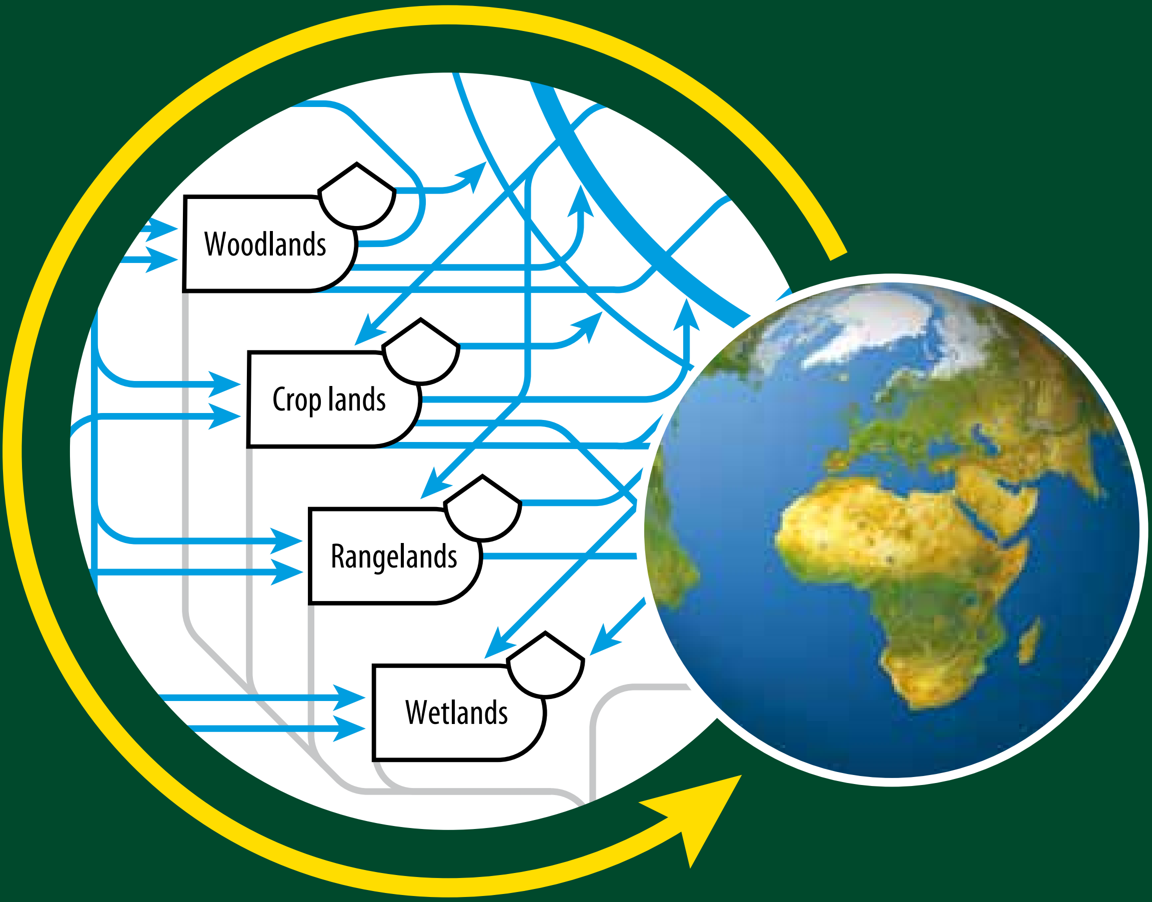
ENVIRONMENTAL ACCOUNTING

of National Economic Systems

An Analysis of West African Dryland Countries within a Global Context



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Abbreviations and acronyms

EA	environmental accounting
EER	Emergy Exchange Ratio
EF	ecological footprint
EIR	Emergy Investment Ratio
ELR	Environmental Loading Ratio
EMR	Emergy Money Ratio
ESI	Emergy Sustainability Index
ETIF	Emergy Trade Inequity Factor
ETWI	Emergy Total Well-being Index
EWI	Ecosystem Well-being Index
EYR	Emergy Yield Ratio
GDP	gross domestic product
GNH	Gross National Happiness
GPI	Genuine Progress Indicator
HDI	United Nations Development Programme's Human Development Index
HWI	Human Well-being Index
ISEW	Index of Sustainable Economic Welfare
MSY	Maximum Sustainable Yields
NEAD	National Environmental Accounting Database
PPP	Purchasing Power Parity
RES	Reducing Environmental Stresses
RHV	Reducing Human Vulnerability
SIC	Social and Institutional Capacity
SITC1	Standard International Trade Classification, Revision 1
SOM	soil organic matter
TSWI	Total System Well-being Index
UEV	Unit Emergy Value
WI	Well-being Index
YESI	Yale's Environmental Sustainability Index
$	refers to US dollar in this report
tons	Refers to metric tons in this report

Foreword

Ecosystem goods and services from natural capital provide food, fibre, water, health, energy, climate security and other essential services that benefit everyone. However degradation of terrestrial, freshwater and marine ecosystems has accelerated dramatically over the past several decades and there is evidence that in some cases ecosystems may be reaching tipping points beyond which rehabilitation is impossible or prohibitively costly.

Recognition of the scale of the problem of unsustainable use of natural capital and the urgency of the need to act have been growing steadily since the first "Rio" Summit of the UN Conference on Environment and Development in 1992. Key assessments include the *Millennium Ecosystem Assessment* of 2005, UNEP's Global Environment Outlook reports, *The Economics of Ecosystems and Biodiversity* report, and UNEP's *Towards a Green Economy*. At the Rio+20 Earth Summit, in *The Future We Want*, countries urged action "to reverse land degradation" and "to strive to achieve a land degradation neutral world in the context of sustainable development". There was strong global endorsement for a green economy as one of the important tools available for achieving sustainable development and eradicating poverty, as well as an explosion of interest in natural capital accounting.

The basic problem is that ecosystem services, and the stocks of natural capital that provide them, are not adequately valued compared with social and financial capital. Although essential to human wellbeing, ecosystem services often are barely recognized as part of our economic system, generating little incentive to prevent their degradation. This situation will continue until ways are found to recognize and integrate ecosystem services into economic development frameworks.

An essential first step is to identify and quantify the various environmental flows that support economies and the resulting economic flows and to holistically evaluate their relative contributions to national economic systems. The work undertaken here makes an important contribution towards this objective, using a biophysical accounting approach to quantifying natural resource stocks and flows, and their transformations to generate economic activity.

The report focuses on West African countries that are amongst the poorest in the world and which rely heavily on dryland natural resources for their well-being. Environmental accounts are compared with those from other countries around the world. The report makes the link between environmental services and human welfare, and examines the impact of accounting for natural resource depletion on trade and debt inequity. The environmental accounting methods used are a complementary approach to economic accounting methods and could form a basis for analysing policy alternatives, international trade, and national investments. Investment in natural resource management is no longer an option, but a necessity if we are to improve human well-being for the majority of the Earth's population.

Achim Steiner

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Preface

The vulnerability of people living in drylands is closely linked to degradation of the natural resource base upon which people depend for food, fuel, fibre, fruits, freshwater, and income. Climate change and population growth are projected to further intensify pressure on dryland natural resources and increase the vulnerability of dryland populations. While the drylands populations are affected directly, negative impacts from dryland degradation are being felt far beyond its boundaries. Reduced river flows and increased sedimentation are affecting downstream water users and coastal ecosystems. Dust storms are creating health hazards to urban dwellers. Desertification is contributing to regional and global climate change through feedback effects that result from changes in the energy balance of the earth's surface. These biophysical impacts are interacting synergistically to negatively impact human well-being and societal welfare within and beyond the drylands. Over the next ten years, land degradation in drylands may put 50 million people at risk of becoming environmental refugees, imposing further pressure on urban areas and developed countries.

If maintenance of dryland natural resources is so crucial to all, the question arises why are these resources not being safeguarded? Part of the reason is that land degradation is a diffuse problem occurring over large rural and often remote areas with poor infrastructure, and as a result, tends to be marginalized within development priorities. However, perhaps a more significant reason is that natural resource depletion has not been adequately factored into economic development policy. The concept of wealth has captured human work but ignored the role of environmental services in generating products that comprise real value, such as food, minerals, electricity, and biodiversity. Frameworks for quantifying environmental work alongside economic values are poorly developed, preventing a rational, science-based approach to development decision-making. As a complement to recent progress in economic approaches to integrating the value of nature's work into decision-making, this report takes an alternative, biophysical approach to quantifying values of ecological services. Environmental accounting is a tool for holistic evaluation of systems of people and nature, based on our understanding of the physical energy and material flow through systems.

The work undertaken evaluates implications of natural resource use on the economic systems of five West African dryland nations and puts these results into a global context through comparison with other nations. The first chapters introduce the concepts and methods of environmental accounting and describe the compilation of an associated global database. Temporal trends in environmental indicators are explored and the value of natural capital depletion assessed in relation to other countries. Later chapters explore the implications of including environmental flows in accounting of international trade and international debt, and examine the links between the resource base, human development and sustainability. The final chapter provides succinct recommendations for policy action. The main findings of this report are also illustrated in a separate summary for decision makers.

It is hoped that the results of this report will raise awareness of the critical importance of increased investment in natural resource management for improved human well-being in drylands, and lead to policies that are of long-term public benefit. While the focus is the drylands of northern Africa, the methods, concepts, and principles applied here are valid for all countries.

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Summary

NATURAL RESOURCE DEPLETION AND DEVELOPMENT DECISION MAKING

Over the last several decades, increasing human population, economic development and emergence of global markets have driven unprecedented land use and global change, resulting in immense pressure on natural resources; these pressures are projected to intensify further over the next few decades. Sahelian rural populations are especially dependent on land resources for their subsistence, including food, fibre, livestock fodder, and medicine, and they also constitute their main source of income. Human well-being in drylands is therefore particularly vulnerable to desertification, which undermines the resource base that provides these services. However, this reliance goes far beyond the provisioning services that land provides, and includes services such as maintenance of biodiversity; regulation of hydrological and nutrient cycles, disease, and climate; and cultural services such as aesthetic value and ecotourism. Maintenance of stable agro-ecosystems in the Sahel is a key strategy for sustainability, and a prerequisite for maintaining adaptive capacity in the face of climate and global change.

Although the threat to sustainable development posed by natural resource degradation and loss of ecosystem services has been recognized for decades, including by Our Common Future in 1987, the 1992 Earth Summit, the 2002 World Summit on Sustainable Development, and Rio+20, the fundamental principles of sustainable land and natural resource management are yet to be translated into globally effective policies and tools. Overemphasis on financial capital optimization, often at the expense of natural and social capital, remains the norm. Clearly, a new paradigm regarding the value of nature's work is needed for redirecting policy at the local, national and global scales.

It is essential for sustainable policy that the costs of environmental work be incorporated into decision making. Currently, in economic systems money exchanged for resources is paid only for the human services embodied in obtaining those resources and the work of nature, or ecosystem services, are considered as free. However, as stocks and flows of environmental systems are now declining it is paramount that their true value be incorporated into decision making if further development is to be sustainable. Natural resources such as forests and topsoils may accrue over hundreds of years and are only slowly renewable: they constitute a significant source of national wealth or capital, similar to the stocks of financial capital. Land resource stocks are effectively non-renewable, and their depletion represents loss of national wealth: it is usually extremely expensive to pay for replacements. However, there are strong incentives to over-exploit land resources because they are effectively free – the costs of their extraction (e.g. soil erosion) are borne by society, now or in the future, and not by individual land users.

One of the primary challenges facing policy makers attempting to incorporate social or natural capital into their decision process is that these forms of wealth are neither traded nor priced. For natural capital in particular: what is the value of topsoil, virgin rain forest, river flows and clean water, coastal fisheries, or geologic work that concentrated and made useful metals and minerals? As evidence accrues that all these services are being lost, the grand challenge of including natural capital and ecosystem services in national accounting grows.

ENVIRONMENTAL ACCOUNTING

Environmental valuation is a relatively new field and rapidly developing. A number of economic methods for valuation of ecological services have been proposed, and have matured considerably in the last decades. These methods seek to integrate the value of nature's work into decision making by direct and indirect inference of people's willingness to pay for those services. Problems arise where services are diffuse or not obvious, or where multiple values overlap. Moreover, measures of people's perceived value of nature's work aren't based on the biophysical system that is being valued, leading to significant conceptual dissonance.

