Impacts of the Nitrogen Cascade on Ecosystems

Presentation to NYSERDA

October 8, 2003

Reactive N and *Unreactive N_2*

- **Unreactive N is N_2 (78% of earth's atmosphere)**
- **Reactive N (Nr) includes all biologically, chemically and physically active N compounds in the atmosphere and biosphere of the Earth**
- **N controls productivity of most natural ecosystems**
- **N_2 is converted to Nr by biological nitrogen fixation (BNF)**
- **N_2 is converted to Nr by humans fossil fuel combustion, the Haber Bosch process, and cultivation-induced BNF.**

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  - **Challenge is to reduce anthropogenic Nr creation.**
- **But, this is complicated by fact that Nr creation sustains most of the world's food needs.**
  - **The real challenge is how can we provide food (and energy) while also reducing Nr creation rates and *arresting the nitrogen cascade*?**

Reactive Nitrogen Cuts Across Multiple Global Issues and Environmental Agreements

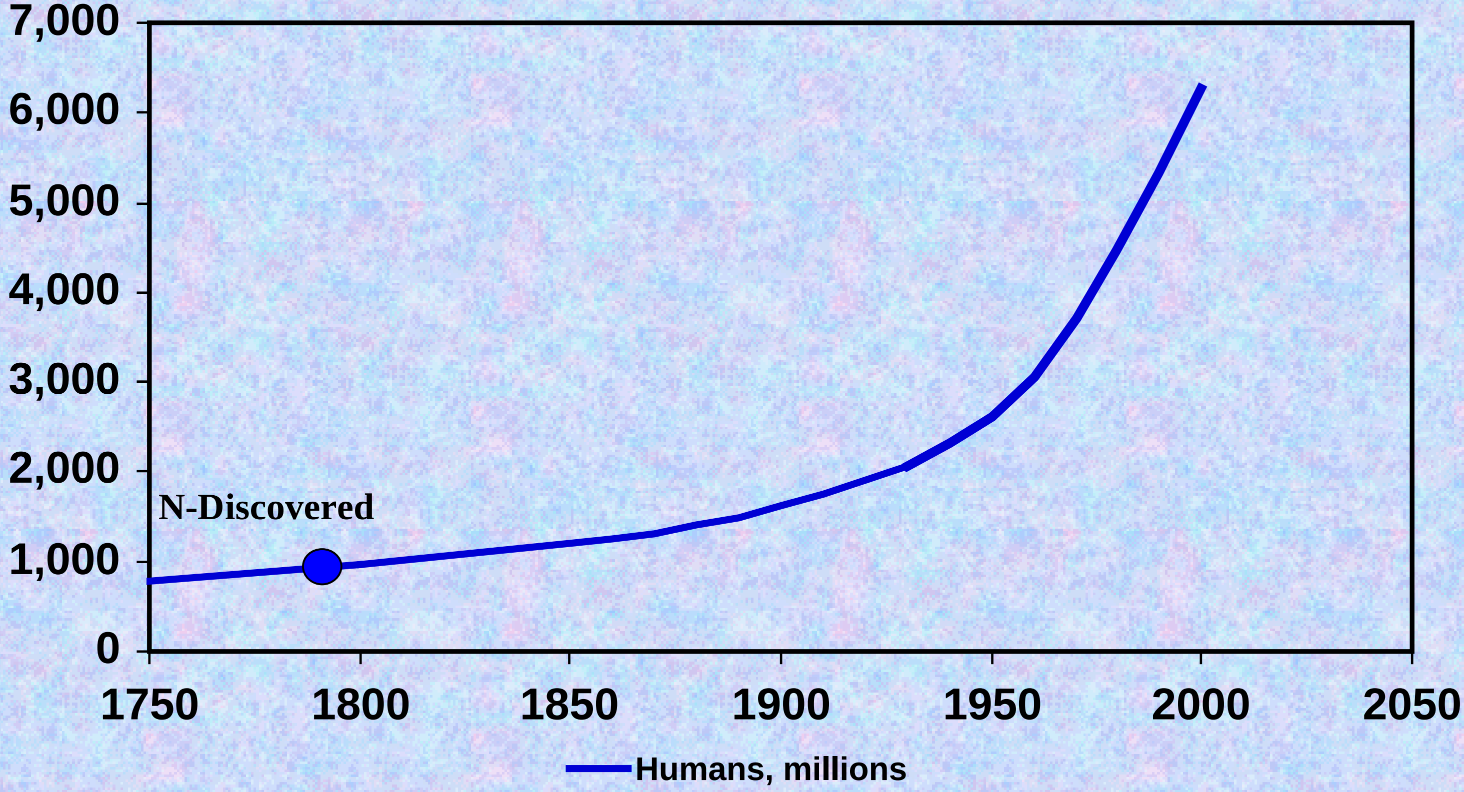
- Regional air quality (LRTAP)
- Climate change (UNFCCC & Kyoto Prot.)
- Ozone Depletion (Montreal Protocol)
- Biodiversity loss (CBD)
- Transboundary water quality (Non-navigational Uses of International Water Courses
- Estuary damage (Regional Seas)
- Fisheries loss (Law of the Sea?)

Need for an Integrated Analytical Policy Approach to Reactive Nitrogen

- First explain history of human alteration of nitrogen cycle
- Identify the reasons why reactive nitrogen cascades through so many segments of the global ecosystem
- Describe the International Nitrogen Initiative

