Integrated Industrial-Ecological Systems

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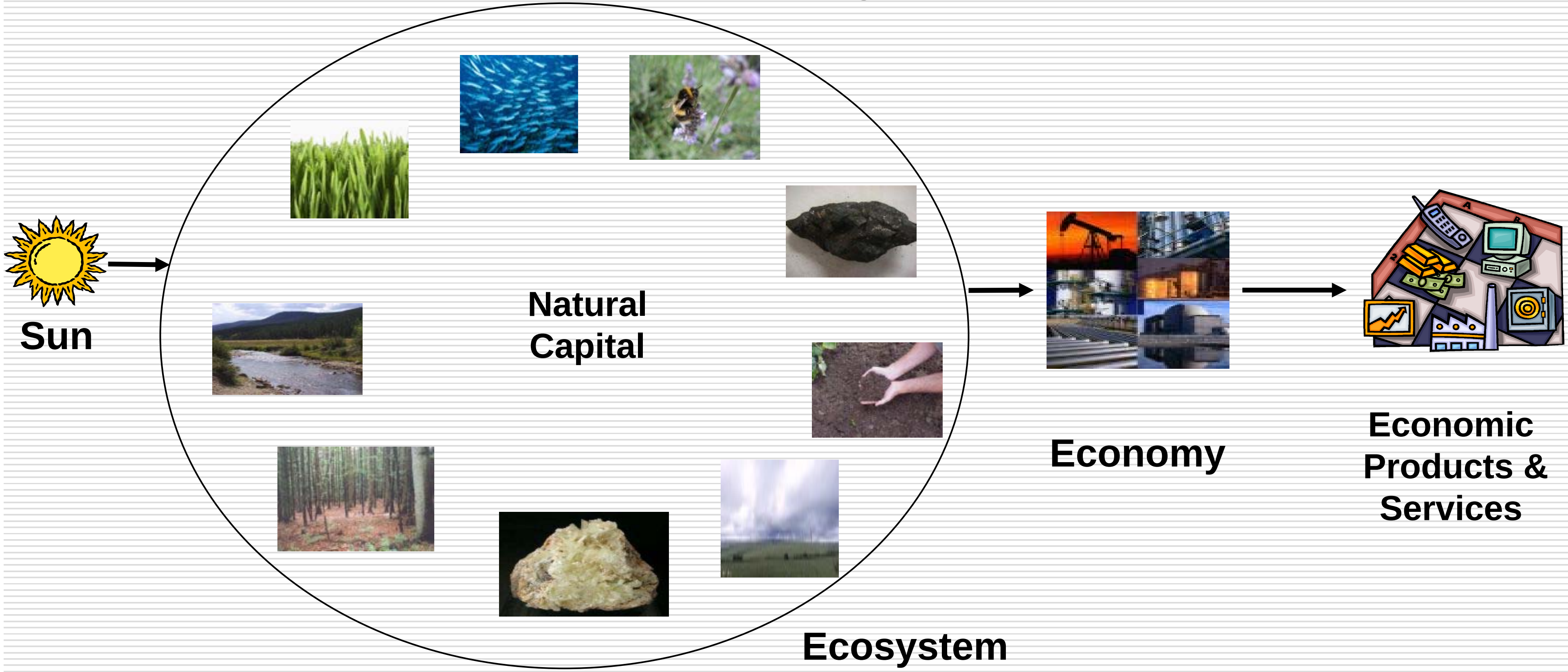
TARDIS workshop, Schloss Seggau, Austria
October 26-28, 2008

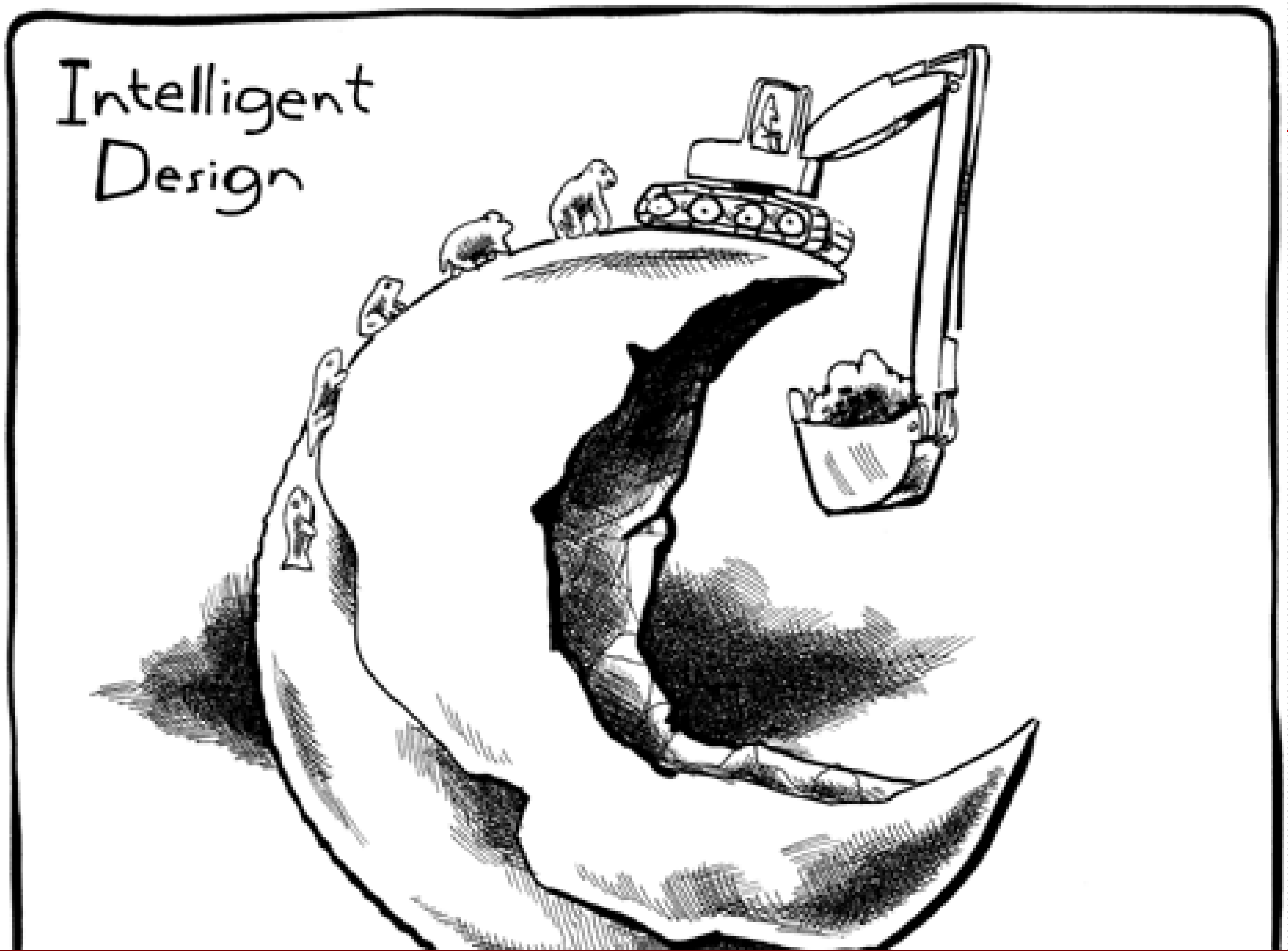
Sustainability and Natural Capital

- Availability of ecosystem goods and services (Natural Capital) is essential for sustainability
- It is the source of **all** other goods and services