In this study we take an alternative, biophysical approach to quantifying values of ecological services. Specifically, we track the environmental work necessary to generate the services, reasoning that the more work embodied in ecosystem services, the greater the cost of losing that service. As such, environmental accounting is a tool for holistic evaluation of systems of people and nature; since environmental work is in both environmental and human systems, a common framework for analysis is made possible. The foundation of the method is our physical understanding of energy and material flow through systems. Accounting for basic physical flows, and transformations of energy and materials used in economic processes, permits direct linkage with the macroeconomic value of flows, both where there is a market (that is, where money is a measure of value) and for flows for which no market exists (that is, where we have previously assumed that services are free).

The central premise of environmental accounting is that sunlight, along with earth heat and tidal momentum, is the basic energy source for the geobiosphere, and therefore a useful common currency for all global processes; solar energy has been transformed to make all goods whether environmental or economic. All processes rely on energy and are, therefore, subject to energy laws. Flows in environmental accounting are reported as the quantity of solar energy required to make them; we call this quantity solar ***emergy*** (Odum, 1988; 1996).

Environmental accounting using emergy involves four basic steps:

1. For any system of interest (in this work we focus on national systems) energy systems diagrams are drawn that depict all the major types of natural resources (e.g. forests, wetlands, croplands), and economic activities (e.g. agricultural processing, manufacturing, mining). The diagrams depict flows that connect system components, both within the system and across the system boundary. These include both environmental flows (e.g. rivers, solar energy, precipitation, forest harvesting) and economic flows (e.g. purchases of fuel, goods and services, and sale of natural resource products and manufactured goods).
2. Acquire data on each of the system components and annual flows in the diagram in standard units (Joules, grams).
3. Convert energy and material flows into emergy using conversion factors called Unit Emergy Values (UEV) to quantify the emergy in units of solar emjoules, the basic accounting unit. This conversion operationalizes the fundamental recognition that different types of energy are not of equivalent quality, and indeed require different amounts of solar energy for their creation.
4. Synthesize the disparate flows of emergy into and among the system components. This synthesis, where all flows are in common units, permits unique insight into the resource basis of the system and patterns of human-environment interactions. Emergy flows can ultimately be expressed in monetary terms via a simple imputation process to aid in the communication of resource values.

An advantage of expressing different types of environmental and economic work in the same units is that the impact of alternative policy or intervention options can be evaluated in terms of trade-offs between economy and environment, and between the environmental flows themselves. A fundamental philosophical feature of the approach is that it is based on 'donor value', derived from summing the resource investments made in each step required to make a product, rather than 'perceived value', which is the utility of a product as perceived by what people think it is worth. Emergy, which is defined as the amount of energy that went into creating something, is thus taken as a measure of 'real' public wealth that complements market-based or use-value measures. By explicit accounting of resource values, emergy analysis aids in the identification of policies and practices that sustain natural resources for long-term benefits. As such, environmental accounting can be viewed as an ecosystems approach that is complementary to economic valuation.

This report presents results of detailed environmental accounting of 134 national economies, with a strong emphasis on the dryland countries of West Africa. Environmental accounting is used for four primary tasks in this work: 1) understanding the comparative resource basis of nations, 2) determining the value of global losses of natural capital, 3) quantifying links between a nation's resource basis and indicators of human welfare, and 4) examining implications of biophysical valuation on international trade and debt.

NATIONAL ENVIRONMENTAL ACCOUNTING DATABASE

An economy is the total system of people, resources, culture, money and the links among them. Though national-scale economic systems are often viewed primarily as flows of money circulating internally and exchanged externally, a broader natural-resource based perspective is urgently needed if we are to meet the global challenges of attaining sustainability in the coming decades. Economies, like all open systems, are based on the inflow and transformation of energy and material resources. Examining the material and energy basis for national economies is the central objective of this work.

For the first time, global energy, material, and money flows, aggregated by national political boundaries, were compiled within a database producing standardized, automated emergy syntheses for 134 nations for the year 2000. The National Environmental Accounting Database (NEAD) compiles data from a variety of national-level databases with global coverage, such as from the Food and Agriculture Organization (agricultural sector production, natural resource use) and the United Nations Statistics Division (trade data). Primary raw unit data are linked to energy content values and emergy conversion factors from the literature. Emergy calculations are organized according to existing national templates; summary flows and indices are output. This report describes results of this effort, including the use of NEAD for examining the various attributes of human-environment interactions at the national and global scales.

RENEWABLE AND NON-RENEWABLE RESOURCE USE

Figure A.1 illustrates a simplified national system, with the brown frame illustrating national geographic boundaries. Renewable resources (sunlight, wind, rainfall, tidal energy, biomass production) are used by an economic system to generate wealth, which is traded in markets for money. In all contemporary systems there is also some flow of both local non-renewable resources (e.g., mined materials, natural resources extracted at rates more rapid than replenishment), and flows of purchased resources. These resources interact in novel ways to generate economic activity, a portion of which is exported outside the system boundary to secure the money necessary to acquire the purchased inputs. The flows can be abstracted to renewable flows (R), non-renewable flows from within the country (N), purchased inputs (F) and exports (Y); the flows of money (GDP) flow countercurrent to the flows of resources (Figure A.1).

Among the key insights of environmental accounting is this schematic understanding of the resource basis of human systems, and a formal estimation of the degree to which contemporary resource use exceeds renewable supply. Globally, in terms of total emergy use, we estimate that humans are nearly 70% reliant on non-renewable resource flows derived from historical accumulations of energy (soils, fuels, minerals) that are now being rapidly depleted. This serves as a quantitative reminder of the unsustainable nature of our development.

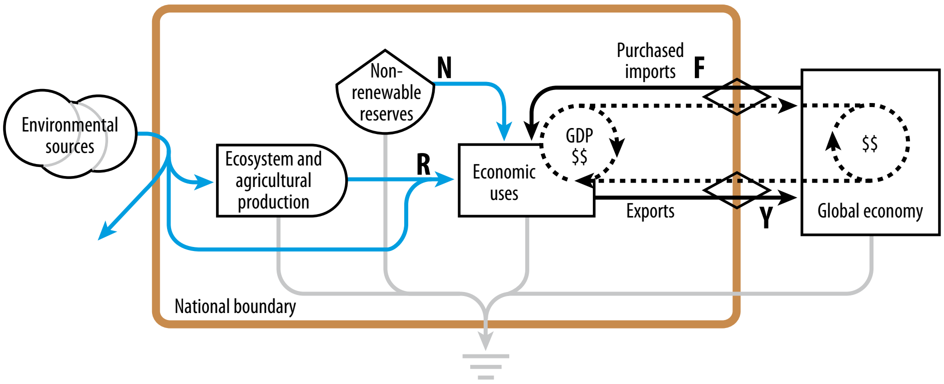
Total emergy use globally is estimated to be 48 x 10^{24} sej per year (sej is solar emergy joules); 15 x 10^{24} is derived from renewable flows, the remainder from non-renewable stocks. However, emergy use per nation is far from evenly distributed; Sahelian nations, specifically Niger, Mali, Mauritania, Senegal and Burkina Faso, use much less emergy than most nations, ranking from 107–117 of the 134 nations analyzed. Highest ranking in terms of total emergy use is the United States of America, with approximately 12.6% of total global use.

Total emergy use is a useful metric, but confounded by nation size and/or population. Expressing total emergy use per unit area of each country places Niger, Mauritania and Mali among the four lowest-ranking emergy users in the world. Small, highly industrialized nations, such as Japan, South Korea, and Western European nations, operate with intense spatial concentration of emergy flows, 100 or more times higher than the Sahelian nations.

Total emergy use per capita provides considerable insight into the general well-being of populations. A high emergy per person ratio generally translates into a high standard of living; interestingly, though emergy per capita is correlated with GDP per capita, the emergy metric accounts for more than just monetary income, specifically the unpaid, direct wealth to people from the environment. As might be expected, West African countries fall below the global average levels, indicating a lower average well-being in general terms relative to other countries. What might not be expected is

FIGURE A.1

Schematic diagram of a nation showing a boundary, renewable (R) and non-renewable flows (N) from within that boundary, purchased inputs (F) from outside the boundary, and exports (Y) to the larger global system, as well as the interactions among these flows to generate economic activity (GDP). The critical point is that resources are the foundation of human economic activity, and sustainability is the move towards reduced dependence on sources that cannot be maintained in perpetuity (i.e., non-renewable). The definitions of some of the core metrics used in this summary are provided.



Total Energy Use = R + N + F
Emergy Yield Ratio (EYR) = [N + R + F] / F
Emergy Investment Ratio = F / [N + R]
Environmental Loading Ratio (ELR) = [N + F] / R
Emergy Sustainable Index (ESI) = EYR / ELR
% Renewable (%R) = R / [R + N + F]
Emergy Money Ratio (EMR) = [R + N + F] / GDP
Imports: Exports = Y / F
Total System Well Being = HDI * % R

Note: HDI is the UN's Human Development Index, a measure of human well-being.

that metrics of human welfare, though generally correlated with resource use, tend to increase initially and then stabilize, suggesting that some level of resource reduction would not adversely affect measures of human welfare. Moreover, identifying nations particularly adept at creating human opportunity with constrained resource use become models for sustainable development. Nations that accomplish this appear to be Switzerland, France, Norway and Iceland.

Perhaps the most fundamental metric of long-term sustainability is the fraction of total use that is from renewable sources, as opposed to non-renewable sources. Globally, this value is ~30%, but strongly uneven across nations. Dryland countries rely significantly upon indigenous renewable flows. For instance, Mali, Mauritania and Niger obtain around 75% of their total emergy use from free environmental flows, while many western European nations derive less than 1% of their emergy use from these flows, operating instead principally on imported non-renewable emergy from outside the system.

Non-renewable resources can further be divided into concentrated non-renewable use (fuels, metals, minerals) and diffuse non-renewable use (extraction of water, forest, fish, and losses of soil organic matter at rates faster than they can be replenished). The West African nations rely on natural capital depletion for between 5–27% of total emergy use; potential shocks due to simultaneous depletion of natural capital, while relying on natural capital flows for system sustenance, represent a major policy challenge. Interestingly, nations that rely heavily on local depletion of natural capital tend to be classified as less developed. The fact that most developed nations obtain a small fraction of their resources from the depletion of natural capital suggests both that they are better positioned to regulate depletion rates, and, perhaps more important, that they can export resource depletion to other parts of the world.

The flexibility, transmissibility and generality of electricity as a flow of energy make it the principal resource underlying technology and information. As such, the fraction of national resource use that occurs in the form of electricity is an excellent indicator of development status, and a useful benchmark for development trends over time. Electricity use as a fraction of total use highlights areas with relatively low development, such as sub-Saharan Africa (~1%) vs. places like Japan, USA and France where that figure exceeds 15%. Trends are upwards for West African nations, but the pace of increase is slow.

It has also been widely recognized that the use of fossil energy has been a catalyst for global and regional development. Fuel use as a fraction of total emergy use is lowest in sub-Saharan Africa (1–2%) and highest in Kuwait and Saudi Arabia (60% of total use).

ENVIRONMENTAL LOAD

The ratio of non-renewable (both local and imported) to renewable use, called the Environmental Loading Ratio (ELR), reflects the magnitude of the difference between the historic and current local environmental system in terms of non-renewable resource-use intensity. It can be interpreted as a measure of environmental load/impact on local systems that increasingly absorb the waste flows associating with resource-use intensification. Using this index, most of sub-Saharan Africa has comparatively low environmental load (ELR < 1), with the exception of Botswana, South Africa and Kenya. In contrast, the ELR for Germany, Israel, and Belgium approaches or exceeds 100:1.

A second aggregate index, the Emergy Investment Ratio (EIR), quantifies the degree to which a national economy is dependent on external investment for its resource base. It is the ratio of imported to indigenous sources, whether renewable or non-renewable. This metric measures the degree of participation in globalization and the degree to which locally available resources are sought after by the global system. Notably, in sub-Saharan Africa only Nigeria, Benin, Cote D'Ivoire and Lesotho have values comparable with the global average (~1.6). Nations with high values, which are those most strongly dependent on the global economy for resource acquisition, include Japan, Sweden, Switzerland, Netherlands and Italy, with values as high as 10. The Sahelian nations have values around 0.1.

