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Soil, Water, Fish and Forests: Natural Capital in the Wealth of Nations

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ABSTRACT

The importance of natural capital stocks for current and future economic and ecological production is difficult to overstate. Strong sustainability requires that stocks of soil, water, fish and forests remain unchanged through time. As these stocks degrade, often precipitously, quantification of their value becomes a central means to direct policy towards their protection. We developed a database using emerging information resources at the global scale to construct a snapshot of national environmental accounts for the year 2000; this database compiles information typically used in environmental accounting, but improves our ability to quantify natural capital stock depletion. Further, by using a uniform methodology across all countries for a single time, we enhance the interpretive value of national environmental accounting. The fraction of total use derived from the depletion of natural capital stocks varies from >55% to less than 0.1%; the average fraction of total use from natural capital stock depletion across all 134 countries is 7.3%. Depletion of all four stocks (soil, water, fish and forests) figures prominently in overall use, but soil erosion and forest clearing are the most significant losses on a global basis. Converting each flow to macroeconomic flows (using the global emergy money ratio) suggests that losses of soil, water, fish and forests represent costs to society annually of $610 billion, $290 billion, $295 billion and $390 billion, respectively. This loss of natural capital is compared with other environmental accounting indices to orient interpretation. Among the more significant findings is the relationship between the Emergy Sustainability Index (ESI) and the % Natural Capital (%NC); we observe that countries with both low and high ESI values appear to be protecting their natural capital stocks and countries with moderate ESI values (~1) are depleting natural capital stocks most rapidly; this relationship holds for metrics of wealth creation as well as sustainability. This emergy–based Kuznets curve may have significant implications for both the interpretation of ESI and broader macro-scale policy.

INTRODUCTION

Natural capital, which we define as the accumulated stores of material, energy and information in the biosphere, is the resource foundation of economic production. From mined materials and fuels to soil and forests and biodiversity, natural capital represents the embodied work of nature that is exploited for the benefit of human users. When exploitation occurs more quickly than the stock can be replenished, natural capital depletion ensues; global declines in natural capital and associated losses in intrinsic value are well documented (e.g., Costanza et al. 1998).

Because free market prices do not reflect the embodied work of nature in providing goods and services, incentives derived from prices encourage use of these "free" resources that is frequently unsustainable. Society bears the external costs of their depletion – so called because they accumulate to society external to the market – now or in the future. As we have begun to appreciate the finite character of a spherical planet, tools that can quantify externalities and consequently help correct market failures (that is, failure to communicate appropriate incentives) are a valuable contribution to ongoing policy dialog. For this purpose, we employ environmental accounting using emergy as a means to place the biophysical flows associated with the creation and depletion of natural capital (energy, materials) into a framework that permits direct and meaningful comparison with flows more commonly associated with the policy arena (money). Emergy has been described elsewhere (Odum 1988, Odum 1996, Brown and Ulgiati 1999). Briefly, environmental accounting examines all flows (energy, materials, information, money) in terms of the energy of one kind required to produce them. For purposes of convenience, our analytical benchmark is solar energy, which couples with tidal momentum and nuclear decay within the Earth to supply exogenous available energy that is transformed sequentially into products and flows in the geobiosphere. The central premise is that flows in biophysical systems are comparable only when the process to create them is understood in energetic detail, and units of comparison are common. An accounting framework emerges in which the flows of obviously different commodities (e.g., soil, electricity, human labor) can be compared, added and related in a meaningful way because they are reported on an equal basis: the energy required for their creation. Those units are solar emergy (abbreviated sej) and the systems-level techniques for quantifying ecological efficiency using emergy are emergy synthesis.

Natural capital is effectively non-renewable. Whether such stocks accrue over millions of years (e.g. minerals, fossil fuels) or hundreds of years (e.g., top soils, forests, groundwater, fish stocks) is of limited importance when the rates of exhaustion can be measured in years or decades. However, in an effort to delineate geological storages from those that are more dynamic (slow-renewables), we divide natural capital into dispersed and concentrated uses (Figure 1). Dispersed sources are those that accumulate across landscapes and generally over decades: soil, water, fish and forests. Concentrated sources are geological stocks that accumulate over much longer time scales: fossil fuels, metal ores and mineral deposits. This delineation is clearly artificial (e.g., stocks of deep groundwater or boreal peat may be considered in both categories) but convenient. In particular, nations reliant on dispersed sources are primarily agrarian or pre-industrial, while those dependent on concentrated natural capital tend to be industrial or in transition. This paper focuses on the emergy costs of depleting stocks of dispersed natural capital at the scale of nations, and aggregates that information to estimate global costs; we focus our attention on soil, water, fish and forests, ignoring for this effort the natural capital stocks of biodiversity and landform. In all instances, costs are assessed using emergy (embodied environmental work) and related to economic measures of costs using standard protocols of national environmental accounting (Odum 1996, Doherty et al. 2002).

METHODS

Accounting for natural capital depletion within the wealth of nations required three steps. Data and methods for each natural capital resource are described below.

1) Determine the physical flows of each natural capital stock (soil erosion, water extraction, fish extraction, and logging of primary forest) for each nation globally; we include in our calculation only the portion of each flow in excess of the replacement rate for that resource.
2) Develop a suitable unit emergy value (UEV) to convert physical flows into emergy units (sej). The UEV quantifies the amount of solar energy embodied in a product after accounting for all direct and indirect inputs.
3) Embed computed emergy flows for natural capital stocks in a comprehensive national accounting scheme that offers context and a means to quantify each flow in emergy-imputed monetary units (Emdollars).

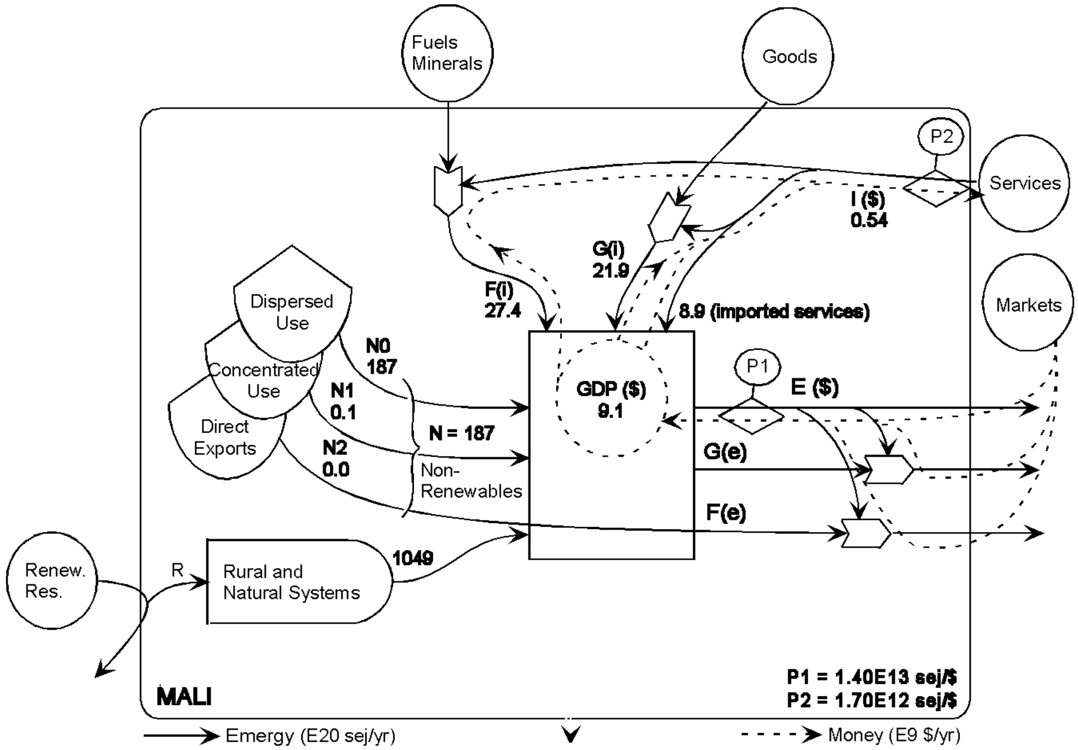

Figure 1. *Standard summary diagram (adapted from Odum 1996) of the resource basis of a national economy (Mali, ca. 2000) showing direct support of non-renewable resources (N) of dispersed (N0 – natural capital) and concentrated (N1) origin; resources exported without use (N2) are also shown. Letters R, F, G, I and E refer to renewable inputs, fuels, goods, imports and exports, respectively. P1 and P2 refer to the emergy money ratio (EMR) for the country and global economy, respectively.*

Physical Flow Accounting

In developing the National Environmental Accounting Database (NEAD – Sweeney et al., 2007) we have assembled global scale datasets that estimate flows of physical resources. Global data sets quantifying each of the four natural capital flows for each country (n = 134) were identified and imported into the biophysical framework of a standard national environmental accounting table (Ulgiati et al. 1994, Odum 1996); the NEAD is essential to step 3, above, to provide the global and national context within which flows of depleted natural capital can be interpreted.

