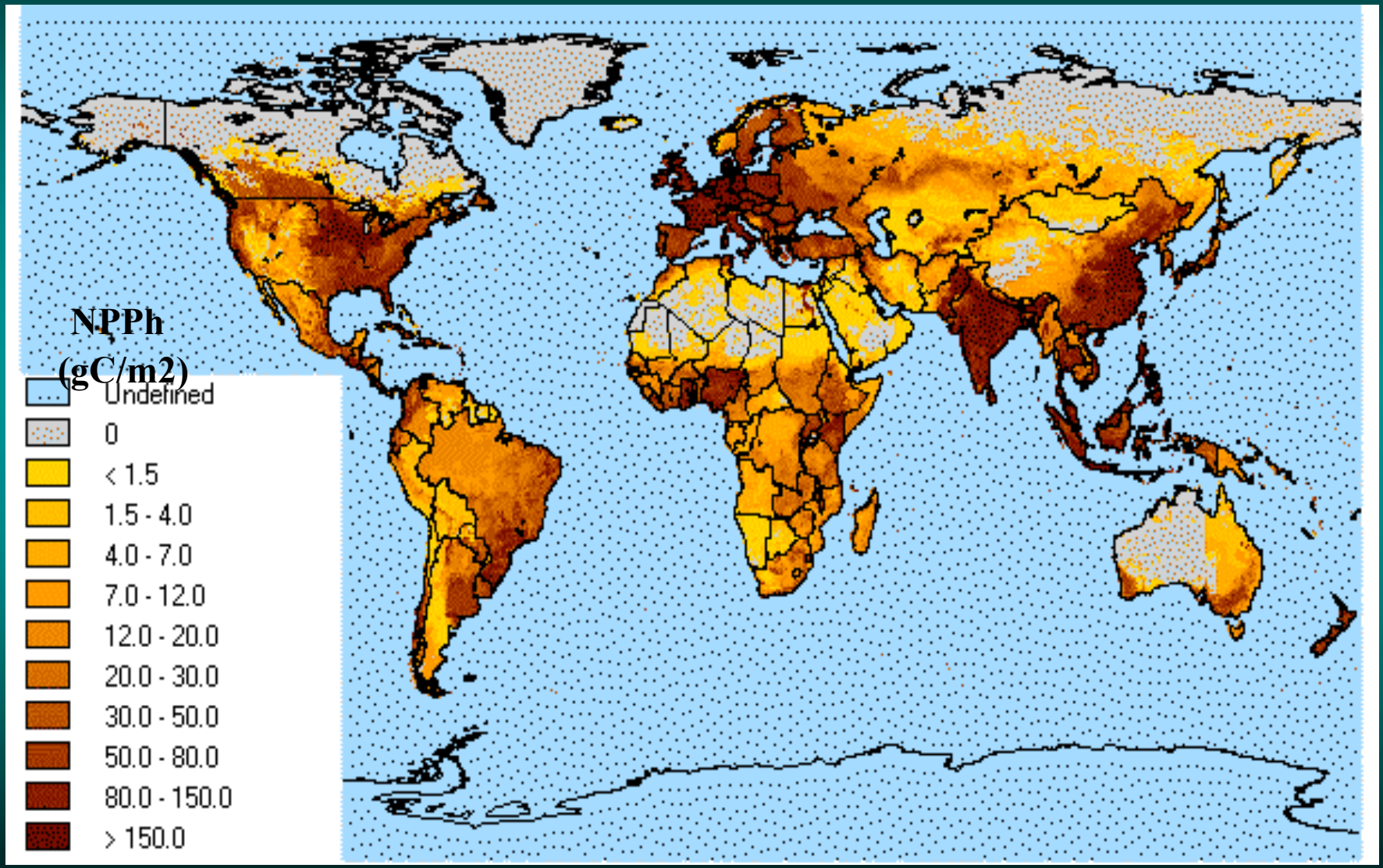
- Estimates NPP balance in situ
  - NPP removed for food and fiber vs, NPP left behind on landscape
- Based on Harvested NPP (Darwin et al.) FAOSTATS
  - Country and state-level data on crop, livestock, and wood products harvested.
- Distributed country- and state-level harvested products to 0.5° lat./long. grids based on land-cover, agro-ecological, and population factors.
- Estimated NPP by converting the measures of crop (mt), livestock (mt), and wood (m^3) products in 0.5° lat./long. grids into Pg C.