Status of Natural Capital

- Millennium Ecosystem Assessment
  - "… assessed the consequences of ecosystem change for human well-being…
  - … the MA involved the work of more than 1,360 experts worldwide.
  - Their findings provide a state-of-the-art scientific appraisal of the condition and trends in the world's ecosystems and the services they provide, …
  - … as well as the scientific basis for action to conserve and use them sustainably."
- Many ecosystem goods and services are highly degraded
- http://www.maweb.org



Must account for the role of natural capital in human activities

Natural Capital and Decision Making

- Most methods across disciplines ignore the role of natural capital
- This includes methods for "Green Engineering"
  - Life Cycle Assessment focuses mainly on
    - Emissions and their impact, and
    - Some resources
- Decisions based on ignoring natural capital could encourage its depletion
- **Goals** – Develop rigorous methods to account for the role of natural capital in,
  - Economic products and processes and their life cycles
  - Engineering decision making

Ecologically-Based LCA

- Approach that accounts for natural capital in LCA
  - Process-based approach considers network of selected processes
  - Economic Model-based approach considers aggregate sectors in entire economy
- Define hierarchy of metrics
  - Delay aggregation of results to prevent loss of information
  - Consider various methods for resource aggregation

Resources in Eco-LCA

- **Lithosphere**
  - Fuels
    - Crude Oil; Natural gas; Coal; Nuclear fuel
  - Ores
    - Iron; Copper; Silver; Zinc and lead; Gold; Other metallic ores
  - Non-metallic
    - Minerals; Crushed stone; Sand
  - Mineralization
    - Nitrogen; Phosphorous
  - Soil
    - Nitrogen deposition from atmosphere; Detrital matter; Erosion
  - Land
    - Cropland; Rangeland and pasture; Timber
- **Biosphere**
  - Grass
  - Wood
  - Fish & related species
- **Hydrosphere**
  - Irrigation water
  - Thermoelectric power generation water
  - Public supply water
- **Atmosphere**
  - CO_2 for photosynthesis
  - Oxygen*
  - Nitrogen*
- **Human Resources**
- **Ecosystem Services**
  - Sunlight
  - Hydropotential
  - Geothermal
  - Wind
  - Geochemical cycles*
  - Pollination*
- **Emissions**
  - SO_2
  - NO_x
  - PM10
  - CO_2
  - Methane
  - Ammonia
  - Toluene
  - Styrene (air, water, soil)
  - CFC*; TCE*

*To be included

Results from Eco-LCA Model

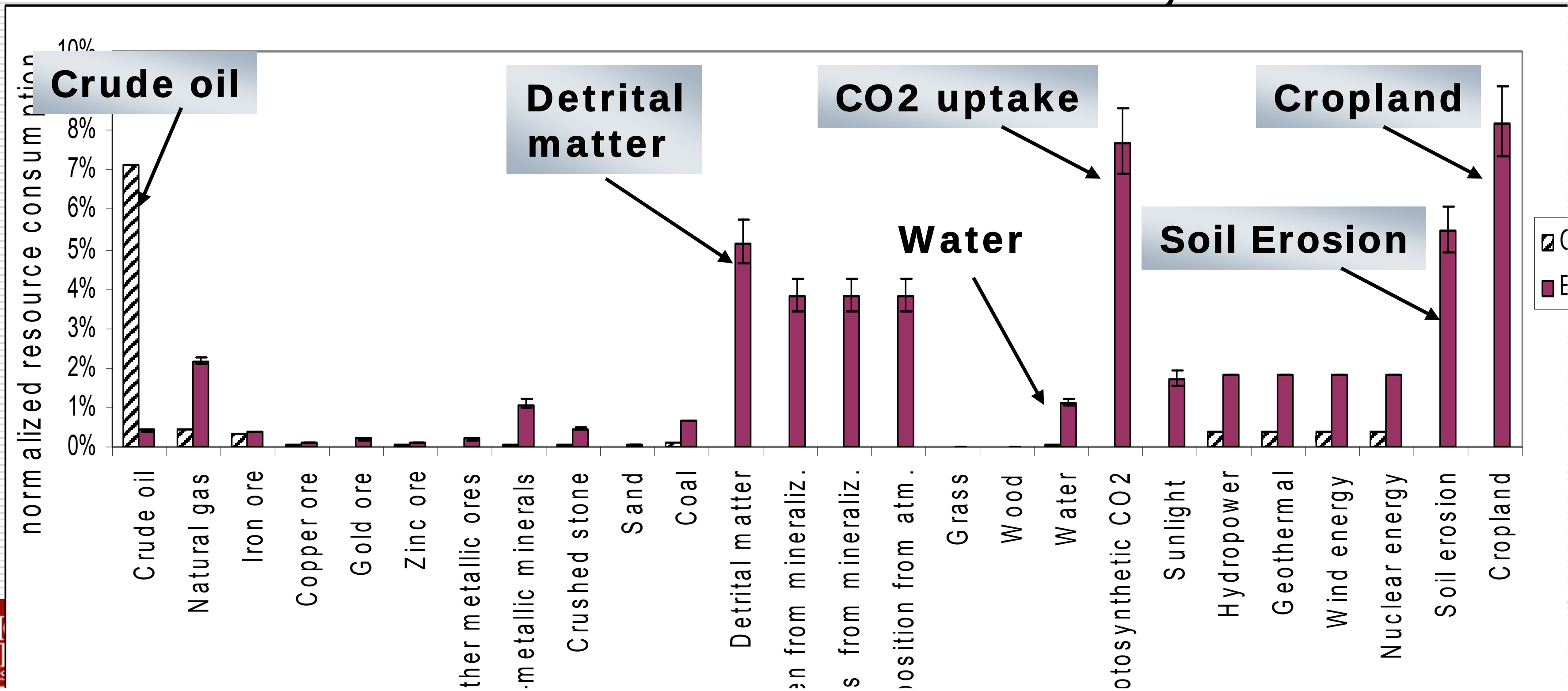
- Information about cumulative use of each resource per dollar of economic activity
- Results may be used in many ways
  - Life Cycle Assessment
  - Relationship between flow of natural versus economic capital in supply chains
  - Modeling effect of losses in natural capital on the economy
- Developed Eco-LCA model of 1997 U.S. economy
  - 488 sectors
  - Included role of natural capital
  - Based on publicly available data
- Free software tool being developed