Soil Loss

Soil losses are typically evaluated based on soil organic matter lost (via erosion by wind or water, oxidation after tillage). While SOM stocks globally are relatively well known (Figure 2A), the physical loss of SOM is difficult to estimate at the large scale because of significant uncertainties in the quantity of eroded soil. In fact, the only available global data resource on soil erosion is from the Global Assessment of Human Induced Soil Degradation (GLASOD), a qualitative map product produced by the International Soil Resource Information Center (ISRIC). That map (Figure 3) shows soil degradation categorically, with no explicit connection to quantitative rates of soil degradation, though causal mechanism is reported. To infer quantitative rates of soil loss from this spatial representation of soil degradation severity required several simplifying assumptions (Figure 4):

1) We assumed that all soil degradation was due to erosion. This assumption, though clearly problematic for areas where salinization, laterization, and/or organic matter oxidation are the primary mechanisms, is warranted because the majority of global soil degradation arises from erosion by wind or water.
2) We assigned a soil loss rate based on literature synthesis uniformly across the globe within each degradation category (Table 1). The resulting product is a raster map (cell size = 0.5 deg) with soil loss rates per unit area, as well as a global estimate of total soil erosion that can be compared to previous literature estimates (Lvovich 1991, Pimentel et al.1995).
3) To estimate eroded soil organic matter, we multiplied the soil loss rate for a given raster pixel by the estimated organic matter content of soils (% in the upper 1 m of soil profile) in that pixel. The SOM content map (Figure 2A) was obtained from the FAO/UNESCO Digital Soil Map of the World CD-ROM.
4) We assumed that only 10% of eroded material is ultimately exported (sediment yield ratio – Figure 4). While it is true that the landscape has multiple locations wherein eroded sediments and SOM are deposited, leading to a sediment yield in rivers much lower than estimated gross erosion, we consider accounting only for eroded material that leaves carried in rivers to be a substantial underestimate of true soil erosion costs. The reason is that the functional capacity of material eroded from terrestrial landscapes is lost to regardless of where the material is finally deposited. However, to maintain consistency with other aspects of environmental accounting which consider only cross-boundary flows, we estimate costs of soil losses based only on the 10% sediment yield ratio. This assumption is made regularly in the soil erosion literature (e.g., Lal 2003).

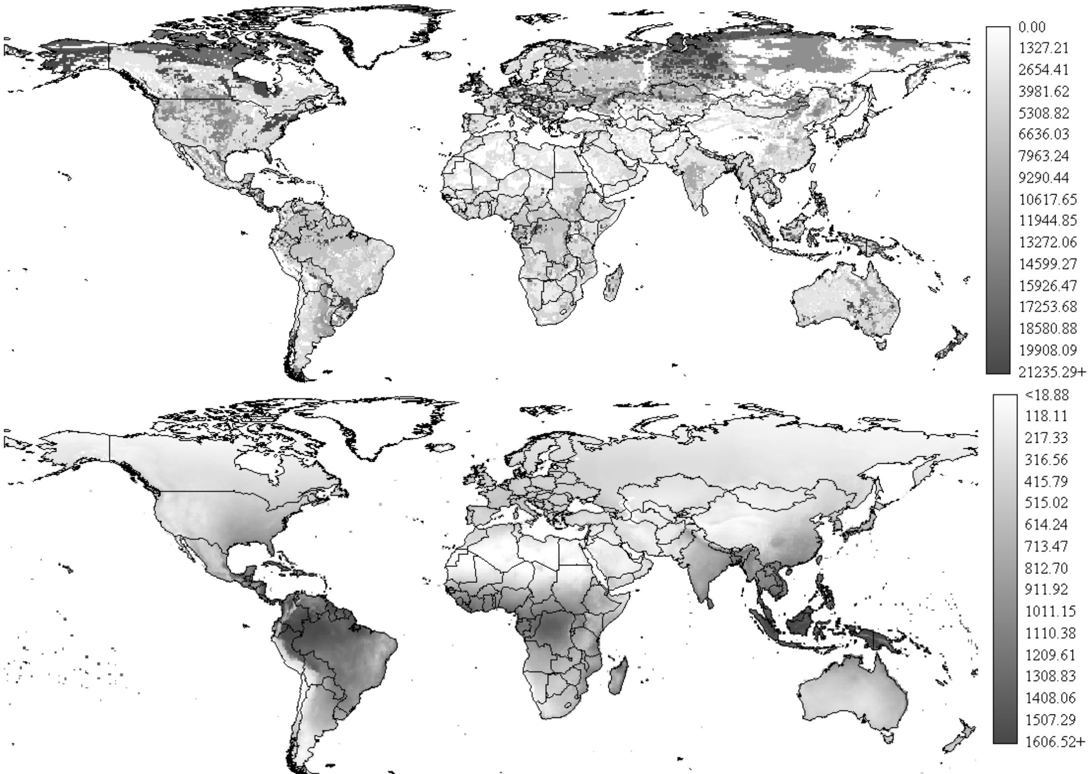

Figure 2. *A. Soil organic carbon pool in upper 1-m of soil profile (g* m^{-2}*), and B. mean annual soil-*CO_2 *emissions (1980-2004) in Mg C* km^{-2}

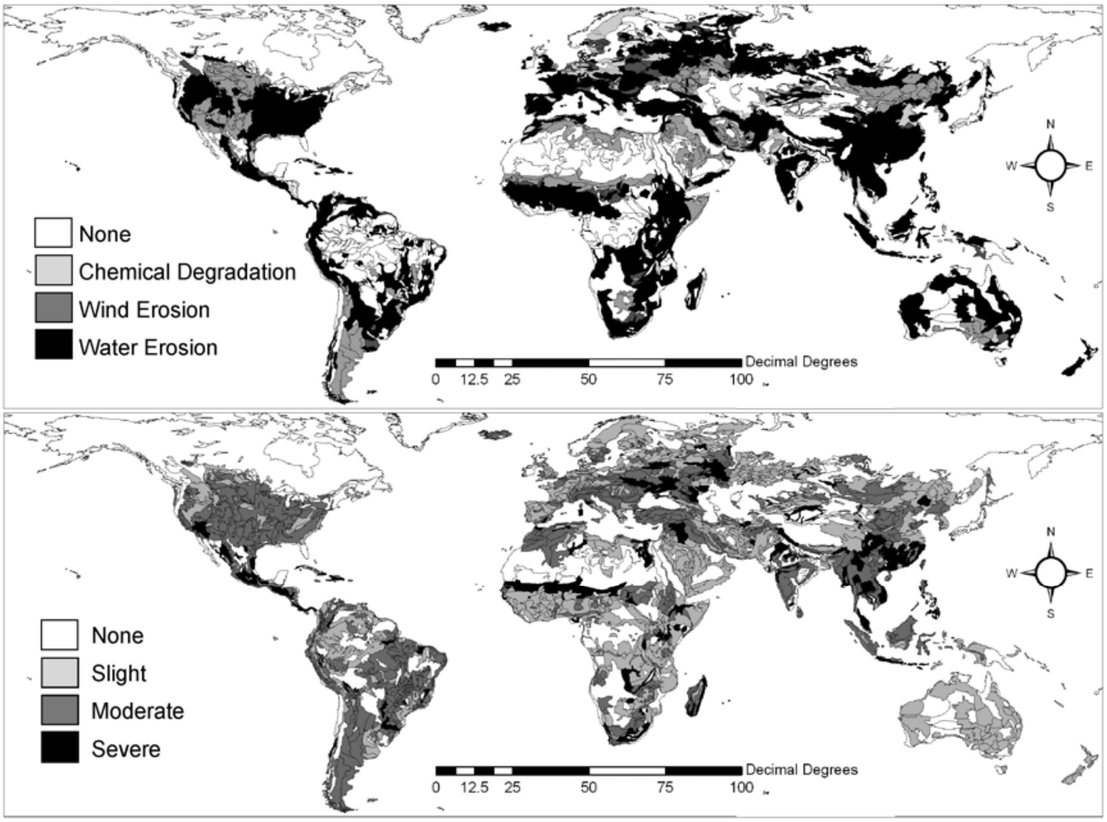

Figure 3. *Global maps of human-induced soil degradation by (A)cause and (B) severity (B) from GLASOD/ISRIC.*

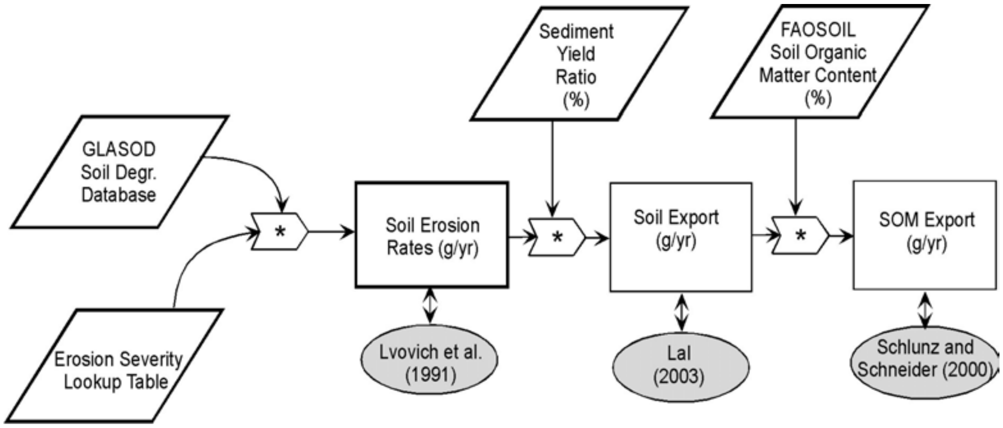

Figure 4*. Analytical scheme for extracting soil erosion from global maps. The erosion severity lookup table (Table 1) is compiled from literature averages; at each stage of the calculation, comparisons with analogous literature estimates are made. Note that erosion rates (g/yr) are at the scale of the entire nation.*

Fish Harvesting

Total global fish production has exceeded 130 million tones per year (FAO 2005), with the vast but shrinking majority coming from wild marine catch. Existing global databases documenting fish harvest rates are available (e.g. the FIGIS database from the Food and Agricultural Organization), but for this purpose we required not only harvest on a country basis but a credible estimate of the fraction of harvest that is unsustainable. While definitions of unsustainable harvest rates are notoriously imprecise and controversial, FAO Fisheries Technical Paper #457 offers quantitative estimates of over harvest based on existing national and international stock assessments and global fisheries statistics submitted to FAO by member nations. Maximum sustainable yields (MSY) for each of 441 species are computed based on organism biology and environmental conditions; these stocks represent over 80% of the global catch. The remaining 20% of the catch (from 143 species) have insufficient data to permit reliable assessment of exploitation. Stocks and exploitation state are reported for each of 17 major fishing zones throughout the globe. Estimated yields from each zone are partitioned into exploitation classes (Figure 5); globally, these classes are under-exploited (2%), moderately exploited (20%), fully exploited (52%), over-exploited (17%) and depleted/recovering (9%) (ftp://ftp.fao.org/docrep/fao/007/y5852e/y5852e00.pdf). These zonal data were then manually collated at the national level based on national fishing rights assigned in each; the results of this national collation are summarized for top fish producing nations in Table 2. Notably, the fraction of total fish

Table 1. Erosion severity lookup table for GLASOD soil degradation map.

