Toward a Macroecology of Sustainability

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Macroecology 101

***Macroecology* is the statistical investigation of broad-scale patterns of ecological distribution, abundance, and diversity (Brown, 1995). Plotting multiple examples across scales to look for broad patterns is a common macroecological approach. This approach uncovers patterns unapparent at small scales or by looking at just a few data points. One macroecological pattern is the tendency for metabolic rate to increase sublinearly with body size (Fig 1).**

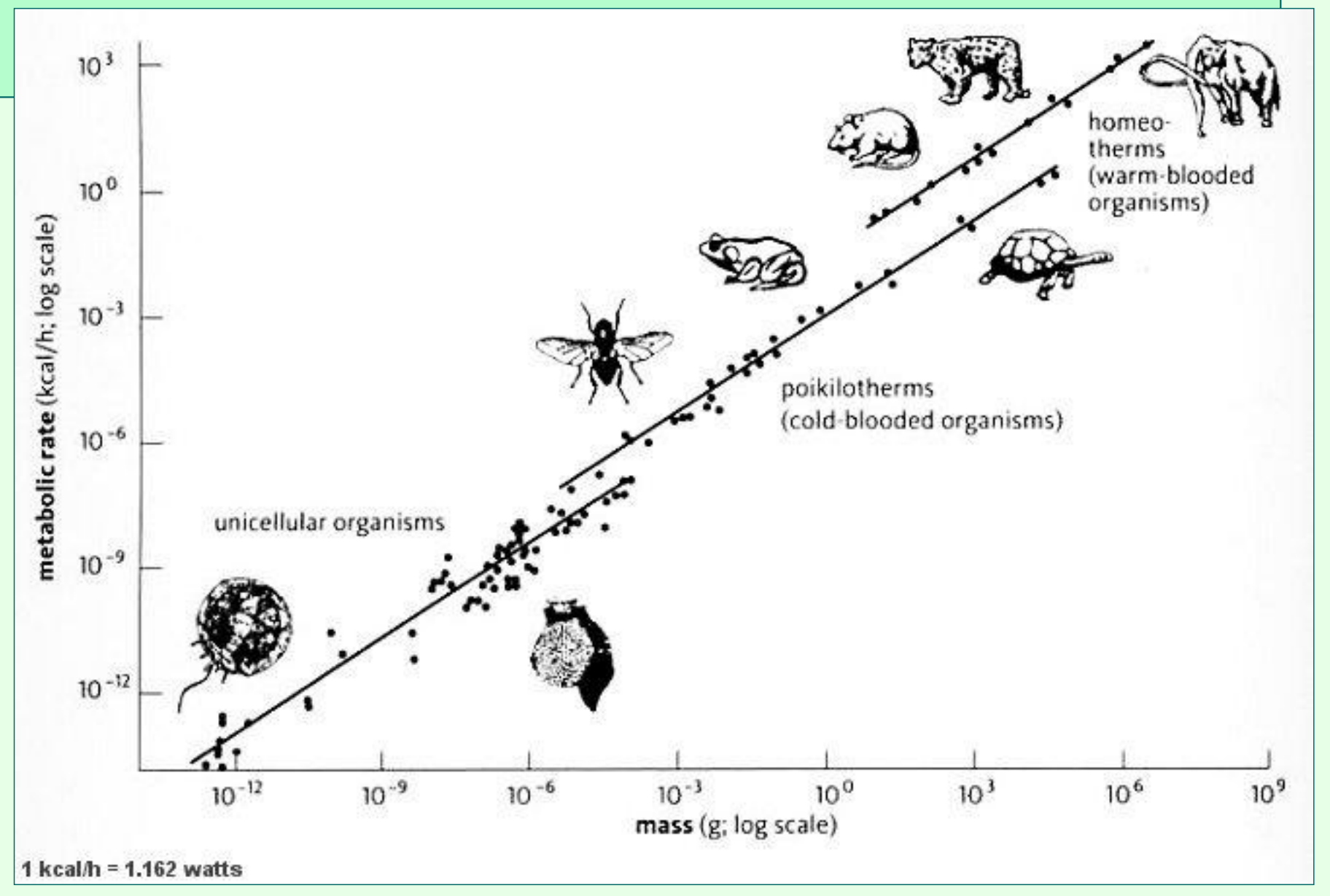


Fig 1: Metabolic rate, the rate an organism uses energy to fuel bodily processes, rises with body mass, but less quickly than expected. So although an elephant burns more calories than a mouse, the elephant burns fewer calories for its size (i.e. fewer calories than its mass in mice burn) (from Hemingsen, 1950).