Normalization, Characterization, Aggregation

- Normalization
  - Normalize by national or regional value for each individual resource, or for aggregated categories
  - Provides insight into resource vulnerabilities
- Characterization
  - Inputs may be combined into various categories
    - Renewable vs. Nonrenewable
    - Biotic vs. Abiotic
    - Material vs. Energy
    - Ecological Products vs. Ecological Services
    - Lithosphere, Biosphere, Atmosphere, and Hydrosphere
- Many aggregation schemes can be defined

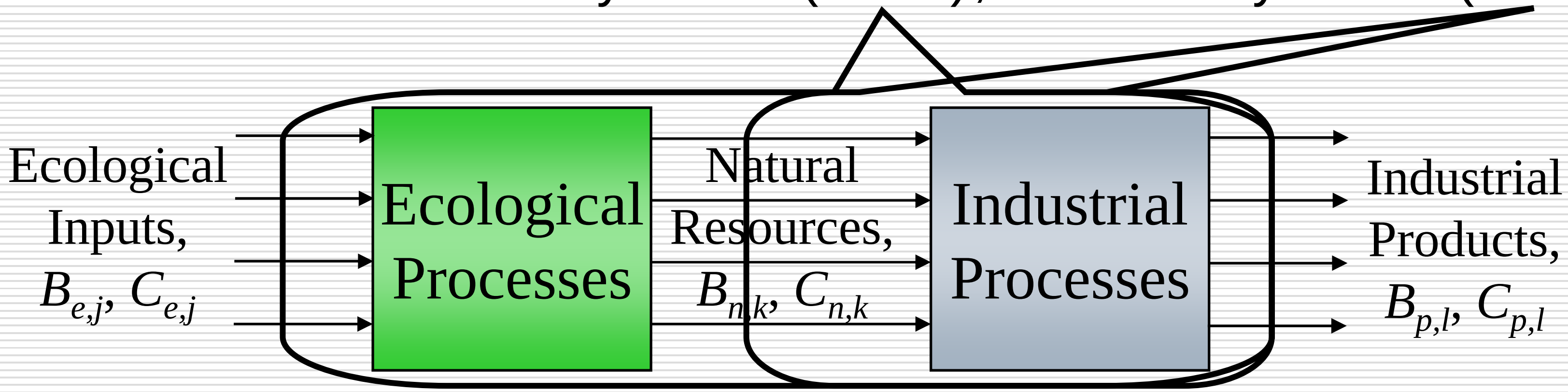
Normalized Resource Consumption

- Hybrid Eco-LCA of corn ethanol and gasoline
- % resource consumed in US
- Indicates vulnerability to resources
  - Gasoline is vulnerable to crude oil depletion
  - Corn ethanol to land use and availability of fertile soil



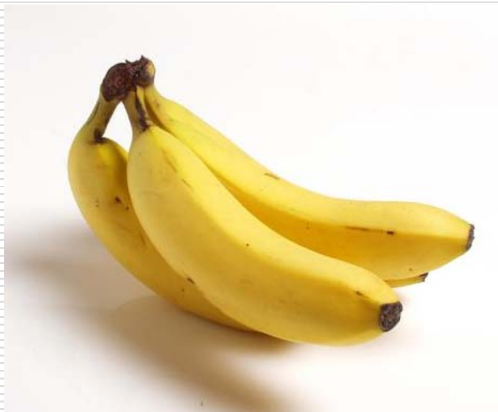
Resource Aggregation

- Need to aggregate resources to develop metrics and indicators
- Mass
  - Ignores fuel value
  - Large mass need not be bad
- Energy
  - Focuses only on fuel value, mainly of nonrenewables
- Exergy
  - Captures the useful energy in material and energy sources
  - Without role of ecosystems (ICEC), with ecosystems (ECEC)



Resource Aggregation – Challenges

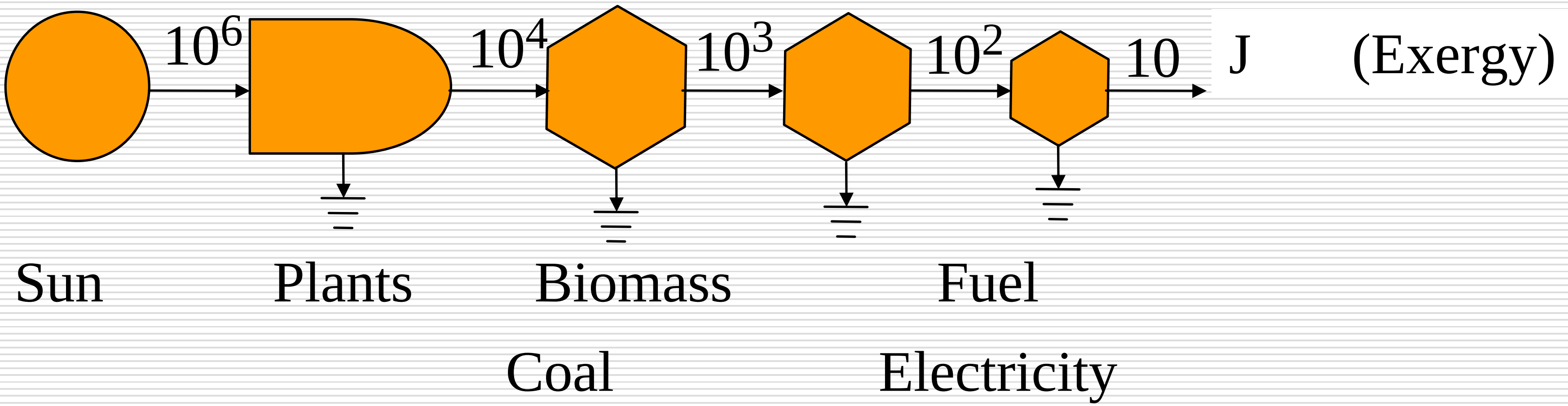
- A 150 cal snack could be a twinkie or two medium sized bananas
- Is it enough to just focus on their energy content?
  - Quality of their energy is different
  - They are not substitutable