The Emergy Sustainability Index (ESI) is a measure of sustainability in terms of the goal of minimizing environmental load while encouraging development. That is, a nation may be considered sustainable only if it can simultaneously facilitate development *and* reduce environmental load. Countries typically regarded as highly sustainable (e.g. Sweden) have very low Emergy Sustainability Index values, indicating poor resource sustainability, largely because they rely heavily on non-renewable energy resources. Mali, Mauritania, Niger and Cameroon, by contrast, have relatively high values, primarily due to their comparative dependence on renewable use fractions. As non-renewable resources decline in importance (due to depletion or protection), economies with larger portions of their resource basis supported by indigenous resources, particularly renewable resources, are less likely to exhibit serious shocks and dislocations of populations. While sub-Saharan Africa is not typically considered sustainable from the perspective of global human welfare, the globe's current reliance on emergy flows three times greater than the annual renewable supply is profoundly unsustainable.

EMERGY AND MONEY

A fundamental observation of economic systems is that money exchanged for resources is paid only for the human services embodied in obtaining those resources; it follows that the work of nature, or ecosystem services, are free. It also follows that market exchange of resources will tend to overuse resources that require little labour to acquire. Moreover, the relationship between money and environmental resource is not fixed; the emergy in raw resources (e.g. minerals, agricultural commodities), that is those with less human value added, tends to require relatively little money, whereas processed goods require more money for the same quantity of emergy (Odum, 1996). This observation yields important insights about both the flow of money and social equity.

Similar issues arise when nations trade resources; nations exchange money for flows of goods and services on the global market. Because prices generally are fundamentally distorted with respect to the environmental work required for the production of goods and services, this exchange may have significant resource consequences, structurally disadvantaging one country over another. One outcome of thinking about trade in units of environmental work is the ability to consider the balance of trade on a non-monetary basis, and examine structural sources of inequity embedded in the financial system, both between national trading partners and among commodities.

A key for doing this is the computation of the Emergy Money Ratio (EMR), which relates the environmental resource basis of a nation to its economic productivity as measured by Gross Domestic Product. In other words, the EMR describes the unit price (in US dollars) of emergy or 'real wealth'. It permits comparison of environmental and economic work in equivalent monetary units (i.e., emdollars), facilitating improved interpretation, since emergy units are unfamiliar to many people. We generally observe that more industrialized countries tend to have lower Emergy Money Ratios, signifying a low price associated with environmental work, whereas West African countries have considerably higher Emergy Money Ratios than the global average. The global average EMR is 2.6×10^{12} sej/$; only Japan and the US are lower, while the Sahelian nations have values between 10 and 30 times higher.

The EMR values are informative by themselves, but offer additional insight into environmental resource equity of international transactions. We compute a metric of inequity called the Emergy Exchange Ratio (EER), which compares the resource purchasing power of a standard unit of currency between two nations. The EER is essentially the ratio of EMR values for trading nations; values different from 1 indicate structural disadvantages when the two nations engage in financially balanced trade. Among the most disadvantaged nations in this regard are those in sub-Saharan Africa; whereas the United States, Switzerland and Japan are among the main benefactors from this structural trade inequity. As an example, our analysis shows that Niger is structurally disadvantaged when trading with the global economy because the resources necessary to generate revenue are 10-fold higher than the resources it receives in return. That is, in order to generate an equivalent monetary value, Niger appropriates a greater amount of environmental work.

The structural conditions that lead to inequity in trade (when trade is made based on monetary balance) are frequently assessed in economics using a measure called Purchasing Power Parity (PPP). We found a strong positive relationship between Purchasing Power Parity and the Emergy Exchange Ratio, suggesting that variability in PPP is at least partly due to the comparative emergy basis for money among nations.

Despite the benefits that international trade confers, less developed countries tend to be resource exporters, while highly developed nations tend to be resource importers; this serves to widen the gap in resource endowment over time. One policy implication is that trade agreements could be made more consistent with the real wealth that traded commodities represent, so that the compensation to resource exporting countries would more accurately reflect the value of their exported goods.

INTERNATIONAL DEBT

In order to generate international currency to make their debt payments, West African countries (and indeed most of the developing world) export large quantities of local environmental capital, either in the form of mined resources, agricultural commodities or other raw goods. For example, each unit of currency borrowed represents purchasing power in the global market, but to service that debt Niger appropriates approximately 12 times the environmental resource for repayment. Loan interest serves only to exacerbate the problem. When loans and debt service are put in units of environmental work, the need for debt relief becomes clear. When debt repayments are compared in emergy units, all five of the targeted West Africa nations have repaid their loans, and have indeed become emergy creditors. This is most pronounced for Mauritania and Senegal, which officially owe $4.8 and $8.9 billion, respectively, but have overpaid by $77 and $18 billion respectively if the flows are examined in emergy units. This conclusion supports debt relief efforts for these five nations. The general framework for assessing inequity is expected to imply the same conclusion for all of sub-Saharan Africa.

COMPARATIVE ASSESSMENT AND TIME TRENDS FOR WEST AFRICAN NATIONS

We examined trends in various emergy metrics over time for the five Sahelian nations between 1965 and 2000. In general, trends indicate increasing total resource use and increasing reliance on non-renewable sources of emergy for the generation of economic product. However, paralleling trends globally, the emergy use per capita has been systematically declining, both overall and in comparison with the global average.

One of the more interesting trends that we observed was in a metric that tracks the total well-being of the national economic system. Typically, well-being is viewed through the lens of the human condition using metrics like the UN's Human Development Index (HDI), which combines measures of life expectancy, literacy, educational attainment, and GDP per capita, to track social aspects of development. Notably, however, HDI explicitly does not consider the environmental resource basis of human well-being, which disconnects these two intrinsically coupled components of system sustainability. That is, a system that produces high levels of well-being but does so using resources at a rate that cannot be sustained may be temporarily desirable, but may prove to be a poor model for long-term development. The fraction of total resource use from renewable sources (%R) is one metric that could be used to enumerate environmental aspects of development. Since both metrics (HDI and %R) vary between 0 and 1, and because the goal is to maximize both simultaneously, their product (which we call the Total System Well-being Index and which also varies between 0 and 1), is a new index proposed for wider consideration as a metric of total system performance, with high values indicating more socially *and* environmentally sustainable development. It is important to note that the two variables are significantly negatively correlated; that is, across the population of nations for which both %R and HDI are available, countries with low %R tend to have high HDI. This implies centrally that a significant component of human welfare is derived from the use of non-renewable resources, and should therefore be judged as unsustainable in the long term. However, some countries appear to create conditions of high human welfare despite also deriving much of their resource use from renewable resources. Similarly, there are countries that use substantial non-renewable resources, and still do not create high levels of human welfare. The TSWI captures this variability in nations, and may point to national systems for environmental, social and economic governance that may be useful as models for other parts of the world.

The Sahelian nations are generally in the lower half of TSWI globally, with Niger occupying the lowest position among the 124 nations for which TWSI could be computed and Mali, Senegal, and Burkina Faso ranked 56th, 59th and 88th, respectively; no HDI data were available to compute TSWI for Mauritania. Perhaps more importantly, values have been declining over the period of record. This suggests that despite comparatively high levels of renewable resource use (all 5 nations fall in the upper 20% of nations globally), recent increases in the HDI have been outpaced by the increasing dependence on non-renewable emergy. Moreover, the rate of decline appears to have increased over the last decade. Comparable data are not available for all 134 nations, but we propose that an analysis of trends for that larger sample size could be exceedingly useful for sustainability benchmarking.

VALUING THE GLOBAL DEPLETION OF NATURAL CAPITAL

One of the principal insights of national-scale environmental accounting is the role of ecosystem stores and services in the generation of wealth. Amongst the key policy challenges of the 21st century is protecting natural capital stores so that future generations can benefit from the services they provide. Soil erosion, deforestation, over-fishing and over-use of water resources are well documented resource-management challenges; placing these flows in emergy units and contrasting them with other sectors of the economy can aid in providing some scale to the magnitude of the resource loss. Declining natural capital was observed to represent an annual cost of over $1.5 trillion in 2000. Soil erosion was the largest cost (~$640 billion annually), but all four declining stocks represent significant losses.

In addition to quantifying the global losses and the losses accruing in each nation, we quantified the fraction of total resource use from natural capital. We observe several interesting trends; notably, natural capital use in nations at the high and low end of the sustainability spectrum (measured using ESI) is small compared with total use, while the fraction is largest for nations at intermediate sustainability. This suggests that richest nations (typically those lowest on the sustainability spectrum) protect their natural capital, perhaps by exporting environmental load, while the most sustainable nations haven't yet over-exploited these resources. We also observe a strong inverse correlation between GDP and natural capital use.

POVERTY, RESOURCES AND HUMAN WELL-BEING

As described above, we compare the Human Development Index with Total System Well-being Index (TSWI) across nations. Note that is it possible to get a high TSWI score at both high and low levels of non-renewable resource use; the key to a high score is achieving high levels of human welfare given the fraction of non-renewable resources that are used. As such, the countries at the top of the list (Iceland, New Zealand, Argentina, Ireland, Canada, Australia, Paraguay) tend to have comparatively high standards of living *vis-à-vis* their rate of using non-renewable resources. Other nations, at the bottom of the list (Belgium, Israel, Germany, Kuwait, Italy), are there not because they have low standards of living, but because achieving those levels appears to have been due to high levels of non-renewable resource use; Niger is the exception, which remains at the bottom of the list because of low HDI scores. The United States falls in the same location as nations like Cote d'Ivoire and India, though clearly via a different arrangement of the two input variables to the TSWI. These results point to national systems that may be of interest for comparing environmental and social policies between nations. Notably, Burkina Faso, Mali, Niger and Senegal all have lower values of HDI than would be predicted based on their renewable resource use. Despite low HDI values, the West African focal nations, with the exception of Niger, which has the lowest TSWI of the 124 nations studies, have moderate values of this index due to the high percentage of their emergy use from renewable resources.

POLICY IMPLICATIONS

The five West African countries in the study are extremely vulnerable to natural and economic catastrophes due to the fact that their economies are strongly reliant on natural capital flows while simultaneously depleting their natural capital. Large and immediate investments in sustainable natural resource management are vital to the security of these countries. The main priority for investment in natural resource management is improved soil management in all five countries, while in Senegal sustainable fisheries management is also of high priority. One key implication of our analysis of natural capital depletion costs is that soil erosion figures prominently in each nation as a hidden, but significant annual cost to society. We estimate, for example, that soil erosion is equivalent to $1.2 billion (in 2000 currency) across the five nations (led by erosion in Burkina Faso), a hidden cost equivalent to nearly 10% of the combined GDP of those nations. These fluxes are comparable in magnitude to the economic value of national exports from the five nations, underscoring both the severity of the problem, and the utility of the emergy approach in being able to place these disparate flows in common units for comparison.

Central to achieving goals of sustainability and equity is support for policies that result in immediate and total debt relief since, when exports of natural resources are accounted for, all five focal nations have not only repaid their debts but have become emergy creditors to developed nations. Equally important is the need for vigorous restructuring of trade agreements to address the gross disadvantage that West African nations face when trading with developed countries. West African nations export up to ten times more resources than they receive when trading with developed nations. Trade agreements must be made more consistent with the real wealth that traded commodities represent, and ensure that compensation to resource exporting countries accurately reflects the value of the exported goods. Maximizing processing of natural resources in each country will also contribute to redressing the trade emergy imbalance.

Increased emergy use, including greater use of fossil fuels and electricity generation, will be an essential component of the development of the focal nations. Environmental pollution due to industrial development is currently of lower priority for the focal countries than natural-resource management, but preventative measures are strongly recommended to ensure environmental loads stay low as these countries develop.

Further policy studies are warranted to establish why the focal countries have lower values of the HDI than would be predicted, based on their resource use, and to investigate how some countries manage to generate relatively high level of human well-being using a relatively low level of non-renewable resources or total resources per person. Indeed, using our Total System Well-beingIndex, which combines social welfare and environmental sustainability, provides a policy benchmark. Nations with high values provide model systems for development without compromising environmental sustainability, and nations with upward trends are model systems for policy initiatives and development priorities that do the same.

For the rest of the world there is much policy revision to be achieved. The globe's current reliance on emergy flows that are three times greater than the annual renewable supply is profoundly unsustainable, and efforts to live within the planet's means should be amongst the grand policy challenges of this century. Many developed nations, in particular, derive less than 1% of their emergy use from renewable flows, operating instead primarily on imported emergy from outside the system. These imported resources are often obtained from less developed countries under inequitable trade conditions in terms of emergy exchange, in effect exporting resource depletion to other parts of the world. Developed country economies are also in effect extracting resources from poorer developing countries by receiving debt repayments at inequitable Emergy Money Ratios. In many developed countries Environmental Loading Ratios are also high, detracting from sustainable development.