Terrestrial NPP 'Supply' in 1997

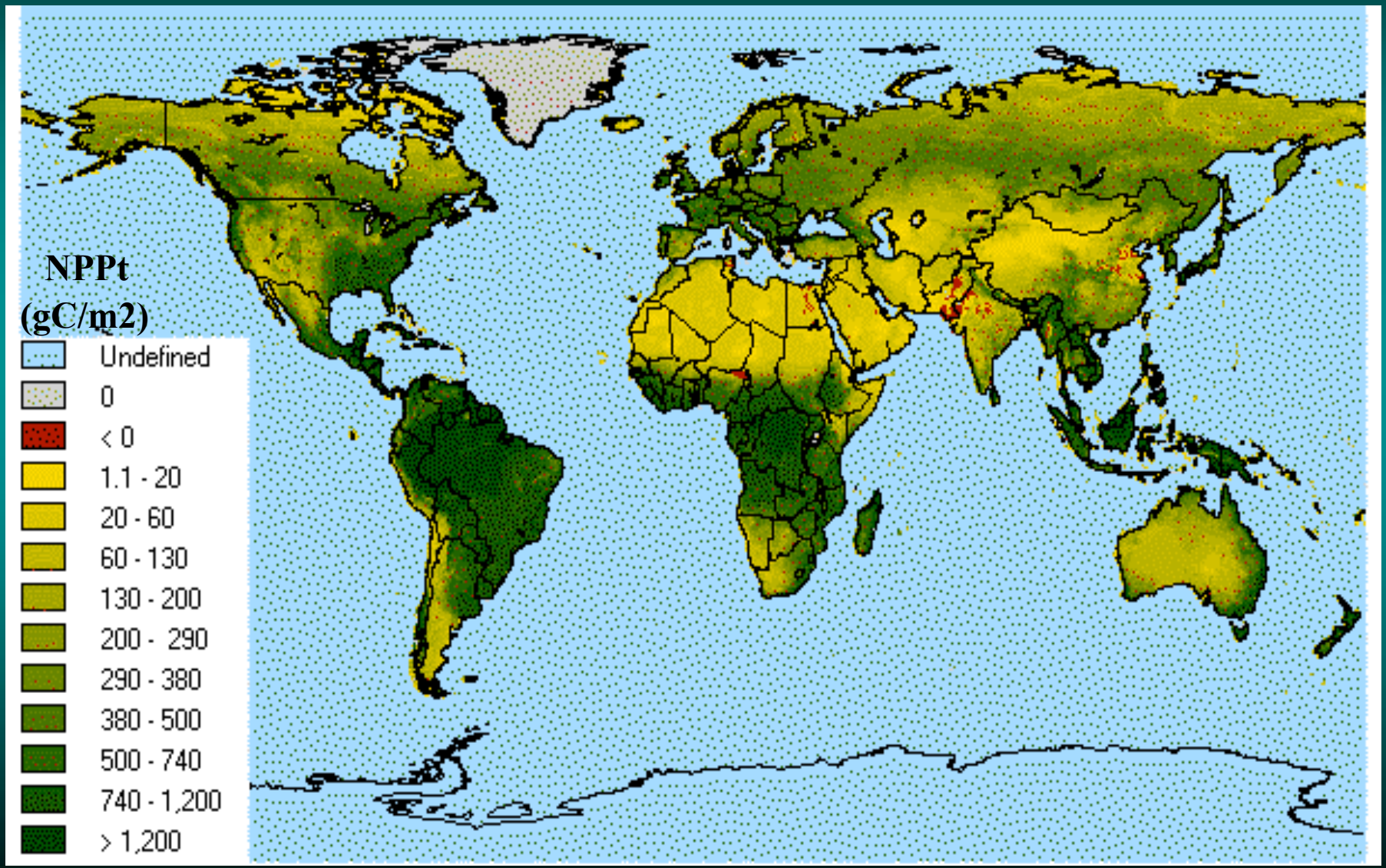
AVHRR/CASA



NPP Harvested by Humans in 1997



NPP Remaining After Human Harvest



Concluding Remarks

- Human NPP appropriation is a powerful measure of aggregate human impacts on the biosphere.
- Global NPP demand is 20% of supply with large regional and local variation:
    - 6% (South America) to over 70% (Europe and Asia), and from near 0% (e.g., central Australia) to over 30,000% (e.g., New York City).
- Spatial data on NPP supply and demand illustrate the degree to which local populations depend upon NPP "imports,".
- The HANPP model structure allows *quantitative* assessment of changes and potential impacts to NPP-carbon use resulting from different policy and development scenarios.

2004-2003 Publications

Marc L. Imhoff , Lahouari Bounoua, Ruth DeFries, William T. Lawrence, David Stutzer, Compton J. Tucker, and Taylor Ricketts (in press). The consequences of urban land transformation for net primary productivity in the United States. *Remote Sensing of Environment*.

Luck, G.W., T.H. Ricketts, G.C. Daily, M. Imhoff , 2004. Spatial conflict between people and biodiversity. *Proceedings National Academy of Sciences*, vol. 101, No. 1, pp 182-186 (www.pnas.org/cgi/doi/10.1073/pnas.2237148100).

L. Bounoua, R. S. Defries, M. L. Imhoff, and M. K. Steininger, 2003. Land use and local climate: A case study near Santa Cruz, Bolivia. *Meteorology and Atmospheric Physics*, Publisher: Springer-Verlag Wien, ISSN: 0177-7971, DOI: 10.1007/s00703-003-0616-8.

Ricketts, T. and M. Imhoff. 2003. Biodiversity, urban areas, and agriculture: locating priority ecoregions for conservation. Conservation Ecology 8(2): 1. [online] URL: http://www.consecol.org/vol8/iss2/art1