- Need to consider quality and substitutability of resources before aggregation or comparison
- A joule each of sunlight, wood, coal, oil and electrical energy are very different
  - They should not be added without quality correction

Energy Quality and Aggregation

- May account for quality and substitutability by considering life cycle of resource
- 10 J of fuel is equivalent to 10^6 joules of sunlight
- Must consider exergy flow in industrial and ecological systems
- Adopted by emergy and ECEC analysis



Odum, 1996; Hau & Bakshi, 2004

Aggregation Schemes

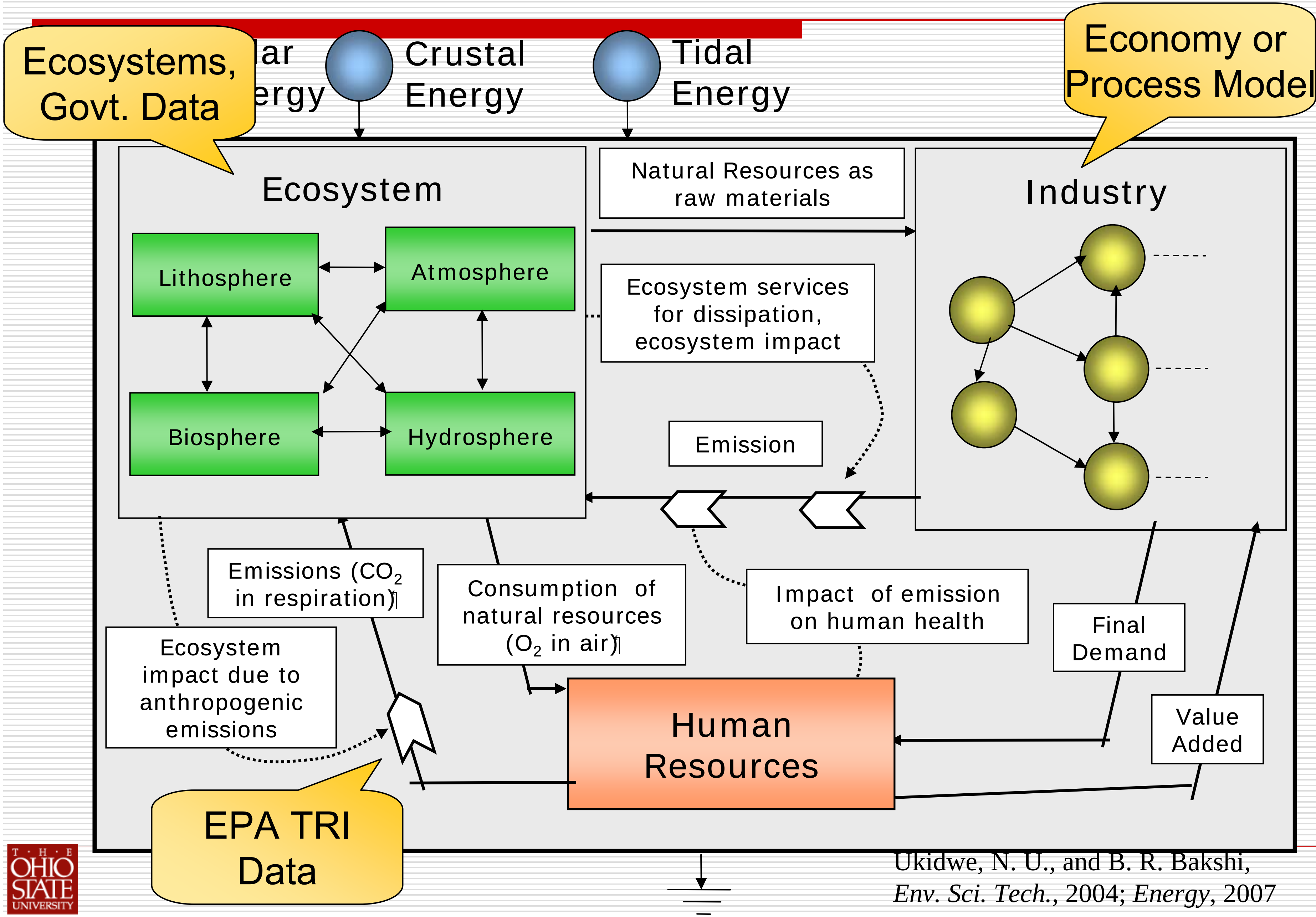
Energy ROI | Renewability Index | Sustainability Index | Ecological Footprint

Renewable Resources | Nonrenewable Resources | Human Resources

Litho-sphere | Hydro-sphere | Atmo-sphere | Bio-sphere | Human Resources | Ecosystem Services

Wind Coal Water Wood Iron Land Oil Zinc Soil Fish Labor
Sunlight Geothermal Oxygen Detritus Grass Pollination ...