Countries should gauge their development progress not only by basing them on measures such as the human development index and economic performance, but also in terms of the degree to which their total resource use is derived from renewable as opposed to non-renewable energy sources, and on environmental loads. This work has provided a framework and database system with which to monitor these additional indicators to provide a more holistic evaluation of total system well-being and sustainability. National environmental accounting tracking systems should continue to leverage the massive improvements in whole-earth surveillance technologies that can help parameterize and refine the simple models used in this study. This kind of integrated thinking – economy, society, environment – when implemented on a project-by-project and policy-by-policy basis, and evaluated at the national scale via high quality standardized data, could be used effectively to judge development strategies and learn efficiently from successes and failures.

CHAPTER 1

Introduction to environmental accounting and global database development

Systems of people and the environment are characterized by complex interactions of natural, social and financial capital organized for capture and transformation of available resources. Our collective perception of optimal resource use has been profoundly altered over the course of the last 50 years by the growing realization that human actions are adversely affecting environmental systems. Overemphasis on financial capital optimization, often at the expense of natural and social capital, has been revisited and challenged by many. The science of sustainability, which has emerged from such critiques of current decision-making processes, is charged with offering a new breed of holistic decision support.

One of the primary challenges facing policy makers attempting to incorporate social or natural capital into their decision process is that these forms of wealth are neither traded nor priced. For natural capital in particular: what is the value of topsoil? Virgin rain forest? Geologic work that concentrated and made useful metals and minerals? River flows and clean water? Coastal fisheries? The human economy depends on these ecosystem services as the basis for wealth, both directly and indirectly. The well-documented reports of their global depletion trends result directly from the failure of markets to incorporate natural capital costs into decision calculus. This situation fails the fundamental intergenerational equity tenet of sustainability (World Commission on Environment and Development, 1987) and necessitates interventions to ensure that society's true costs are reflected in our collective decisions.

Within the limited confines of markets and price signals, the work of environmental systems is free (Figure 1.1). No money is paid for many of the basic ecological stocks and processes that are the fundament of productive economies. That is, the costs of nature's work are external to the market. Indeed, money is paid only for the human service of extraction or redirection of ecological work. As such, the costs to society of over-extraction of resources (i.e. beyond some renewable rate) are not reflected in market prices, generating a distortion between true costs and benefits that requires some form of regulation. Numerous efforts over the last decade have sought to quantify and ultimately internalize the costs of depleting ecosystem services. This work can be described as "valuation" of ecological work. Our work summarized herein is a contribution to that collective effort at the national and international scale. Most importantly, we take an alternative approach to quantifying values of ecological services based on the biophysical work necessary to generate them.

This approach, referred to hereafter as environmental accounting, or EA, links the work of ecosystems, measured in units of energy, with the work of economies, where value is measured in currency. Equating these two notions of value (energy and money) demands either that the work of nature be estimated in monetary units (ecological economics), or, conversely, that the economy be evaluated in ecological units (e.g. carbon, energy, land). Environmental accounting takes the view that all systems, ecological or economic, are based on the use and transformation of available energy; as such, thermodynamics provides the most comprehensive framework in which to develop a generic ecological-economic currency. This report rests on the premise that accounting for the energy invested in producing goods and services of both the environment and economy is a fundamentally important complement ato considerations of money alone.

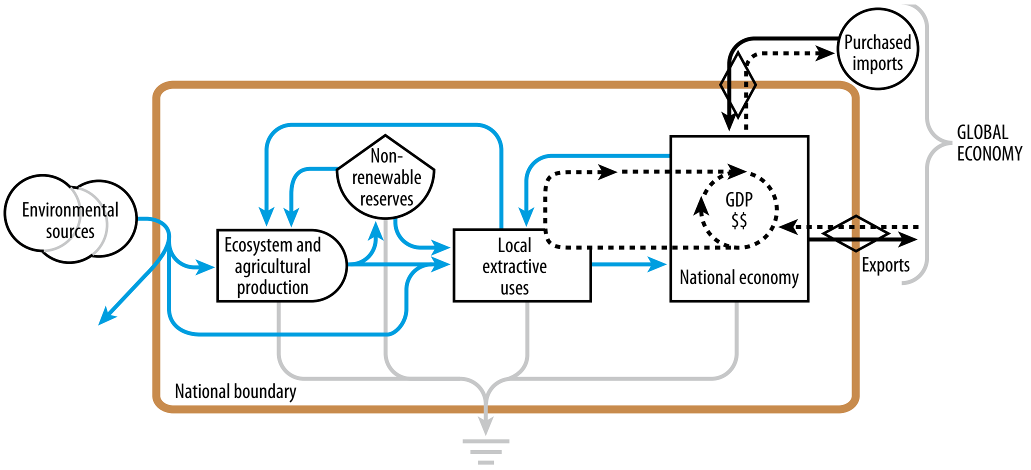
FOCUS ON DRYLANDS

There are few places in the world where conditions of profound human dependence on natural capital coincide with declining natural resources more than in dryland ecosystems, making their management among the most pressing development problems. Drylands represent the extremes – where the world's ecosystems are most fragile and people most vulnerable to environmental and global change. The problems are severe and of large extent –the drylands support one billion rural poor across 110 countries. The natural resource base on which the rural poor depend for their livelihoods is rapidly degrading, although controversy remains on the actual degree and extent of degradation. Many dryland populations will face acute water shortages over the next few decades and increased climatic variability as a result of climate change. Without urgent policy action there is a high risk of further rapid environmental degradation and increasing poverty.

About 40% of sub-Saharan Africa is covered by drylands, in which 36% of the total population lives. Poverty levels are extremely high – the average Human Development Index in sub-Saharan African countries that have large dryland areas is as low as 0.35. In West Africa in particular, there are increasing burdens placed on the natural resource basis of production; in order to achieve the Millennium Development Goals, agricultural productivity in this area will need to increase dramatically, at a rate of about 6% per year, without harming the environment. Agriculture-poverty-environment

FIGURE 1.1

Systems schematic of the interface of environmental and economic systems showing flows of energy and materials (solid lines) and money (dashed lines). See Appendix B for description of symbols.



linkages are particularly important in the semi-arid lowlands of West Africa (the Sahel), due to the sensitive environments and extreme poverty levels. The Sahel, a 700,000-km^2 belt extending across Mauritania, Senegal, Mali, Burkina Faso, and Niger, contains over half of the total population of these countries. The area is characterized by a 9-month dry season and frequent droughts. Abject poverty is prevalent and population growth rates, at 3% per annum, exceed food production growth rates of only 2% per annum. The predominant land use systems are rapidly degrading – woody biodiversity and cover is being lost, and soil fertility is declining from already low levels through exhaustive cropping practices and soil erosion.

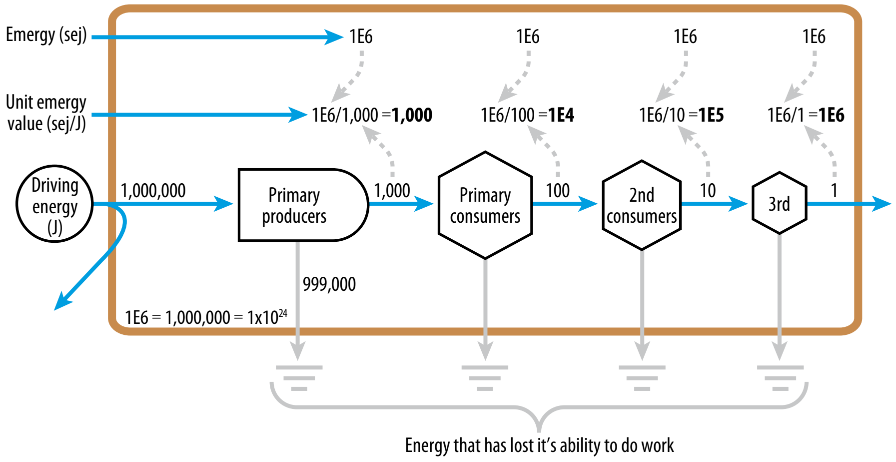
This work represents a first step towards a deeper contextual understanding of the scope and magnitude of natural resource issues in the Sahelian drylands by putting the resource issues of West Africa in a global context.

ENVIRONMENTAL ACCOUNTING

Environmental accounting is a tool for holistic evaluation of systems of people and nature. The foundation of the method is our physical understanding of energy and material flow through systems. Energy flows through systems in many different forms, and the processes that develop within any system are designed to transform available energy and materials into new forms to do new types of work. For example, a forest ecosystem transforms energy and material flows (sunlight, rainfall, nutrients) into leaves, wood, soil, herbivores, carnivores and so on (Figure 1.2). Each product represents a transformation (e.g., plants to herbivores to carnivores) in which a substantial fraction of the original energy loses its ability to do work (flows exiting the bottom of Figure 1.2); this inexorable process is predicted by the 2nd Law of Thermodynamics. All transformations are less than 100% efficient, and most real processes are much less efficient. The result is that it takes a large amount of solar energy to make a small amount of energy in the form of plant biomass. Similarly, a transformation of the energy in wood into a different form (for example, electricity) results in a significant loss of available energy. Consequently, energy alone is not a numeraire that permits meaningful comparison, even though we can report different flows in energy units. That is, the environmental or economic work embodied in different flows of energy is not the same, even though the heat potential can be measured in the same physical units. Specifically, their "quality" differs. In order meaningfully to compare the many sources of energy driving a system, we require units that permit similar quantification of different quality flows.

FIGURE 1.2

Conceptual diagram of energy transformations, emergy and the computation of Unit Emergy Values (UEV = emergy per unit). A linear transformation chain representing an ecological system is shown, with plants (primary producers), herbivores (primary consumers) and so on. In each transformation, 90% or more of the original energy is lost. In order to make 10 units of the right-most component, 1,000,000 units of driving energy (e.g. sunlight) is required. Emergy is the same at each level, so the UEV goes up with each transformation.



The central premise of environmental accounting is that sunlight, earth heat and tidal momentum, the energy sources for all global processes, are a useful common currency; solar energy is embodied in all goods whether environmental or economic. Flows in environmental accounting are reported as the quantity of solar energy required to make them; we call this quantity solar ***emergy***, sometimes referred to as embodied energy or energy memory. For example, the emergy in wood is the quantity of solar energy required to make it, accounting for all inputs to the process. Rainfall and nutrient flows, which are clearly required inputs, can also be reported in emergy units (i.e. equivalent solar energy required for production), allowing flows of different kinds to be added to compute the total environmental work required.

This accounting process, whereby all physical flows (materials, energy) are converted to common units (solar emergy), permits comparison of both environmental and economic products. Economies are, at their most basic level, mechanisms for the transformation of available energy and materials into new forms. The process of quantifying the environmental work embodied in an economic product simply requires tracing the amount of solar energy required for production of each input and summing them. The amount of solar emergy required per unit (mass or energy) of production is called a Unit Emergy Value (UEV); it is the measure of the degree of transformation from sunlight. UEVs have been computed for many hundreds of products, permitting relatively straightforward tabulation of emergy values once the physical flows (mass or energy) driving each process is

TABLE 1.1

Example Unit Emergy Values (UEV) for environmental and economic products.

Product	Units	UEV (sej/unit)	Source
Sunlight	J	1	By definition
Wind	J	2.50E+03	Odum et al (2000)
Rainfall	J	3.10E+04	Odum et al (2000)
Earth heat	J	5.80E+04	Odum (2000)
Tidal energy	J	7.40E+04	Campbell (2003)
Forest wood (average)	J	3.80E+04	Doherty (2002)
Groundwater	J	2.40E+05	Buenfil (2001)
Topsoil organic matter (average)	J	2.10E+05	Cohen et al (2007c)
Fish biomass (average)	J	8.40E+06	Brown et al (1993)
Corn/maize	J	6.40E+04	Cohen (2003)
Soybeans	J	4.28E+05	Brandt-Williams (2001)
Rice	J	9.26E+04	Brown and McClanahan (1992)
Beer	J	5.80E+04	Brown (unpublished)
Bovine meat	J	8.70E+05	Brandt-Williams (2001)
Eggs	J	1.08E+06	Brandt-Williams (2001)
Milk	J	1.30E+06	Brandt-Williams (2001)
Iron	g	1.20E+10	Cohen et al (2007b)
Copper	g	9.80E+10	Cohen et al (2007b)
Aluminum	g	5.40E+09	Cohen et al (2007b)
Gold	g	5.00E+11	Cohen et al (2007b)
Cement	g	3.30E+09	Buranakarn (1999)
Natural gas	J	6.80E+04	Bastiononi et al (2005)
Crude oil	J	9.40E+04	Bastiononi et al (2005)
Electricity (average)	J	2.90E+05	Brown and Ulgiati (2001)
Phosphate fertilizer	g	5.62E+09	Brandt-Williams (2001)
Textiles (average)	g	8.72E+09	Brown (unpublished)
Machinery (average)	g	1.13E+10	Odum et al (1987)

known; emergy is the product of the physical flow (units of mass or energy) and UEV (emergy per physical unit). Many of the methods for estimating UEVs are summarized in Odum (1996). Table 1.1 summarizes some examples of UEVs. Naturally, the analysis frame depends on the accuracy and specificity of the UEVs, which can only be assumed. However, for macro-scale decision-making, the uncertainty in each UEV is comparable with the uncertainty associated with the physical flows.