The history of *Homo sapiens* has been fueled by increasing the flows of energy and materials from the Earth system to support geographic expansion and increases in population, standard of living, and societal complexity. These flows are subject to the laws of energy and the principles of ecology, but these flows are rarely tracked in their entirety within systems or across subsystem boundaries. The fact that subsystems are vitally connected to the global socioeconomy necessarily limits the honest consideration of them in isolation. To illustrate this point, we track the flows of energy and materials through the Bristol Bay salmon fishery.

Assessing sustainability: the Bristol Bay salmon fishery

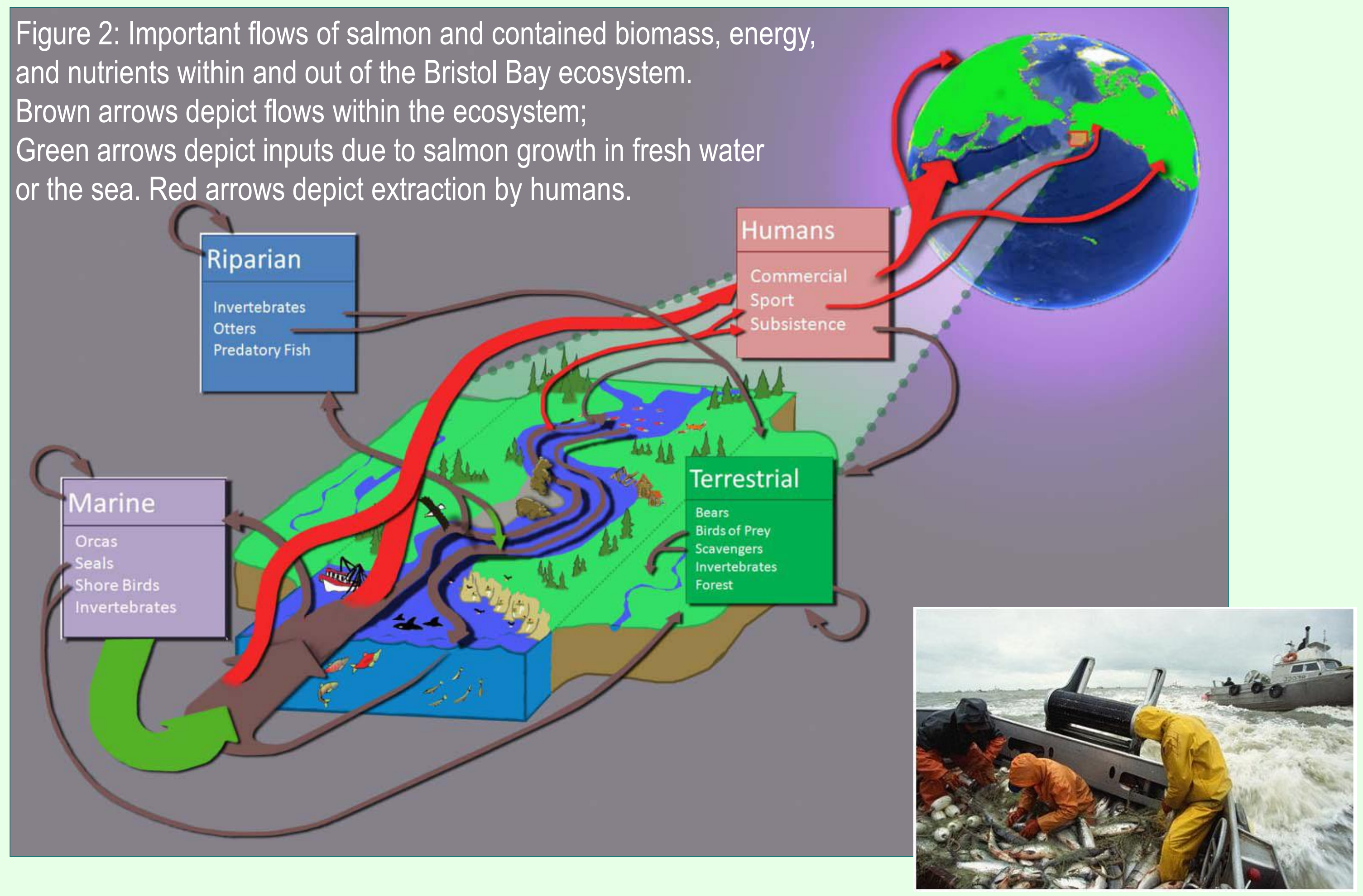


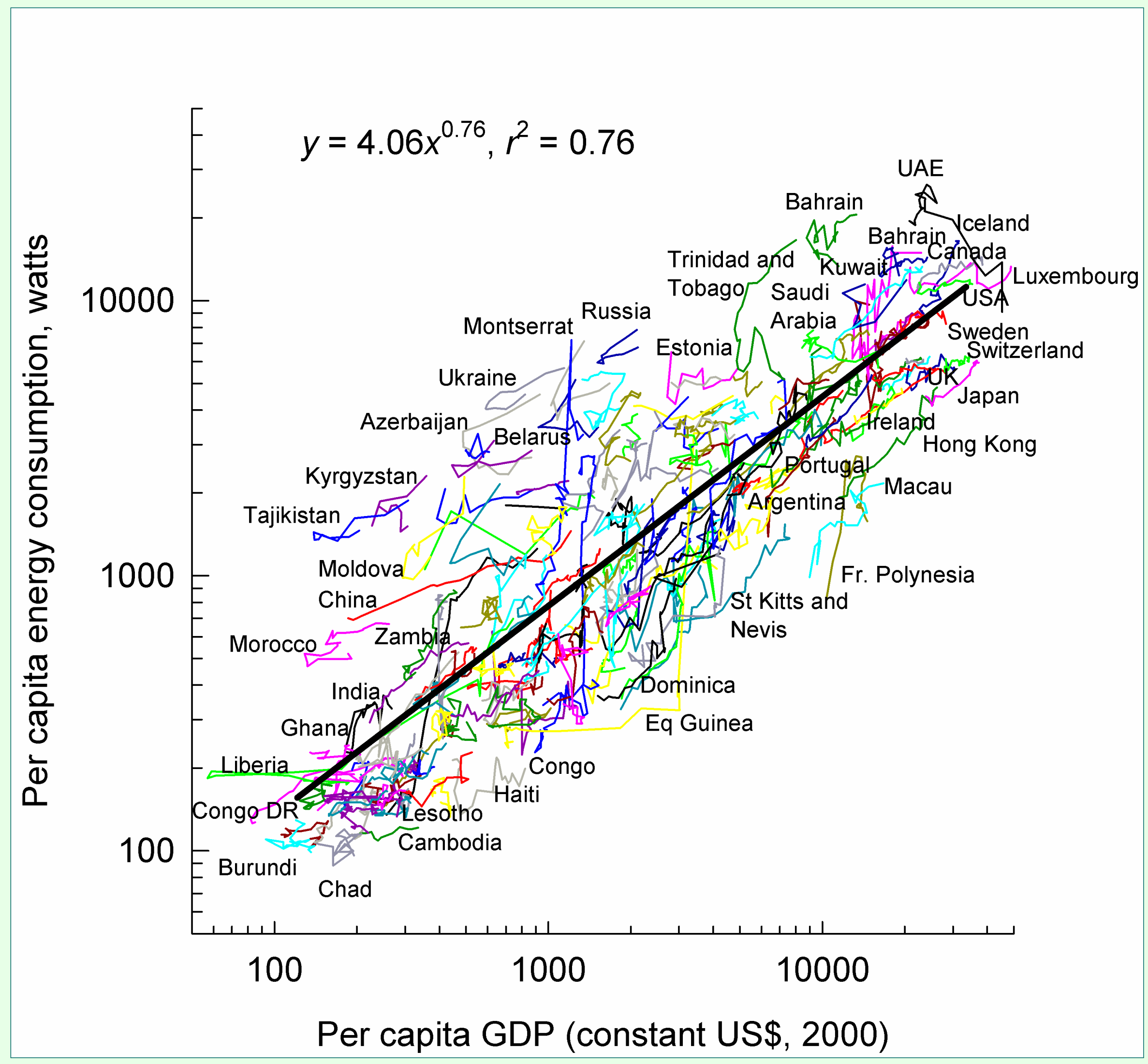
Figure 2: Important flows of salmon and contained biomass, energy, and nutrients within and out of the Bristol Bay ecosystem.
Brown arrows depict flows within the ecosystem;
Green arrows depict inputs due to salmon growth in fresh water or the sea. Red arrows depict extraction by humans.