The History of Nitrogen

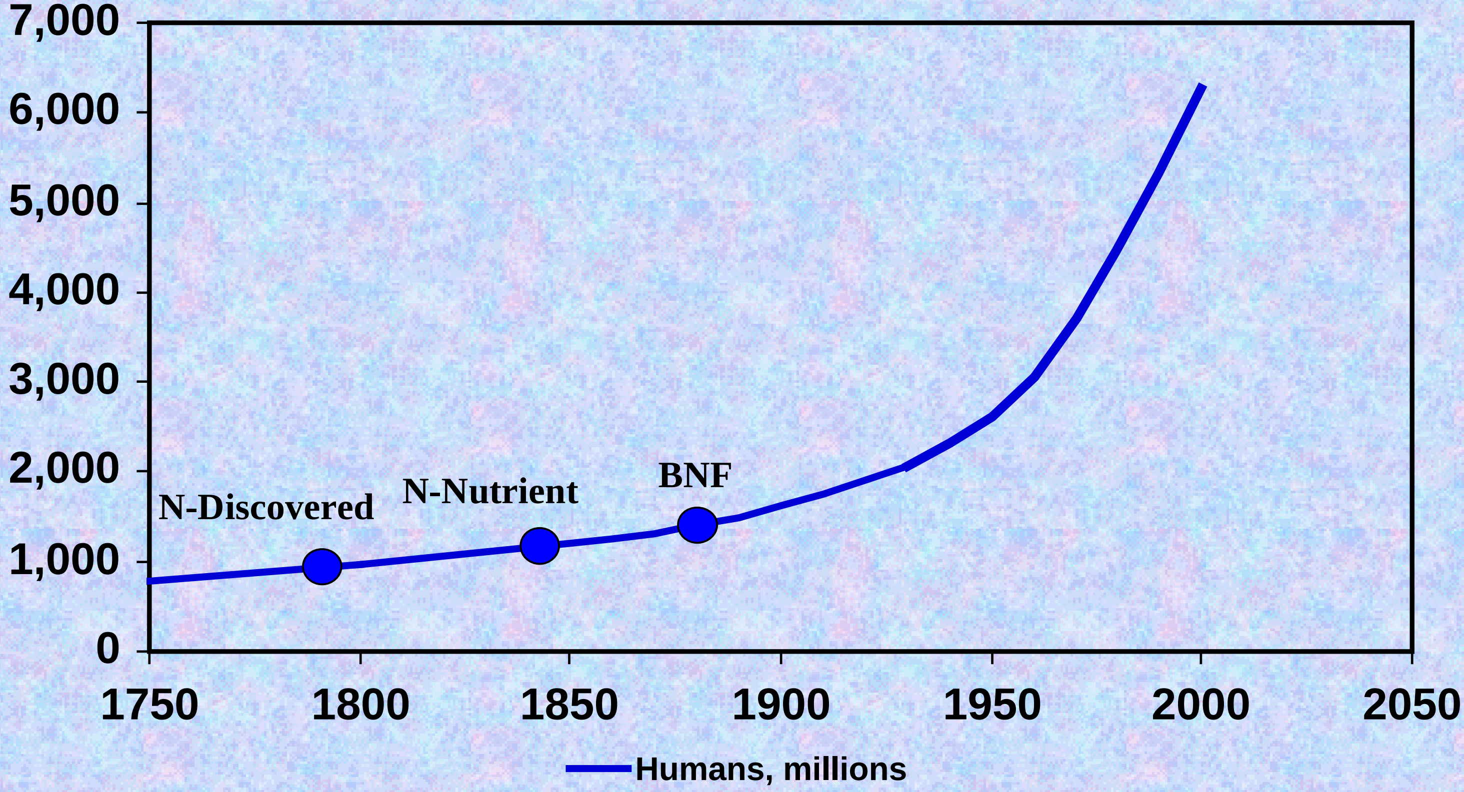
--Global Population & Discovery of N--



Galloway JN and Cowling EB. 2002; Galloway et al., 2002a

The History of Nitrogen

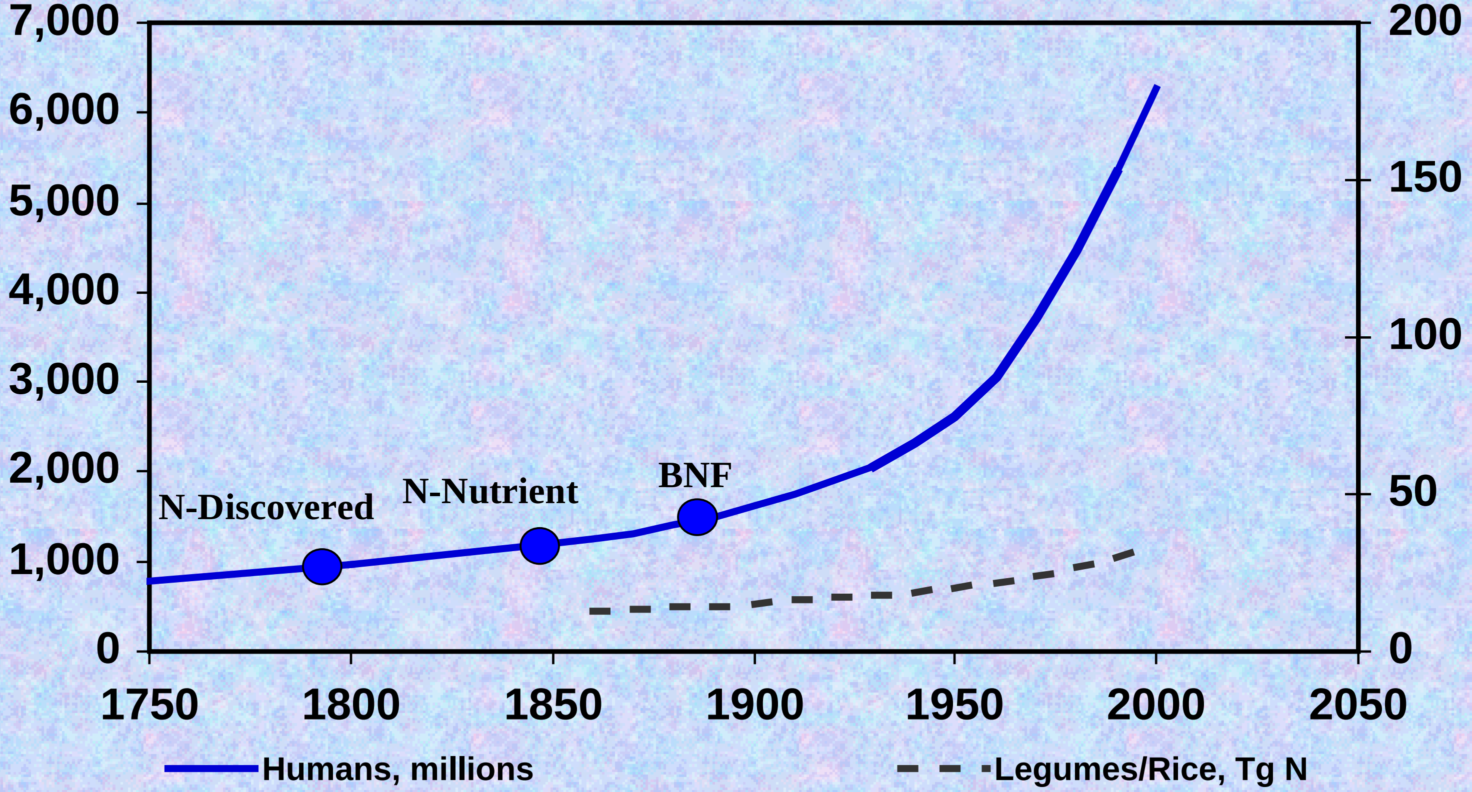
--Major N processes--



Galloway JN and Cowling EB. 2002; Galloway et al., 2002a

Nr Creation by Cultivation

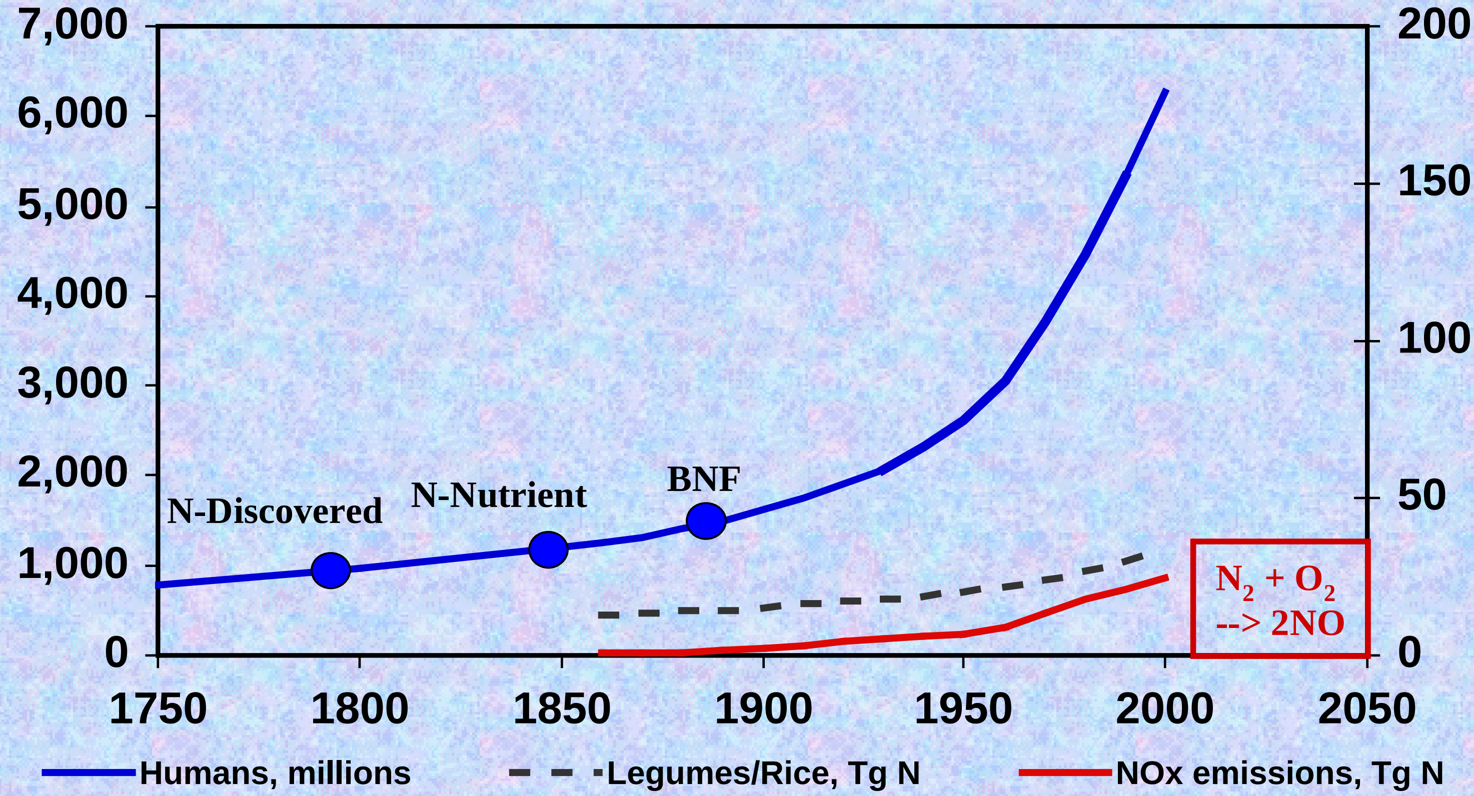
--So that's why we plant soybeans--



Galloway JN and Cowling EB. 2002; Galloway et al., 2002a

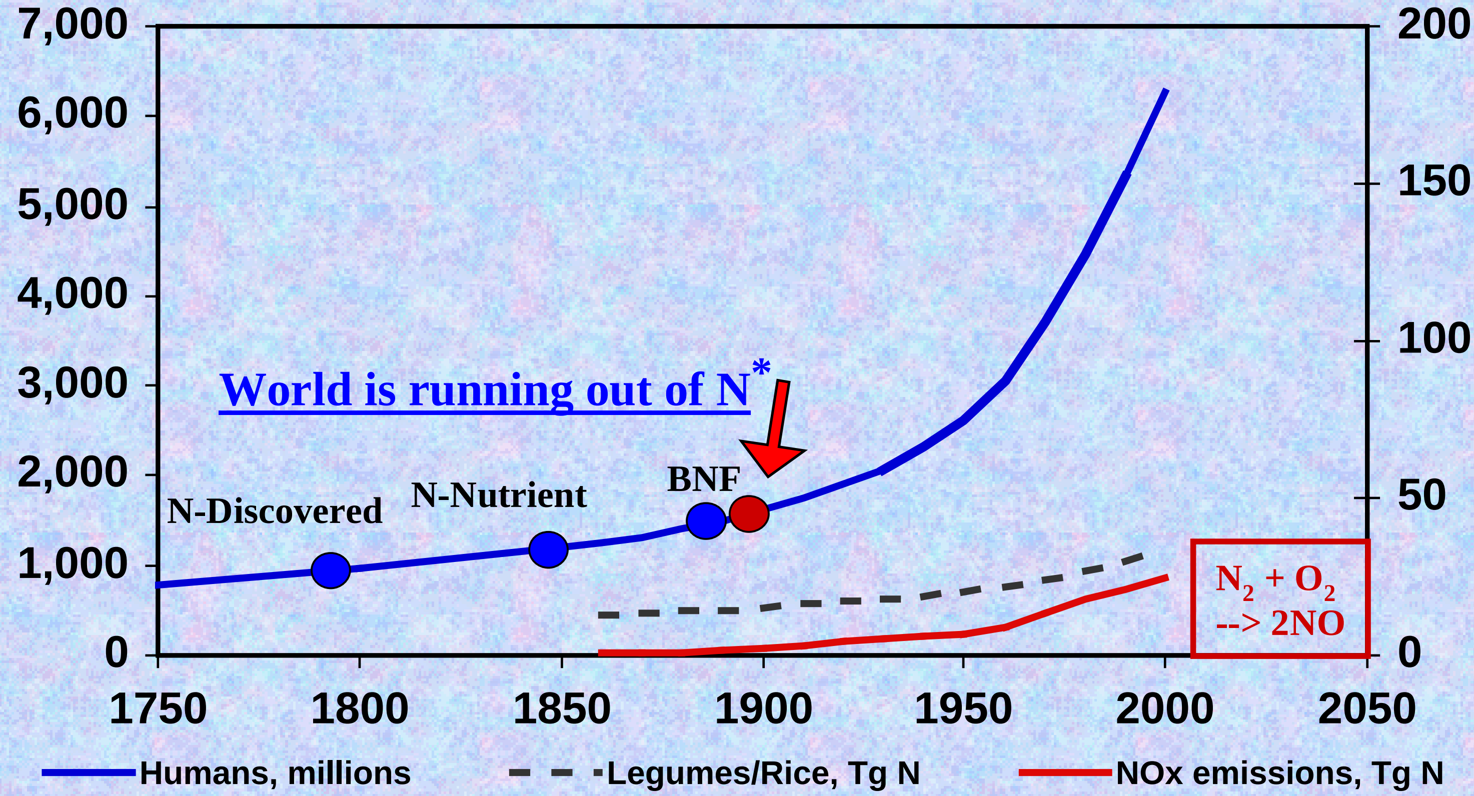
Nr Creation by Fossil Fuel Combustion

--Nr produced by accident--



Galloway JN and Cowling EB. 2002; Galloway et al., 2002a

The History of Nitrogen
--A British chemists view--

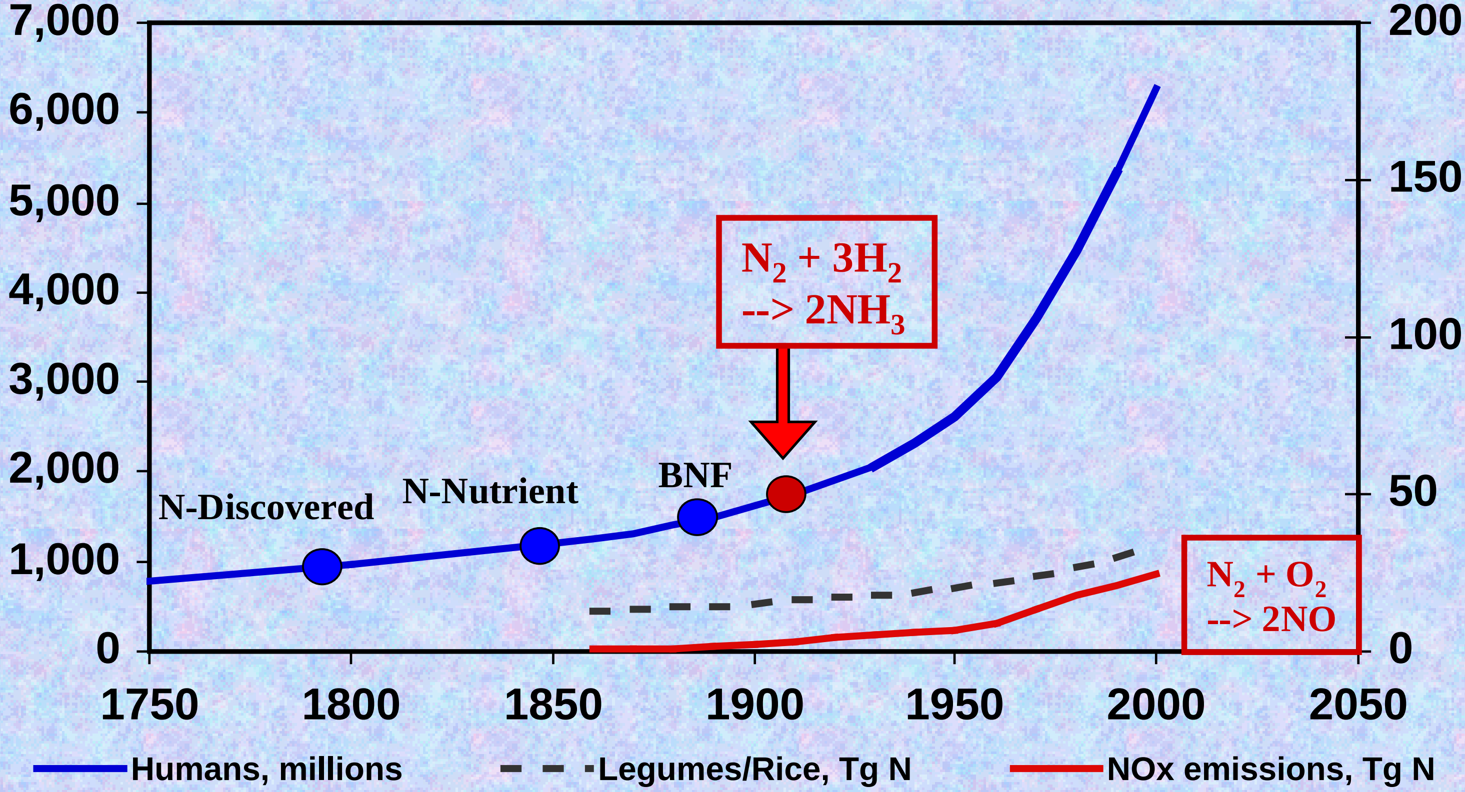


*1898, Sir William Crookes, president of the British Association for the Advancement of Science

Galloway JN and Cowling EB. 2002; Galloway et al., 2002a

The History of Nitrogen

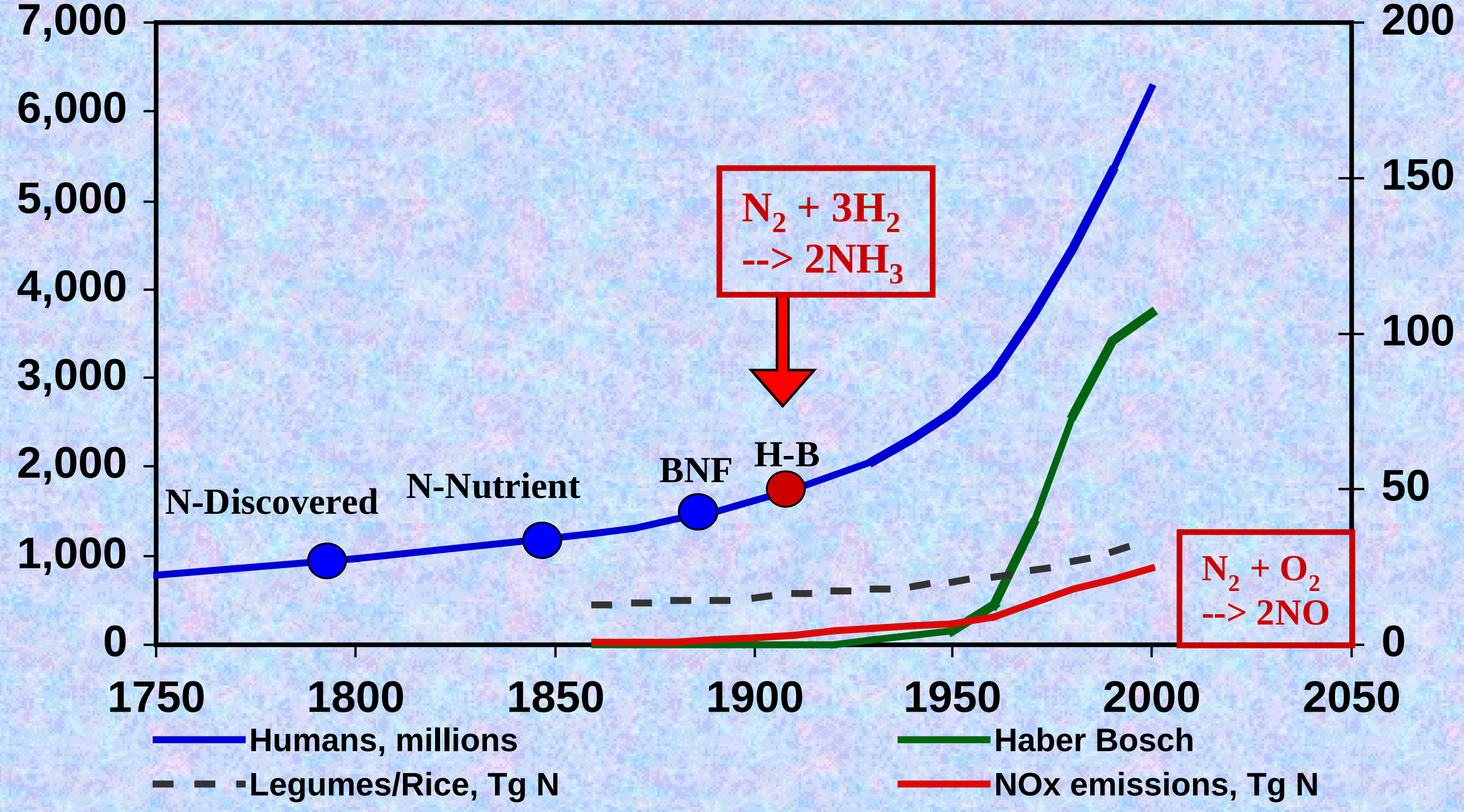
--German science at the forefront--



Galloway JN and Cowling EB. 2002; Galloway et al., 2002a

Nr Creation by Haber-Bosch

--most used for fertilizer--



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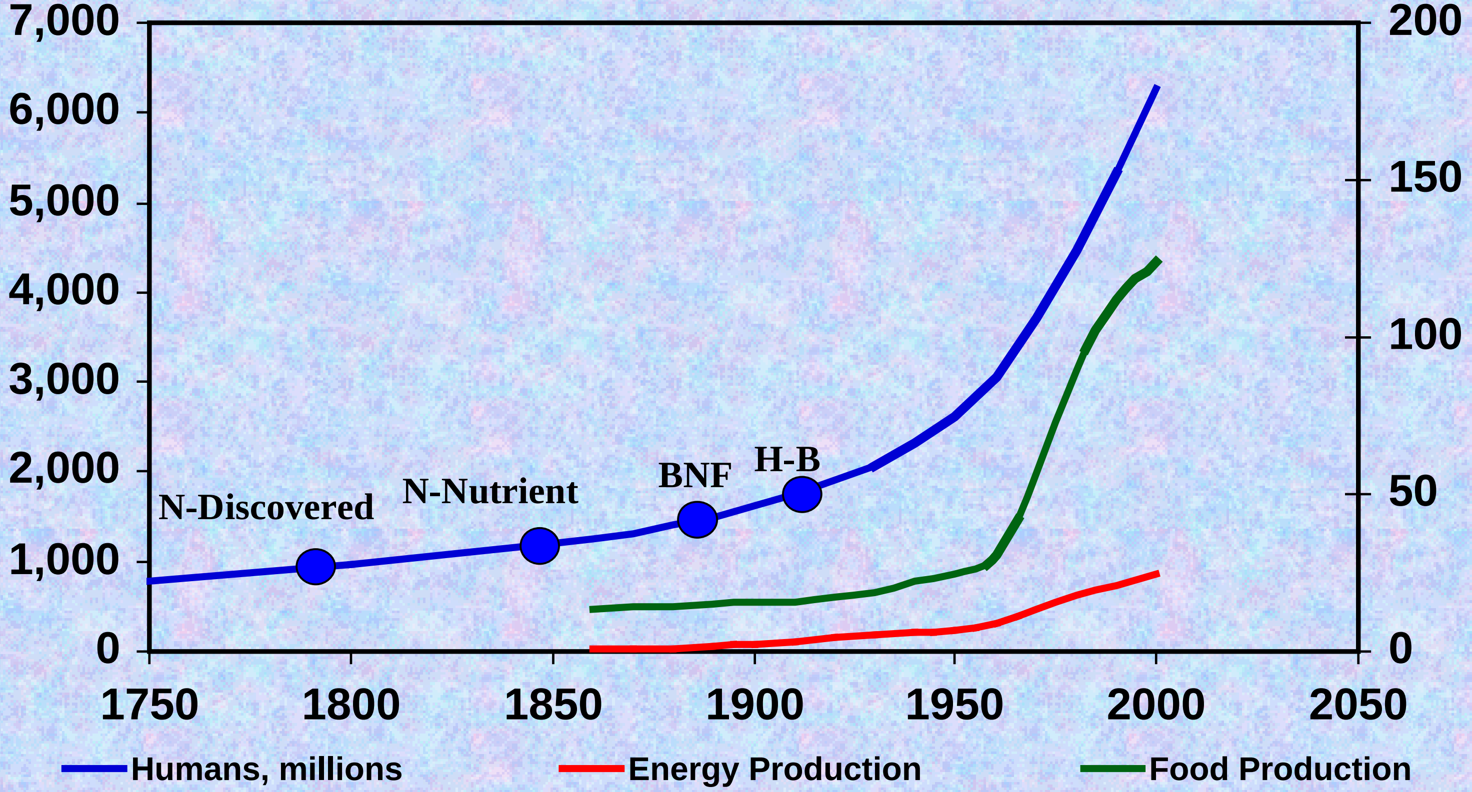
N_r Creation by Food and Energy Production



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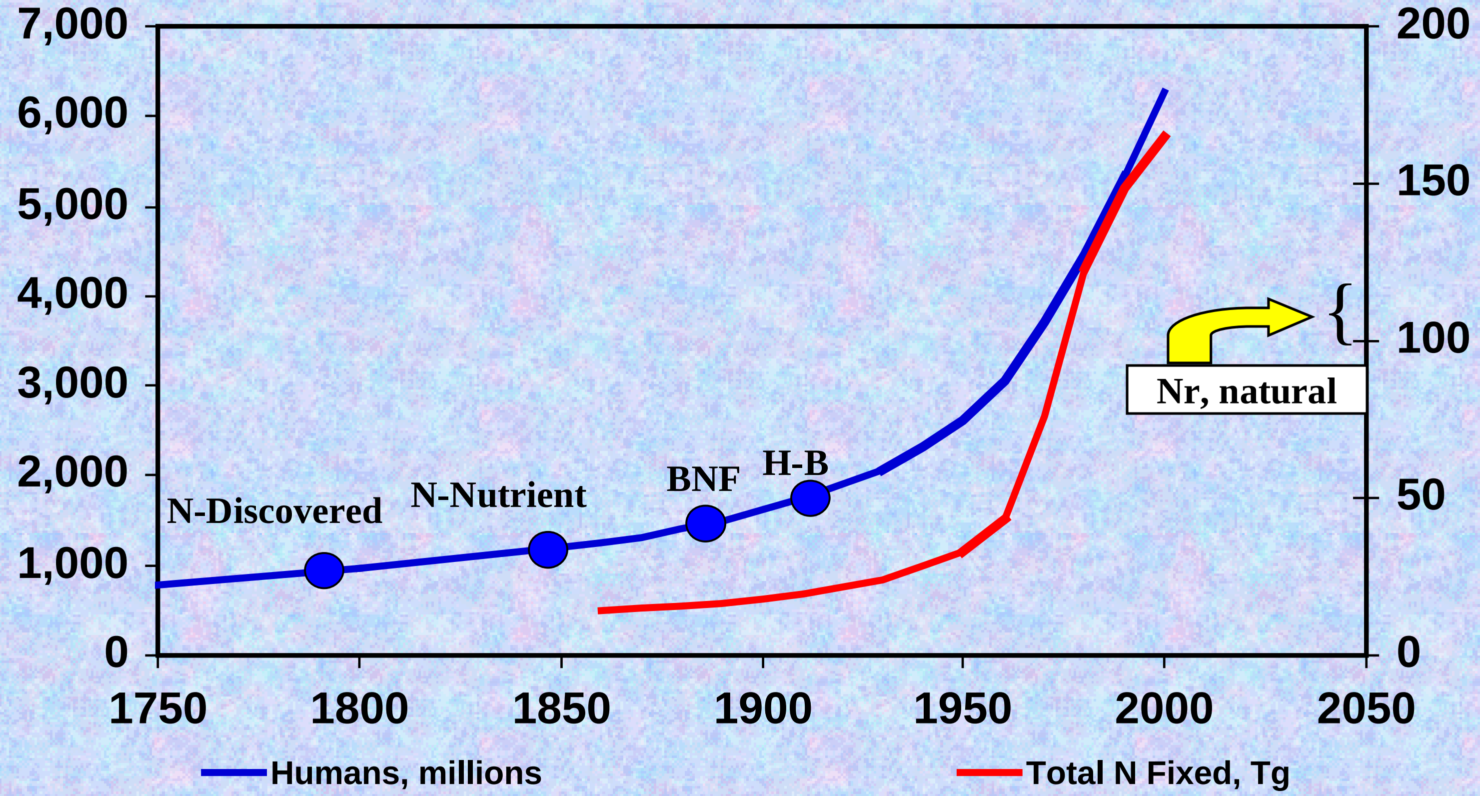