GLASOD Soil Degradation Mechanism	GLASOD Soil Degradation Type	Soil Erosion Rate ($g/m^2/yr$)	Literature Range ($g/m^2/yr$)
None	None	100	5-150
Chemical Degradation[†]	Slight	330	No data
	Moderate	830	
	Severe	3,300	
Wind Erosion	Slight	250	300-3,500
	Moderate	750	
	Severe	2,500	
Water Erosion	Slight	250	150-40,000
	Moderate	1,000	
	Severe	3,000	

[†] - Because soil loss rates are in area/year (e.g., 16 million hectares annually lost to soil salinization), equivalent erosion rates were based on estimated lost soil functional capacity of 0.1%, 0.25% and 1% annually in slight, moderate and severe chemical degradation classes. Topsoil mass (to 20 cm depth) was assumed a surrogate for soil functional capacity.

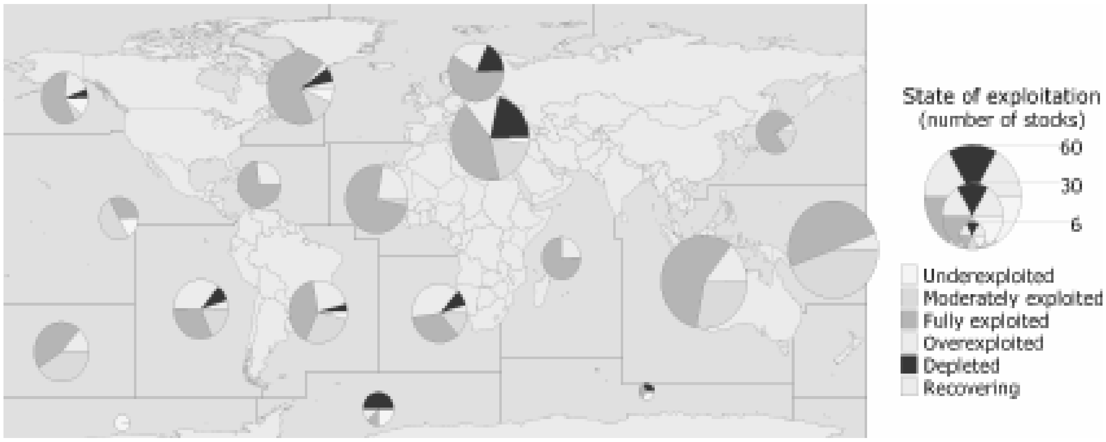

Figure 5. *Summary of fish stock exploitation by region; pie size corresponds to the number of stocks, not total catch.*

Table 2. Summary of national fish catch statistics for major national producers. Total catch and unsustainable catch are from FAO Fisheries Technical Paper 457.

Country	Total Catch (MT)	Unsustainable Catch (MT)	% Unsustainable
Peru	1.066E+07	9.918E+06	93.0%
Chile	4.547E+06	2.888E+06	63.5%
China	1.719E+07	2.582E+06	15.0%
USA	5.013E+06	1.835E+06	36.6%
Russian Fed.	4.041E+06	1.797E+06	44.5%
Norway	2.902E+06	1.759E+06	60.6%
Japan	5.124E+06	1.573E+06	30.7%
Iceland	2.000E+06	1.252E+06	62.6%
Indonesia	4.174E+06	8.668E+05	20.8%
Denmark	1.534E+06	7.805E+05	50.9%
Philippines	1.899E+06	7.521E+05	39.6%
Republic of Korea	1.839E+06	6.602E+05	35.9%
Thailand	3.002E+06	6.124E+05	20.4%
Morocco	8.813E+05	4.479E+05	50.8%
India	3.726E+06	4.469E+05	12.0%
Myanmar	1.070E+06	4.245E+05	39.7%
Argentina	9.163E+05	3.975E+05	43.4%
Taiwan	1.094E+06	3.952E+05	36.1%

harvest that is deemed unsustainable ranges from a low of 12% (India) to a high of over 93% (Peru). This follows from Figure 5, which shows a very large fraction of overexploited stocks in the Antarctic and South American Pacific, but a small fraction of over exploited and depleted stocks in the Indian Ocean.

Water Extraction

Estimation of water use in excess of renewable supply is the least refined computation in this research. While estimates of total water use are relatively well established, there is no agreed upon protocol for delineating excess from sustainable use rates. Further, data compiled at the national level for use quantity and sustainability neglect the substantial within-country variability in water resource availability. We have selected to use the Food and Agricultural Organization's AQUASTAT database to defined both national water resource availability and use, but also provide guidance on quantities of water use considered unsustainable (http://www.fao.org/waicent/faoinfo/agricult/agl/aglw/aquastat/dbase/index.stm). While there is no formal delineation of sustainable vs. unsustainable water use, it is assumed in this database that water use in excess of 25% of total renewable supply puts adverse stress on the system, both with respect to inter-annual variability and environmental consequences. We adopt this assumption, and report excess water use for a nation only when use is greater than 25% of total renewable supply. The consequence of this assumption is that numerous countries with known water supply sustainability issues, at least locally, are not listed among those exceeding their water resource carrying capacity. For example, the United States withdraws just over 15% of the renewable supply nationwide for consumption, and consequently extracts no water unsustainably for the purposes of our calculation. Table 3 summarizes water availability, use and sustainability for some of the 134 nations examined in this study, focusing primarily on those countries with unsustainable water use.

Forest Clearing

We assumed that the only natural capital costs of forest operations accrue when lands are deforested; this excludes plantation forests from consideration, which may suggest that estimates offered here are conservative because of changes in forest structure and function associated with production uses. Annual deforestation rates by nation are published by the Global Forest Resource Assessment, which reports data through the United Nations Environment Programme's GEO-3 data compendium (http://geocompendium.grid.unep.ch/data_sets/forests). The estimates for 2000 were made based on average annual deforestation rates between 1990 and 2000.

Area loss rates are useful, but environmental accounting requires physical flows of mass or energy; to convert area to biomass, we used published data on above-ground biomass in forests on a country basis from a report on land use and land cover change produced by the Intergovernmental Panel on Climate Change (IPCC). In particular, we employed data published in the good practice guidance document Annex 3.2 which provide forest biomass (dry weight) statistics (http://www.ipcc-nggip.iges.or.jp). The energy content of forest biomass was assumed to be 1.8E10 J ton^{-1} (dry weight

Table 3. Water supply, withdrawals and use in excess of sustainable supply for selected nations from FAO-AQUASTAT database.

Country	Total Renewable Supply (E9 m^3/yr)	Total Withdrawals (E9 m^3/yr)	Unsustainable Water Use (E9 m^3/yr)
India	1260.5	1896.7	645.8
Pakistan	52.4	222.7	169.4
Egypt	1.8	58.3	68.3
Uzbekistan	16.3	50.4	58.3
Iran	128.5	137.5	72.9
Iraq	35.2	75.4	42.7
Sudan	30.0	64.5	37.3
Turkmenistan	1.4	24.7	24.7
Saudi Arabia	2.4	2.4	17.3
Syria	7.0	26.3	20.0
Azerbaijan	8.1	30.3	17.3
Germany	107.0	154.0	47.1
Tajikistan	66.3	16.0	12.0
Spain	111.2	111.5	35.6
Kazakhstan	75.4	109.6	35.0
Afghanistan	55.0	65.0	23.3
China	2829.0	630.3	0.0
USA	3051.0	479.3	0.0
Japan	430.0	88.4	0.0
Thailand	409.9	87.1	0.0
Indonesia	2838.0	82.8	0.0
Bangladesh	1210.6	79.4	0.0
Mexico	457.2	78.2	0.0
Russian Fed.	4507.3	76.7	0.0
Viet Nam	891.2	71.4	0.0
Brazil	8233.0	59.3	0.0
Canada	2902.0	46.0	0.0

Table 4. Summary of annual forest loss (or gain) and the associated change in biomass for select countries.