The Bristol Bay salmon fishery is cited as a success story in sustainable fisheries management (e.g. Hilborn et al., 2003). From 2007-2009 about 70% of the annual wild Bristol Bay salmon run was harvested commercially (15). The fishery is considered sustainable because annual runs have not declined. But consider the magnitudes, currencies, and scales of flows of energy and materials (Fig. 2): 70% fewer mature salmon returning to spawn; 70% fewer salmon to support populations of predators (e.g. brown bears, bald eagles); removal of about 12,000, 2,500, and 330 tonnes of carbon, nitrogen, and phosphorus per year in salmon bodies, which provided nutrient subsidies to stream, lake, riparian, and terrestrial ecosystems. Instead, enormous quantities of materials are exported to eastern Asia, western Europe, and the continental U.S. Data: Alaska Game & Fish; Cederholm et al., 1999; .Coupland et al., 2010; Gende et al., 2002.

Scaling up: From the economy of a fishery to that of a nation

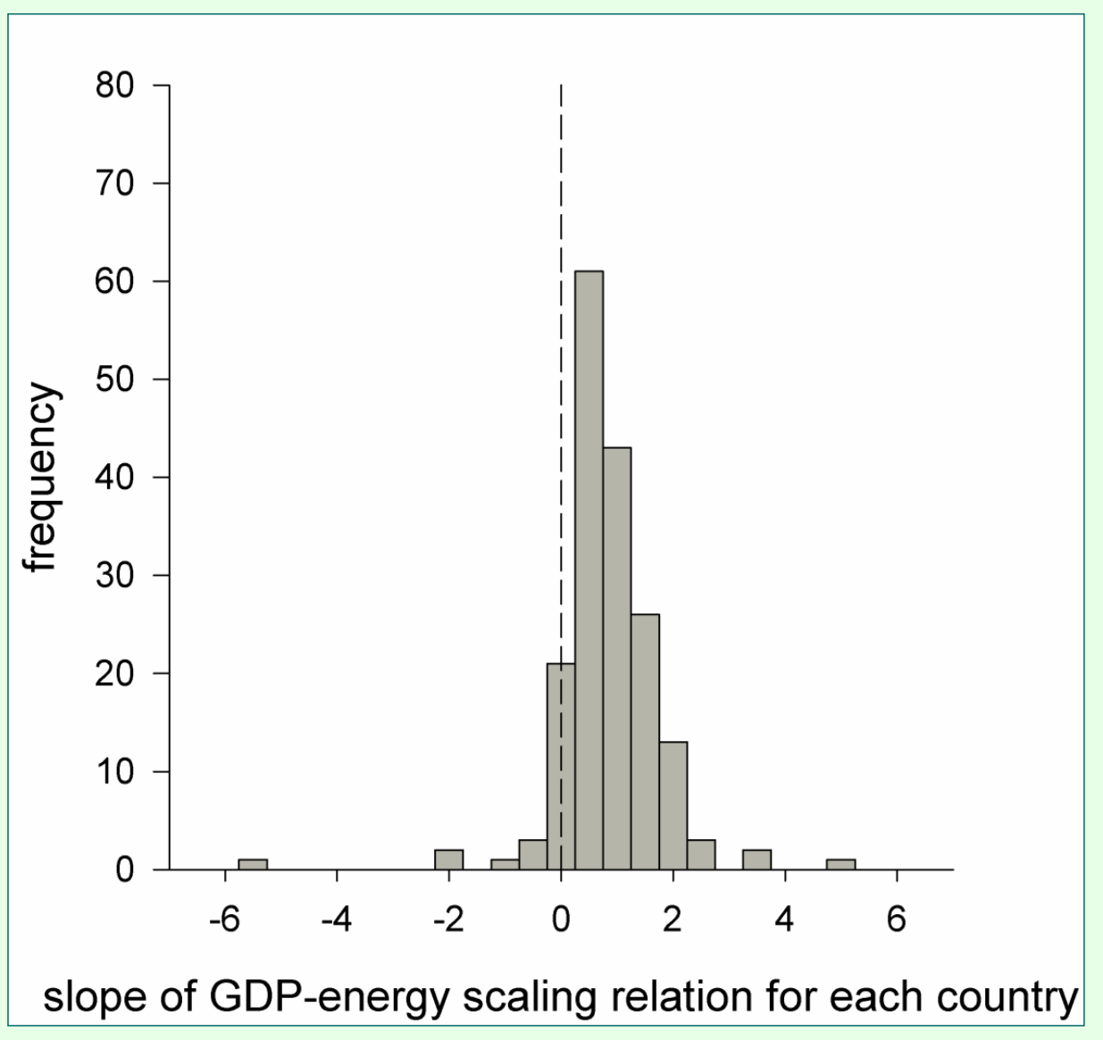
The fact that coupled human and natural systems (CHANS), like Bristol Bay, are *complex systems* has another implication as well: that like linked systems everywhere, from ant colonies to immune systems, the maintenance and growth of the overall system must ultimately be fueled by increasing energy supplies. We use a macroecological approach in analyzing global macroeconomic data to show that energy indeed imposes fundamental constraints on economic growth. We find a positive scaling relationship between per capita energy use and per capita Gross Domestic Product (GDP) both across nations and within nations over time. Other indicators of socioeconomic status, standard of living, and ecological impact are correlated with energy use and GDP as well (e.g. log per capita E consumption vs infant mortality per 100K people, r = -0.65, vs. ecological footprint, r = 0.74).