Galloway JN and Cowling EB. 2002; Galloway et al., 2002a

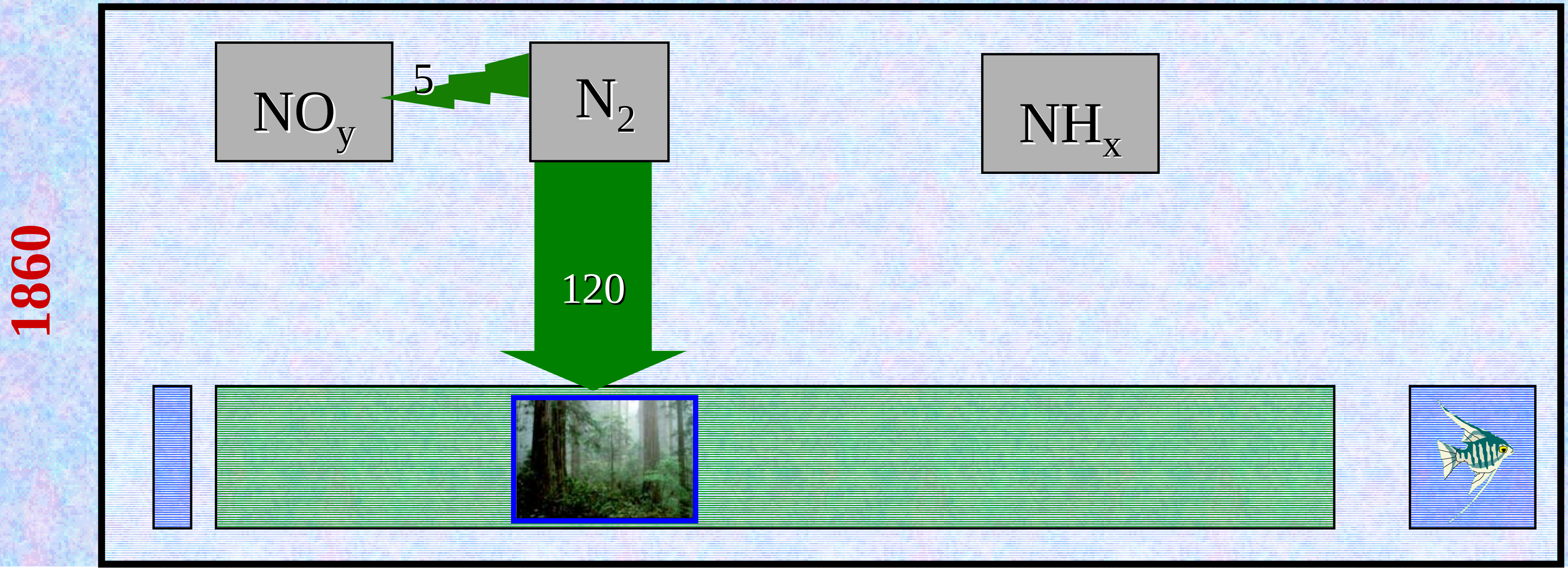
N Drivers in 1860

Grain Production

Meat Production

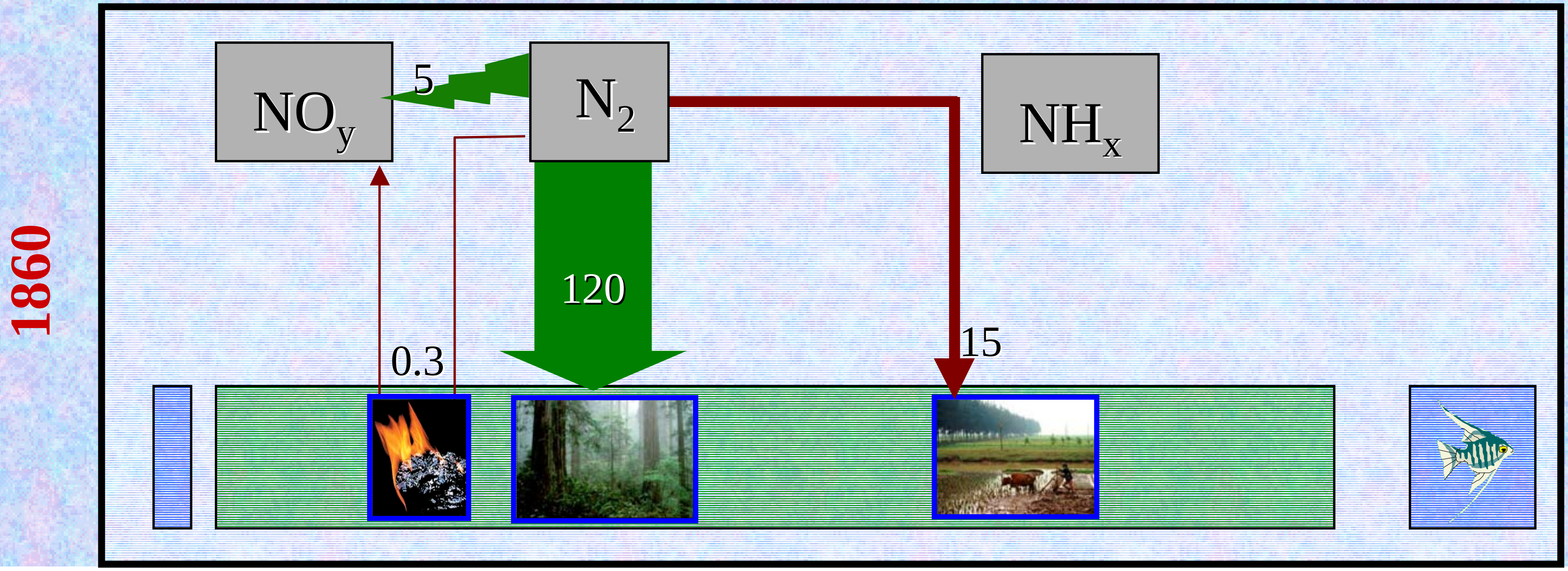
Energy Production

The Global Nitrogen Budget in 1860 and mid-1990s, TgN/yr



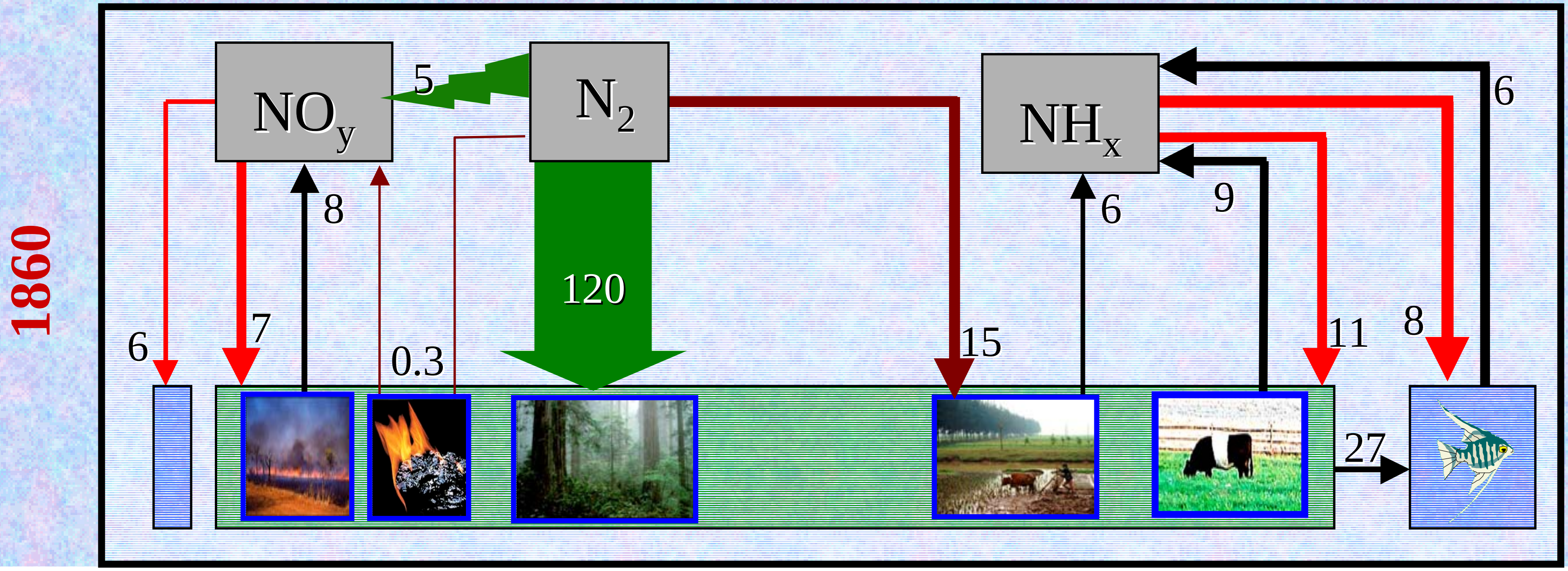
Galloway et al., 2002b

The Global Nitrogen Budget in 1860 and mid-1990s, TgN/yr



Galloway et al., 2002b

The Global Nitrogen Budget in 1860 and mid-1990s, TgN/yr



Galloway et al., 2002b

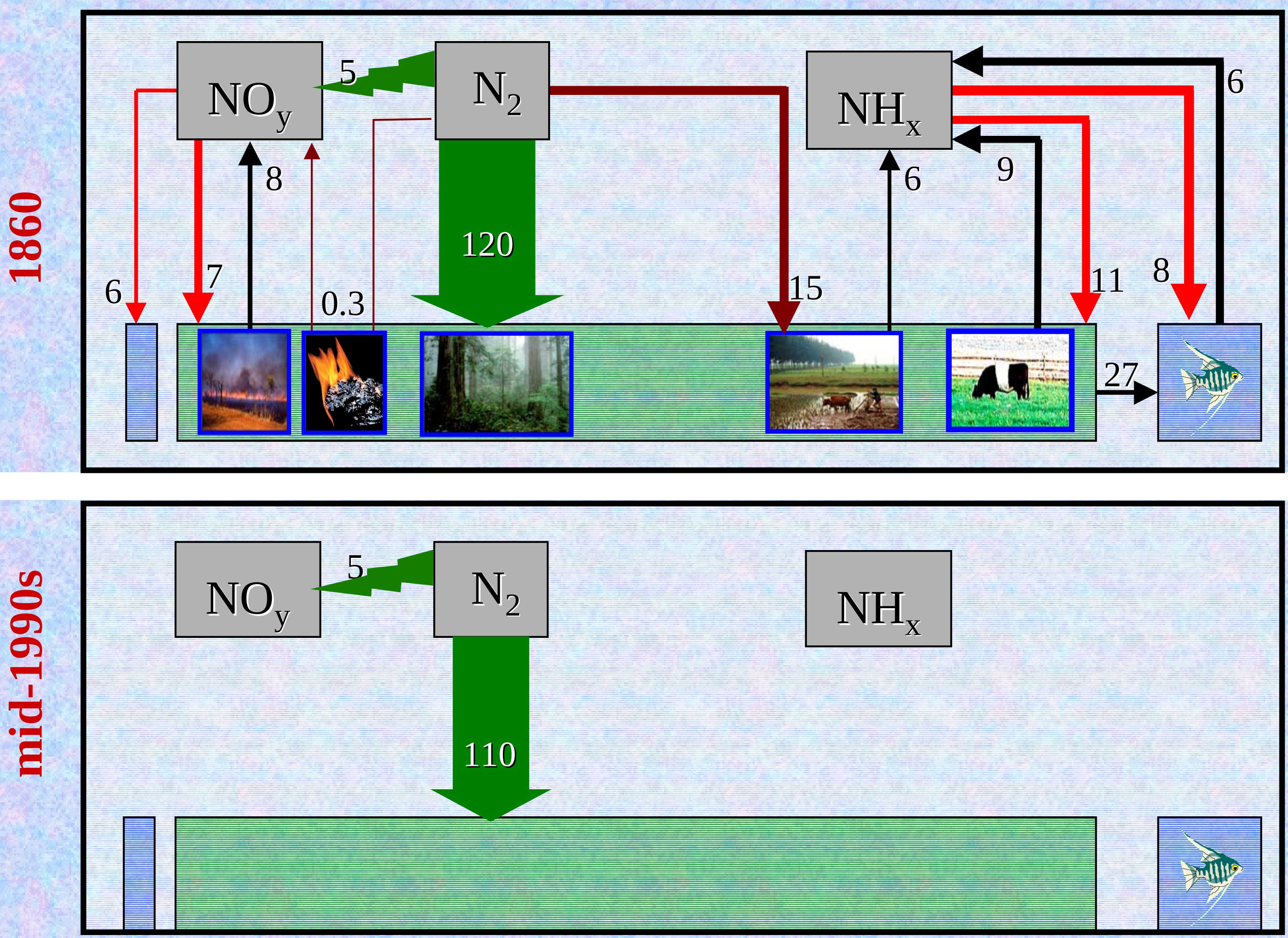
Nitrogen Drivers in 1860 & 1995

Grain Production

Meat Production

Energy Production

The Global Nitrogen Budget in 1860 and mid-1990s, TgN/yr



Galloway et al., 2002b

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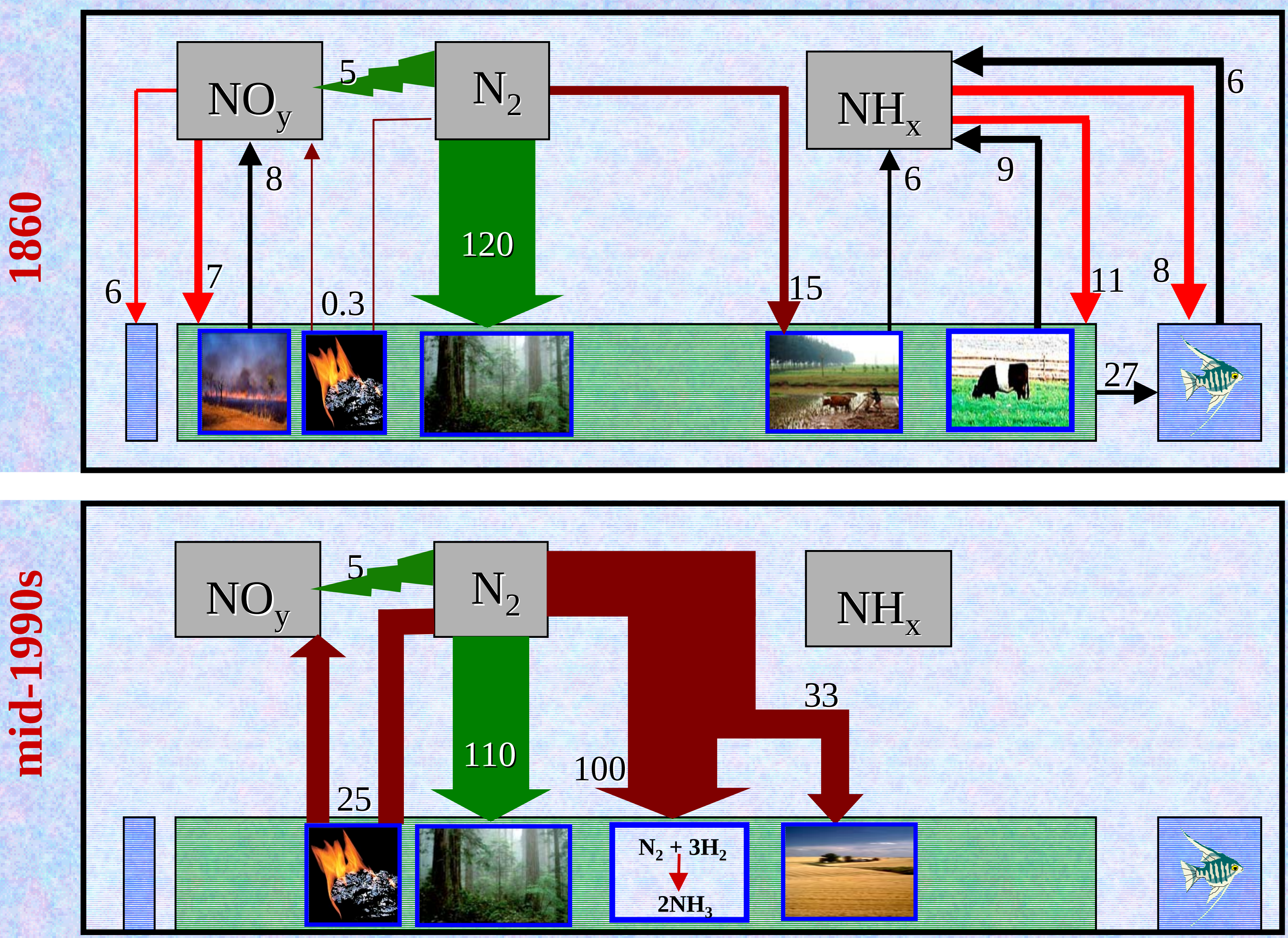

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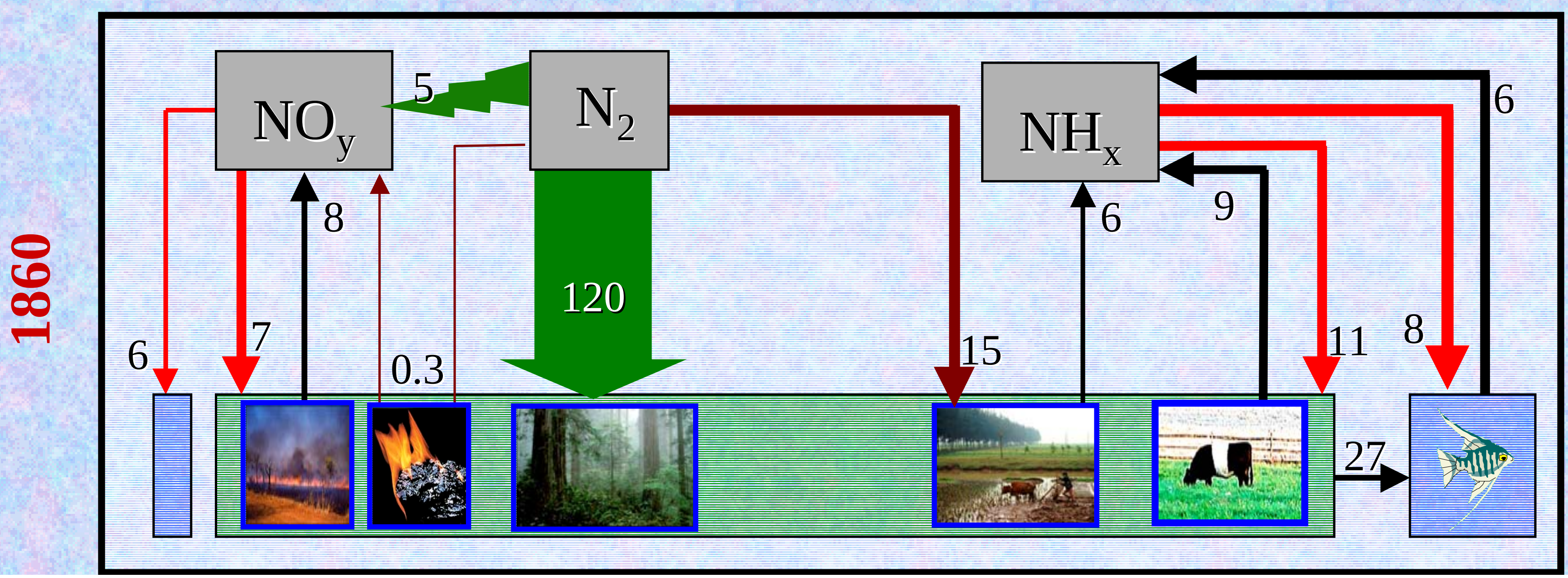
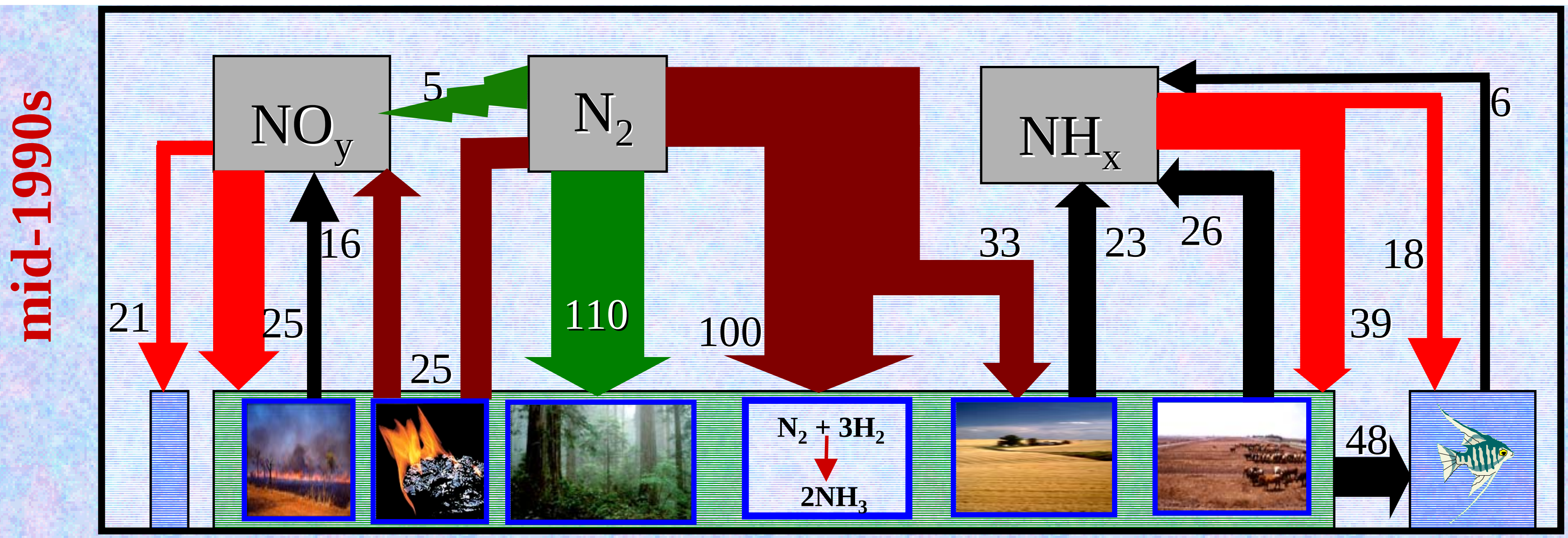
The Global Nitrogen Budget in 1860 and mid-1990s, TgN/yr

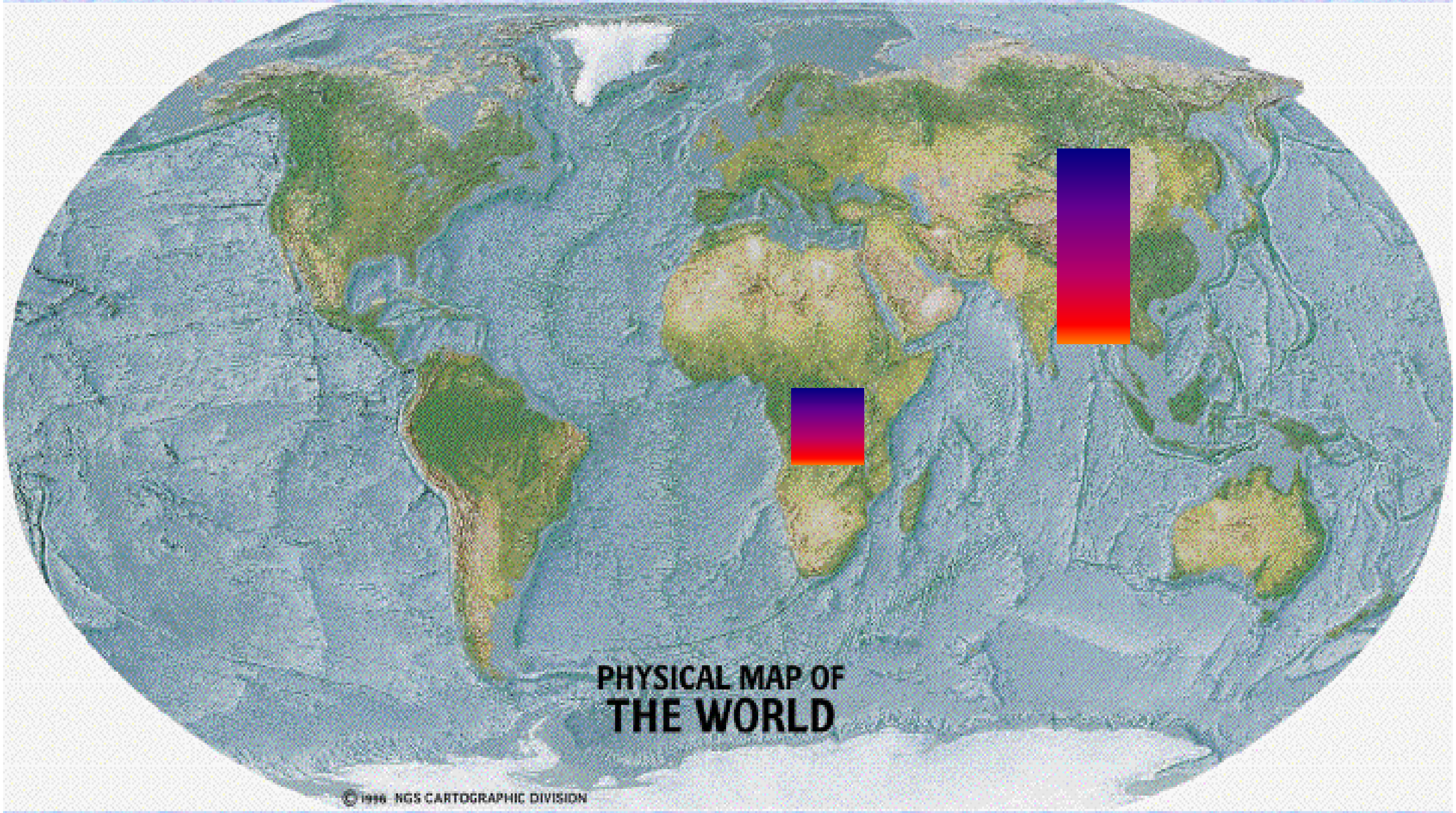




Galloway et al., 2002b

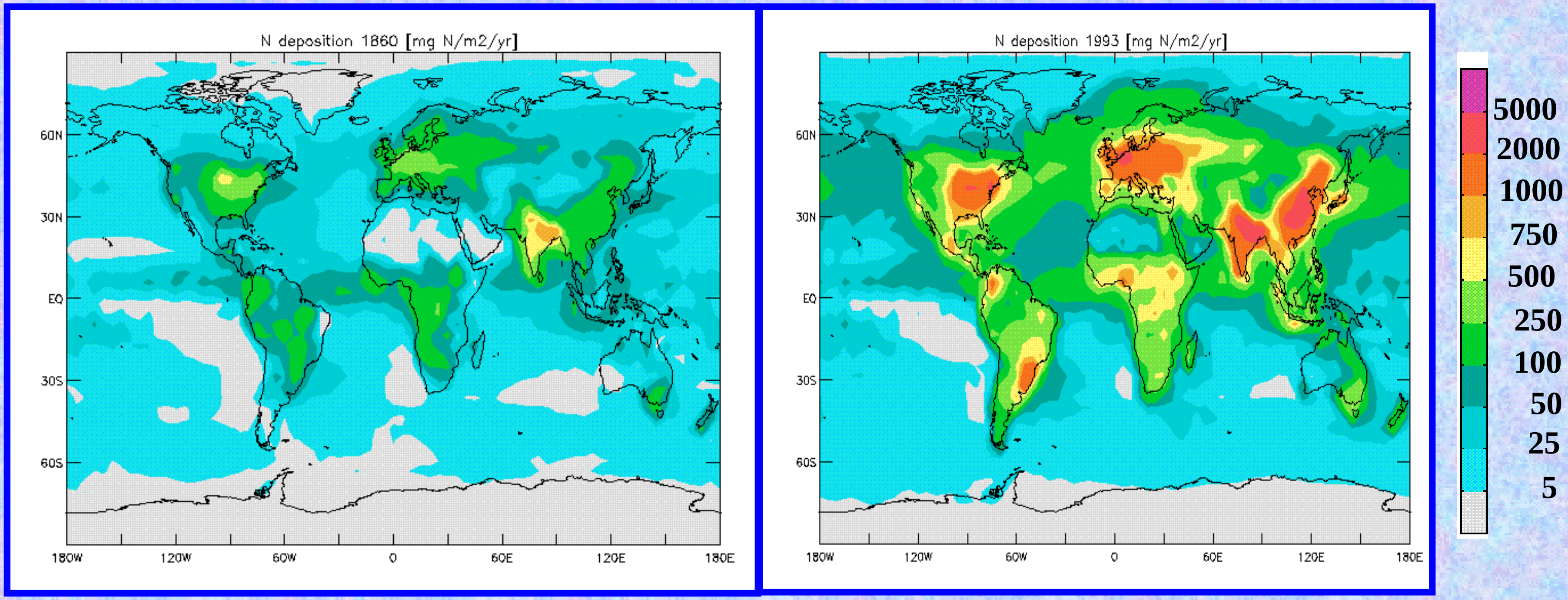
Nr Riverine Fluxes
1860 (left) and 1990 (right)

TgN/yr



Nitrogen Deposition
Past and Present

mg N/m²/yr



1860

1993

Galloway and Cowling, 2002; Galloway et al., 2002b

Mid-Course Summary

Summary

- Humans mobilize ~50% more Nr than natural terrestrial ecosystems.
  - *Food production accounts for 75%*
- Nr is widely dispersed
  - *Atmospheric Nr emissions have increased 3-fold since 1860; NH_3 twice as important as NO_x*
- Nr is accumulating in ecosystems and the atmosphere.