The process of environmental accounting at the national scale, which is our focus here, is centrally the same as for any process. The physical flows driving economic production are quantified; these are flows of energy or materials crossing the boundary or resource stocks (minerals, fuels, forests) that are depleted within the system. Identification and quantification of these flows is, in many ways, easier than for particular processes, because of the increasing availability of global production data, global environmental datasets, international trade statistics and the primacy, with regard to record keeping, of national boundaries.

After converting physical flows to emergy via multiplication by UEVs, the various flows comprising a national resource basis may be added together. The synthesis of flows permitted by conversion to common emergy units not only permits their addition, but also their fractional contribution to the economy. For example, the total resource use by a nation can be quantified in this way, as well as the fraction of use from renewable sources, or the fraction from local versus imported sources. Similarly, formal rules for aggregating flows into categories permits computation of numerous indices (described in detail later). Among these indices are measures of environmental load, sustainability, total system well-being, and trade/debt equity. These indices were developed to synthesize complex information into actionable measures; we consider this synthesis as a first step towards benchmarking of global integrated resource use.

All environmental accounting indices are defined based on physical flows of resources, and not on money, which makes them important complements to the indices typically used to evaluate national systems (e.g. GDP, GDP per capita, Index of Sustainable Economic Welfare – ISEW – Daly and Cobb, 1989). Comparisons between environmental accounting indices and these economic metrics not only permits examination of ecological-economic links, but also allows the imputation of macroeconomic value for stocks and flows for which no market exists. For example, with knowledge of the broadly averaged exchange rate between money and resources (emergy) and the emergy value of a stock (e.g., soil organic carbon), we can estimate the equivalent value in units that can be used for comparison with economic product. While these are not "values" per se, they offer insight into the ecological work necessary for their creation and maintenance in monetary equivalents. Among the important features of the various national environmental accounting indices is that they can be compared with other metrics of national environmental condition (e.g., ecological footprint, Yale Environmental Sustainability Index) and standard national-scale measures of human welfare (e.g., Human Development Index, Human Poverty Index). No single tool is able to provide sufficient information on which to base policy, so understanding where different analytical tools agree and disagree is likely to be of considerable value. Finally, given the multitude of resources that underlay a national economy, and the dynamic nature of that resource basis, indices are essential for providing benchmarks against which policy interventions and future development can be assessed.

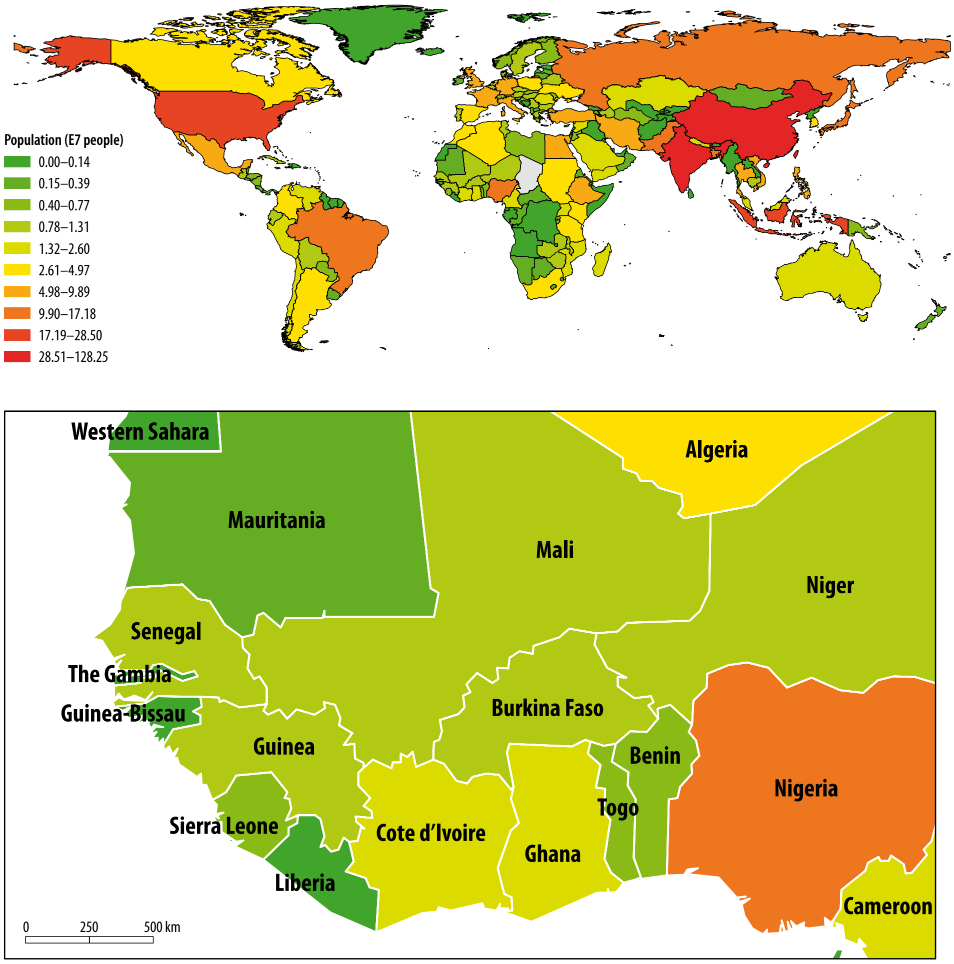
OBJECTIVES

The primary purpose of this report is to summarize progress towards quantifying the natural resource basis of nations. Our efforts have culminated in a national database that summarizes environmental accounts for 134 countries (Figure 1.3) globally for the year 2000. This database, hereafter called the National Environmental Accounting Database (NEAD), compiles detailed information about the full array of resources that underlie economies, including environmental flows (sunlight, rainfall), natural capital stocks (soil, water, forests, fish), mined materials (metals, fuels) and economically transformed goods and services (agricultural commodities, manufactured goods, services). Nations were omitted from the database (Figure 1.3) if some aspect of their environmental accounts could not be quantified using current data sources (summarized in Appendix A).

There are four core areas of insight that the NEAD makes possible. These will be presented as separate sections this report.

FIGURE 1.3

Map of national boundaries. Countries excluded from our study due to lack of data are shown in white. Populations of countries included in the database are shown. West African nations, which are the primary focus, are shown inset.



1) Assessment of comparative resource use, use intensity, and sustainability among 134 nations.
2) Assessment of temporal trends in national indices (for a subset of countries, in this case five Sahelian nations).
3) Evaluation of the global and national role of diffuse natural capital (soil, water, fish, forests) as an input to wealth.
4) Environmental basis for trade among nations, with implications for trade equity and international debt.
5) Links between human welfare and environmental services.

Next we outline the basic methodology, with an emphasis on concepts. We summarize the methods and data processing, and further information is available in several key references on the topic of environmental accounting (Doherty et al, 1993; Odum, 1996; Brown and Ulgiati, 1997; Cohen et al, 2006), and at our project website (http://sahel.ees.ufl.edu). After a brief introduction to the method as it pertains to national-scale systems, we present results of the NEAD, with an emphasis on how nations of West Africa compare globally. In this way, we hope to shed light on the magnitude of natural resource depletion concerns both in the Sahel and globally, and demonstrate tools for environmental systems analysis that can aid in the global pursuit of sustainability.

CHAPTER

2

Environmental accounting concepts and methods

CONCEPTUALIZING THE SYSTEM

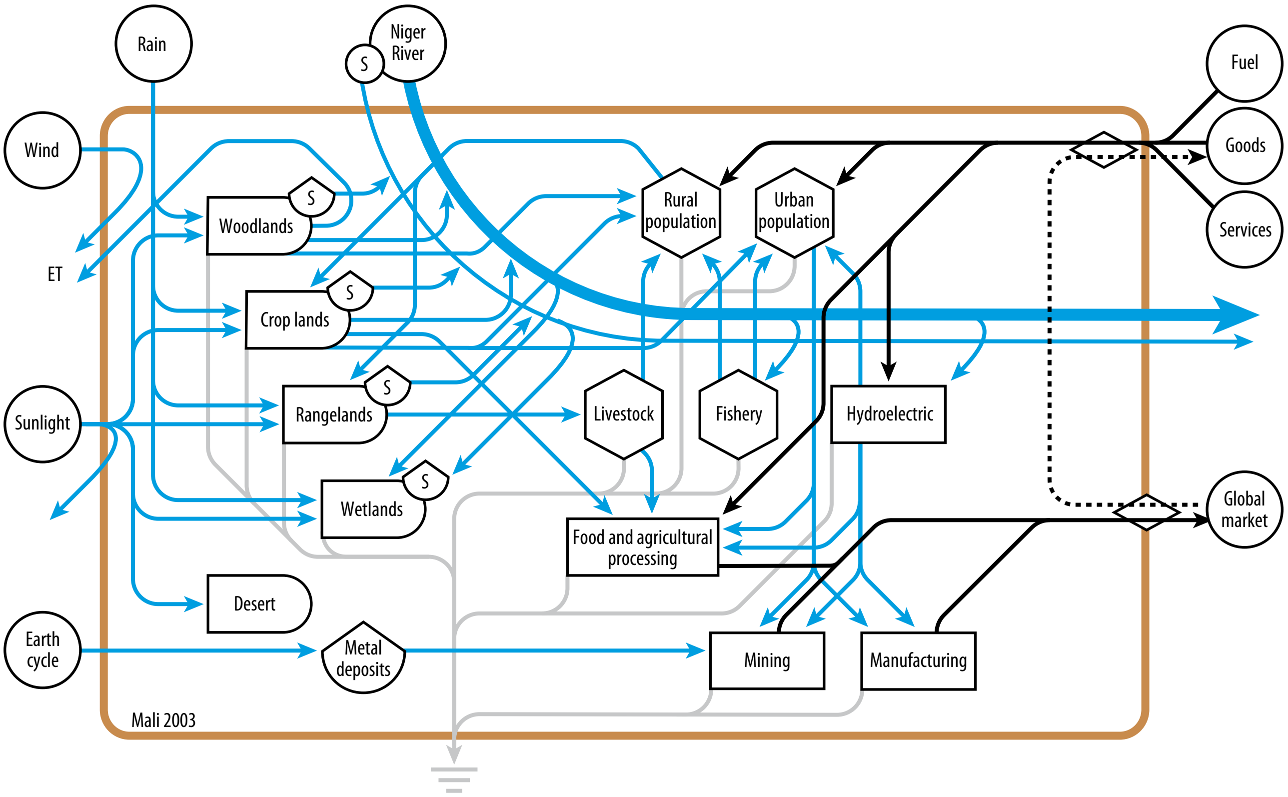
In order to permit holistic assessment, environmental accounting requires careful conceptualization of the system; its boundaries, primary inflows, important internal stocks, transformations, and exports must all be included for the whole systems perspective that is sought. To help visualize systems prior to analysis, diagrams are always a starting point in the process; developing visual representation of the system organizes and allows consensus regarding the key components of the system under study. The energy system language (Odum, 1994) is usually used (Figures 1.1 and 1.2; symbol definitions are given in Appendix B).

For national analyses, two diagrams are typically created. First, a detailed diagram inventorying the key sources, stocks, transformations and exports is drawn. An example of this is given for the nation of Mali (ca. 2003) in Figure 2.1. This diagram shows the flows of energy and materials from external ecosystem sources (sunlight, rainfall, the Niger River), depletion of internal stocks (mineral deposits, soils [S]), transformations (agriculture, hydroelectricity, food processing), imported fuels, goods and services, and exported goods and services. Also shown is the flow of money (dashed lines) through the economy.