Country	Annual Change (1000 ha)	Biomass (tons/ha)	Biomass Change (tons)
China	1806	6.10E+01	1.10E+08
United States	388	1.08E+02	4.19E+07
Belarus	256	8.00E+01	2.05E+07
Kazakhstan	239	1.80E+01	4.30E+06
Russia	135	5.60E+01	7.56E+06
Tanzania	-91	6.00E+01	-5.46E+06
Uganda	-91	1.63E+02	-1.48E+07
Kenya	-93	4.80E+01	-4.46E+06
Mali	-99	3.10E+01	-3.07E+06
Thailand	-112	2.90E+01	-3.25E+06
Papua New Guinea	-113	5.80E+01	-6.55E+06
Madagascar	-117	1.94E+02	-2.27E+07
Nicaragua	-117	1.61E+02	-1.88E+07
Botswana	-118	6.30E+01	-7.43E+06
Ghana	-120	8.80E+01	-1.06E+07
Paraguay	-123	5.90E+01	-7.26E+06
Angola	-124	5.40E+01	-6.70E+06
Ecuador	-137	1.51E+02	-2.07E+07
Bolivia	-161	1.83E+02	-2.95E+07
Colombia	-190	1.96E+02	-3.72E+07
Venezuela	-218	2.33E+02	-5.08E+07
Cameroon	-222	1.31E+02	-2.91E+07
Malaysia	-237	2.05E+02	-4.86E+07
Côte d'Ivoire	-265	1.30E+02	-3.45E+07
Peru	-269	2.45E+02	-6.59E+07
Australia	-282	5.70E+01	-1.61E+07
Argentina	-285	6.80E+01	-1.94E+07
Zimbabwe	-320	5.60E+01	-1.79E+07
Nigeria	-398	1.84E+02	-7.32E+07
Zaire	-532	2.25E+02	-1.20E+08
Mexico	-631	5.40E+01	-3.41E+07
Zambia	-851	1.04E+02	-8.85E+07
Sudan	-959	1.20E+01	-1.15E+07
Indonesia	-1312	1.36E+02	-1.78E+08
Brazil	-2309	2.09E+02	-4.83E+08

basis) across all forest systems. A summary of the data showing forest loss rates and estimate forest biomass per area is given in Table 4; note that countries with positive annual change has reported afforestation over the 10 year period between 1990 and 2000.

Development of Unit Emergy Values

For fish, forests and water, we used existing UEVs from recent sources; all values were either reported using the revised global emergy baseline (15.84E24 sej/yr), or adjusted appropriately from older baseline values. For soil, we present a new spatially explicit method for computing UEVs for soil organic matter (SOM) based on renewable emergy inputs (precipitation), SOM storage (to 1 m depth) and respiration rate (g m^{-2} yr^{-1}).

Soil

Previously, the UEV for soil came from a single study of organic matter accretion in the temperate environment (Odum 1996). This value (1.10E5 sej/J) represents the particular conditions of one study site, and cannot reasonably be applied to areas with dramatically different soil genesis characteristics and, in particular, soil organic matter turnover times. Cohen (2003) developed a dynamic model of soil genesis that computed UEVs for soil under tropical ecosystems; these values (1.91E5 and 1.92E5 for savanna and forest soils, respectively) reflect the greater production per unit SOM storage typical of tropical soils. This approach employed the schematic logic shown in Figure 6, but used a much more complex set of interacting processes to replicate the soil genesis process. In this work, we use the same basic framework, but take a simpler computational approach that permits extrapolation of the method to global datasets. Figure 7 summarizes the flow, with each box representing a raster spatial coverage; map computations were done in Idrisi (Clark Labs, Worcester MA). In that figure, the rainfall chemical potential UEV is constant (3.1E4 sej/J – Odum et al. 2000).

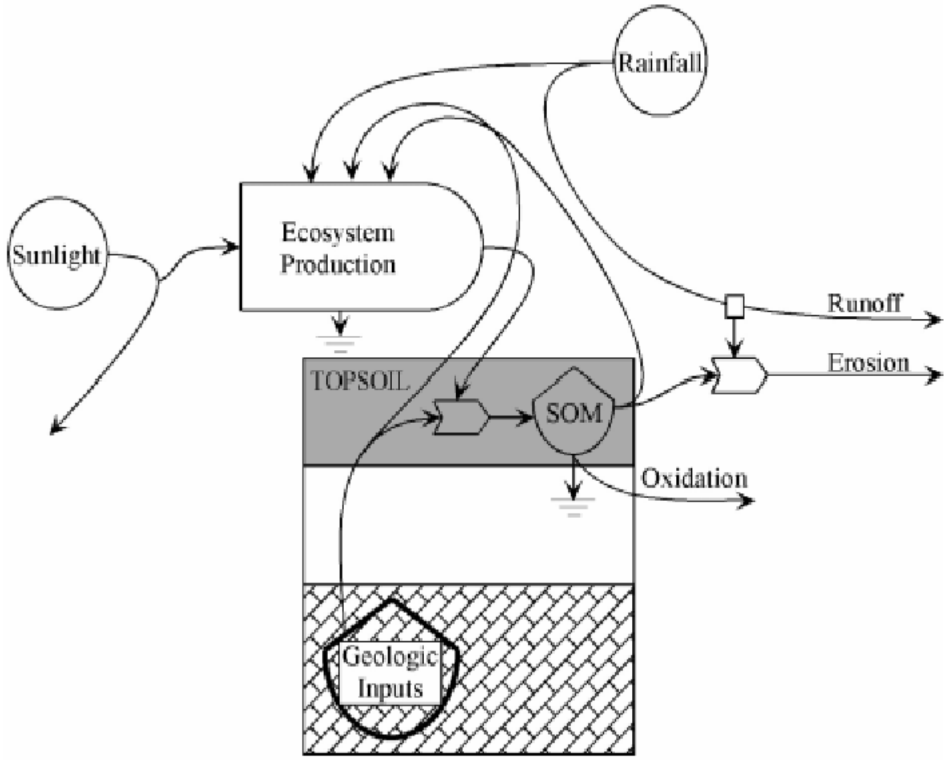

Figure 6. *Systems schematic of soil genesis showing the interaction of ecosystem and geological inputs to produce top-soil.*

The source of rainfall chemical potential is from the UNEP GRID database (see Appendix); Figure 8A shows the product of the UEV for rainfall and the rainfall quantity over a global raster map with cell resolution of 0.5 degrees.

The other sources of data for the UEV computation are SOM stocks (Figure 2A) from the Digital Soil Map of the World v. 3.6 (FAO 2003), and respiration data (Figure 2B) derived from Raich et al. (2002), based on average values between 1980 and 1994. From these maps, we derived a map of SOM turnover times (Figure 8B – in years), and converted annual CO_2 respiration rates to energy units. We assumed that respiration and SOM accumulation are balanced (i.e. the SOM pool is at equilibrium) despite is ample evidence to suggest that, globally, soils are losing SOM stocks due to increased respiration (Lal 2003). If SOM accumulation rates are, in fact, slower than observed respiration rates, then the computed UEVs will be lower than they should be, making this analysis of costs inherently conservative.

The resulting UEV map (produced on a 0.5º grid) can be multiplied by the estimated soil organic matter losses due to erosion and chemical degradation to arrive at a global map of emergy flow associated with lost soil. This map can be summed according to national boundaries to yield an annual emergy flow.

Water

The unit emergy value for water depends substantially on the source of the water. Water overuse typically affects large river systems and/or regional aquifer systems; both have UEVs larger than rainfall because of landscape convergence processes. Buenfil (2000) computed UEVs for several sources of water, both before and after treatment for human consumption, and computed a UEV for