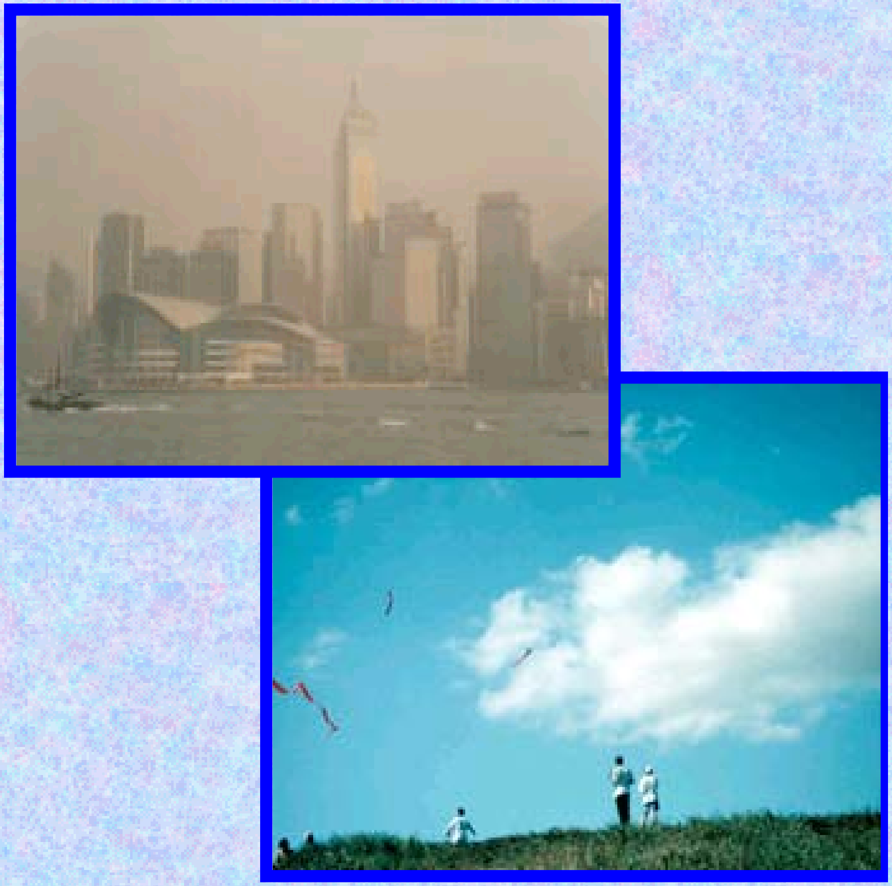
Next Questions

- What are the consequences of Nr accumulation?
- What is projected for future?
- How can science and policy respond?

Nr and Agricultural Ecosystems

- Haber-Bosch has facilitated agricultural intensification
- 40% of world's population is alive because of it
- An additional 3 billion people by 2050 will be sustained by it
- Most N that enters agroecosystems is released to the environment.

Nr and the Atmosphere

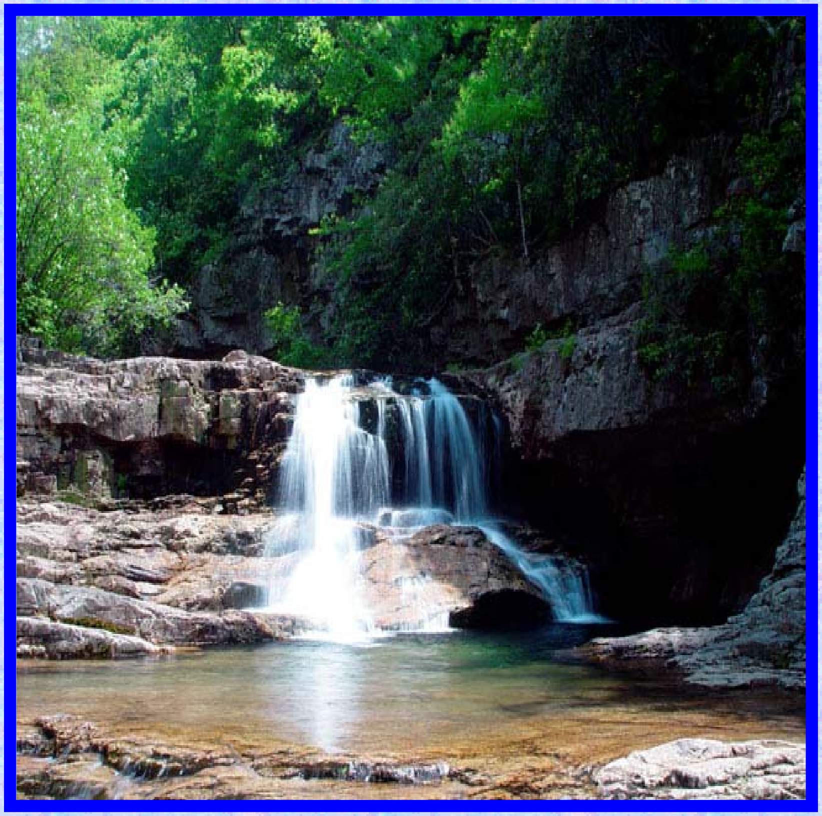


- NO_x emissions contribute to OH, which defines the oxidizing capacity of the atmosphere
- NO_x emissions are responsible for tens of thousands of excess-deaths per year in the United States
- O_3 and N_2O contribute to atmospheric warming
- N_2O emissions contribute to stratospheric O_3 depletion

Nr and Terrestrial Ecosystems

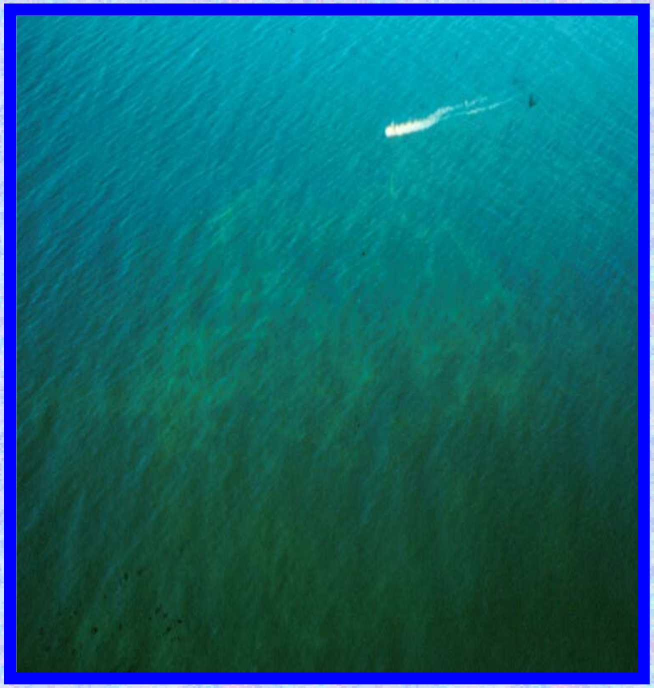
- N is the limiting nutrient in most temperate and polar ecosystems
- Nr deposition increases and then decreases forest and grassland productivity
- Nr additions probably decrease biodiversity across the entire range of deposition

Nr and Freshwater Ecosystems



- Surface water acidification
  - Tens of thousands of lakes and streams
  - Significant biodiversity losses
  - Negative feedbacks to forested ecosystems

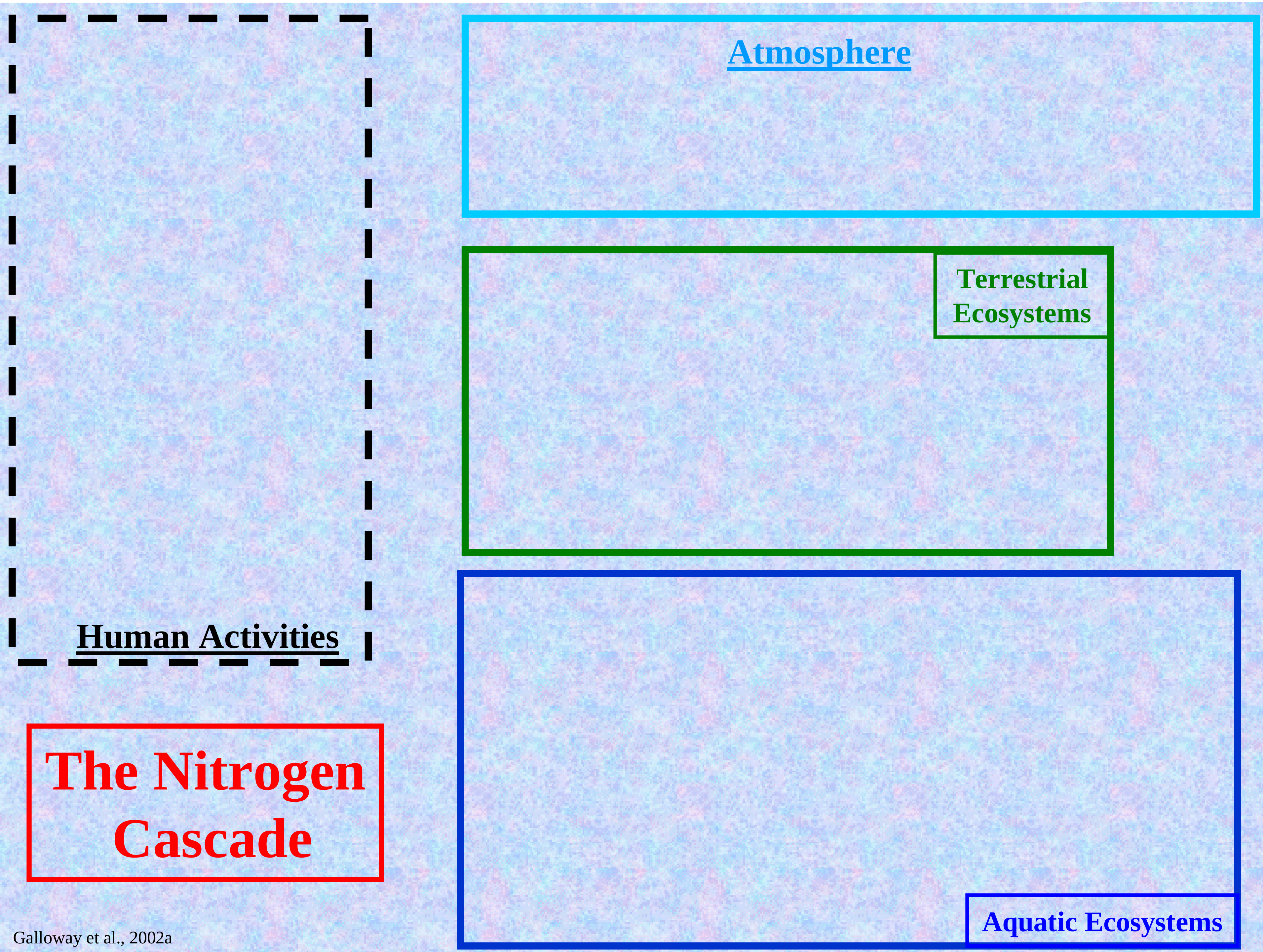
Nr and Coastal Ecosystems

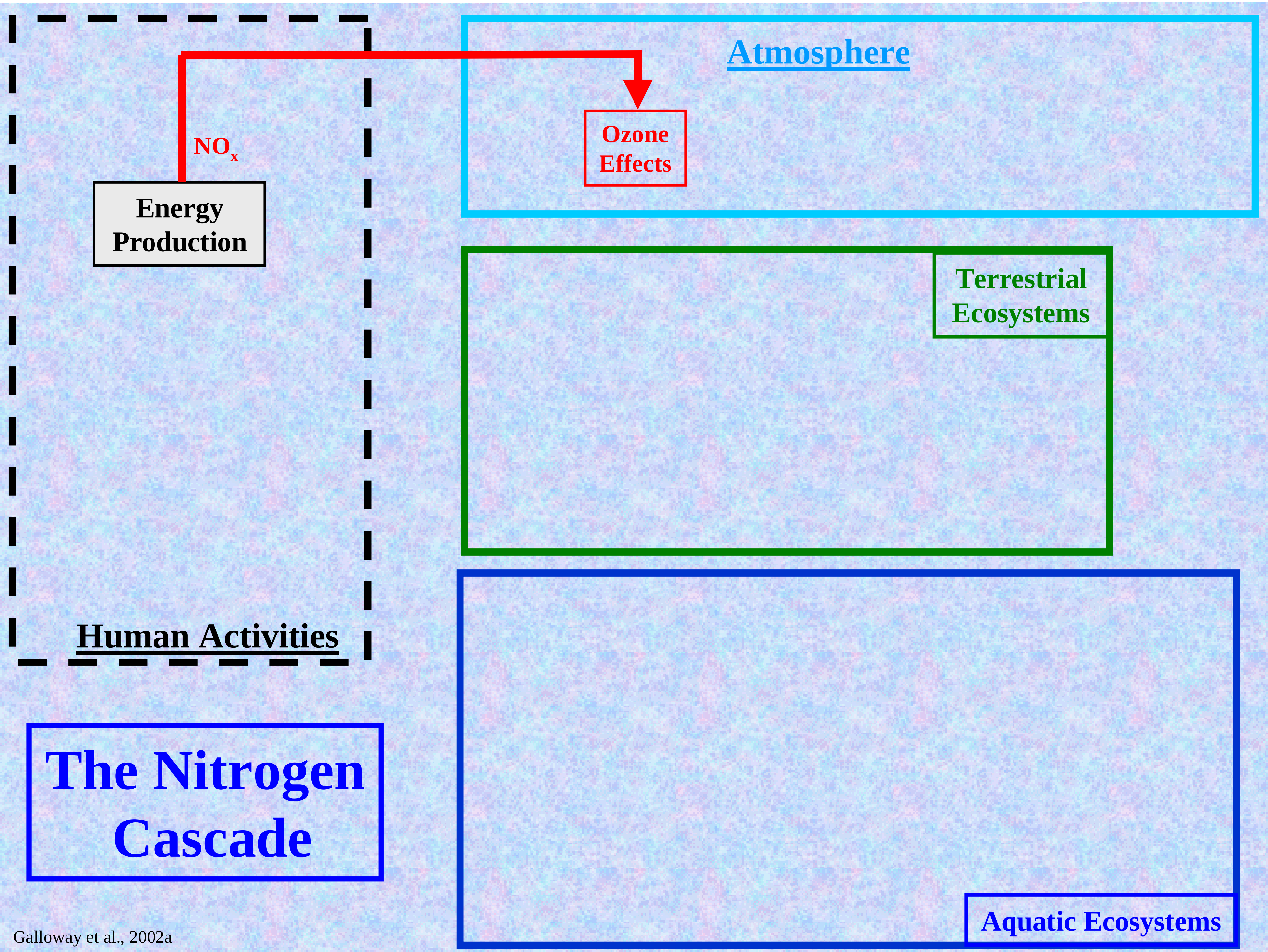


- Riverine and atmospheric deposition are significant Nr sources to coastal systems
- Nr inputs into coastal regions result in eutrophication, biodiversity losses, emissions of N_2O to the atmosphere.
- Most coastal regions are impacted.

There are significant effects of Nr accumulation within each reservoir

These effects are linked temporally and biogeochemically in the Nitrogen Cascade


Atmosphere
Terrestrial Ecosystems
Human Activities
The Nitrogen Cascade
Aquatic Ecosystems
Galloway et al., 2002a


Atmosphere
Ozone Effects
NO_x
Energy Production
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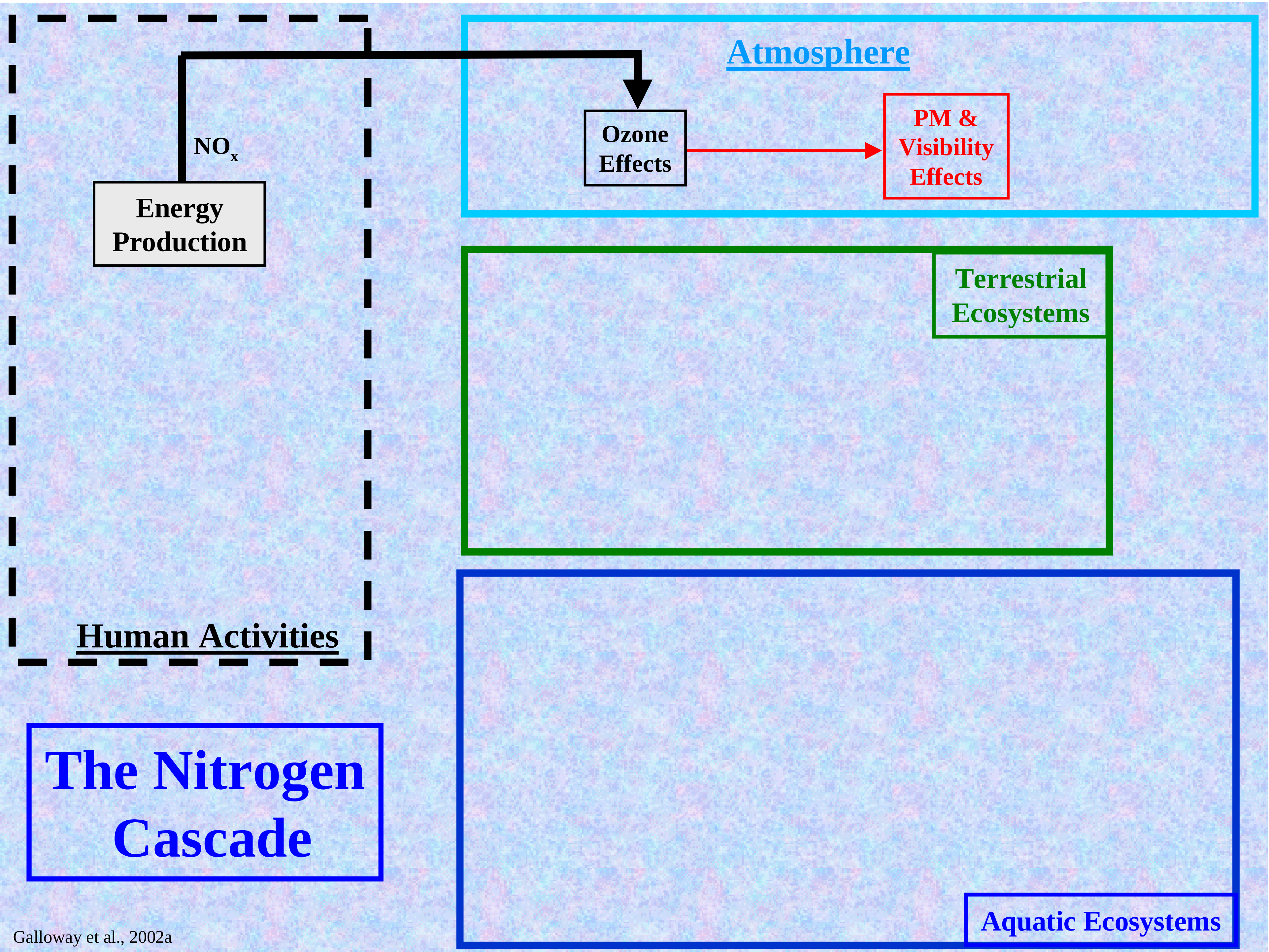