While detailed diagrams are frequently useful for conceptualizing a national system, comparison between nations requires a standard template into which flows of environmental and economic resources can be placed. A second diagram drawn for each country is generic to all nations (Figure 2.2); it shows flows of environmental resources, internal non-renewable resources (both mined materials and depletion of natural capital), imports of goods, fuels and services, exports and the inflows and circulation (GDP) of money. Flows in each category are specific aggregations of flows; for example, internal extraction of mined copper, gold, fuels and building stones are aggregated in the flow labeled N1. Similarly, diffuse flows of natural capital (soil erosion, deforestation, over-extraction of water resources) are aggregated as flow N0. All national indices (described below) are computed based on these aggregations, which are standardized among countries. Note that these aggregations are possible only because each flow has been converted to common units (emergy), which makes their addition meaningful.

FIGURE 2.1

Detailed systems diagram of the nation of Mali (ca. 2003) showing the primary sources of energy and materials, internal stocks, transformation sectors, exports and imports. The Niger River figures prominently in many aspects of national condition.



EMERGY AND UNIT EMERGY VALUES

The practice of environmental accounting at its most basic level is simply multiplication and addition. Physical flows of energy and materials are converted into emergy units via *multiplication* by UEVs, which have either been previously computed or are developed for a local analysis. These emergy values are then, with some important exceptions, *added* together to arrive at the total emergy driving a process. If the analysis is of a product, a UEV is computed by dividing the total emergy required for production by the energy or mass of the product (Figure 2.3). For national analyses, where particular products are not the focus, a variety of indices are computed which permit comparison among nations, or for a single nation over time.

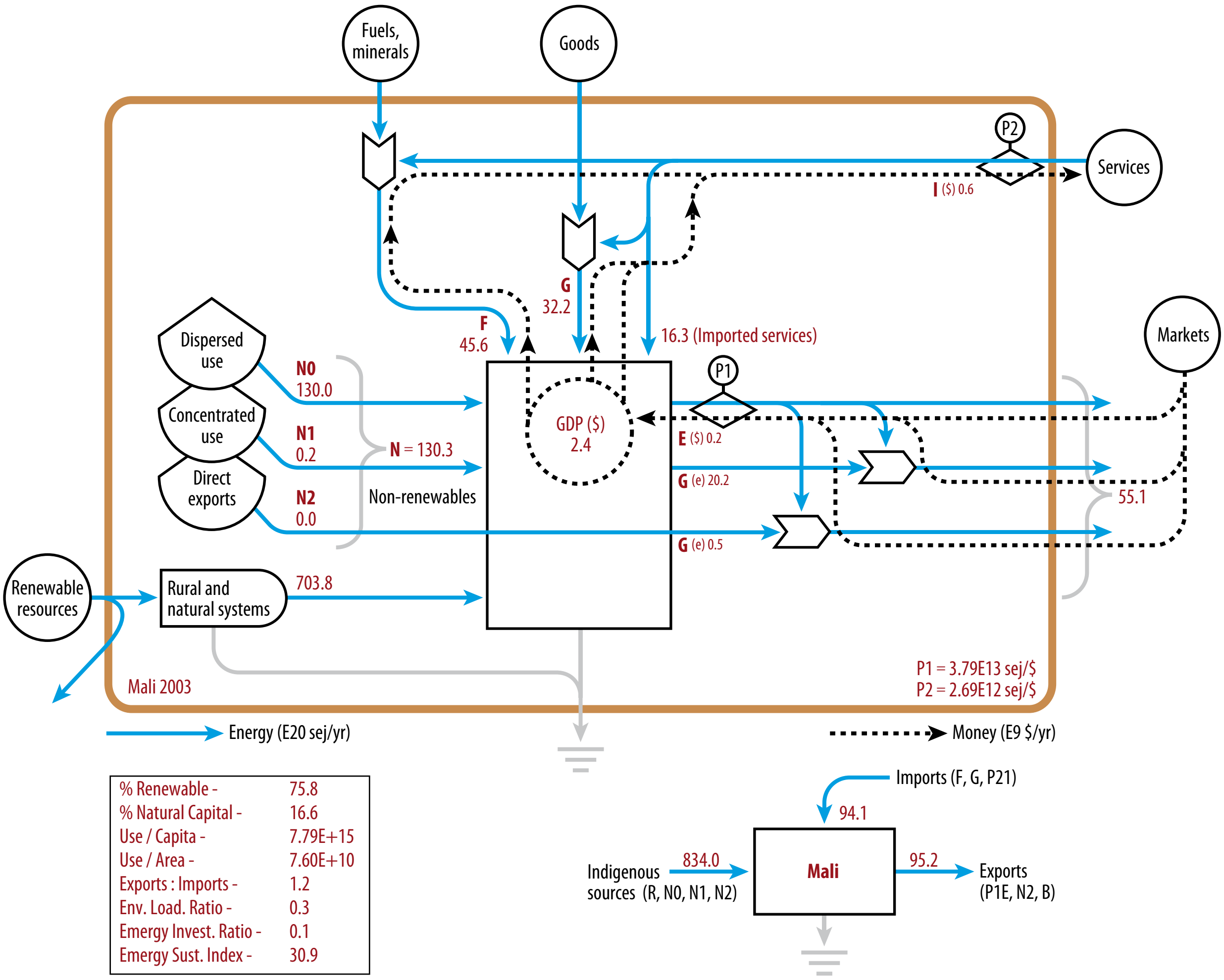
The adoption of previously computed UEVs represents an important implicit assumption of our work. There are often structural differences in the production of commodities (e.g. maize production between the United States and sub-Saharan Africa) that would render the assumption of UEV uniformity problematic. In general, UEVs can vary substantially between parallel processes producing the same output, particularly where the modes of production are qualitatively different (e.g., different ways of producing electricity). As such, local UEVs are computed for important inputs to a system under study, where possible. However, for standardized analysis of 134 national systems, this is not feasible; as such, our results should be treated as an estimate of the resource basis of nations.

ENVIRONMENT-ECONOMY INTERACTIONS

Among the most important aspects of analysis of systems using environmental accounting is that the method does not depend on money flows. Money pays for human service only, and, as such, is not adequate for inference of ecological value where nature's work is provided free to human systems. However, while there is significant utility in trying to reduce the influence of money in determining the

FIGURE 2.2

Generic national diagram with flows of renewable resources (R), non-renewable sources from within the country (N), imports of fuels (F), goods (G) and services (I), exports of goods (B) and services (E), and GDP (X). Flows on each line are for Mali (ca. 2000).



% Renewable -	75.8
% Natural Capital -	16.6
Use / Capita -	7.79E+15
Use / Area -	7.60E+10
Exports : Imports -	1.2
Env. Load. Ratio -	0.3
Emergy Invest. Ratio -	0.1
Emergy Sust. Index -	30.9

FIGURE 2.3

Conceptual depiction of the computation of Unit Emergy Values (UEV) from summation of incident resources necessary for production. Each input requires a UEV to convert flows into common units – e.g., solar emergy); consequently emergy is frequently referred to as "energy memory". Flows in common units can be meaningfully added.

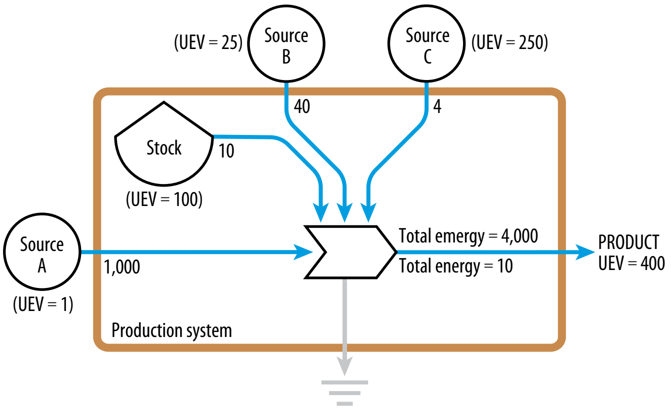
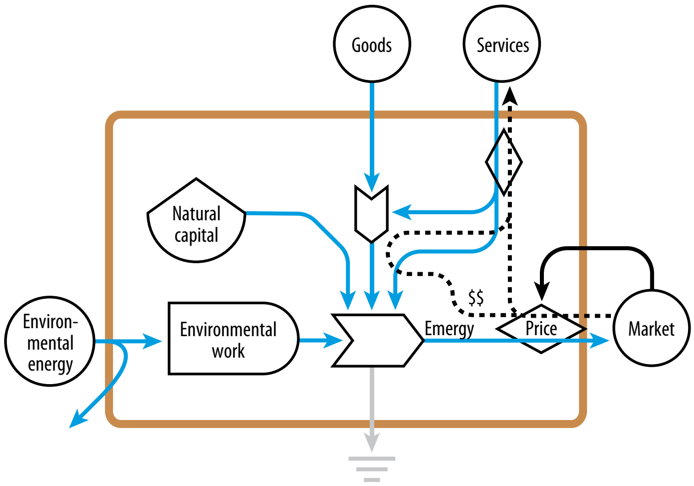


FIGURE 2.4

The relationship between biophysical work embodied in production and the money paid for a product. Money flows (dashed lines) pay only for human services; products that are relatively highly dependent on nature's work are, therefore, undervalued.



value of natural systems, it is imperative that the two methods of valuation be fundamentally compatible and at least partly interchangeable.

Figure 2.4 shows the relationship between energy and materials (solid lines – "real wealth") and money (dashed lines). The transaction is defined by the price, depicted as a diamond regulating both flows; the price is a function of market forces of demand and supply. Money flows only to services, either directly or indirectly for the services of embedded in goods. The work for production, which couples natural capital, environmental work and the purchased inputs, is not reflected in the price. As a result, goods for which free ecosystem services represent a high proportion of the work necessary for production are undervalued by price; the degree of undervaluation decreases with the number of economic transformations.

Part of the appeal of environmental accounting follows from the widespread observation that money has differential buying power (i.e. differential Purchasing Power Parity, or PPP), both among nations and within nations. By quantifying the relationship between embodied environmental work (emergy) and money, we uncover important information about the equity of trade, both between national trading partners, and, within a nation, between regions and among commodities. We revisit later the idea that environmental accounting can identify important structural inequities between trading partners when the emphasis is solely on fiscal trade balance. In Figure 2.4, this differential buying power would be expressed by defining the fraction of the inputs that are purchased (i.e. goods and services) compared with the fraction provided free (i.e. natural capital and environmental work).

CHAPTER 3

National Environmental Accounting Database

DEVELOPMENT OF A NATIONAL ENVIRONMENTAL ACCOUNTING DATABASE (NEAD)

Emergy accounting at the national scale provides unique insight into the resource basis of economic organization, due to the inclusion of environmental services often ignored in economic analysis, as well as the use of common units, which allows for direct comparison of all flows. National emergy accounts allow the quantification of sustainability, environmental load, resource-use intensity, and economic performance, among a suite of other assessment indicators. In turn, these indicators can then be related to a host of national-level indicators produced by other organizations. For the first time, global energy, material and money flows, aggregated by national political boundaries, have been compiled within a database producing standardized, automated emergy synthesis for 134 nations for the year 2000. Previous efforts to provide this global synthesis (e.g., Stachetti-Rodrigues et al, 2003) were hampered principally by the lack of availability of global datasets that are integrated into the current effort.

Database schematic

Figure 3.1 illustrates the organization of the NEAD. Within Excel spreadsheets, primary raw unit data are compiled by country codes and linked to energy content values and UEVs from the literature. Emergy calculations are executed and organized according to the standard template format, with results loaded into forms which display the main emergy table, main table notes, and the summary flows and indices table. Worksheet files within the database are dynamically linked, allowing for rapid updating if changing source data, UEVs, or calculations.

National Analysis Framework

The framework for emergy analysis at the national scale is well defined, using tables of quantified system inputs, and standardized calculations of aggregate flows and indices to summarize condition (Odum, 1996). Emergy evaluation at the national scale starts with a diagram identifying the major flows of energy and materials across the national boundary, usually at the time scale of one year. The lateral boundaries are defined as the political border, and include the continental shelf for nations with a coastline. The upper boundary is 1,000 m above the earth and water surfaces, and the lower boundary is 2 m below the earth surface or floor of the lakes or seas (Odum, 1996),

FIGURE 3.1

Schematic of the global emergy database. See Figure 2.2 for summary flow diagram.