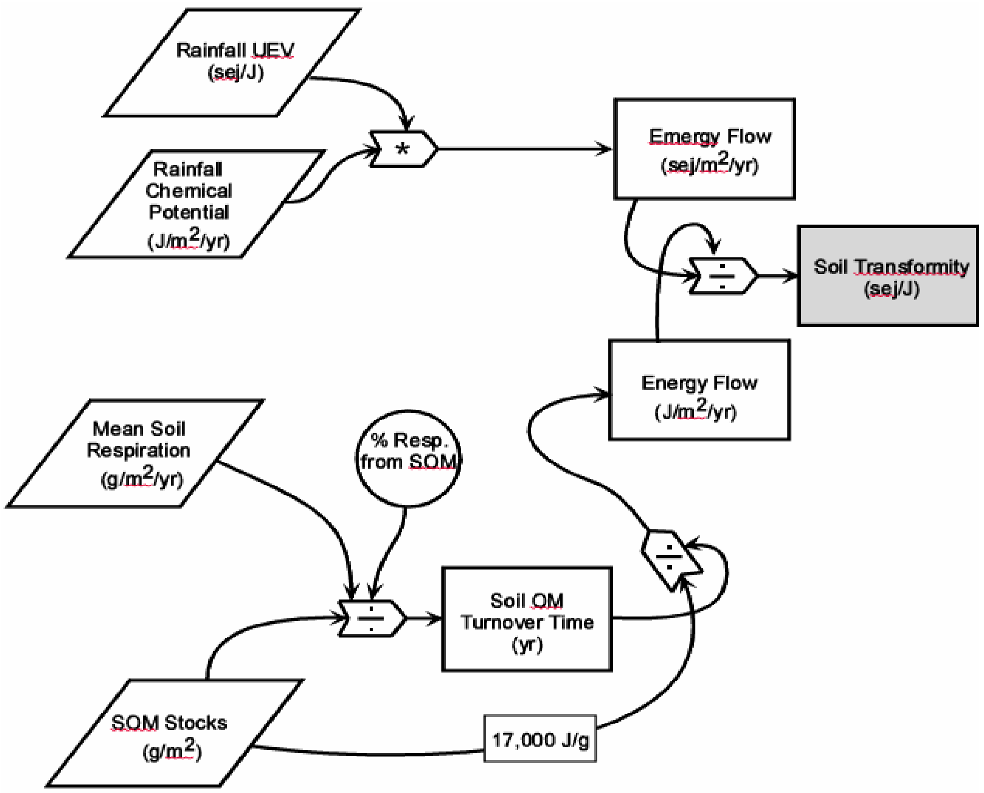

Figure 7. *Analysis flow chart used to compute UEVs for soils globally.*

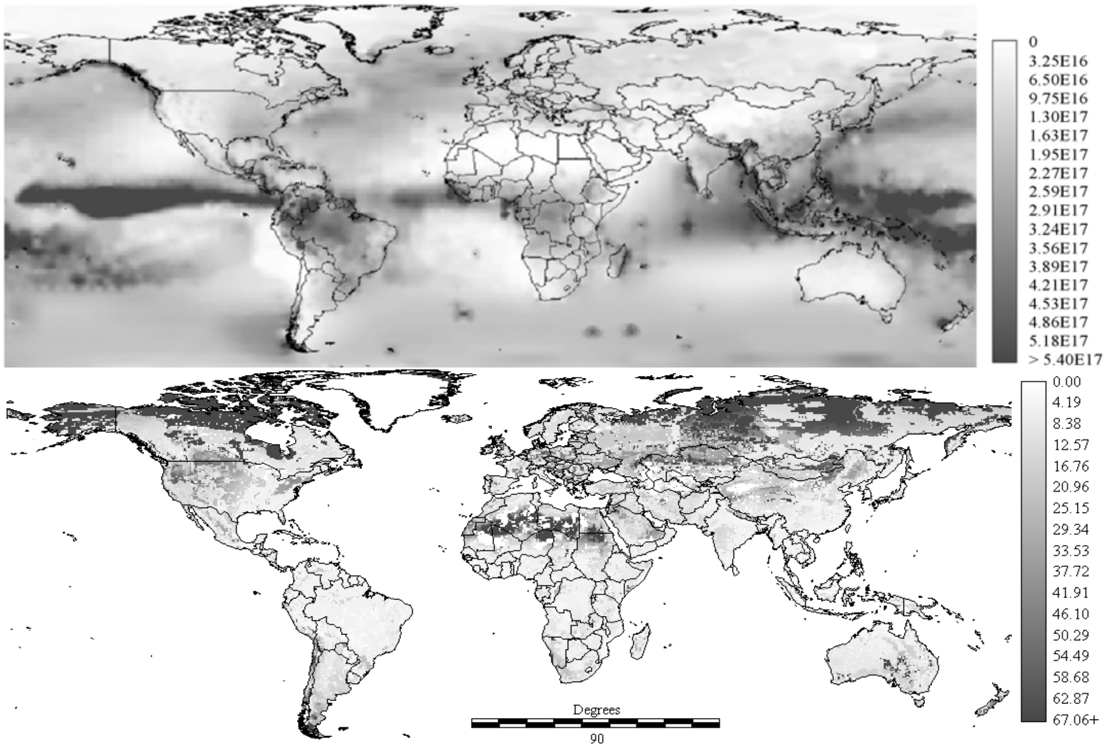

Figure 8. *Global maps of A) rainfall emergy (sej* km^{-2} yr^{-1}*) and B) SOM turnover time (years). Rainfall emergy is the product of total rainfall in each cell and the UEV for rainfall (3.1E4 sej/J). The SOM turnover map is derived from estimates of soil respiration (Raich et al 2002) and the global topsoil SOM pool (FAO 2003).*

groundwater of 2.82E5 sej/J, addressing only the chemical potential energy of freshwater vis-à-vis seawater. We assume this value for all estimated water overuse flows ascertained above from the FAO-AQUASTAT database because that database provides no information about the source of water. Partitioning water use among the actual sources (with UEVs computed for each) is an important refinement that can best be accomplished with higher resolution national data. Given that the estimates of unsustainable water use are likely to be significant underestimates, and that the UEV computed for groundwater is for the Floridan aquifer, which is among the most transmissive in the world and consequently of lower UEV, we suggest that our computed water capital depletion costs are significant underestimates.

Fish

The UEV for fish is the most complex of the four natural capital flows; fish harvested for human consumption may be obtained from multiple trophic levels, be of profoundly variable size, and be from dramatically different ecosystems. As such, specifying a global UEV estimate is challenging. We took the same basic approach as used for water in erring on the low side of the actual expected emergy cost. In this case, we selected a UEV for herbivorous fish (Brown et al. 1993) from a tropical system (8.0E+06 sej/J), and applied that number uniformly to biomass estimates from the various sources of physical flow data. A limited meta-analysis of fish UEVs reveals little consensus on the methods, but a general convergence of values at levels substantially higher than equivalent trophic positions in terrestrial ecosystems.

Forests

Like fish harvesting, the emergy value of overused forest resources depends substantially on the forest type. Our computation of the physical flow of forest resource over-use is crudely-forest specific, with published deforestation area rates on a country by country basis adjusted by the biomass per area typical of forests in that country. However, we do not attempt to adjust the UEV of forest biomass based on forest type. Despite several efforts to quantify the UEV of biomass from forests of different kinds, the values are still substantially uncertain. An obvious refinement of this work would be to examine deforestation in more detail within each country and assign emergy costs in a more specific manner. The UEV that we have applied to all forest biomass lost to deforestation is 3.8E+04 sej/J, which is comparatively low; Doherty (1995) and Odum et al. (2000) report a UEV for secondary tropical forest biomass of 5.5E+04 sej/J and Tilley and Swank (2003) report a UEV of 8.9E+-4sej/J for temperate hardwood biomass. While lower UEVs exist in the emergy literature (Doherty 1995 reports boreal spruce = 1.7E+04 sej/J, slash pine = 3.3E+04 sej/J, and loblolly pine = 1.9E+04 sej/J), these are typically for production forest operations, and not mature ecosystems. We consider the selected UEV to be conservative.

Resource Flows in Context – Integration in the NEAD

We used the National Environmental Accounting Database to scale the magnitude of natural capital flows to more familiar aspects of national and global accounting. We report several indices to facilitate comparative inference:

1) Total Natural Capital – natural capital depletion in emergy units
2) % Natural Capital – natural capital emergy flow divided by total national emergy consumption.
3) % Soil/Water/Fish/Forests –disaggregated by type for clarification.
4) Emergy money value – we impute the macroeconomic value (costs) of natural capital depletion by dividing the natural capital emergy flow (sej) by the global emergy money ratio (EMR - sej/$).
5) Sustainability – we explore relationships between the magnitude and fractional dependence of an economy on natural capital depletion, and various indices of development and sustainability (GDP per capita, Emergy Sustainability Index, Electricity Use).

RESULTS

We first present the results of a new computation of the unit emergy value of soil organic matter. Figure 9A provides a map of UEVs globally; the median value globally is 1.34E5 sej/J, which concords well with previous computations (1.1E5 sej/J – Odum 1996, 1.91E5 sej/J - Cohen 2003), and the range from the 5th to 95th percentiles is 3.2E4 to 3.3E5 sej/J.

Multiplying the UEV by SOM export (derived by multiplying the erosion rate by the SOM fraction and a sediment yield ratio of 10%) yields the total emergy loss. This quantity, shown in Figure 9B (natural log transformed for map clarity) was parsed by country boundaries to yield a total annual emergy cost.

Next we present tabular and map summaries of the global estimates of natural capital losses. Figure 11 A through D show the extent and severity of natural capital globally, by specific natural capital source. We report the total emergy flow, which tends to highlight large countries because natural capital depletion is an extensive process. Mapping based on fraction of total use (%) is represented across all sources of natural capital in Figure 10.

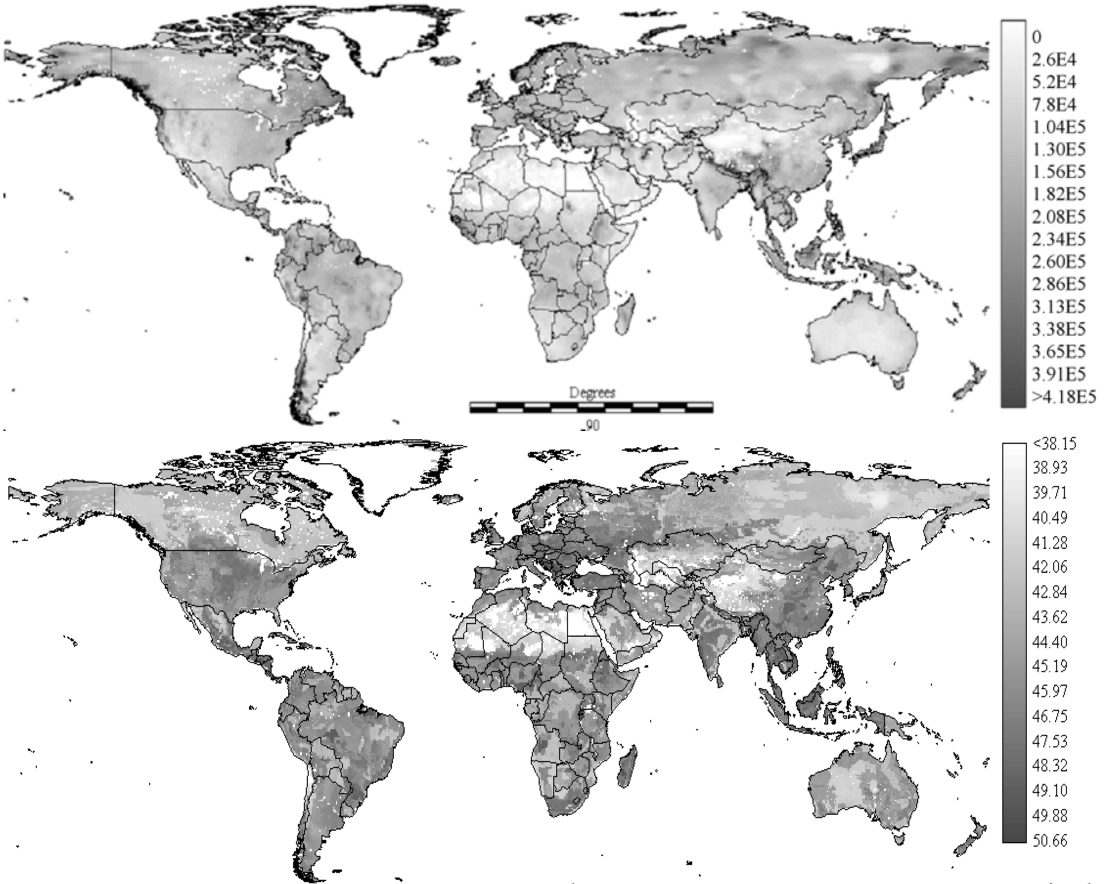

Figure 9. *Maps of A) soil unit emergy value (UEV – sej J^{-1}), and B) natural-log emergy of soil loss (sej km^{-2} yr^{-1}).*