Atmosphere
NOx
Ozone Effects
PM & Visibility Effects
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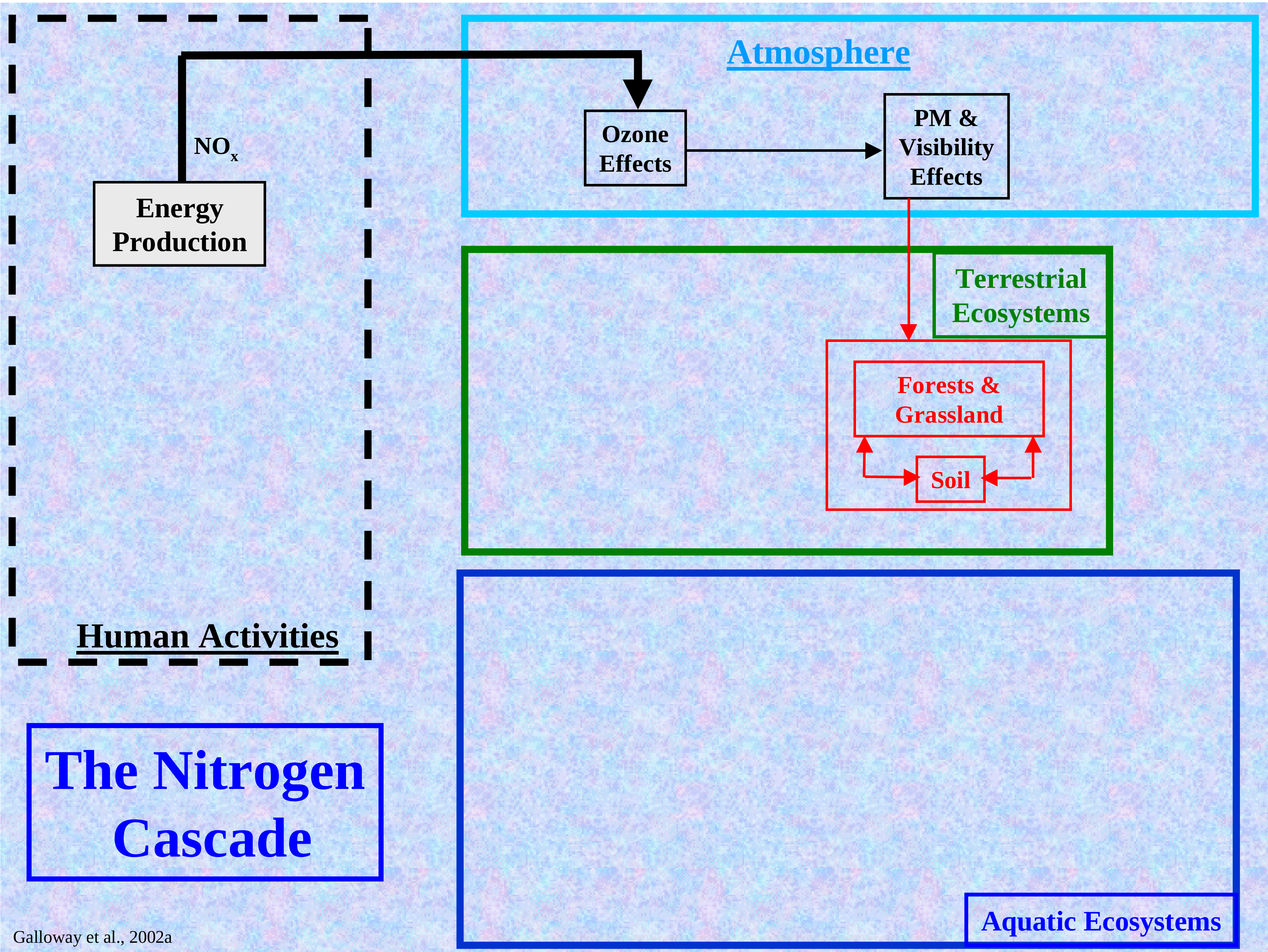

Atmosphere
NO$_x$
Energy Production
Ozone Effects
PM & Visibility Effects
Terrestrial Ecosystems
Forests & Grassland
Soil
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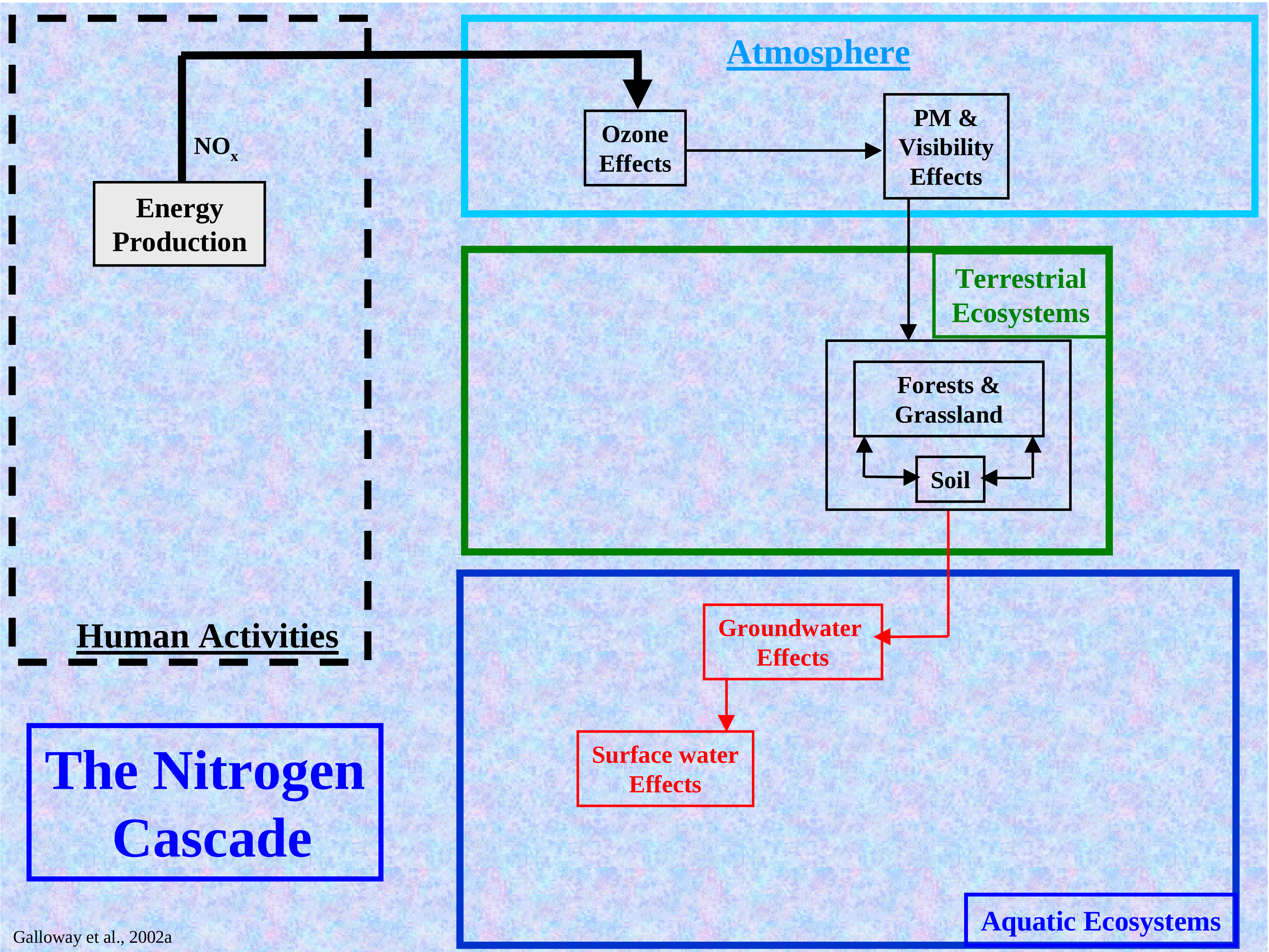
The Nitrogen Cascade
Aquatic Ecosystems
Galloway et al., 2002a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NOx
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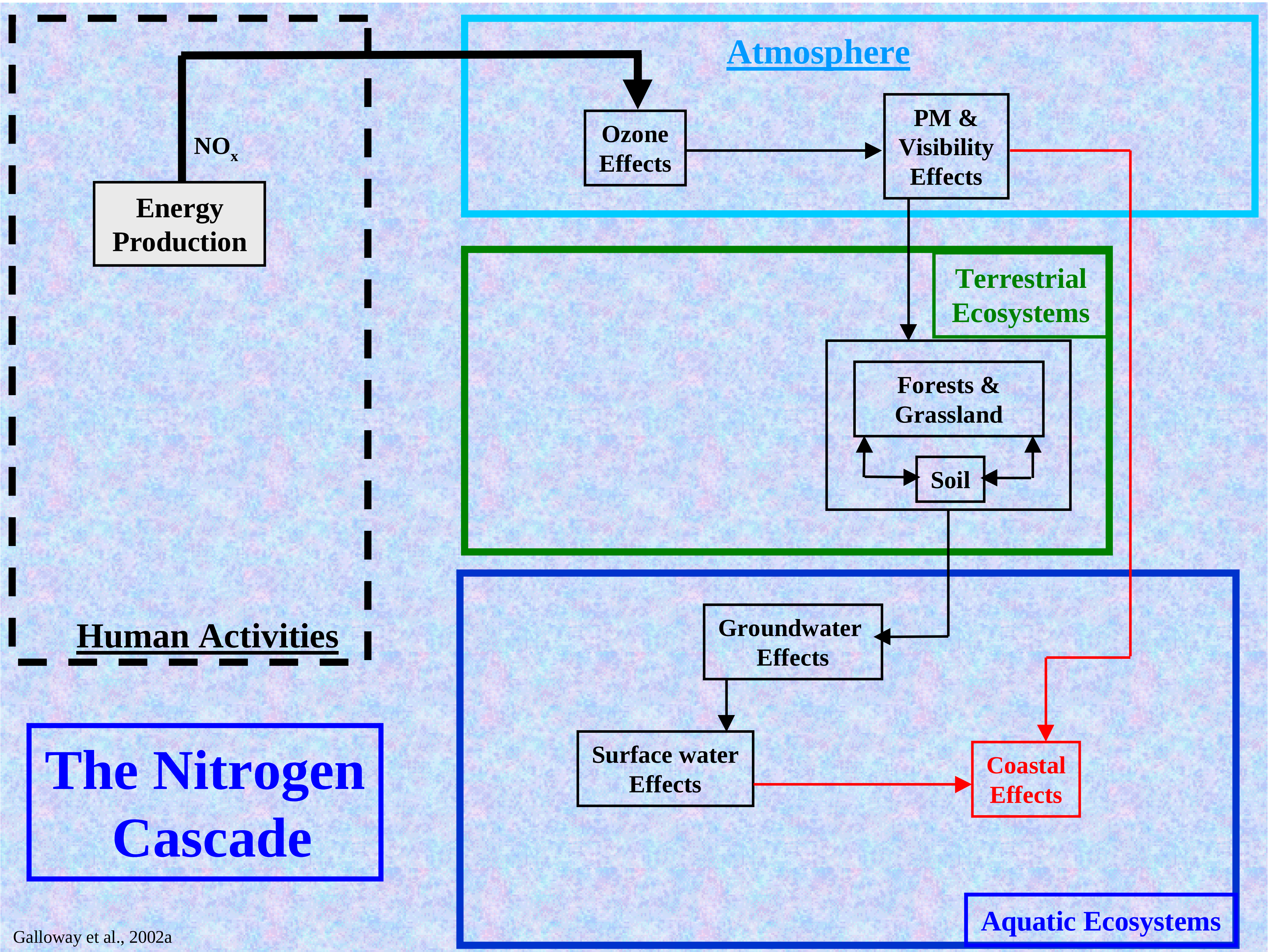
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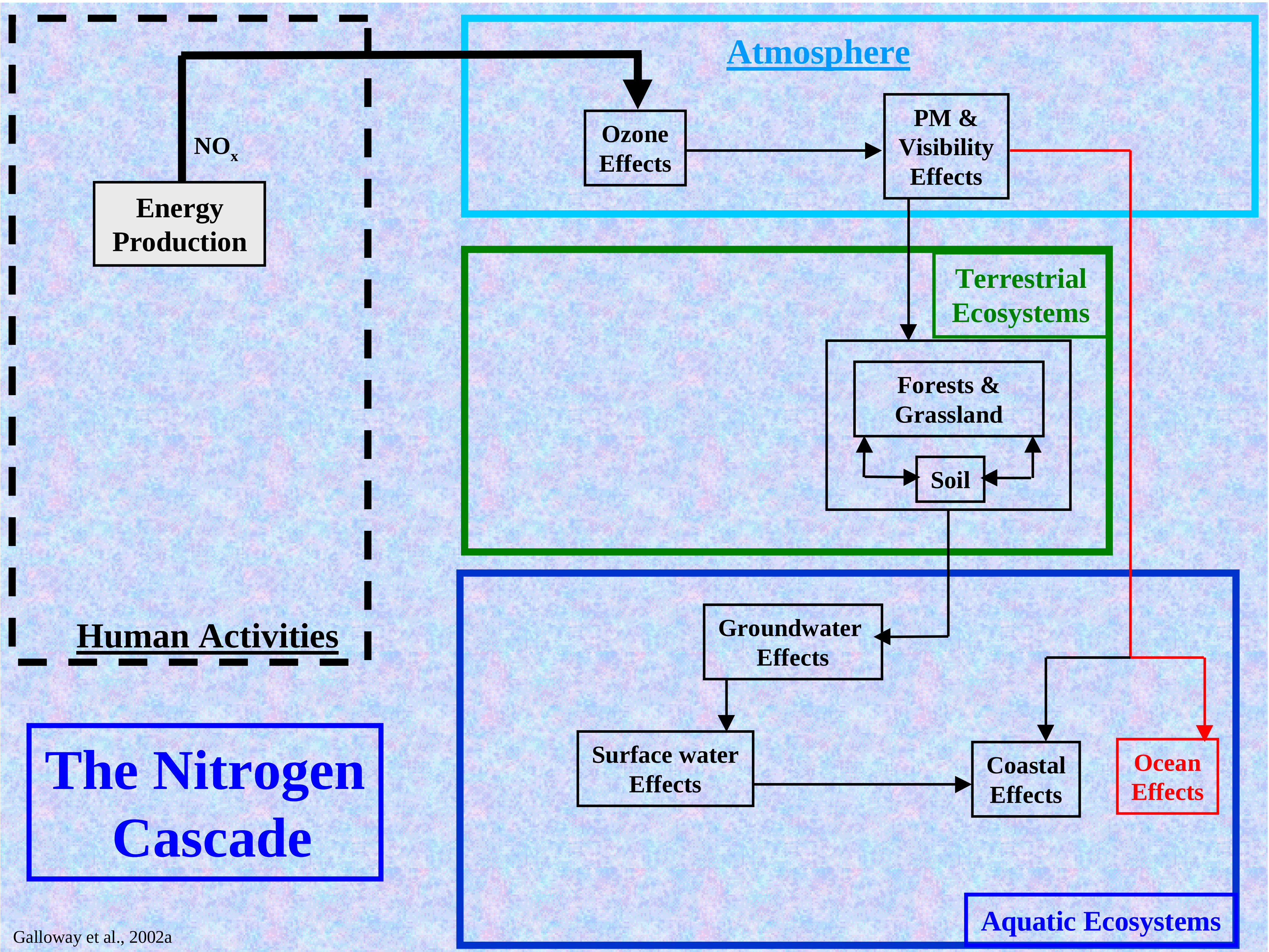