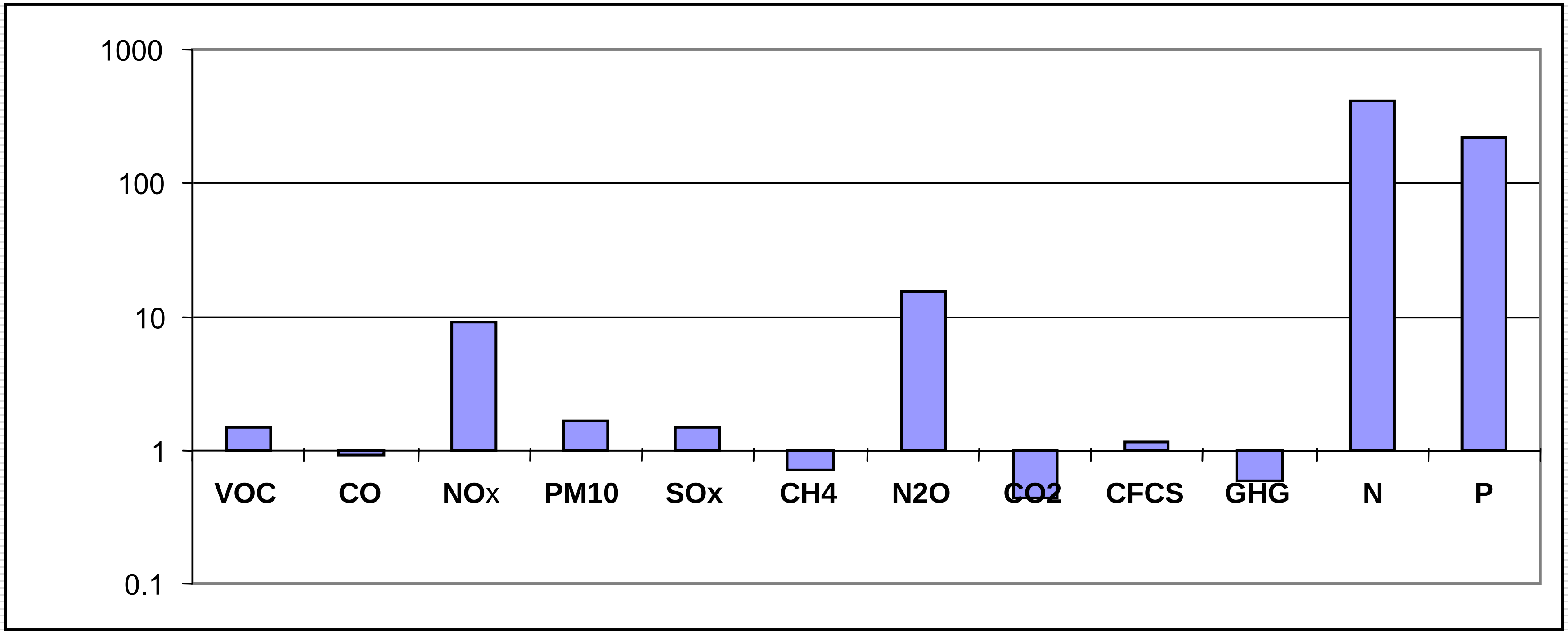
Eco-LCA Model



Ukidwe, N. U., and B. R. Bakshi, *Env. Sci. Tech.*, 2004; *Energy*, 2007

Emissions – Gasoline vs. Corn Ethanol

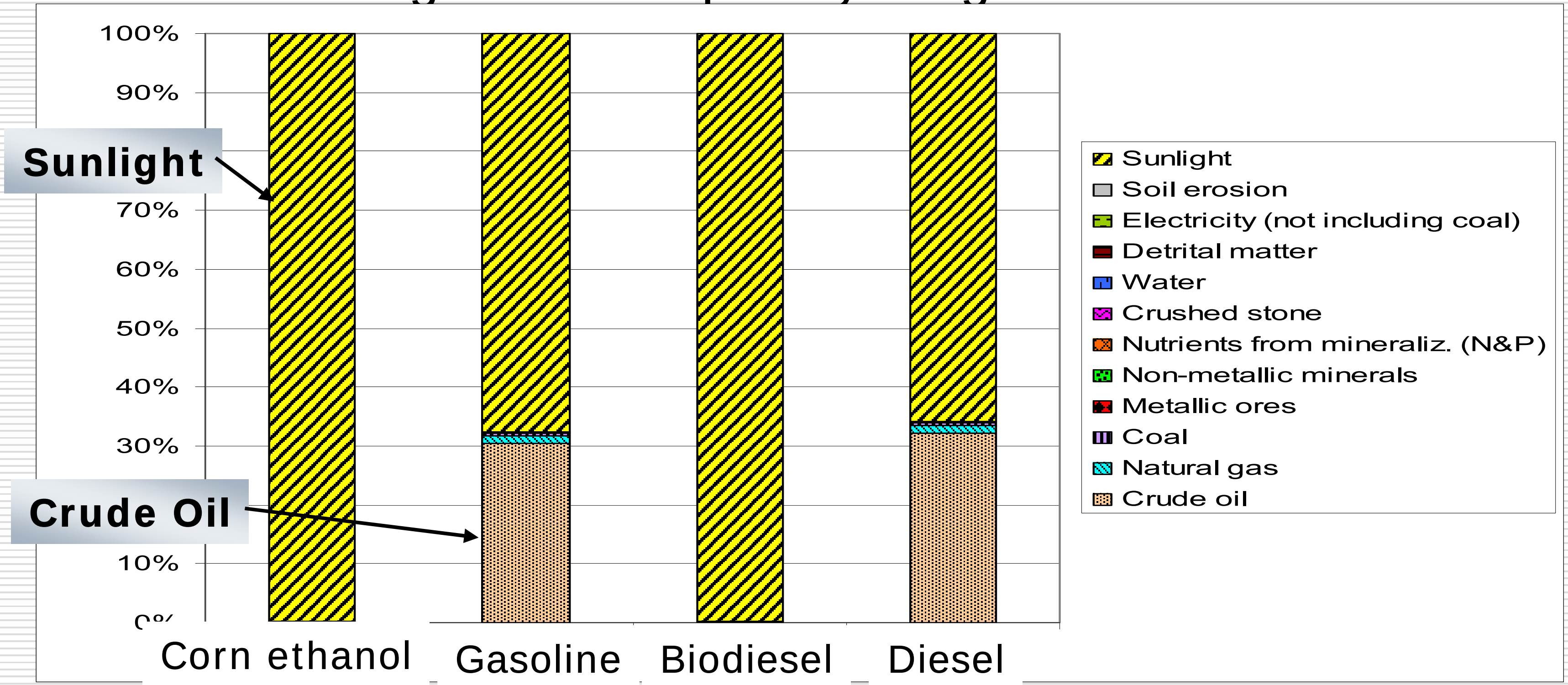
- Use of E85 increases emissions of VOC, PM10, N2O, NOx, SOx but decreases emissions of GHG
- Similar trend for biodiesel