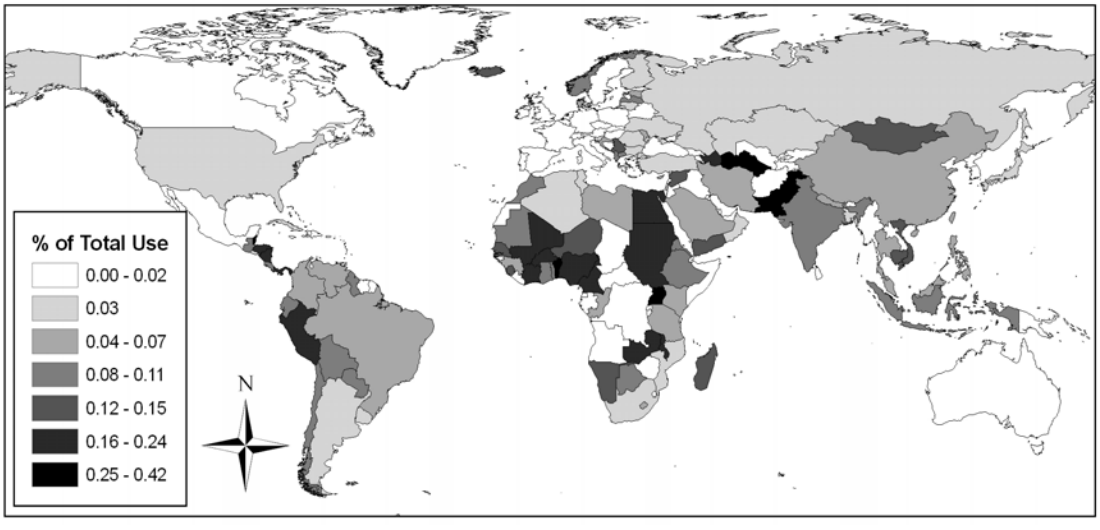

Figure 10. *Global summary of natural capital reliance as % of total emergy use.*

Table 5 presents information on emergy flows and imputed macroeconomic value based on the global EMR (2.64E12 sej/$ - Sweeney et al. 2007). We elected to use the global EMR not the national EMR because we were interested in global costs; imputed macroeconomic costs for each country can be obtained using the appropriate national EMR. Countries in Table 5 were selected based on total emergy flow in each category, which tends to bias towards larger countries.

The annual global costs of natural capital depletion, compiled from the cost estimate for full list of 134 nations, are summarized for each category in Figure 12. The largest annual cost is soil erosion ($610 billion annually), but all flows are approximately equal magnitude. The sum of these costs, which can be added because the flows are independent, is $1.5 trillion annually.

Finally, Figure 13 shows the relationship between natural capital depletion rates, both as a percentage of use and in raw emergy units, and the emergy sustainability index (Ulgiati and Brown 1998, Brown and Ulgiati 1999). Both show a marked bell shape, with nations at either end of the ESI spectrum exhibiting low natural capital depletion rates, while nations having intermediate ESI values tend to be those with high reliance on natural capital. Notably, this is not a uniform response; several nations with intermediate ESI values have low natural capital reliance. Nations with ESI values between 0.1 and 10.0 (intermediate sustainability) and low natural capital reliance include Kenya, Russia, New Zealand, China, Algeria, Venezuela, Australia, Saudi Arabia and Iran. We loosely interpret this category of nations to be more reliant on mined capital (e.g., fuels, metals, minerals) instead of dispersed natural capital; mined materials constitute an average of 32% of total use in these 31 countries (Cohen et al. this volume). In that same range of ESI (0.1 to 10.0), there are 43 countries with high natural capital reliance (> 5%). The include Rwanda, Burundi, Nicaragua, Nigeria, Senegal, India, Malawi, Pakistan and Egypt; we loosely attribute these intermediate development status nations to a class that is less reliant on mined capital (% of total use across all 43 nations averages 21%).

DISCUSSION

Natural capital from diffuse sources such as soils, forests, fisheries and aquifers/rivers is a critical base of modern industrial metabolism. Frequently, we focus on natural resources that are mined when we consider nonrenewable support for society's work, but clearly, the depletion of slowly renewable stocks represents a significant and unsustainable source of national wealth. Globally, diffuse natural capital represents 3% of total emergy use, and nearly 18% of total renewable use.

Comparison with other aspects of economic metabolism is one of the important properties of the environmental accounting approach. In this work, we observe that the depletion of natural capital (note, ***not total use***, just that fraction deemed beyond sustainable levels) is approximately equal in magnitude with the combined flows of aluminum, copper, manganese, magnesium and zinc (five of the six most mined metals), and nearly 25% of total electricity use globally (Sweeney et al. 2007). By imputing the economic value of the lost ecosystem stocks, we can also infer that natural capital depletion represents an annual cost to global society of over $1.2 trillion annually; as before, this cost estimate is for the loss of stocks only, not the total service provided. Moreover, this cost is for the loss of service that the stock provided, not the costs that are incurred elsewhere as a result of excess sediment movement, reduced water flows, reduced carbon sequestration or reduced marine productivity. These environmental costs are much harder to estimate at the global scale, but may be of even greater significance.

One of the key refinements to the environmental accounting method developed in this work is the global estimation of soil UEVs. The concordance between our new spatially explicit method (average – 1.34 E5 sej/J) and previous methods (1.1E5-1.9E5 sej/J) is encouraging. This technique also gives us the opportunity to evaluate UEVs for particular soil types (on an average basis) and to estimate the value of global soil stock. The former output is beyond the scope of this work, but, using the maps employed in our UEV estimation procedure, we estimate the total value of global stocks of

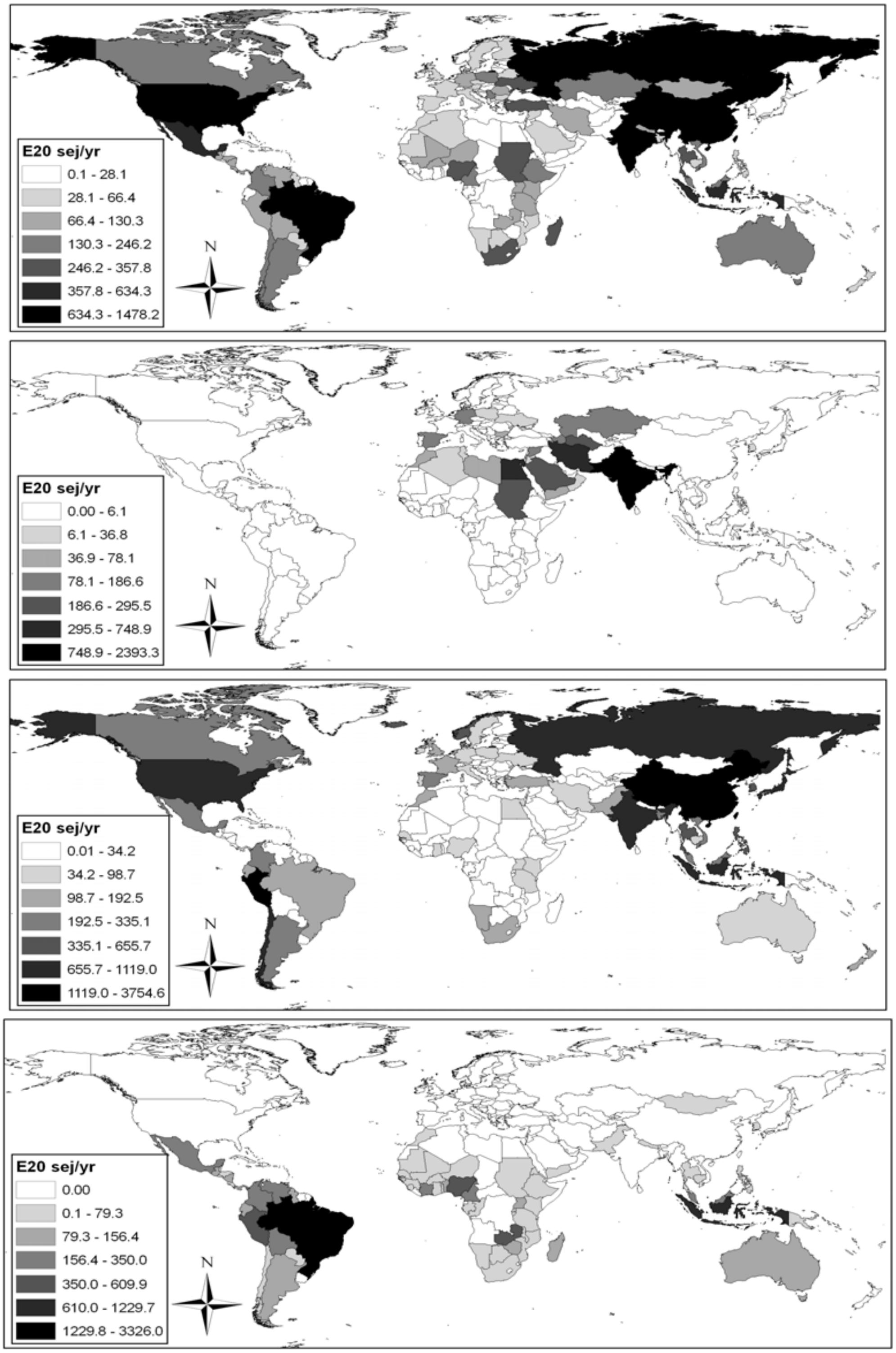

Figure 11. *National emergy flows of natural capital in E20 sej/yr for A) soil loss, B), water overuse, C) overfishing and D) deforestation.*

Table 5. Summary of natural capital depletion by total emergy flow, fraction of total national use and imputed macroeconomic cost for selected countries.