Powering size and fueling growth in modern economies



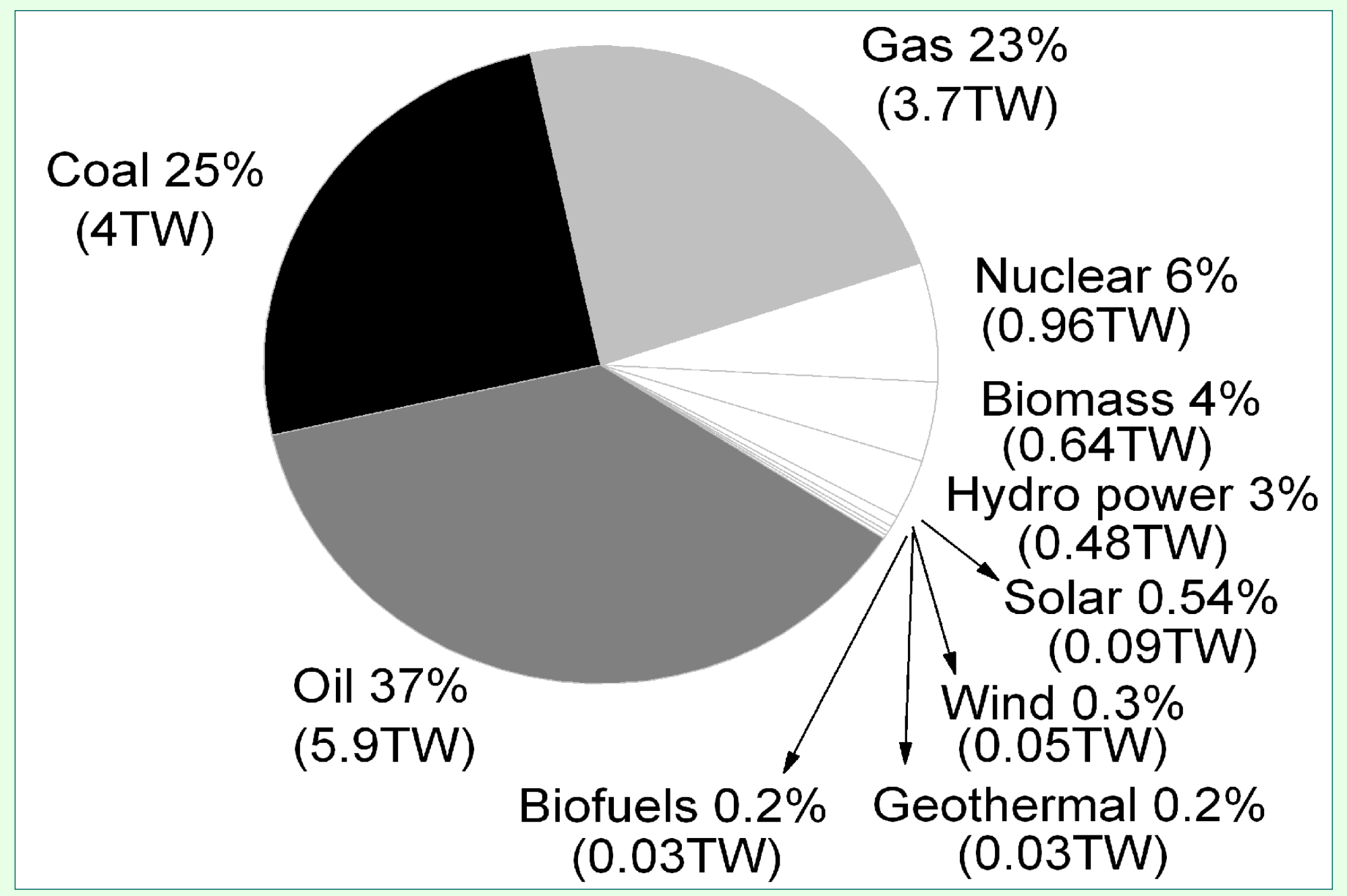
←Figure 3a: The relationship between energy use and GDP among modern nations (plotted on log axes, each colored line indicating the trajectory for a single country from1980-2003.) GDP data from World Resources Institute; energy data from the International Energy Agency.