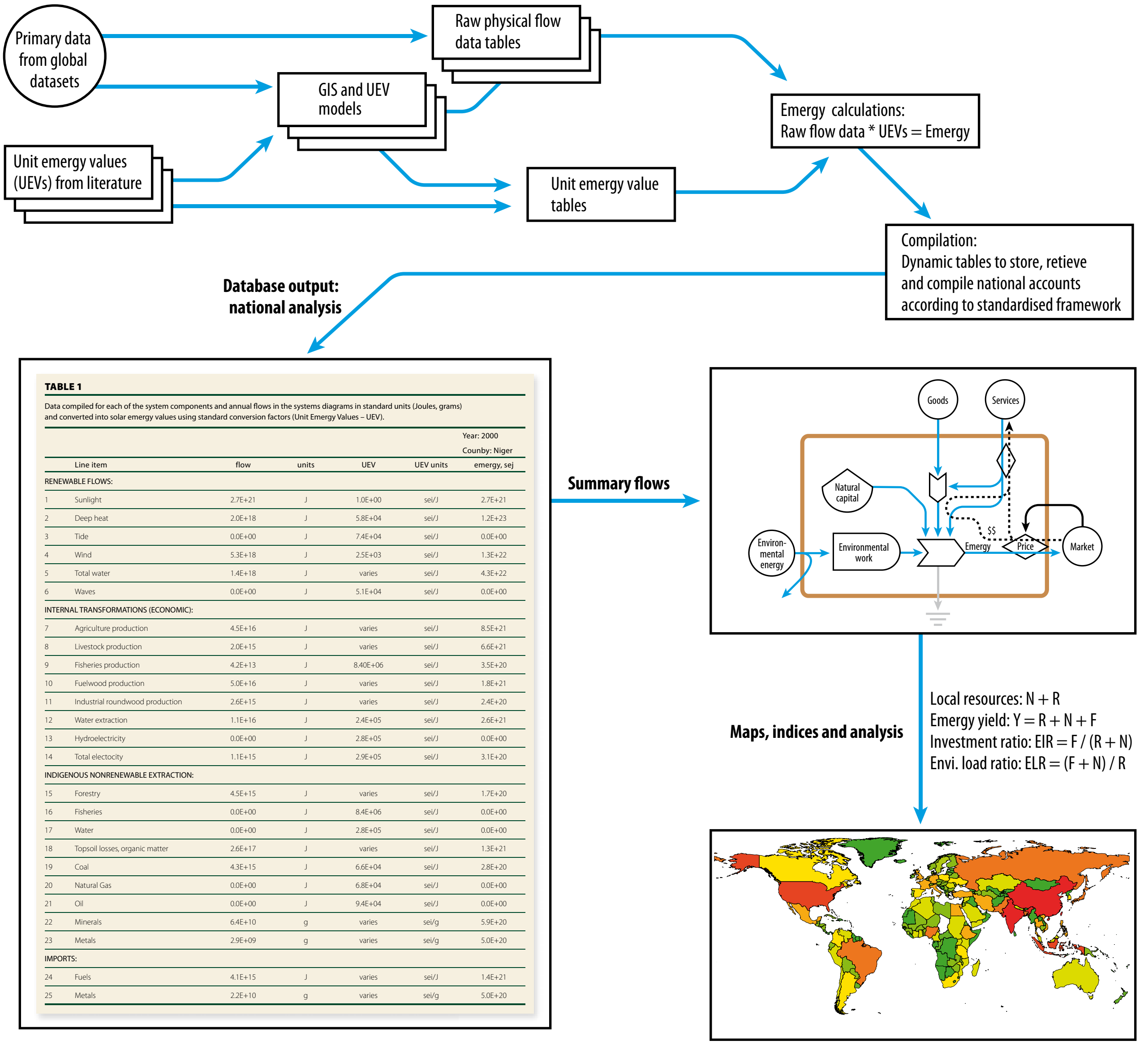


TABLE 1

Data compiled for each of the system components and annual flows in the systems diagrams in standard units (Joules, grams) and converted into solar emergy values using standard conversion factors (Unit Emergy Values – UEV).

Year: 2000
Counby: Niger

	Line item	flow	units	UEV	UEV units	emergy, sej
RENEWABLE FLOWS:						
1	Sunlight	2.7E+21	J	1.0E+00	sei/J	2.7E+21
2	Deep heat	2.0E+18	J	5.8E+04	sei/J	1.2E+23
3	Tide	0.0E+00	J	7.4E+04	sei/J	0.0E+00
4	Wind	5.3E+18	J	2.5E+03	sei/J	1.3E+22
5	Total water	1.4E+18	J	varies	sei/J	4.3E+22
6	Waves	0.0E+00	J	5.1E+04	sei/J	0.0E+00
INTERNAL TRANSFORMATIONS (ECONOMIC):						
7	Agriculture production	4.5E+16	J	varies	sei/J	8.5E+21
8	Livestock production	2.0E+15	J	varies	sei/J	6.6E+21
9	Fisheries production	4.2E+13	J	8.40E+06	sei/J	3.5E+20
10	Fuelwood production	5.0E+16	J	varies	sei/J	1.8E+21
11	Industrial roundwood production	2.6E+15	J	varies	sei/J	2.4E+20
12	Water extraction	1.1E+16	J	2.4E+05	sei/J	2.6E+21
13	Hydroelectricity	0.0E+00	J	2.8E+05	sei/J	0.0E+00
14	Total electocity	1.1E+15	J	2.9E+05	sei/J	3.1E+20
INDIGENOUS NONRENEWABLE EXTRACTION:						
15	Forestry	4.5E+15	J	varies	sei/J	1.7E+20
16	Fisheries	0.0E+00	J	8.4E+06	sei/J	0.0E+00
17	Water	0.0E+00	J	2.8E+05	sei/J	0.0E+00
18	Topsoil losses, organic matter	2.6E+17	J	varies	sei/J	1.3E+21
19	Coal	4.3E+15	J	6.6E+04	sei/J	2.8E+20
20	Natural Gas	0.0E+00	J	6.8E+04	sei/J	0.0E+00
21	Oil	0.0E+00	J	9.4E+04	sei/J	0.0E+00
22	Minerals	6.4E+10	g	varies	sei/g	5.9E+20
23	Metals	2.9E+09	g	varies	sei/g	5.0E+20
IMPORTS:						
24	Fuels	4.1E+15	J	varies	sei/J	1.4E+21
25	Metals	2.2E+10	g	varies	sei/g	5.0E+20

except where mined products are extracted from deeper strata. A table is then made of all known flows across the boundary, including dispersed environmental flows, concentrated raw material flows from mining, imported goods and services, exported goods and services, and money flows. Raw data on flows are compiled and converted into emergy units. Flows for the main emergy table can be seen in Appendix C. The flows are summed to provide a value for total emergy use in the system, and additional aggregated summary flows and indices are calculated, integrating the major inputs from the human economy and inputs coming "free" from the environment. A new standard template for national evaluations has been developed for the NEAD (Sweeney et al, 2006, based on Odum, 1996). This template is the most comprehensive national-level template used for emergy analysis to date, and is the first to employ standardized primary input datasets and standardized UEVs, enabling reliable comparative analyses of nations for the year 2000.

Global data sets for National Environmental Accounting

Data compiled from a diverse set of published international data sources serve as the primary input to the NEAD (Appendix A). Datasets were chosen based on the following criteria: global coverage, availability of documentation and literature references, and publication/dissemination by a recognized organization. Additionally, spatial coverages were chosen for renewable flows to allow for calculations within a GIS environment and future analysis at sub-national scales. Conversions of primary data to energy and emergy values are automated within the standardized accounting template, which references look-up tables of standardized energy conversion ratios and Unit Emergy Values.

Typically, data sources selected were from FAO (agricultural sector production, natural resource use) and UN (trade data) sources. For the flows of renewable energies (sunlight, wind, rainfall, earth heat) individual data products were identified. Mineral extraction statistics were from the British Geological Survey (BGS) and soil degradation estimates were obtained from the Global Assessment of Soil Degradation (GLASOD) from the International Soil Reference and Information Center (ISRIC – Oldeman, 1994). Where possible, each data layer was cross-checked with other existing data products of the same extent. In all cases, analyses are only as reliable as the data used, and global data sets employed here are presumably of uneven quality. Our analysis points to areas where better data are clearly warranted.

Global Unit Emergy Values (UEVs)

Unit emergy values (UEV) are the crucial link between energy, mass, or dollar flows, and the emergy required to produce that flow. Emergy values are calculated within the national accounts by multiplying the mass, energy, or money content of flow (grams, joules, $) by the UEV (sej/gram, sej/J, sej/$) assigned to that flow. In the absence of a comprehensive set of location specific UEVs for every product and process in the globe, it is essential to use a standardized set of UEVs in order to perform a reliable comparative analysis of nations.

Renewable flows are assigned UEVs from Odum et al (2000). Agriculture, forestry and fishery internal production flows are assigned UEVs based on FAO commodity codes for 223 items, with UEVs compiled from numerous publications and documented within the database. Soil organic matter UEVs vary spatially over the global landscape and were calculated within a GIS model (Cohen et al, 2007c). Fuel production UEVs are compiled from various sources, documented within the database. Metal UEVs originate from a model constructed by Cohen et al (2007b), for 51 crustal elements. Mineral UEVs are compiled from Odum (1996) and Odum et al (2000) for 31 items. Trade commodities are assigned UEVs based on the first revision of the Standard International Trade Classification (SITC1) classification at the four digit level (622 commodities). These UEVs are compiled from numerous publications and are documented within the database. This standardized set of UEVs is organized into look-up tables which are dynamically linked to the main template, allowing for automatic updates if UEVs are refined or calculated for additional flows.

National system indicators

Within NEAD, flows in primary units (J, g, $) are converted to emergy (sej) using standardized templates and UEVs. Once flows are in the same units, summary flows and indices are produced. Table 3.1 lists summary flows and indices and formulas used in the calculations.

A detailed description of all indicators of a nation's resource basis is beyond the scope of this report; we describe some of key indices for which global results are presented later.

Indices in Table 3.1 are classified into categories based on the kind of information that they provide. These categories (and the indices that populate each category) are:

1) Resource Use and Partitioning
    - Includes Total Use (U), Total Renewable (R), Total Non-Renewable (N), Percent Renewable (%R), Imports (IMP), Exports (EXP), Fraction Indigenous (%Indig)
2) Metrics of Use Intensity
    - Includes Use per Capita (U/#), Use per Area (U/A), Fraction Electricity (%Elec), Concentrated vs. Dispersed sources (Conc:Disp), and Fuel per Person (Fuel/#)
3) Environmental Load, Economic Attraction and Sustainability
    - Includes the Environmental Loading Ratio (ELR), Emergy Investment Ratio (EIR), and Emergy Sustainability Index (ESI).
4) Natural Capital Stocks and Depletion
    - Includes Percent Natural Capital Depletion (N0/U), Soil Loss (%Soil), Forest Loss (%Forest), Fish Loss (%Fish), and Water Loss (%Water).
5) International Trade and Debt
    - Includes Emergy money ratio (EMR), Emergy Exchange Ratio (EER, defined as P1/P2),

exports-to-imports on an emergy basis, and emergy metrics of indebtedness and debt servicing.

6) **Poverty, Resources and Total System Well-Being**
   - Here we focus on links between a nation’s resource basis and the welfare of its citizens. There are numerous indices that summarize human condition; we propose an index of total system well-being that integrates information regarding resource-use sustainability with measures of human welfare. We reason that nations capable of providing high levels of human development while simultaneously supporting economic processes with renewable resource inputs are models for a global transition to sustainability.

TABLE 3.1

Summary flows and indices for national environmental accounting. Summary flows are linked directly to Figure 2.2. Indices are described further in the text.