Baral and Bakshi, 2008

Industrial Cumulative Exergy Consumption

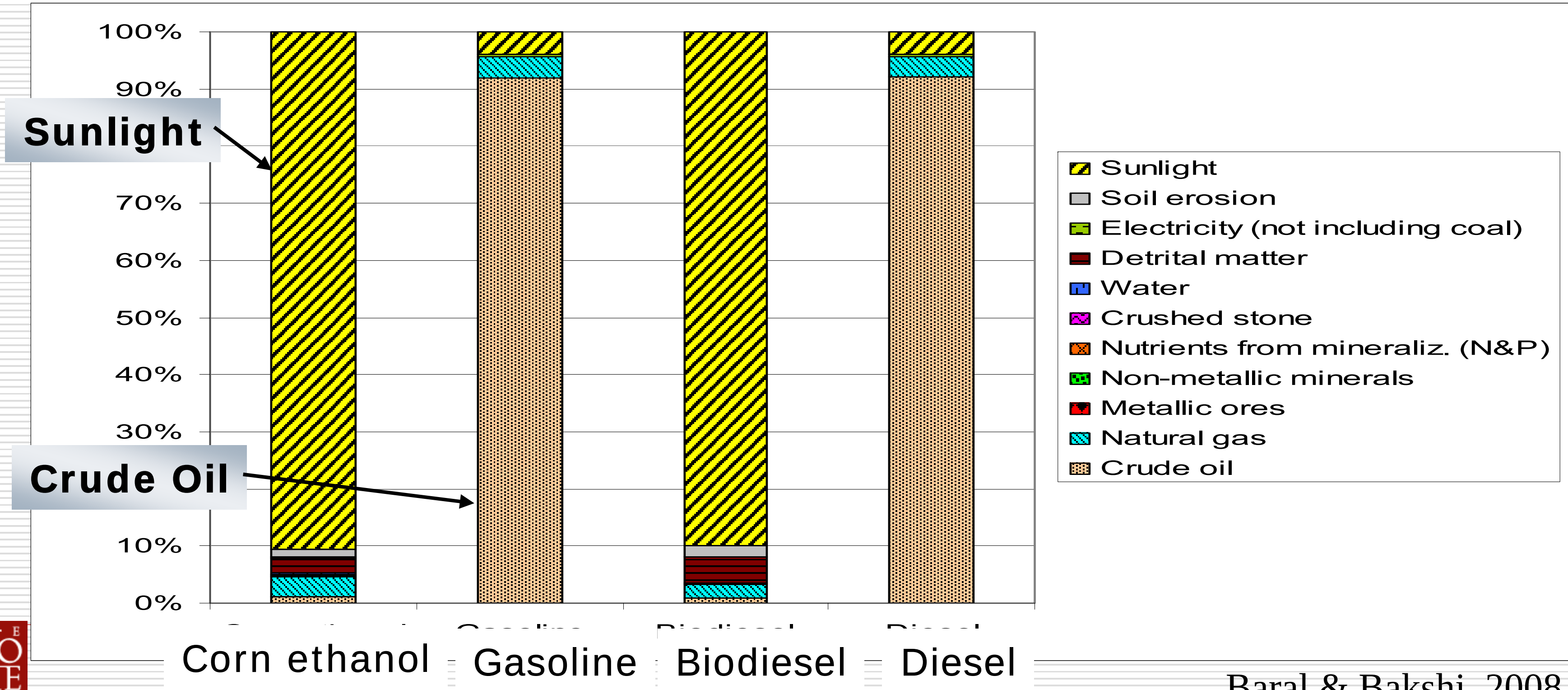
- Exergy without ecosystems (ICEC)
  - Sunlight dominates – even fossil fuels are 70% renewable!
  - Not meaningful since quality is ignored



Baral & Bakshi, 2008

Extracted Exergy from Nature

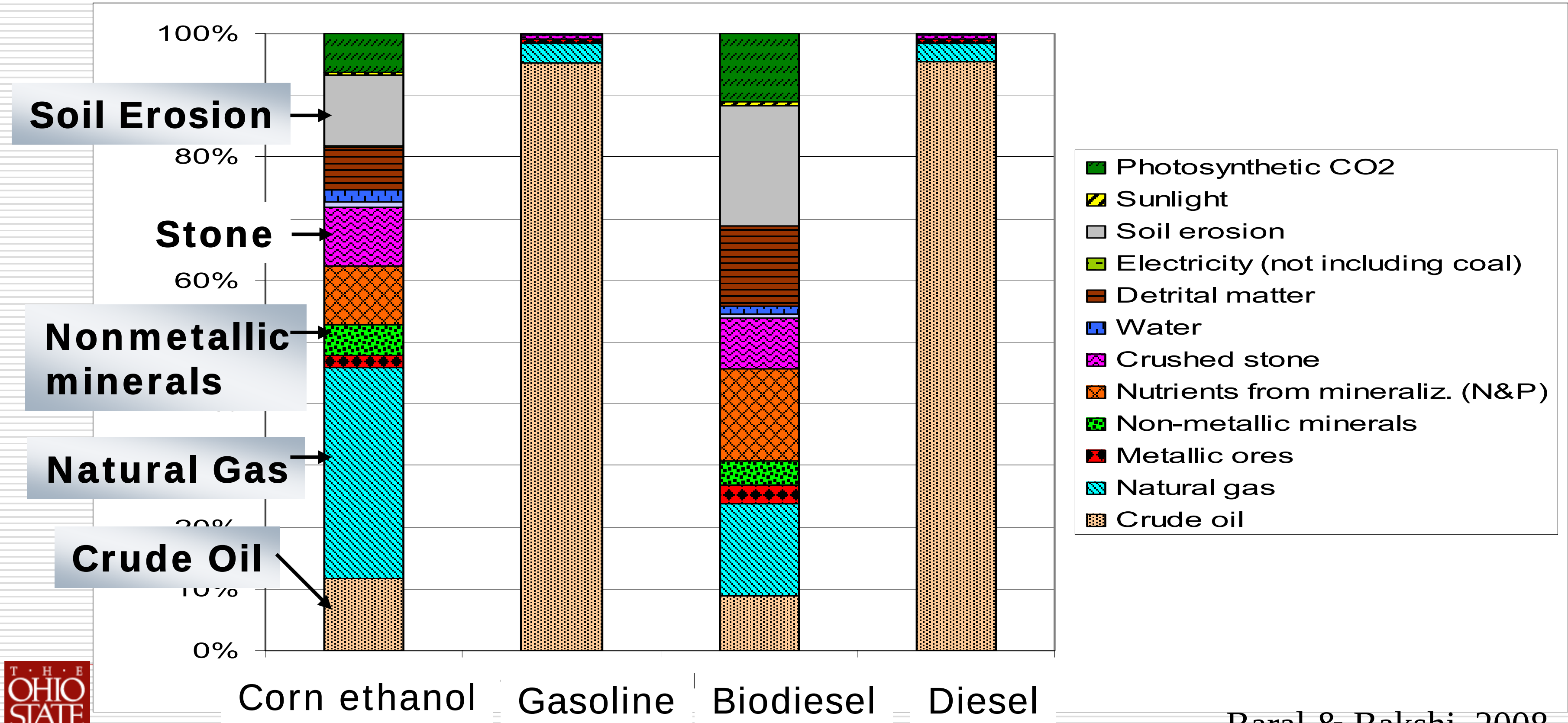
- Only considers metabolized exergy (Dewulf et al., 2007)
  - Focusing only on extracted energy is ad hoc
  - Renewability of fossil fuels still too high
  - Ignores substitutability



Baral & Bakshi, 2008

Ecological Cumulative Exergy Consumption

- Exergy *with* ecosystems (ECEC)
  - Accounts for substitutability
  - More meaningful results than other approach
  - But, uncertainty about ecological processes