Atmosphere
NOx
Ozone Effects
PM & Visibility Effects
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Terrestrial Ecosystems
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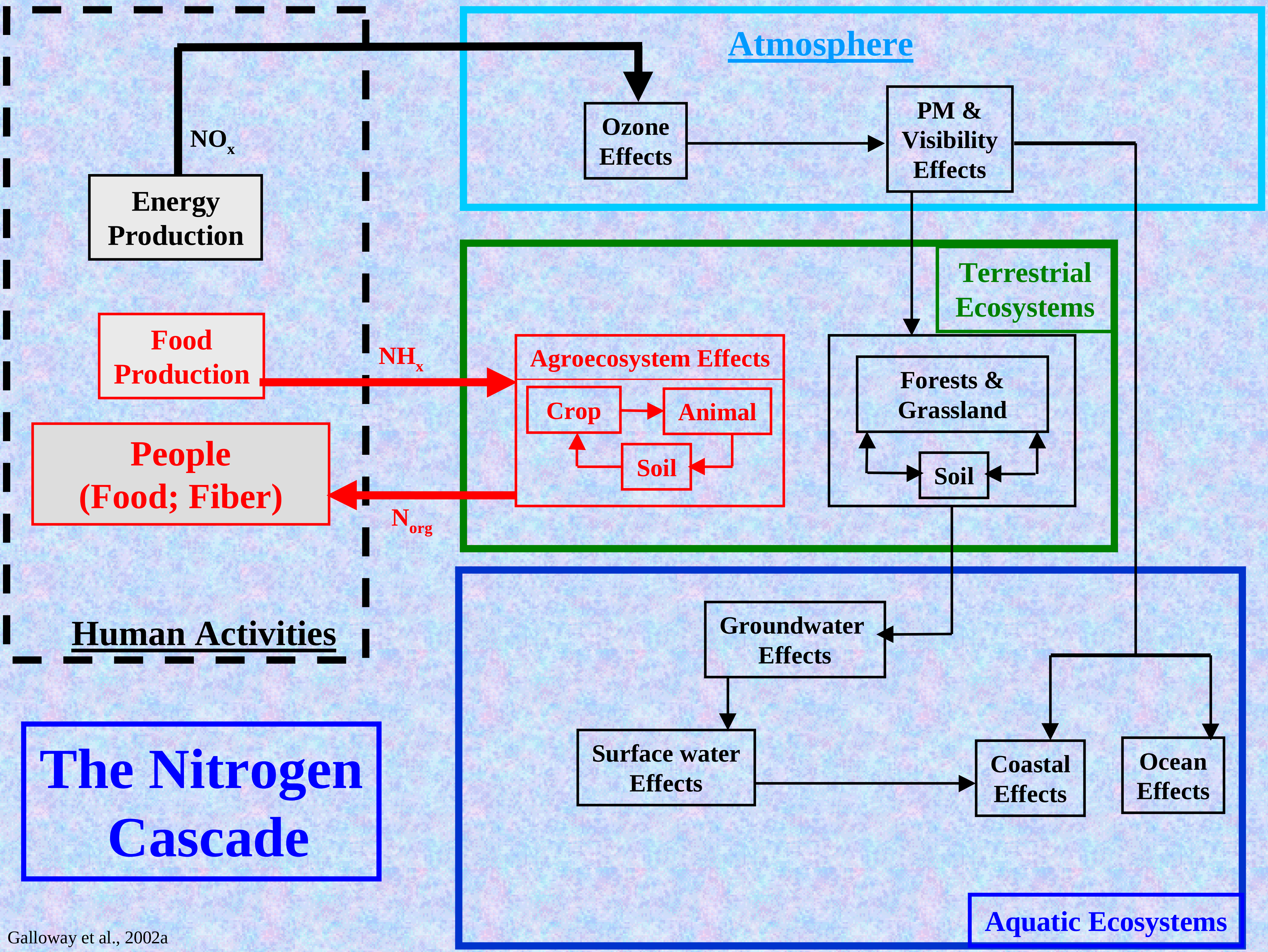
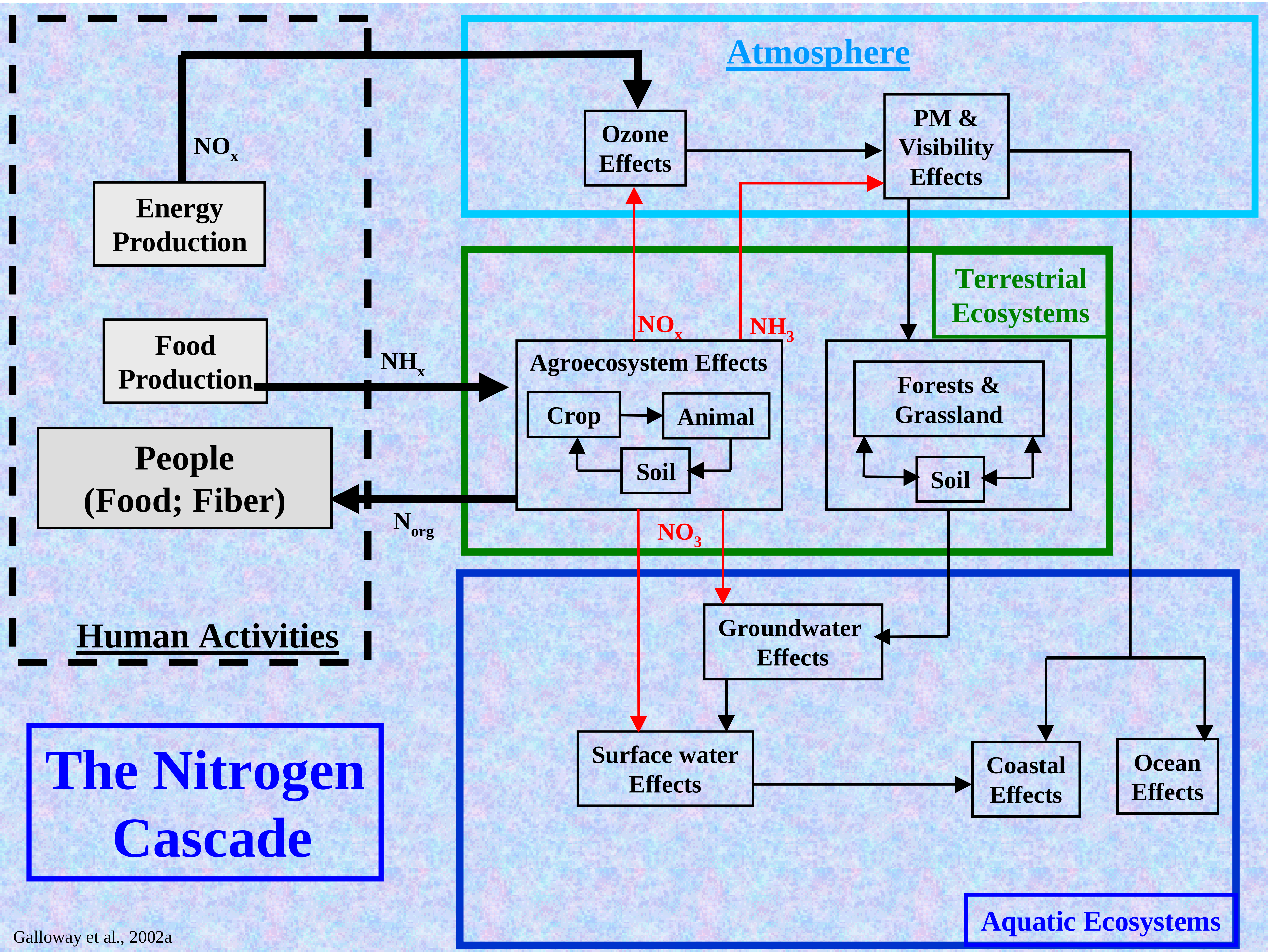
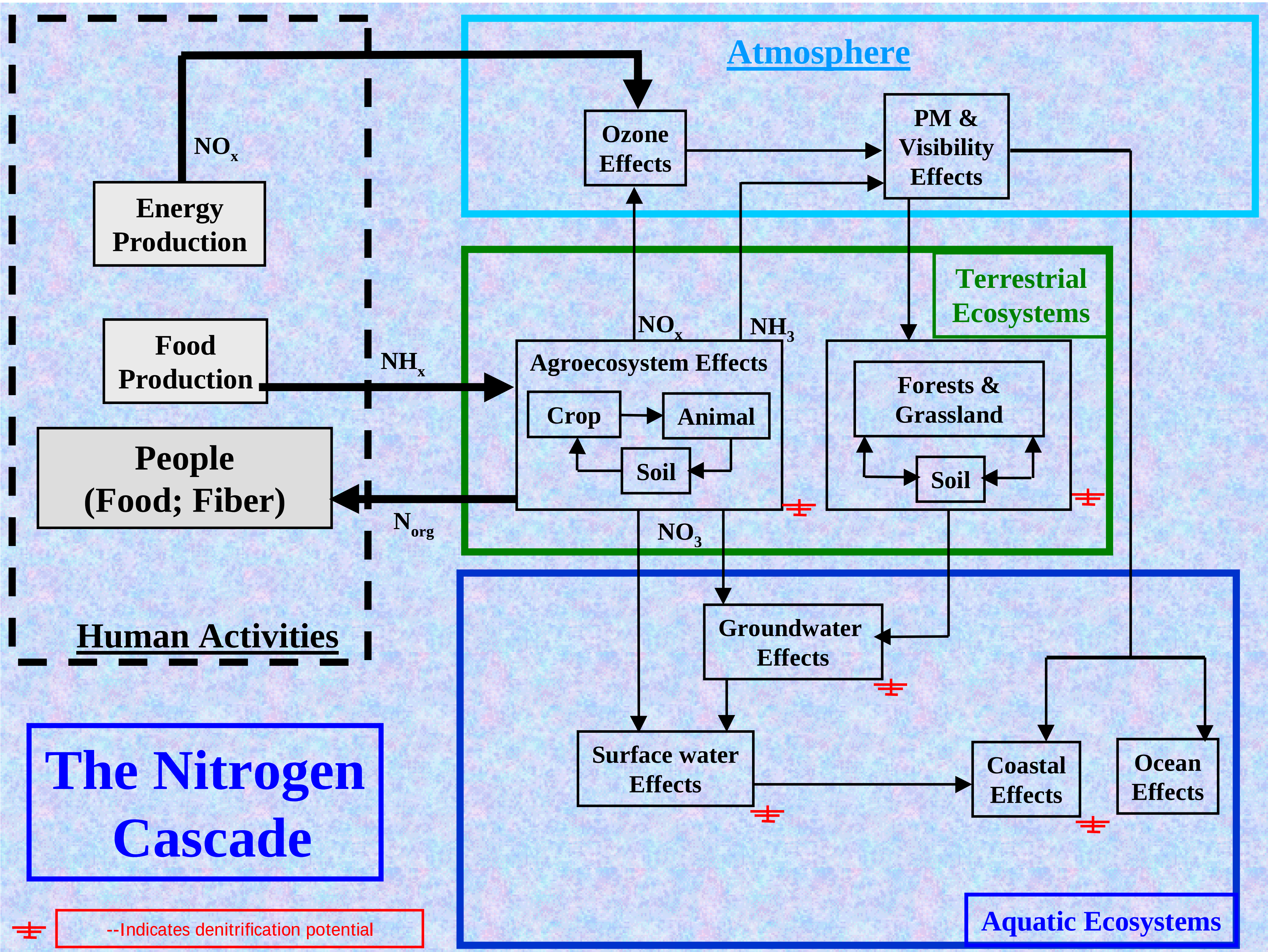


The Nitrogen Cascade

Galloway et al., 2002a



Atmosphere
Ozone Effects
PM & Visibility Effects
NO_x
Energy Production
Food Production
NH_x
People (Food; Fiber)
N_{org}
NO_x
NH_3
Terrestrial Ecosystems
Agroecosystem Effects
Crop
Animal
Soil
Forests & Grassland
Soil
NO_3
Groundwater Effects
Surface water Effects
Coastal Effects
Ocean Effects
Aquatic Ecosystems
Human Activities
The Nitrogen Cascade
Galloway et al., 2002a



Atmosphere
Ozone Effects
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Energy Production
NO$_x$
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Terrestrial Ecosystems
NO$_x$
NH$_3$
Agroecosystem Effects
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Groundwater Effects
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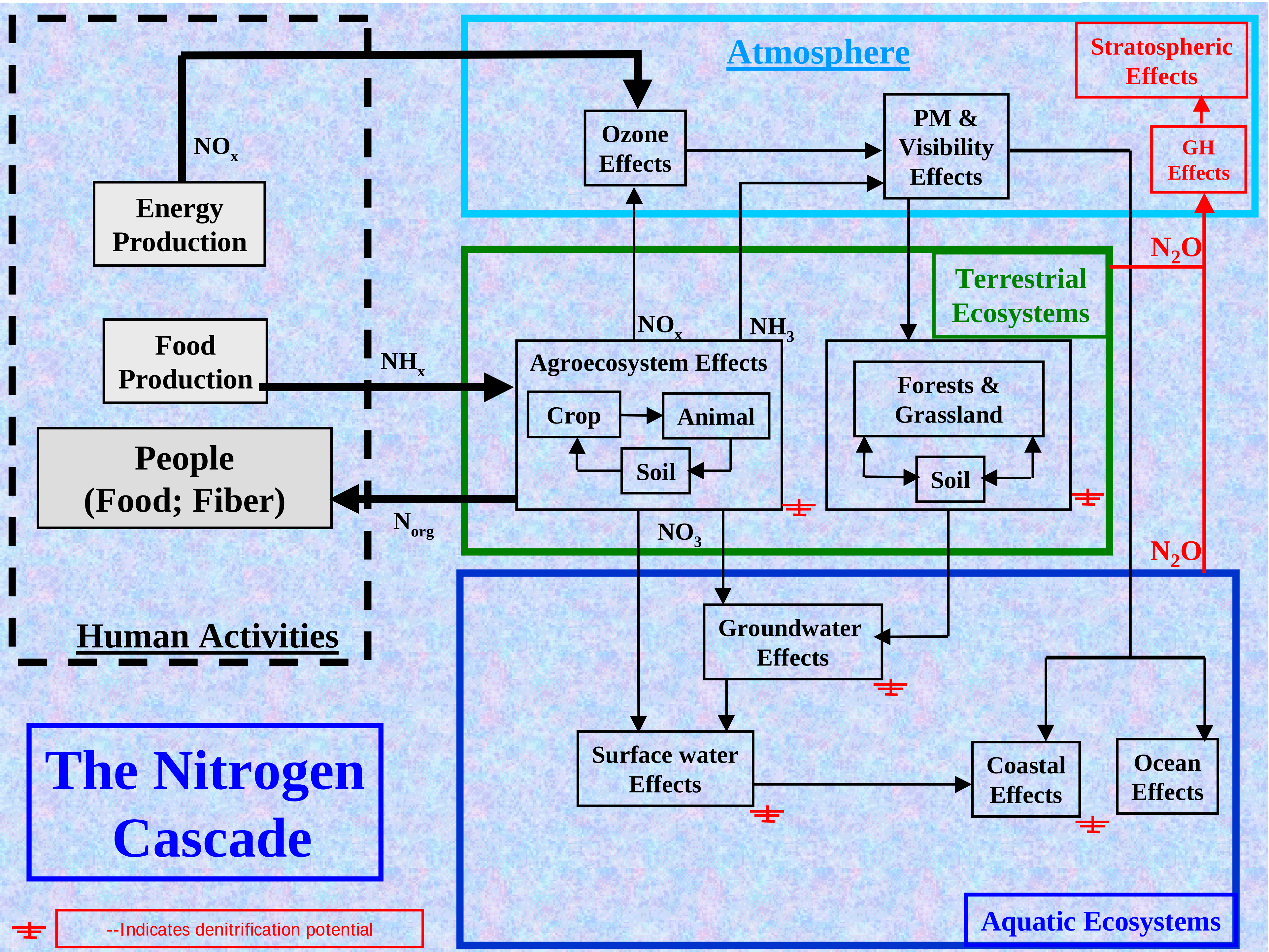
Ocean Effects
Aquatic Ecosystems
The Nitrogen Cascade
--Indicates denitrification potential


Atmosphere
Stratospheric Effects
Ozone Effects
PM & Visibility Effects
GH Effects
NOx
Energy Production
Food Production
NHx
People (Food; Fiber)
Norg
N2O
Terrestrial Ecosystems
NOx
NH3
Agroecosystem Effects
Crop
Animal
Soil
Forests & Grassland
Soil
NO3
N2O
Groundwater Effects
Human Activities
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Surface water Effects
Coastal Effects
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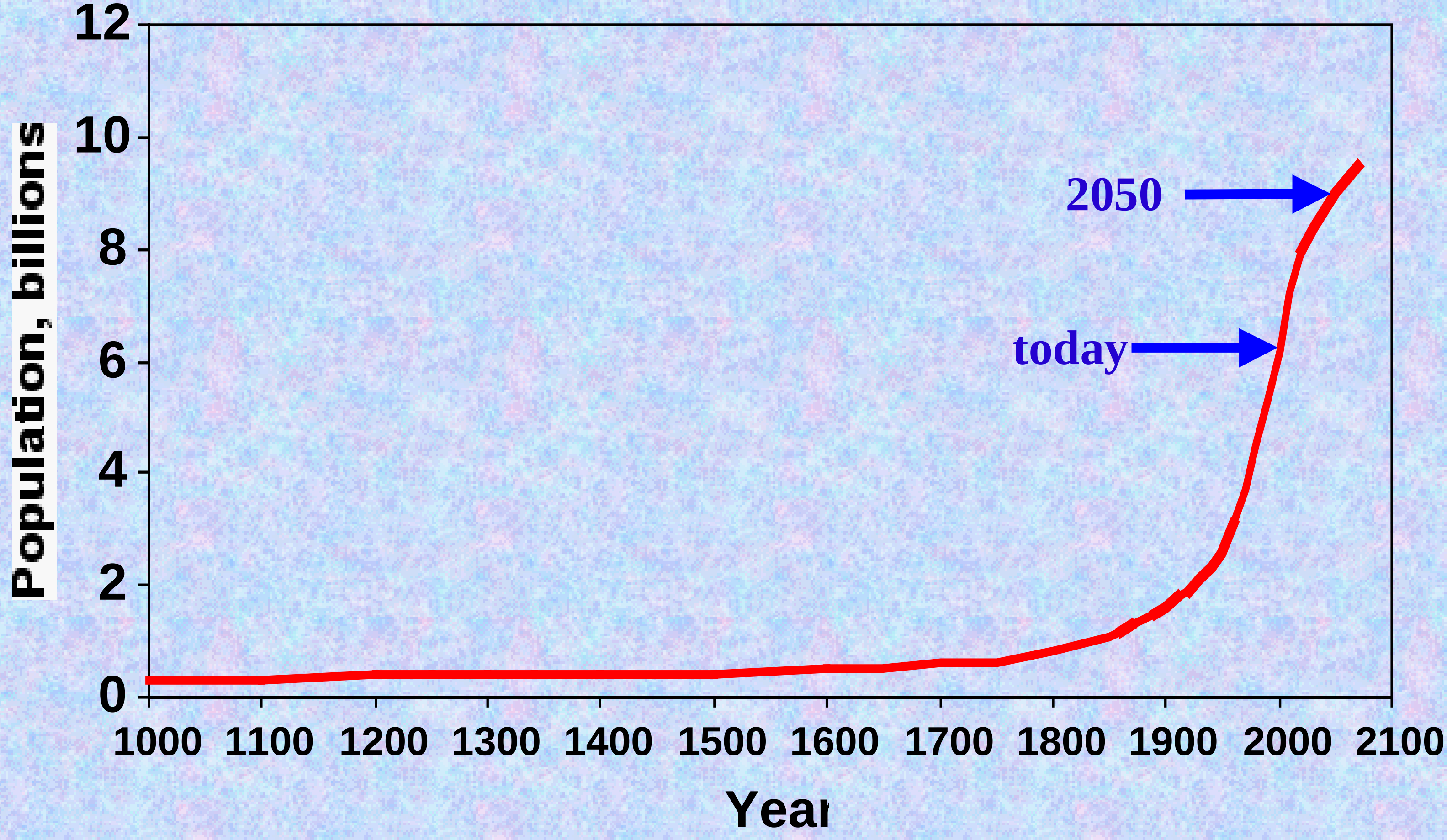
Aquatic Ecosystems
--Indicates denitrification potential

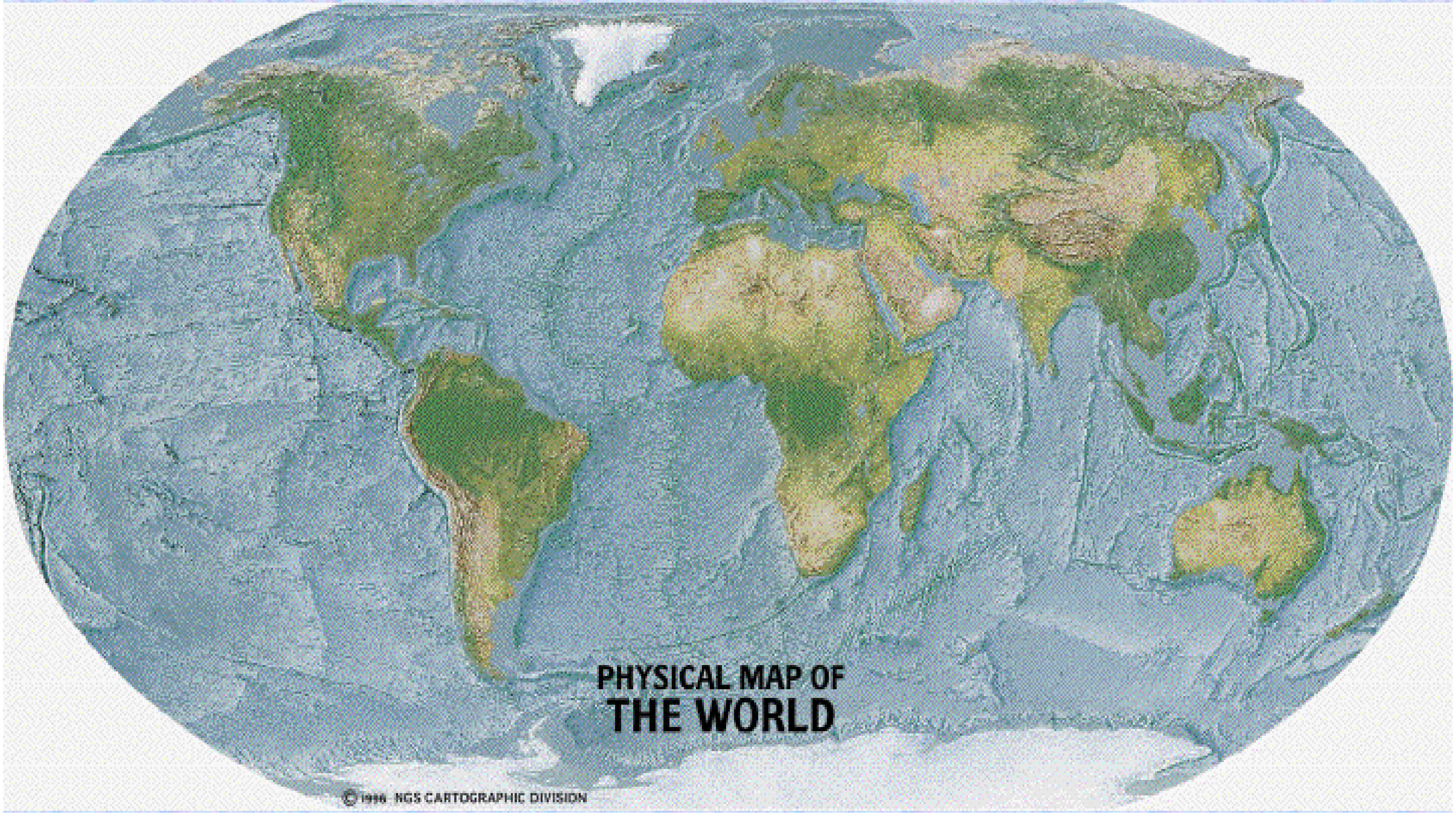
THE BIG PICTURE

- Food and energy production results in creation of ~160 Tg N of new Nr, most of which is released to the environment.
- We know where some of it goes and we generally know what it does when it gets there.
- We do not know:
  - *How much is* <u>*stored*</u> *in ecosystems vs. how much is* <u>*denitrified*</u> *to* N_2*.*
  - *How to* <u>*feed*</u> *and* <u>*fuel*</u> *the global population without releasing excess N to environmental reservoirs.*
- **We know another thing--Nr creation will increase in the future, as will Nr accumulation and an intensification of the N Cascade--but how much?**