3b (below): The frequency distribution of exponents (slopes of colored lines). The mean slope is about 0.6.



"Economy" is the right term, as the sublinear slope in Fig. 3a recalls the increase in metabolic rate with body size in animals shown in Fig 1. Indeed, both slopes are about 0.75. Just as higher metabolic rates are required to sustain and grow larger, more complex bodies (Kleiber 1961, McMahon and Bonner 1983), so higher rates of energy consumption are required to sustain and grow larger, more developed economies that provide higher levels of technological development and higher standards of living. These relationships are not trivial, in either sense of the word. Neither is our very real reliance on fixed and dwindling fossil fuels, as shown in Fig 4.

Fig 4 → : Sources of energy currently consumed by the global human economy. Total annual consumption is approximately 15.9 Terawatts (1 Terawatt = 1012 watts), of which about 85% comes from fossil fuels, 6% from nuclear energy, and the remaining 9% from solar, hydro, wind, and other renewable sources (REN21 2009, British Petroleum 2009)



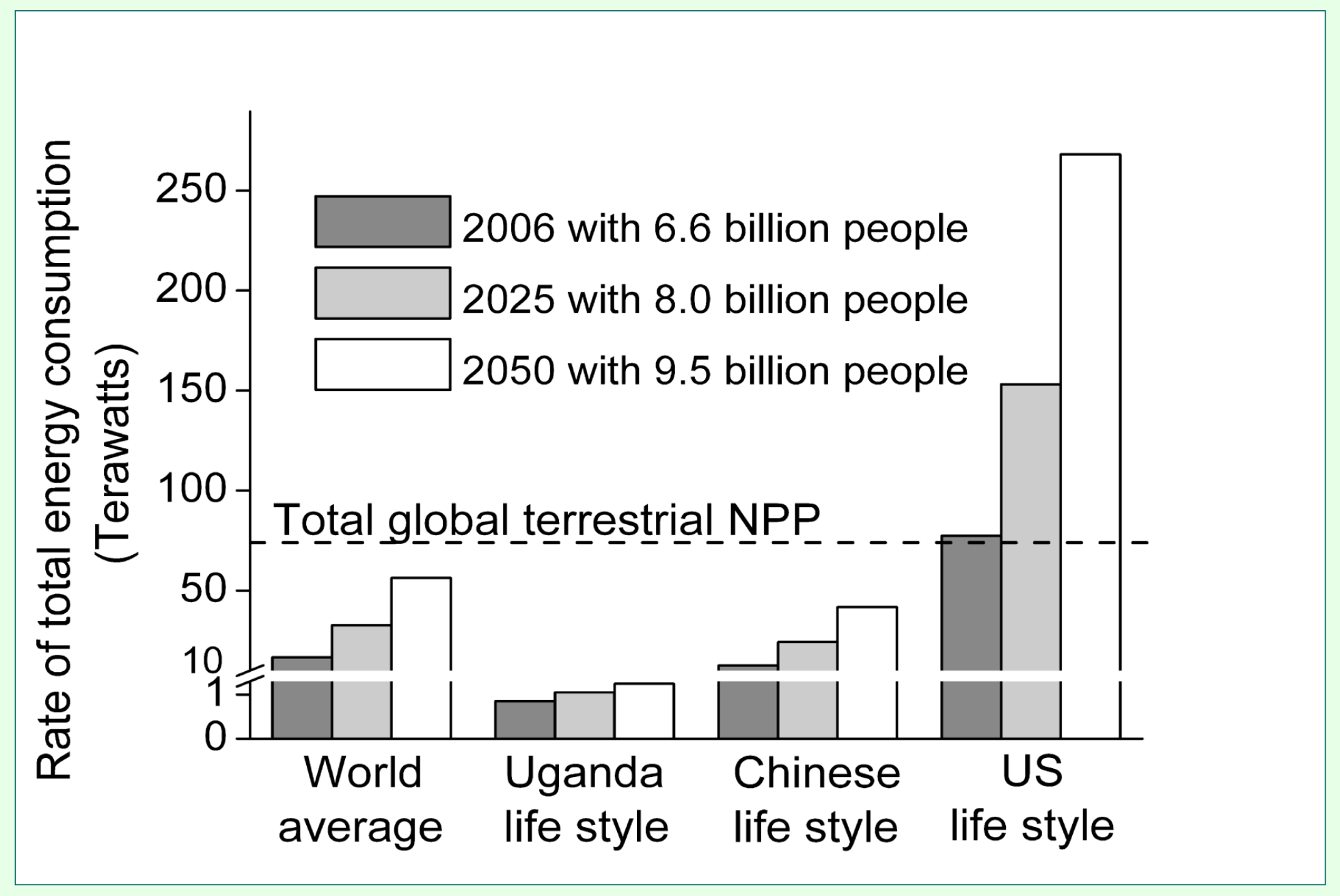


Fig 5: Current and projected global energy consumption based on alternative scenarios of population growth (2006, 2025, and 2050) and standard of living (equivalent to contemporary Uganda, China, and U.S.). Dashed line is total global terrestrial net primary productivity (NPP), 75 Terawatts (Haberl et al. 2007). Data from World Resources Institute.