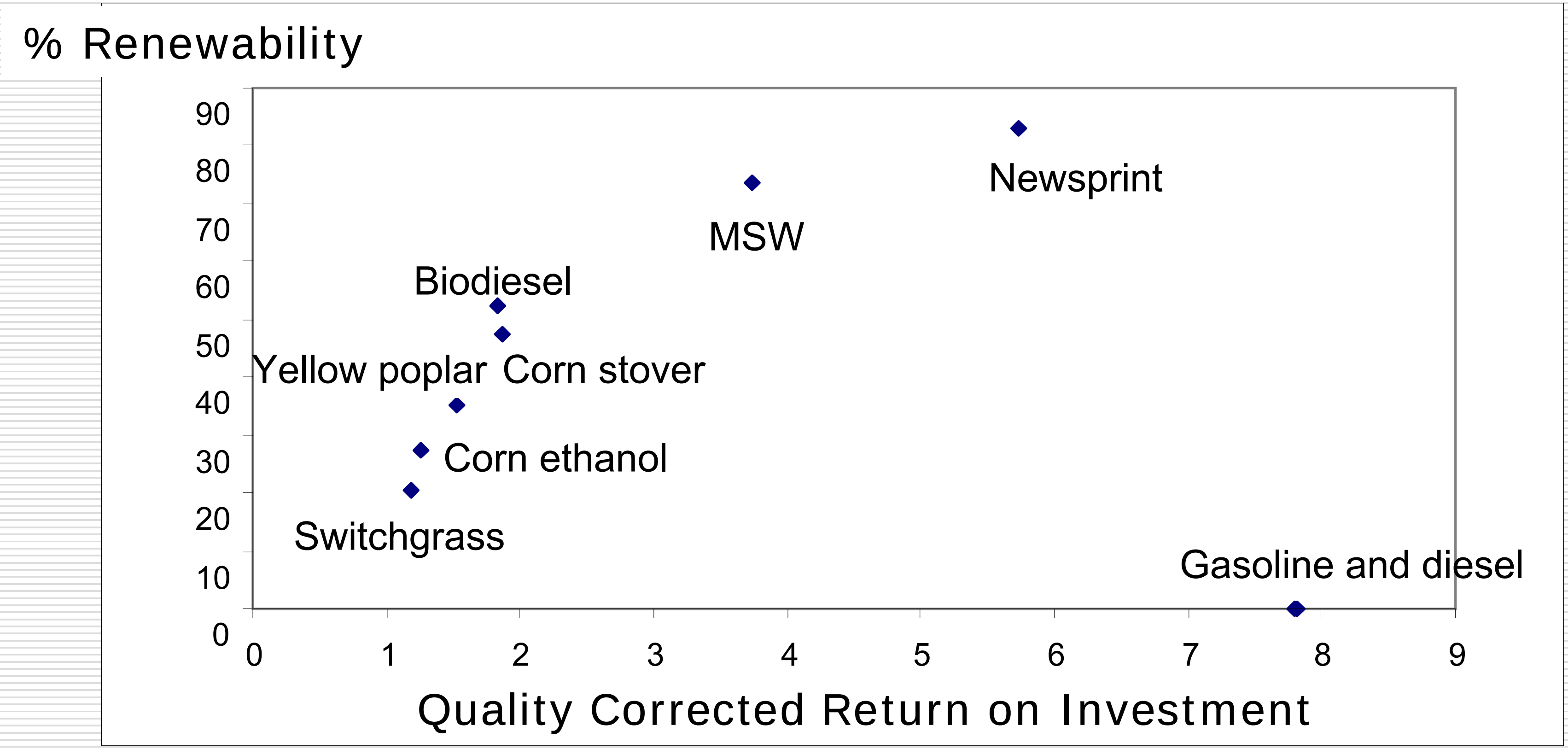
Baral & Bakshi, 2008

Resource Aggregation – Insight

- Energy analysis is too narrow due to ignoring material resources
  - May be good enough for fossil fuel studies
- Conventional exergy analysis ignores role of ecosystems
  - Renewable energy dominates, providing misleading results
  - Focus only on nonrenewables makes it too similar to energy analysis – not worth extra effort
  - Useful for identifying improvement opportunities
- ECEC/emergy analysis seems better at providing aggregate results
  - Also accounts for role of ecosystem goods and services