Nr Creation Rates by Food and Energy Production in 2050

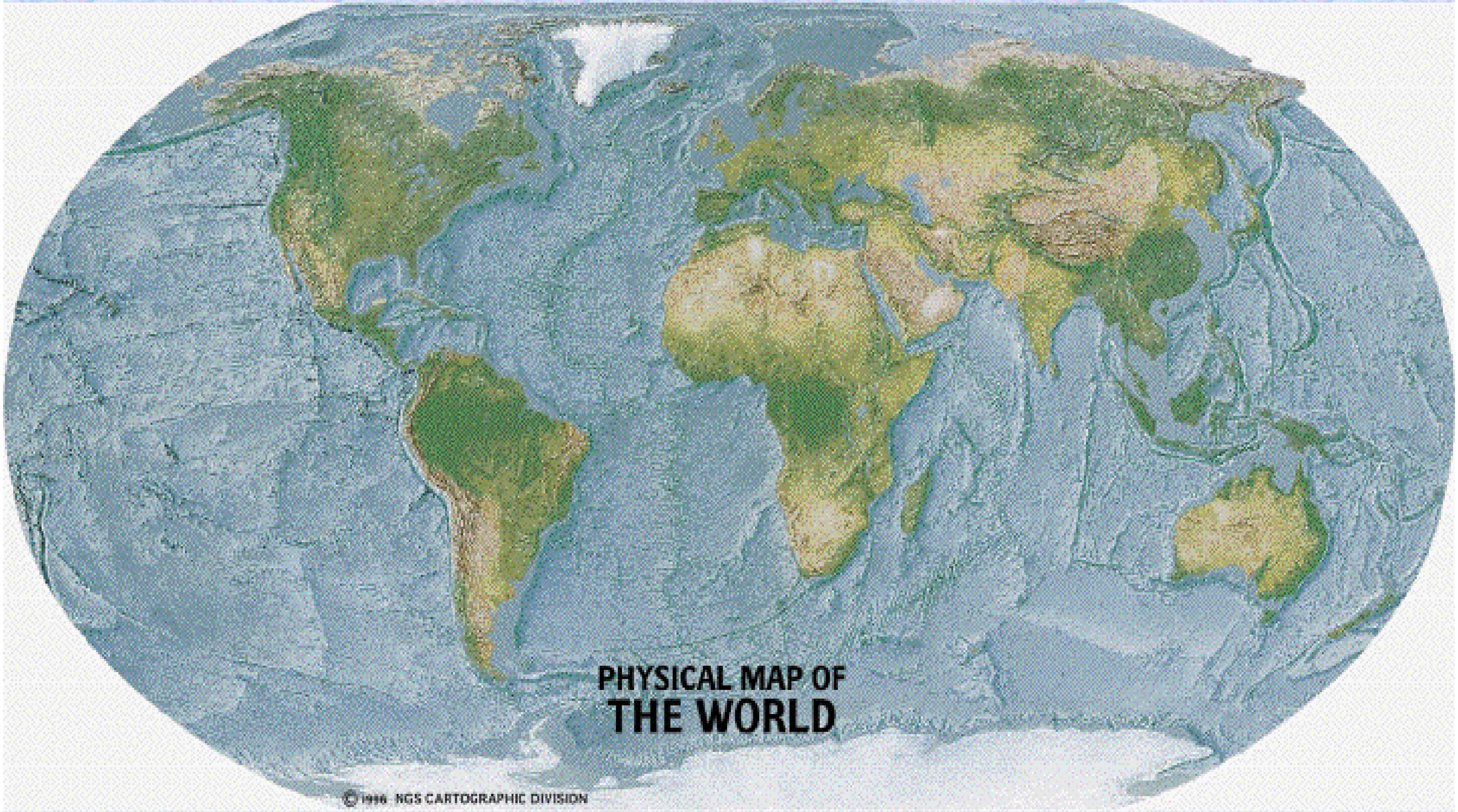


Nr Creation Rates
1995
TgN/yr



Nr Creation Rates
1995 (left) and 2050 (right)

TgN/yr



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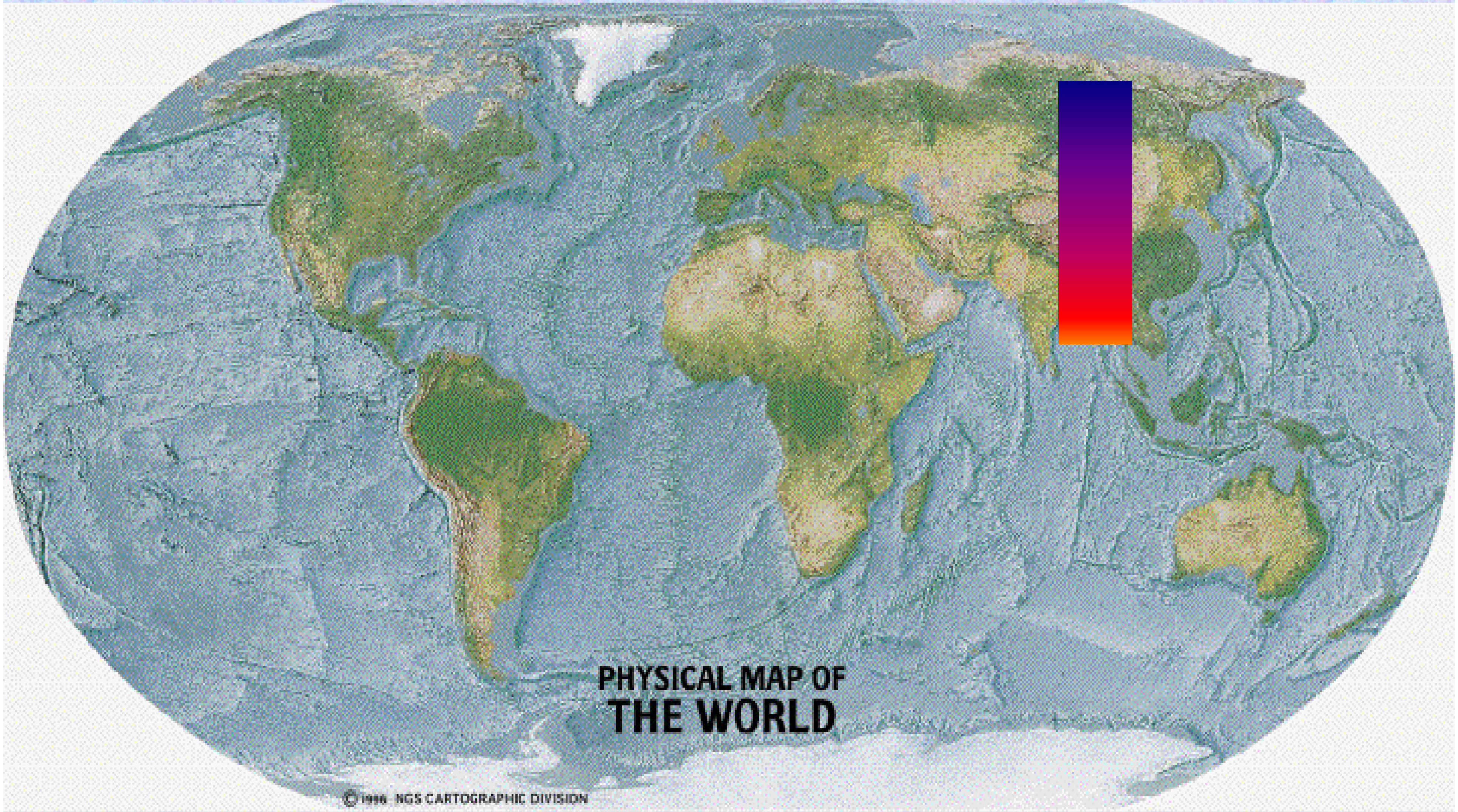
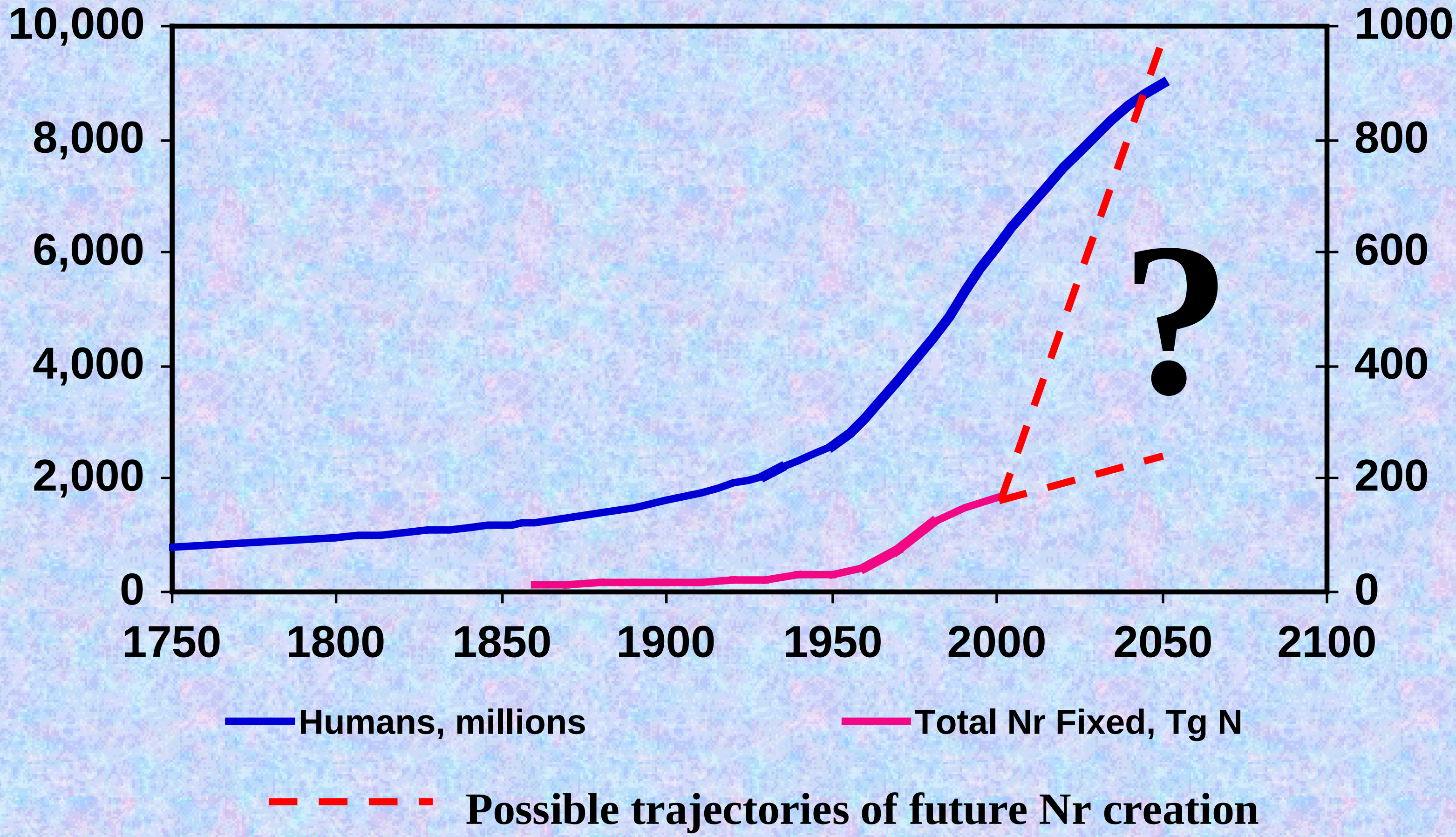


The Future of Nitrogen

--N_r Creation, Total--



after Galloway and Cowling, 2002

The Issues of Nitrogen

- **We need food; we need energy.**
  - **How do we get it without Nr accumulation?**
- **Create less Nr by:**
  - **increasing N use efficiency in food production,**
  - **Reducing NO_x emissions from fossil fuel combustion.**
- **Convert Nr to N_2 before environmental release.**

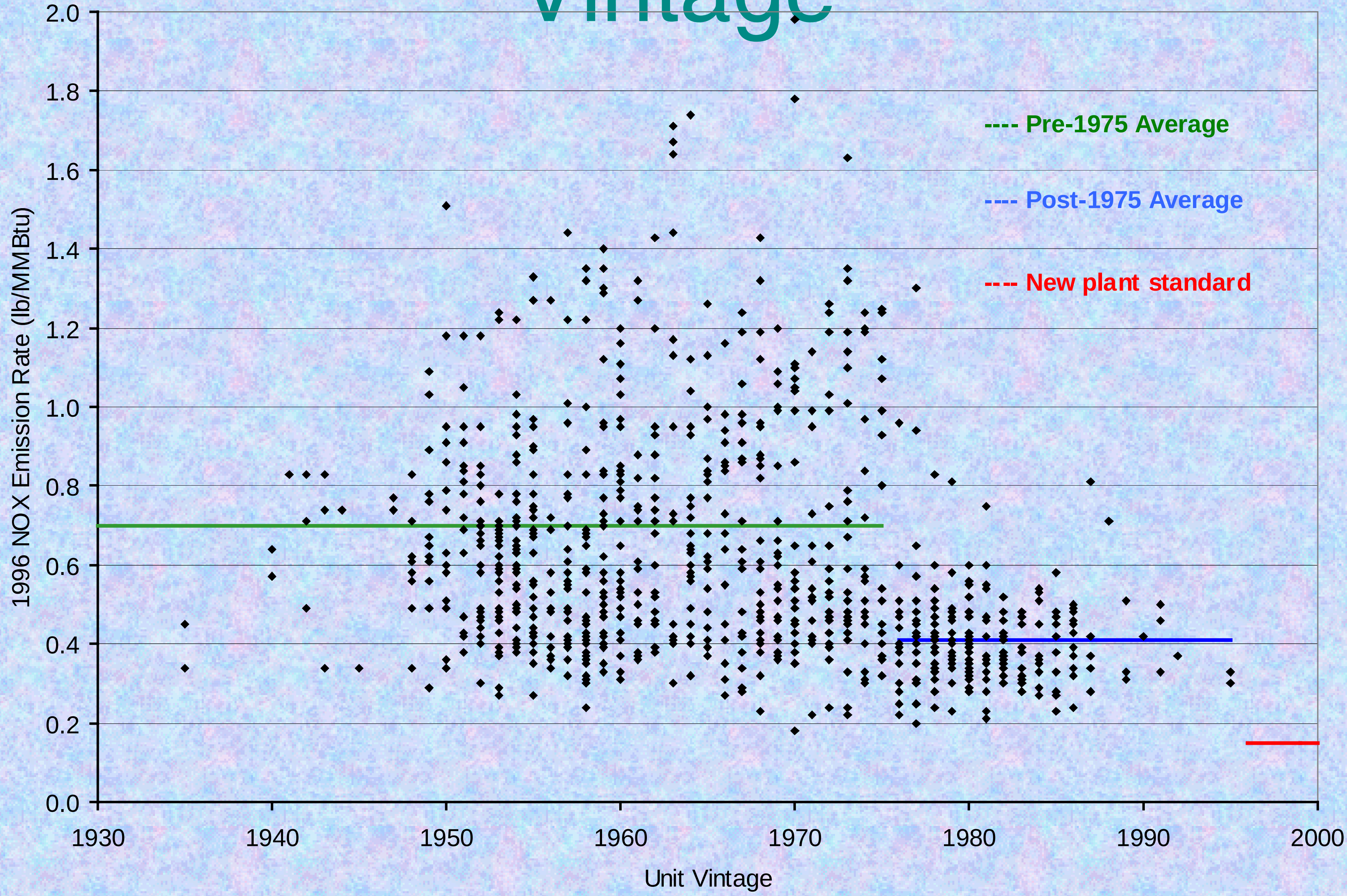
While both are possible, an integrated N management strategy is required.

Maximize food and energy production while maintaining environmental and human health!

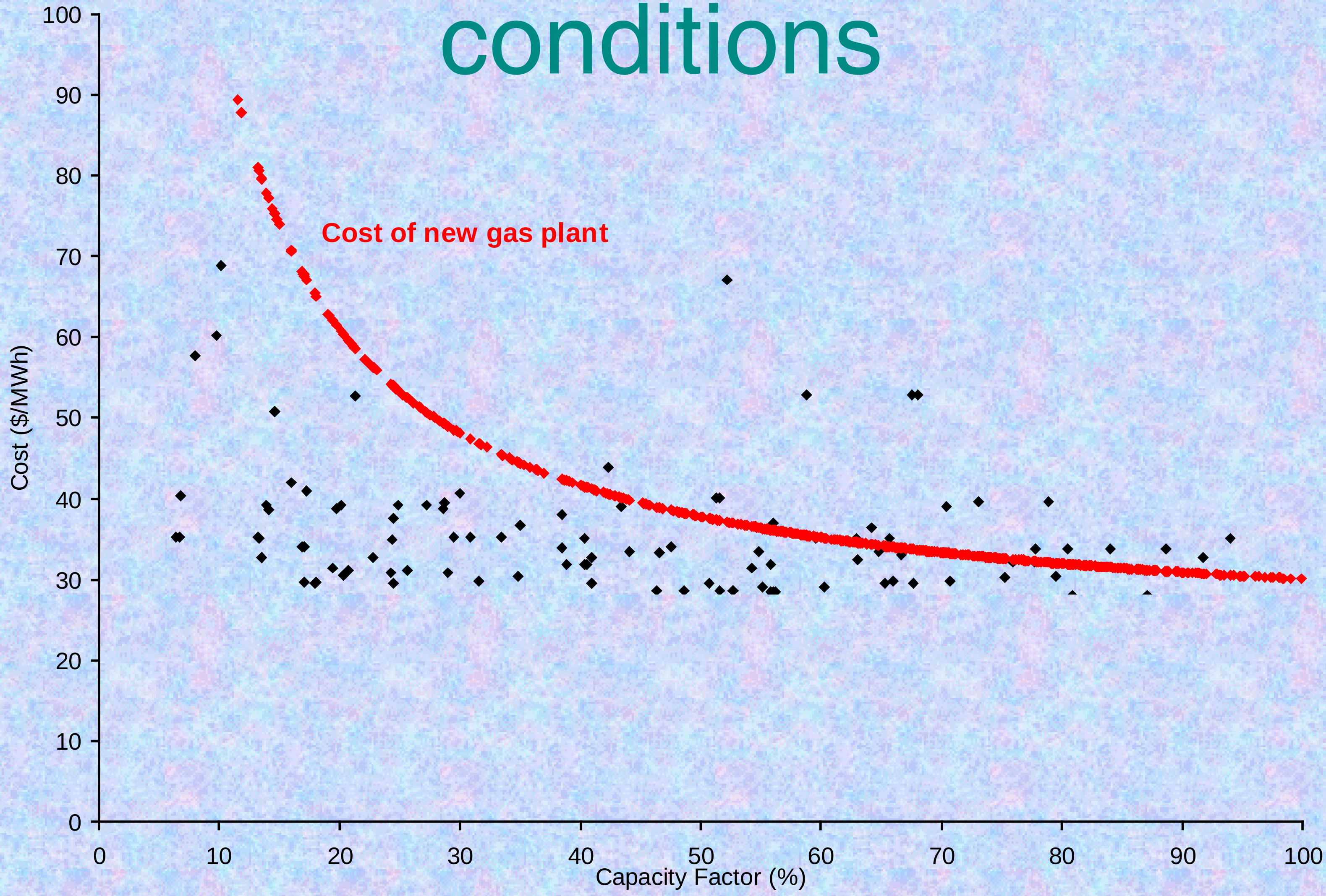
The Clean Air Act

- The Clean Air Act favors existing plants in three ways:
  - In attainment areas, new plants must meet NSPS and PSD; existing plants face no comparable requirements.
  - In non-attainment areas, new plants must meet NSPS and NSR; existing plants face much weaker standards.
  - The SO_2 trading system gives free allowances to existing plants, based on 1980s fuel consumption; others must buy allowances.
- Half of coal plant capacity was built before 1975, a quarter before 1965. More than half of all sulfur emissions nationwide, and a large part of nitrogen emissions, come from pre-1975 coal plants.