	Soil Loss				Water Overuse		
Country	Emergy E20 sej	%U	Costs (Em$)	Country	Emergy E20 sej	%U	Costs (Em$)
China	1478.2	1.1%	$5.60E+10	India	2393.3	4.5%	$9.07E+10
Brazil	1429.9	2.0%	$5.42E+10	Pakistan	1585.4	24.1%	$6.01E+10
Russia	1343.1	1.8%	$5.09E+10	Egypt	749.0	15.2%	$2.84E+10
USA	1158.3	0.6%	$4.39E+10	Iran	536.8	3.3%	$2.03E+10
India	1010.9	1.9%	$3.83E+10	Sudan	295.5	8.3%	$1.12E+10
Indonesia	634.3	2.0%	$2.40E+10	Turkmenistan	257.5	24.6%	$9.75E+09
Mexico	535.0	0.6%	$2.03E+10	Saudi Arabia	233.1	2.6%	$8.83E+09
Ukraine	357.8	2.2%	$1.36E+10	Syria	186.6	10.0%	$7.07E+09
Nigeria	332.9	6.8%	$1.26E+10	Azerbaijan	135.0	14.8%	$5.11E+09
Turkey	332.8	2.2%	$1.26E+10	Germany	119.2	0.2%	$4.51E+09
Thailand	330.9	1.8%	$1.25E+10	Spain	108.1	0.2%	$4.10E+09
Sudan	300.1	8.5%	$1.14E+10	Kazakhstan	105.9	1.3%	$4.01E+09
South Africa	299.0	1.4%	$1.13E+10	Yemen	78.1	9.2%	$2.96E+09
Madagascar	290.5	6.6%	$1.10E+10	Morocco	74.6	2.0%	$2.83E+09
Ethiopia	246.2	7.4%	$9.32E+09	Bulgaria	72.1	2.2%	$2.73E+09
Australia	235.2	0.5%	$8.91E+09	Libya	57.4	3.9%	$2.17E+09
Serbia	220.0	13.4%	$8.33E+09	Ukraine	36.8	0.2%	$1.40E+09
Vietnam	218.5	5.6%	$8.28E+09	Algeria	34.7	1.1%	$1.31E+09
Argentina	208.5	0.7%	$7.90E+09	Israel	22.8	0.7%	$8.62E+08
Chile	201.5	1.8%	$7.63E+09	Tunisia	20.8	1.2%	$7.87E+08

	Overfishing				Deforestation		
Country	Emergy E20 sej	%U	Costs (Em$)	Country	Emergy E20 sej	%U	Costs (Em$)
China	3754.6	2.9%	$3.16E+10	Brazil	3326.0	4.7%	$1.26E+11
Peru	2328.1	15.6%	$8.30E+09	Indonesia	1229.8	4.0%	$4.66E+10
Japan	1119.0	1.6%	$7.50E+10	Zambia	610.0	15.5%	$2.31E+10
USA	1094.9	0.6%	$5.66E+10	Nigeria	504.7	10.2%	$1.91E+10
Chile	993.1	8.9%	$6.63E+09	Peru	454.2	3.1%	$1.72E+10
Indonesia	911.7	2.9%	$4.42E+09	Venezuela	350.1	3.4%	$1.33E+10
Russia	882.6	1.2%	$3.09E+09	Malaysia	334.9	2.1%	$1.27E+10
India	813.9	1.5%	$7.14E+09	Colombia	256.7	2.6%	$9.72E+09
Thailand	655.7	3.6%	$4.39E+09	Cote d'Ivoire	237.4	15.6%	$8.99E+09
Norway	633.7	9.3%	$1.55E+10	Mexico	234.8	0.3%	$8.90E+09
Philippines	414.8	5.1%	$3.91E+09	Bolivia	203.1	5.5%	$7.69E+09
S. Korea	401.7	1.0%	$4.46E+09	Cameroon	200.4	8.8%	$7.59E+09
Denmark	335.1	7.0%	$1.10E+10	Madagascar	156.4	3.5%	$5.93E+09
Vietnam	316.8	8.1%	$2.53E+09	Ecuador	142.6	4.6%	$5.40E+09
Mexico	295.0	0.3%	$1.87E+09	Guatemala	138.1	7.0%	$5.23E+09
Spain	231.6	0.5%	$2.86E+09	Argentina	133.6	0.5%	$5.06E+09
Canada	227.8	0.4%	$2.71E+09	Nicaragua	129.8	12.5%	$4.92E+09
Argentina	200.1	0.7%	$1.95E+09	Zimbabwe	123.5	1.0%	$4.68E+09
UK	163.3	0.3%	$4.31E+09	Panama	115.4	7.1%	$4.37E+09
Sweden	73.9	0.9%	$2.09E+09	Uganda	102.2	11.4%	$3.87E+09

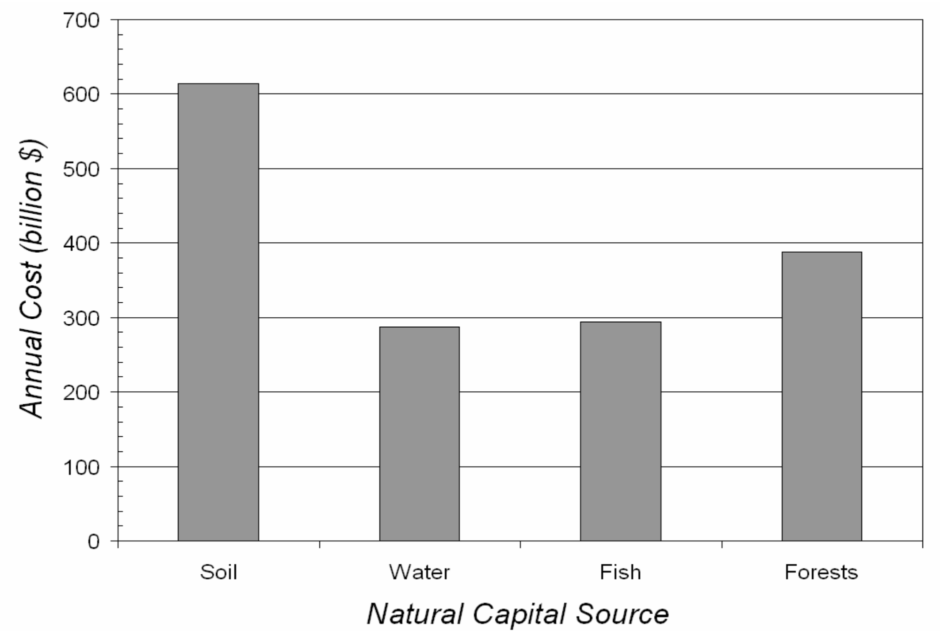

Figure 12. *Summary of global costs of depletion for each of the natural capital stocks examined. Cost estimates (imputed from the global ratio of emergy and money flows) are in billions of US $ in the year 2000.*

soil organic matter (across the 134 nations of NEAD) to be 2.4E27 sej, which corresponds to an imputed economic value of $904 trillion (Year 2000). We note that this value is not for direct services, just the accumulated emergy value stored in the topsoil globally. Similar calculations for the other natural capital flows are not possible under the current framework for multiple reasons, including data availability on stocks, and refined estimation of UEVs. These are primary avenues for future research.

Several issues, in particular, are important for future work. First and foremost, the manner in which we evaluate the global sustainability of water resources is of limited value. Water resources are differentially available within nations; a dramatic demonstration of this limitation of the current approach is that the United States is assumed to be using its water resources in a sustainable manner. We argue that the evidence is strongly to the contrary in parts of the nation, and that ascertaining unsustainable use as extraction exceeding 25% of total national renewable supply is a poor estimator. Various methods could be used to improve this estimate, including global maps of aquifer depletion severity, and national estimates of water sources (extraction and recharge). Further, the manner in which we address the emergy value of water is of limited global utility. The UEV that was used is typically of large rivers and deep groundwater obtained from the Floridan Aquifer. This aquifer is extremely productive, and this level of recharge means that the quantity of surface precipitation necessary to sustain its level is lower than for many other aquifers. More refined data and UEVs would, we believe, lead to the conclusion that the unsustainable use of water is markedly higher than we report here.

The same may be said of fish and forest estimates; in each case, we endeavored to make conservative estimates of stocks, flows and UEVs. For example, several nations (China and the United States, in particular) report negative deforestation rates. While this may be true when considering afforestation initiatives and plantation forests, including these areas assumes that they effectively offset the costs of clearing of virgin forests, which is almost certainly not the case. A global data set that provides national estimates of loss rates for natural forests would permit a more refined, and likely much higher, calculation of the system-level costs.