Rosenqvist, A., Milne T. Lucas R., Imhoff, M. and Dobson C., 2003. *A review of remote sensing technology in support of the Kyoto Protocol.* Environmental Science & Policy, (October 2003) Vol. 6, No. 5, pp 441-455.

Rosenzweig, M.L., W. Turner, J.G. Cox, and T.H. Ricketts. 2003. Estimating diversity in unsampled habitats of a biogeographical province. *Conservation Biology* 17.

Population [P]

- Population is a powerful driver despite vast differences in consumption among nations.
  - Asia, with almost half the world's population, appropriates 72% of its regional NPP supply despite having the lowest *per capita* consumption of any region (1.29 Metric tons C per year).
- Global population growth alone would cause an 83% increase in total NPP demand over the next century.
  - 18.1 Pg C or 32% of global supply by 2050 (8.92 billion people)
  - 21.08 Pg C or 37% of global supply by 2100 (10.4 billion people)

Affluence [A]

Consumption Level

- If *per capita* NPP consumption in the developing countries is increased to that

  of industrialized countries:

  - **NPP demand increases from 11.4 to 18.4 Pg C**

    (i.e., to 33% of current global NPP supply).
  - **In South Central Asia, regional NPP demand grows from 80% to 224% of supply.**
- A change of this magnitude would:
  - **Increase ecological impoverishment in particular regions,**
  - **Require substantial imports of NPP to those regions,**
  - **Create greater pressure on natural and agricultural systems worldwide.**

Technology [T]

- Reported efficiencies for wood production in developing countries are roughly half those of industrialized countries.
- The global annual NPP demand for wood and paper would decrease **1.97 Pg C** if the developing countries achieved the same harvest and milling efficiencies as industrialized countries have now (leading to a 17% total reduction in NPP consumption).