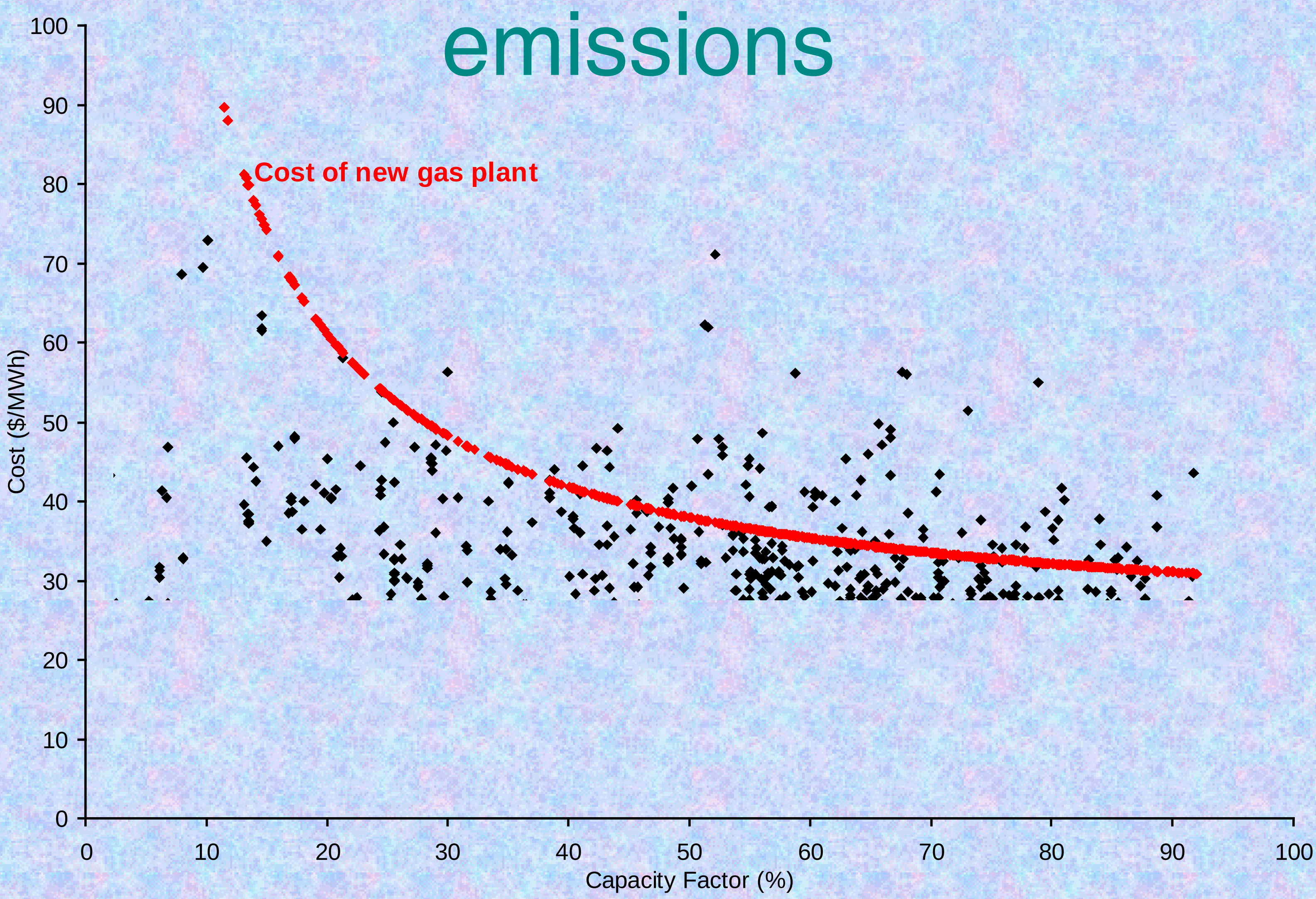
1996 NO_x Emissions by Vintage



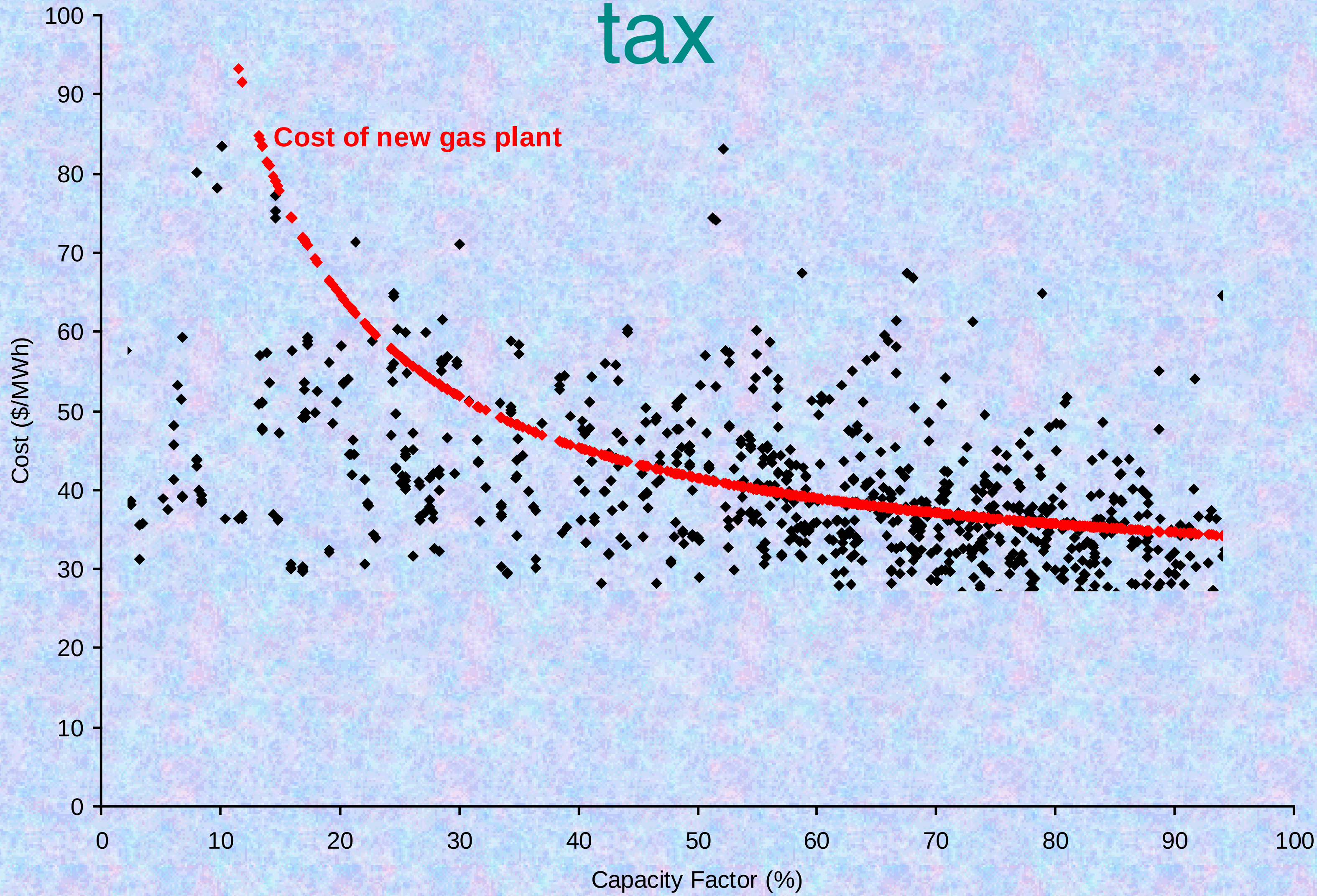
Coal vs. gas: current conditions



Coal vs. gas: Comparable emissions

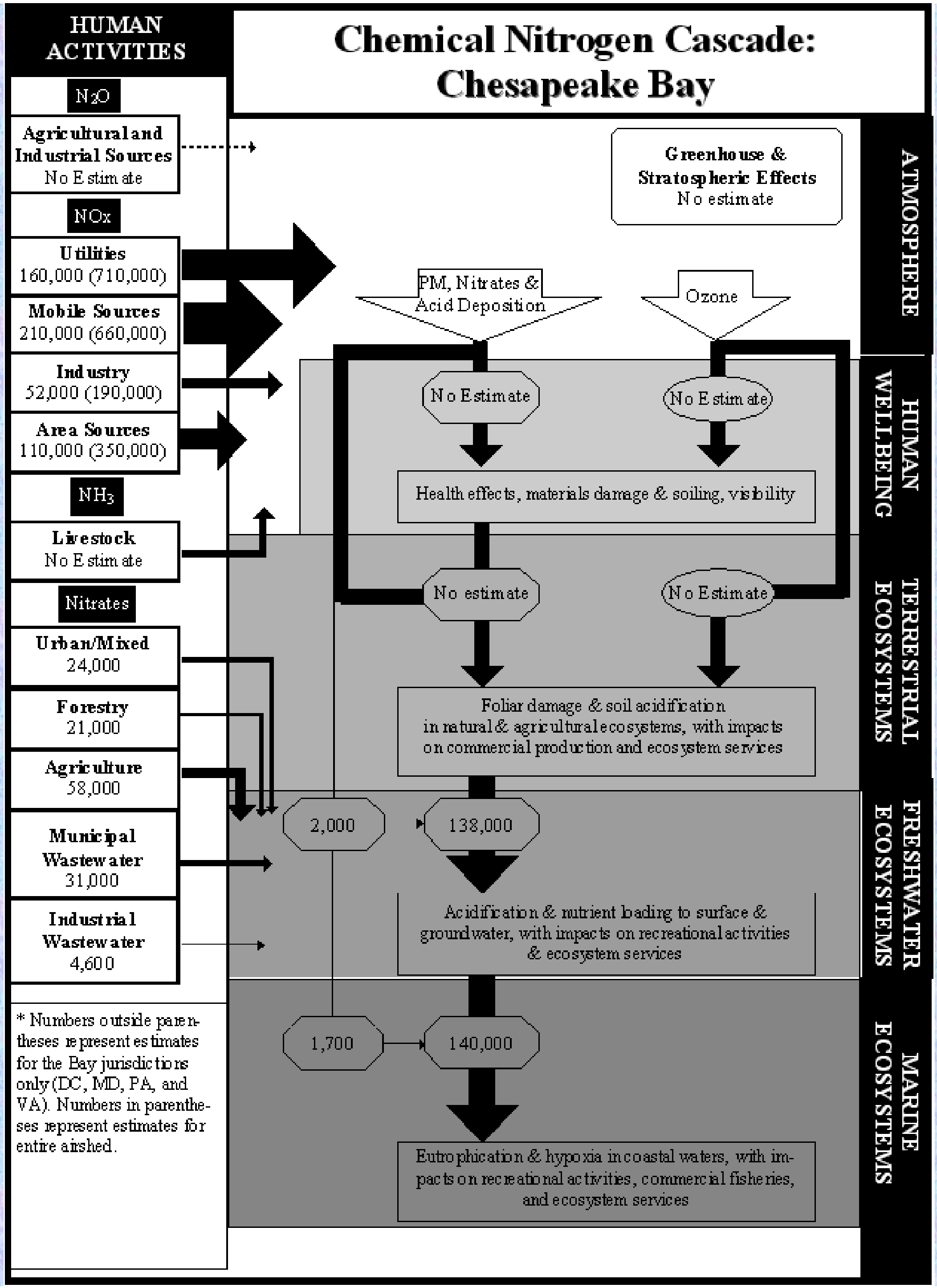


Comparable emissions plus CO_2 tax

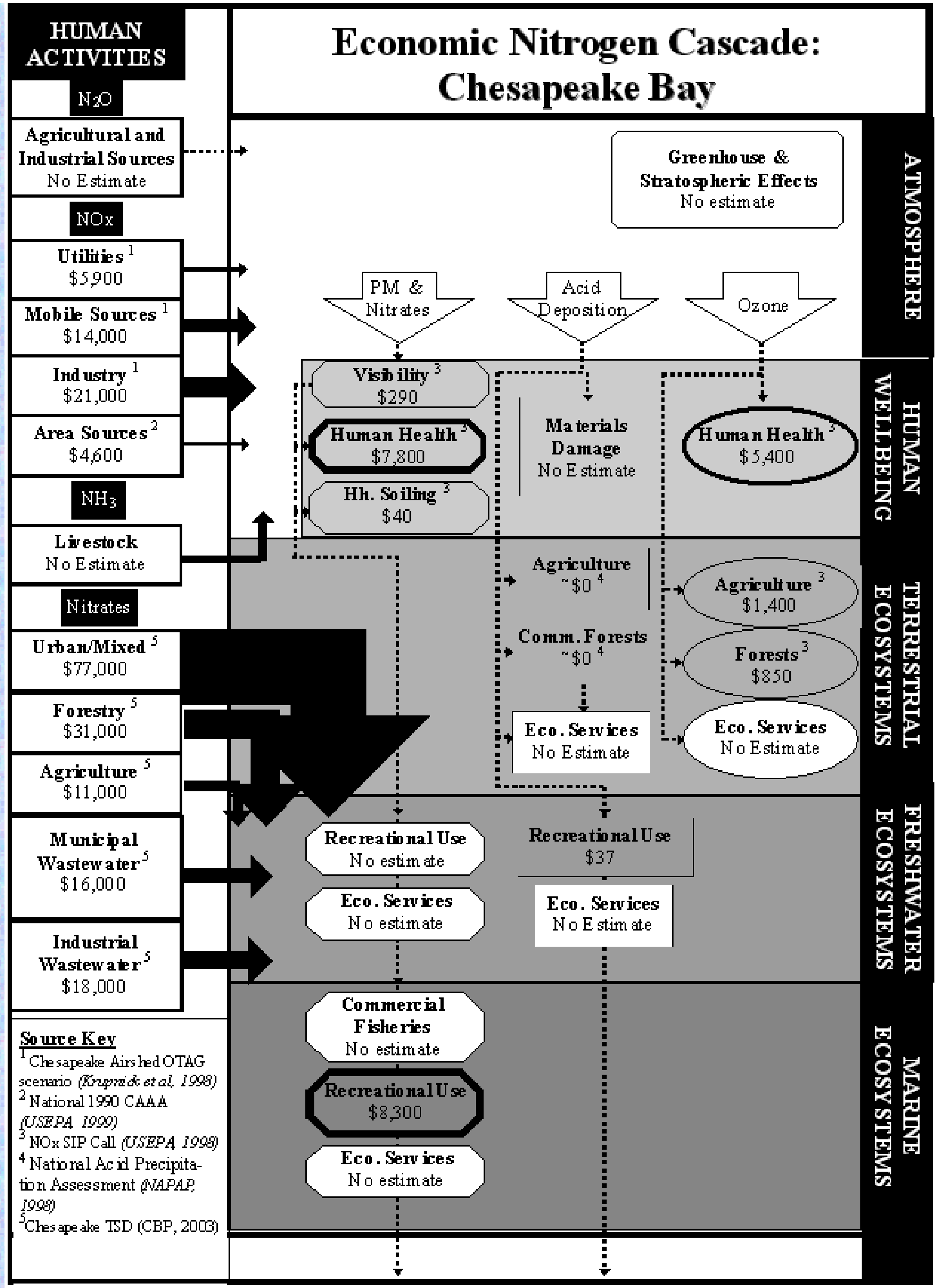


The economics of coal plants

- No one wants to build a new coal plant -- and no one wants to close an old one.
- The key cost comparison: how do *operating costs* of existing coal plants compare to *capital plus operating costs* of a new gas combined cycle plant?
- Three versions of this comparison:
  - Current conditions: > 99% of coal is cheaper than gas.
  - Comparable emissions scenario (meeting new plant standards industry-wide): 94% of coal remains cheaper than gas.
  - Comparable emissions plus \$10/ton CO_2 tax: 64% of coal remains competitive.

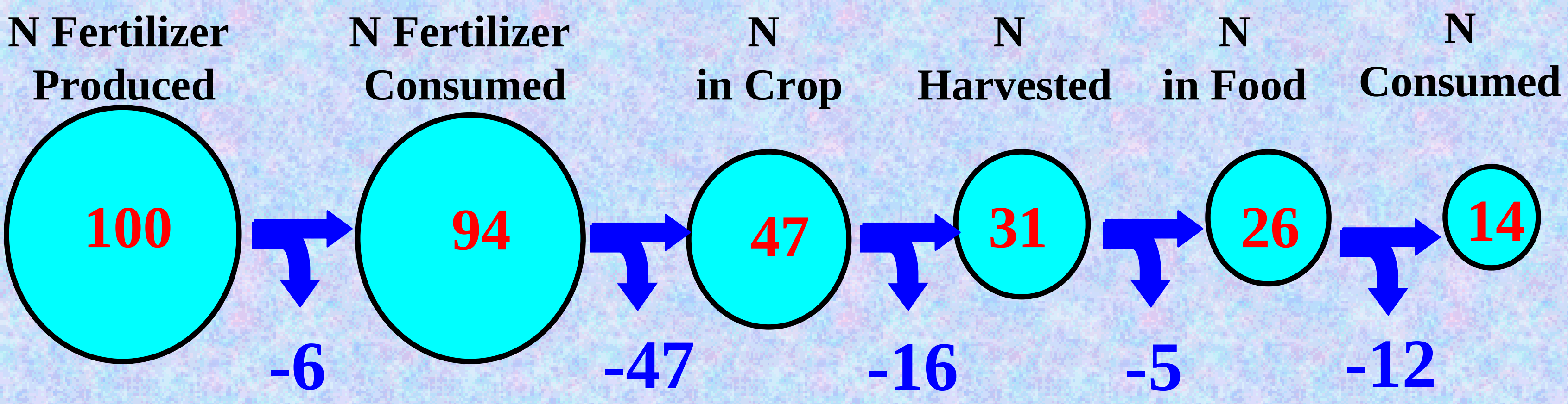


HUMAN ACTIVITIES
Chemical Nitrogen Cascade: Chesapeake Bay
N_2O
Agricultural and Industrial Sources
No Estimate
NOx
Utilities
160,000 (710,000)
Mobile Sources
210,000 (660,000)
Industry
52,000 (190,000)
Area Sources
110,000 (350,000)
NH_3
Livestock
No Estimate
Nitrates
Urban/Mixed
24,000
Forestry
21,000
Agriculture
58,000
Municipal Wastewater
31,000
Industrial Wastewater
4,600
* Numbers outside parentheses represent estimates for the Bay jurisdictions only (DC, MD, PA, and VA). Numbers in parentheses represent estimates for entire airshed.
Greenhouse & Stratospheric Effects
No estimate
PM, Nitrates & Acid Deposition
Ozone
No Estimate
No Estimate
Health effects, materials damage & soiling, visibility
No estimate
No Estimate
Foliar damage & soil acidification in natural & agricultural ecosystems, with impacts on commercial production and ecosystem services
2,000
138,000
Acidification & nutrient loading to surface & groundwater, with impacts on recreational activities & ecosystem services
1,700
140,000
Eutrophication & hypoxia in coastal waters, with impacts on recreational activities, commercial fisheries, and ecosystem services
ATMOSPHERE
HUMAN WELLBEING
TERRESTRIAL ECOSYSTEMS
FRESHWATER ECOSYSTEMS
MARINE ECOSYSTEMS



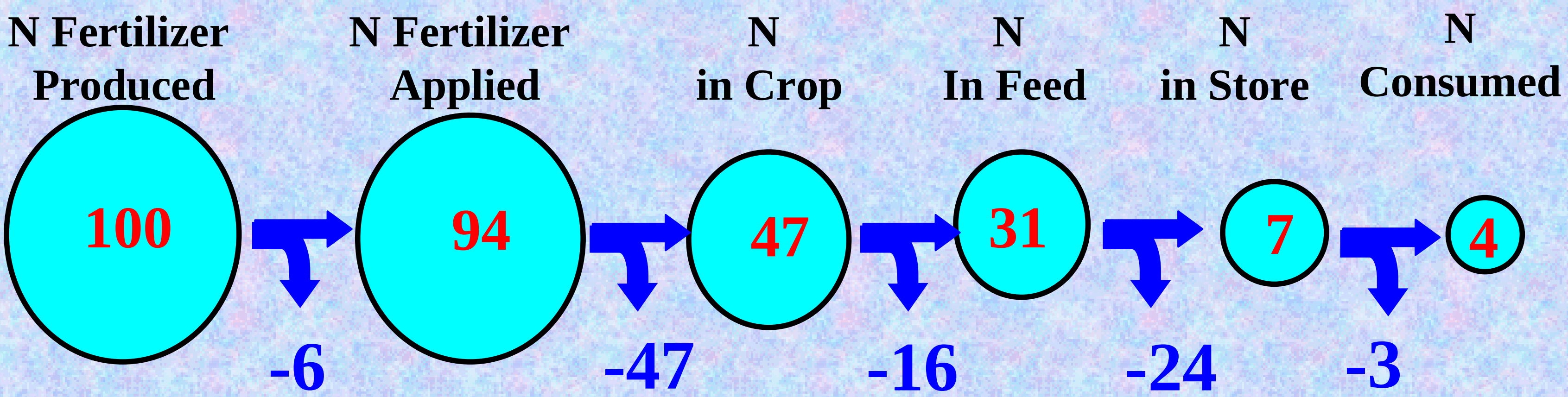
Economic Nitrogen Cascade: Chesapeake Bay
HUMAN ACTIVITIES
N2O
Agricultural and Industrial Sources
No Estimate
NOx
Utilities [1]
$5,900
Mobile Sources [1]
$14,000
Industry [1]
$21,000
Area Sources [2]
$4,600
NH3
Livestock
No Estimate
Nitrates
Urban/Mixed [5]
$77,000
Forestry [5]
$31,000
Agriculture [5]
$11,000
Municipal Wastewater [5]
$16,000
Industrial Wastewater [5]
$18,000
Source Key
[1] Chesapeake Airshed OTAG scenario (Krupnick et al, 1998)
[2] National 1990 CAAA (USEPA 1999)
[3] NOx SIP Call (USEPA 1998)
[4] National Acid Precipitation Assessment (NAPAP, 1998)
[5] Chesapeake TSD (CBP, 2003)
ATMOSPHERE
Greenhouse & Stratospheric Effects
No estimate
PM & Nitrates
Acid Deposition
Ozone
HUMAN WELL BEING
Visibility [3]
$290
Human Health [3]
$7,800
Hh. Soiling [3]
$40
Materials Damage
No Estimate
Human Health [3]
$5,400
TERRESTRIAL ECOSYSTEMS
Agriculture
~$0 [4]
Comm. Forests
~$0 [4]
Eco. Services
No Estimate
Agriculture [3]
$1,400
Forests [3]
$850
Eco. Services
No Estimate
FRESHWATER ECOSYSTEMS
Recreational Use
No estimate
Eco. Services
No estimate
Recreational Use
$37
Eco. Services
No Estimate
MARINE ECOSYSTEMS
Commercial Fisheries
No estimate
Recreational Use
$8,300
Eco. Services
No estimate

The Fate of Haber-Bosch Nitrogen



14% of the N produced in the Haber-Bosch process enters the human mouth……….if you are a vegetarian.

The Fate of Haber-Bosch Nitrogen



4% of the N produced in the Haber-Bosch process and used for animal production enters the human mouth.