Renewability vs. Thermodynamic ROI

- Best fuels have high renewability *and* high ROI



- Depicts dilemma of biofuels

Baral & Bakshi, 2008

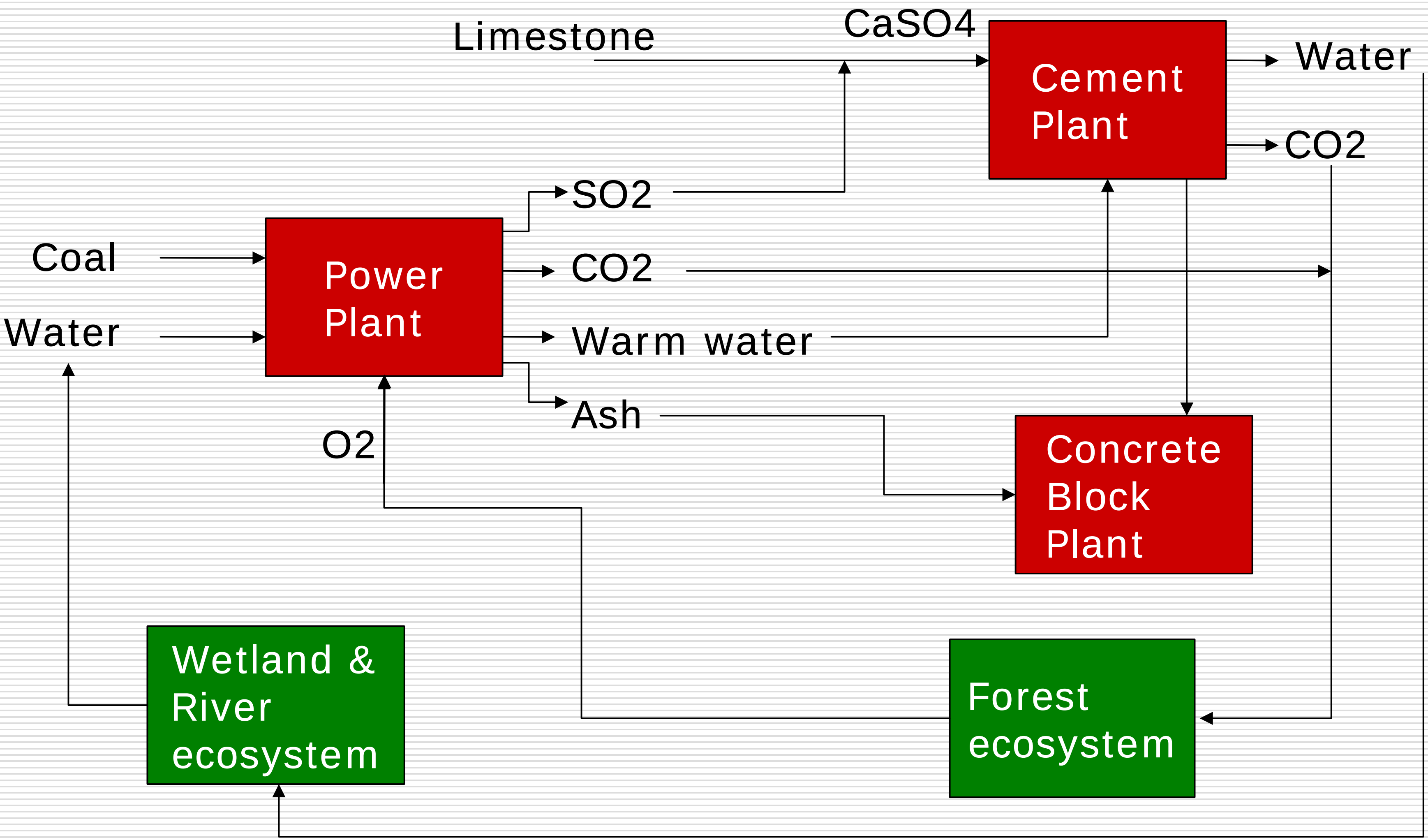
Dilemma of Renewable Resources

- Difficult for biofuels to provide high ROI
- Waste materials are best, but limited availability
- To get high ROI
  - It is best if nature does the work of producing industrial raw materials, or
  - Use waste materials
- Relying on industrial processes to concentrate dilute resources may always yield a low ROI
  - Often translates into higher cost
- Possible approach
  - Don’t farm for cellulose, let it grow ecologically
  - High productivity and free (Tilman et al.2006)

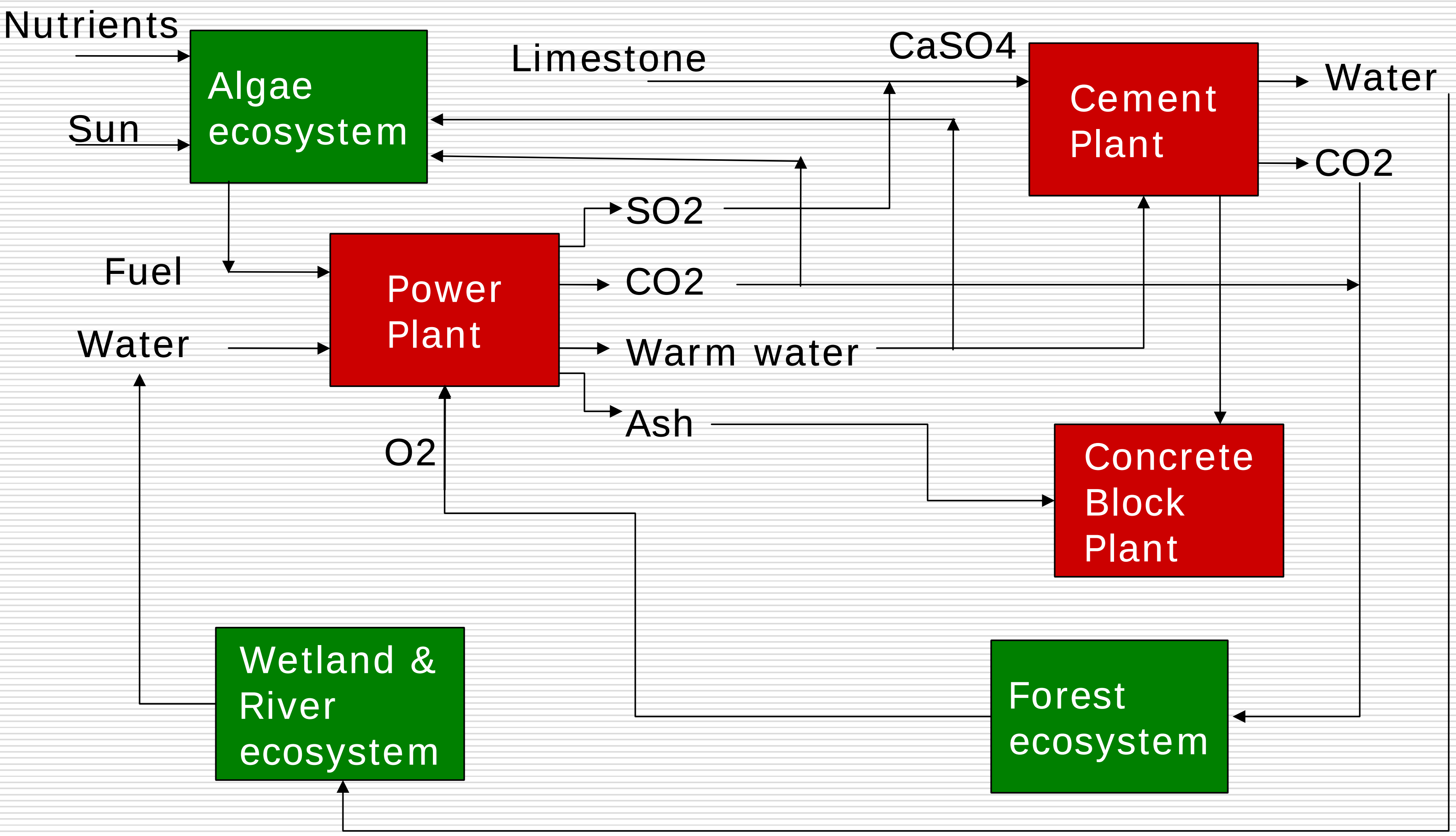
Design of Industrial-Ecological Networks

- The role of ecosystems is critical to sustainability and cannot be ignored
- Consider industrial systems in the context of supporting ecological systems
- Could engineer industrial systems and supporting ecological systems
  - Requires integration of industrial ecology with ecological engineering
- Encouraged via mechanisms such as carbon offsets, trading of ecosystem services, etc.
- Any technology can be sustainable if it can operate with the integrated IE system

Industrial-Ecological Networks



Industrial-Ecological Networks



Summary

- All activities rely on ecosystem goods and services
- Natural capital is often ignored, even by “Green Engineering” methods
- Developed Eco-LCA to account for role of ecosystems
  - Hierarchical set of metrics
  - Eco-LCA model of 1997 US economy
  - Work in progress to include more services
- Need to design “integrated industrial-ecological networks”
- Many opportunities for research

- Acknowledgement – U.S. EPA, NSF for funding

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