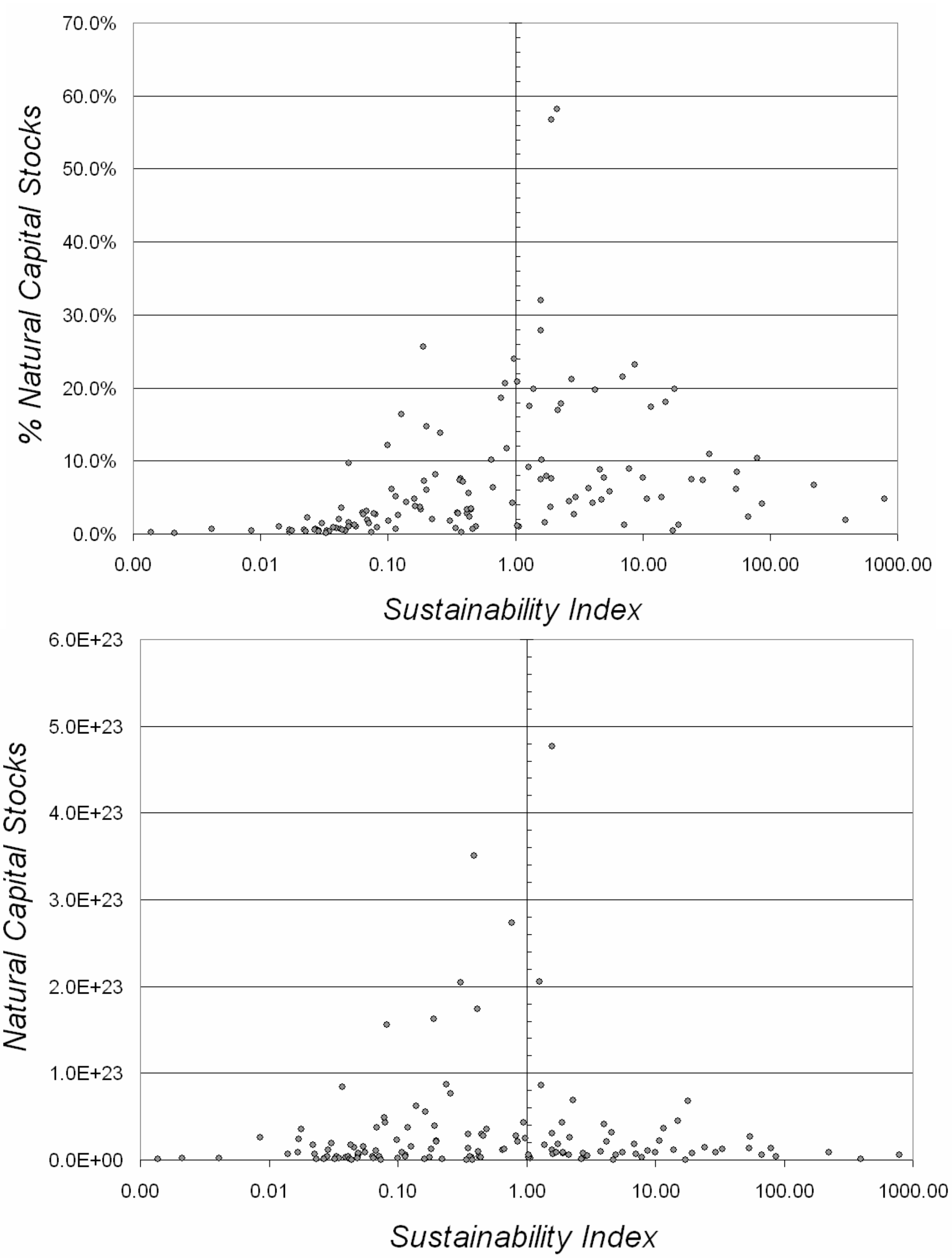

Figure 13. *National-scale natural capital depletion as A) % of total use and b) total emergy flow vs. the emergy sustainability index (ESI).*

One striking feature of the data presented here is that the levels of natural capital input to social metabolism are relatively small compared with total fuels, total metals and minerals, total services, etc. While a value of $1.2 trillion annually underscores the global scope of natural capital depletion, it also is comparatively small vis-à-vis the expected importance of natural systems in supporting modern society. We reiterate that this is, in some ways, a false comparison. The figures presented in this work are for the loss of natural capital, not the total services obtained from them. Soils, for example, have numerous functional capacity that is of profound value to farmers worldwide; our estimation of the costs of soil degradation do not, at all, estimate this intrinsic value. Rather, we estimate the value of incremental depletion of this value. To count the full service value of the natural capital stocks that we have examined would be to double count their emergy value, because those services are engendered via internal transformations of renewable inputs (sunlight, rainfall, geological work); only losses of these services beyond their rate of renewal can be counted in a national accounting scheme.

The costs to society of losing natural capital are real and pressing. We note from a cursory analysis of the relationships between natural capital depletion and conventional measures of wealth, that there appears to be a strong Kuznets-curve trend in the data. That is countries with very low levels of wealth produce little load on environmental systems, but countries with very high levels of wealth also produce light loads. Nations in transition between the two ends of the spectrum are those that are over-using their environmental resources. There are several explanations for this, including greater investment in environmental protections with increasing social wealth, and also export of environmental destruction outside of national boundaries as countries develop increasingly stringent

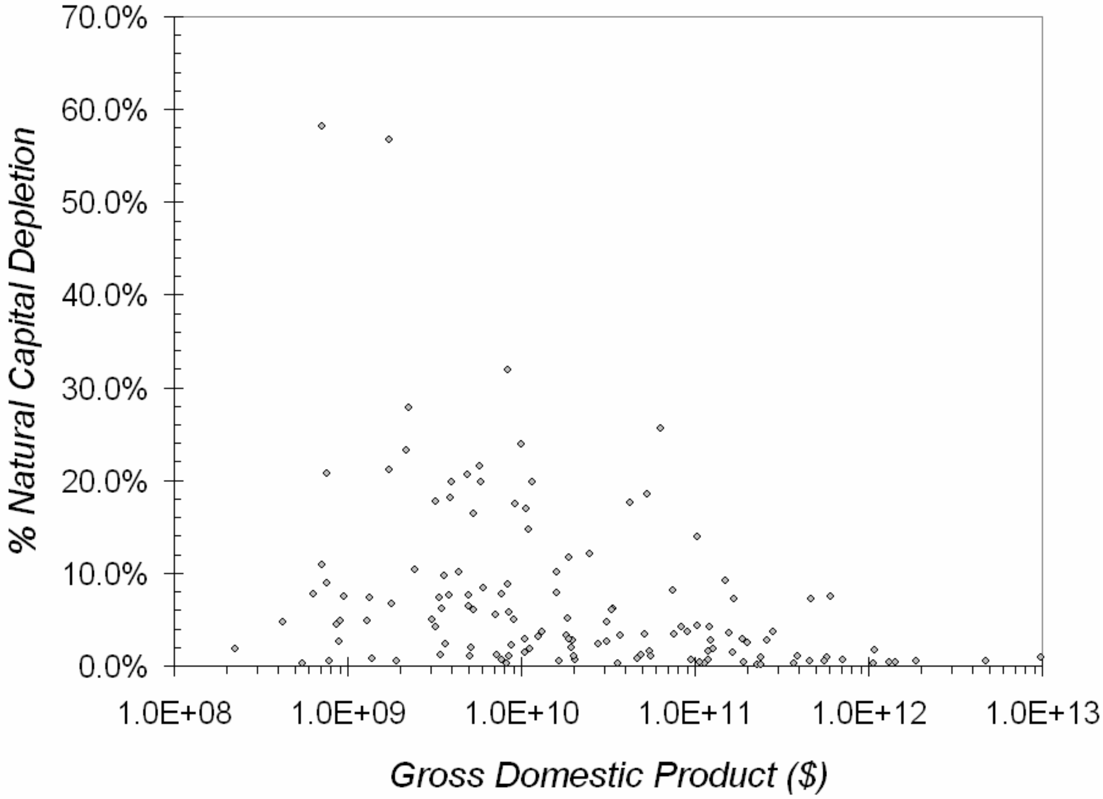

Figure 14. *Gross domestic product vs. the fraction of total emergy use from natural capital sources. Rwanda and Burundi are the two outlier points approaching 60% natural capital reliance.*

environmental regulations. Regardless of the mechanism, we observe strong evidence for it on our graphs of ESI (emergy sustainability index) vs. natural capital depletion, and from Figure 14 which shows the relationship between GDP and natural capital depletion. Both demonstrate that wealthy countries have largely weaned themselves from a reliance of depleting natural capital (possibly in favor of other non-renewable resources, such as fuels); all nations with GDP values greater than $500 billion use less than 2% of their total emergy in the form of depleted natural capital (Figure 14).

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APPENDIX

Variable	Dataset	Accessed through…	URL for dataset
Rainfall	Wilmott grid V.2.01	Center for Climatic Research	climate.geog.udel.edu/~climate/html_pages/download.html
Evapo-transpiration	Ahn and Tateishi, AET grid	UNEP, GEO Data Portal, GNV183	www.grid.unep.ch/data/data.php?category=atmosphere
Fishery extraction	FIGIS	Food and Agriculture Organization	faostat.fao.org/
Nonrenew fisheries	FAO Fisheries Technical Paper 457	Food and Agriculture Organization	ftp://ftp.fao.org/docrep/fao/007/y5852e/y5852e00.pdf
Wood extraction	FAOSTAT	Food and Agriculture Organization	faostat.fao.org/
Wood biomass per area	IPCC report, Table 3A.1.4	Intergovernmental Panel on Climate Change	www.ipcc-nggip.iges.or.jp/public/gpglulucf/
Annual forest extent lost	Global Forest Resources Assessment 2000	UNEP, GEO-3 Data Compendium, 1.1	geocompendium.grid.unep.ch/data_sets/forests/nat_forest_ds
Water extraction	AQUASTAT database	Food and Agriculture Organization	http://www.fao.org/ag/agl/aglw/aquastat/main/index.htm
Soil organic matter content	Digital Soil Map and Derived Soil Properties	FAO/UNESCO	http://www.fao.org/AG/AGL/agll/dsmw.stm
Soil respiration	Interannual Variability in Global Soil Respiration (1980-94)	Carbon Dioxide Information Analysis Center	http://cdiac.esd.ornl.gov/epubs/ndp/ndp081/ndp081.html
Soil degradation	GLASOD database	ISRIC	www.grid.unep.ch/data/grid/soils.html