Human ecology is central to sustainability science, yet many connections are still underappreciated. The fisheries and economic growth examples suggest the value of three key ecological principles to sustainability science: (1) conservation laws that govern the flows of energy and materials between human systems and the environment, (2) effects of scale and embeddedness on these flows, and (3) constraints at the global scale that ultimately limit the flows at smaller scales.

Sustaining flows in a small world

Figure 6: Flows of resources into and out of Portland, OR. This model sustainable city is deeply embedded in and reliant on the broader environment.

Each year Portland consumes 1.25 billion liters of gasoline, 28.8 billion megajoules of natural gas, 31.1 billion megajoules of electricity, and 136 billion liters of water.

Although a complex systems perspective in sustainability science acknowledges these principles, most research focuses on the dynamic aspects of CHANS (Clark & Dickson, 2003; e.g. adaptive co-management, institutional evolution) while focusing less on how the "physiology," "anatomy," and scale of coupled human-natural systems affects their sustainability.

Conclusions & suggestions:

- A macroecological approach complements existing sustainability science research by looking across individual cases and scales to illuminate broad, emergent patterns
- The conceptual framework of metabolism, focusing on the exchange of energy, materials, and information within and among CHANS and their relation to system size, suggests underlying mechanisms and links between ecological and socioeconomic pattern and process.
- Calls to grow economies sustainably while using *less* energy ignore macroscopic patterns that reflect physical and ecological constraints
- The size of modern coupled human and natural systems, necessarily linked to the global version, is the energetic "elephant in the room."