Code	Summary flows	Description
R	Renewable sources	Largest renewable flow to avoid double-counting
N	Nonrenewable resources from within	Sum of indigenous nonrenewable extraction items
N0	Dispersed nonrenewable	Sum of forestry, fishery, soil and water extraction
N1	Concentrated nonrenewable used	Sum of fuel, metal and mineral production minus N2
N2	Portion of N1 exported without use	Sum of raw fuel, metal, mineral export
F_i	Imported fuels and minerals	Sum of fuels, metals, minerals imported
G_i	Imported goods	Sum of remaining imported materials & electricity
I	Dollars paid for imports	Service in Imports, $ value
P2I	Emergy of services in imports	Service in Imports($) * World emergy to dollar ratio(sej/$)
F_e	Exported fuels and minerals	Sum of fuels, metals, minerals exported
G_e	Exported goods	Sum of remaining exported materials & electricity
E	Dollars received for exports	Service in Exports, $ value
P1E	Emergy value of goods and service exports	Sum of all items in Export section
X	Gross domestic product	Use UN statistical data
P2	World emergy/$ ratio, used in imports	Total Global Emergy Use / Gross World Product
P1	Country emergy/$ ratio	National Emergy Use / Gross Domestic Product
Code	Indices	Computation
IMP	Imported emergy	F+G+P2I
U	Total emergy used, U	N0+N1+R+F+G+P2I
EXP	Total exported emergy	P1E+N2
%Indig.	Fraction emergy use from indigenous source	(NO+N1+R) / U
EXP:IMP	Export to Imports	(N2+P1E) / (F+G+P2I)
%R	Fraction used, locally renewable	R/U
%Free	Fraction of use that is free	(R+N0)/U
Conc:Disp	Ratio of concentrated to dispersed	(F+G+P2I+N1) / (R+N0)
U/A	Emergy Use per area	U / area
R/A	Renewable emergy use per area	U / area
U/#	Use per person	U / population
CC	Renewable carrying capacity	(R/U) * population
%Elec	Ratio of electricity to use	(el)/U
Fuel/Cap	Fuel use per person	fuel/population
EIR	Investment ratio, imports/indigenous use	(F+G+P2I) / (R+N0+N1)
ELR	Environmental loading ratio, (NR use)/R	[(F+G+P2I)+N0+N1] / R
EYR	Yield ratio, total use / imports	U / (F+G+P2I)
ESI	ESI, Emergy Sustainability Index	EYR / ELR
%Soil	Soil loss/use	Soil loss / U

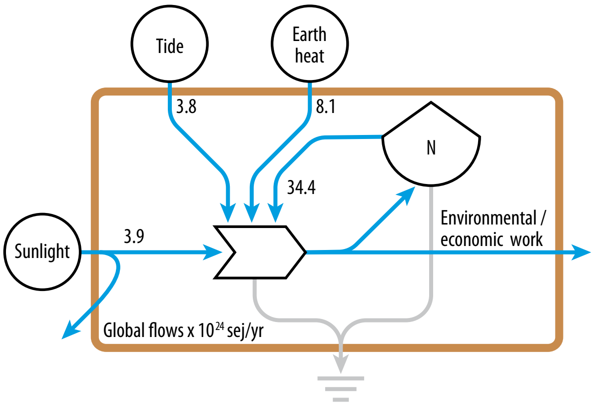
NATIONAL ENVIRONMENTAL ACCOUNTING DATABASE RESULTS

The NEAD permits comparison of the resource basis of nations among 134 countries. The flows of energy and materials are compiled in physical flow units (energy or mass). Recall that the addition of resource flows is meaningful only after physical flows are multiplied by UEV values to place all on a common basis; in all tables and maps in this report, the common baseline energy is solar insolation, so all flows are solar emjoules (sej). For comparative assessment, the global renewable resource flows are summarized in Figure 3.2 (after Odum et al, 2001); annual inputs sum to 15.83 x 10^{24} sej/year (hereafter notated as 15.83E24 sej). Total non-renewable inputs to the global environment/economy system (ca. 2000) total 34.4E24 sej/yr, suggesting that we are collectively nearly 70% reliant on resources representing historical accumulations of energy (soils, fuels, minerals).

Global flows of renewable emergy arrive at differential rates. Some countries receive ample inputs of rainfall or tidal energy, while others receive less. Figure 3.3 displays the aggregation of global datasets regarding each of the key renewable energy inputs forming the basis of ecological production: rainfall, sunlight, tidal energy and earth heat. Coarse maps such as these are central to a global dataset, but more refined information may be necessary for detailed examination within particular countries. These data, coupled with data on internal transformations of energy (agriculture, forestry), extractions of non-renewables (fuels and minerals, soils and water) and imports and exports, form the basis of standardized national resource evaluation. Each flow crossing the national boundary (e.g. Figure 2.1), and all flows of declining natural capital stocks, are listed as line items in a detailed accounting table. Further, each national accounting table is accompanied by a detailed notes section containing primary data inputs, Unit Emergy Values, and calculations. We omit the details of each national accounting for sake of clarity; an example of one (of 134) national tables is given in the appendices[1] along with summary data for 12 West African countries[2]. The overall results for a subset of nations (Table 3.2) provide insight into the range of observed values, and point towards the utility of particular metrics for characterizing national-scale economic attributes. For example, a nation's development status can be captured in part by the % electricity (Elec/U – fraction of total emergy use in the form of electricity), which ranges between nearly 0 for rural nations up to 20% for the United States. Similarly, values of the fraction of total emergy use from renewable sources (R/U) suggest an elegant indicator of resource sustainability. The EMR, which will be discussed at

FIGURE 3.2

Global flows of emergy from exogenous (independent) sources and internal stocks. Note that global processes result in the production of stocks, but at rates slower than they are being used; consequently we treat their use as non-renewable. Also note that the production of other renewable flows (wind, rainfall, currents) is a product of the interactions of the three exogenous sources shown.



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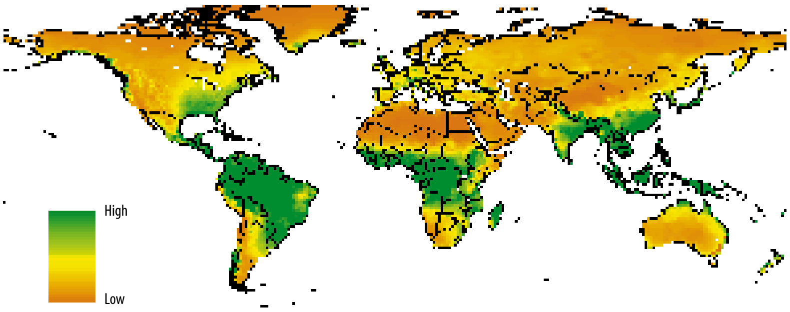
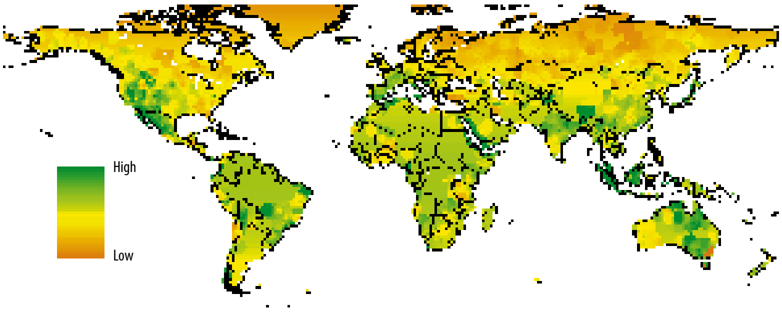
[1] Data and notes for Mali is provided in Appendix C.

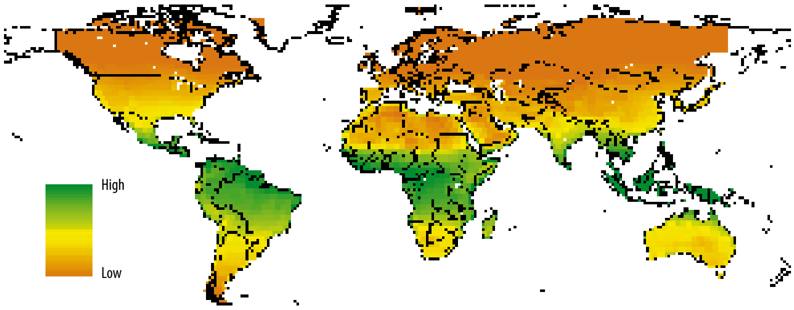
[2] Summary flows for 12 West African countries are given in Appendix D.

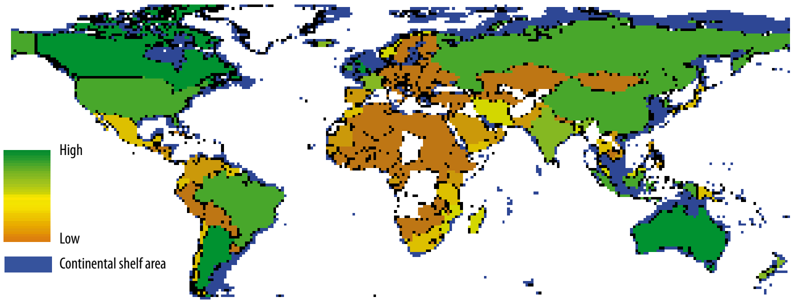
FIGURE 3.3

Inputs of emergy from principal renewable sources. For tidal emergy, allocations to the entire nation (rather than just at the coastal zone) are shown for visualization.


Rainfall emergy


Earth heat emergy


Sunlight emergy


Tidal emergy

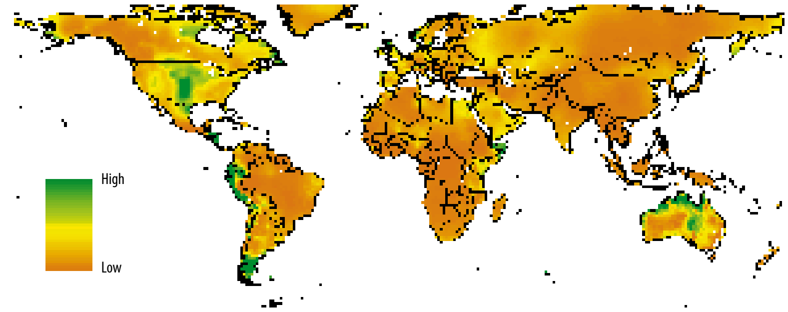

Wind emergy

TABLE 3.2

Selected indices from the National Environmental Accounting Database (NEAD).†

Country	U 22 sej/yr	U/A E11 sej/m^2	U/P E16 sej/#	R/U %	Elec/U %	EMR E12 sej/$	EIR unitless	ELR unitless
United States	1,889.2	20.6	6.6	12%	20.0%	1.9	1.41	7.29
China	1,285.6	13.8	1.0	26%	10.0%	11.9	0.33	2.83
Mexico	917.8	47.7	9.3	4%	2.0%	15.8	3.09	21.51
Russia	742.3	4.4	5.1	35%	11.0%	28.6	0.1	1.86
Japan	710.8	189.7	5.6	3%	13.0%	1.5	2.25	34.75
Brazil	707.7	8.4	4.1	50%	5.0%	11.8	0.12	1
Canada	598.9	6.6	19.5	51%	9.0%	8.4	0.48	0.95
United Kingdom	545.1	225.6	9.3	44%	6.0%	3.8	0.95	1.29
India	533.4	17.9	0.5	28%	9.0%	11.4	0.17	2.53
Germany	525.3	150.4	6.4	1%	10.0%	2.8	10.12	99.76
Australia	482.8	6.3	25.2	49%	4.0%	12.4	0.14	1.04
Spain	455.3	91.1	11.2	2%	5.0%	8.1	0.64	41.24
South Korea	415.2	422.9	8.9	24%	6.0%	9	1.36	3.24
Italy	414	140.8	7.2	2%	7.0%	3.9	2.12	60.32
France	382.2	70.1	6.4	16%	11.0%	2.9	4.58	5.19
Indonesia	310	17	1.5	57%	3.0%	20.6	0.19	0.74
Argentina	291.7	10.7	7.9	79%	3.0%	10.3	0.08	0.26
Netherlands	217.4	641.7	13.7	4%	5.0%	5.9	11.2	22.72
Belgium	209.5	691.9	20.4	0%	4.0%	9.2	5.34	323.1
South Africa	207.2	17	4.7	8%	9.0%	16.2	0.16	11.65
Thailand	183	35.8	3.0	10%	5.0%	14.9	0.62	8.69
Ukraine	165.4	27.4	3.3	7%	9.0%	52.9	0.31	13.07
Malaysia	161.7	49.2	7.0	26%	4.0%	18	0.9	2.87
Iran	160.9	9.8	2.4	22%	7.0%	15.6	0.15	3.61
Turkey	150	19.5	2.2	10%	8.0%	7.5	1.08	9.29
Peru	148.8	11.6	5.7	34%	1.0%	28	0.06	1.93
Poland	134.4	44.1	3.5	3%	9.0%	8.2	0.71	37.29
Zimbabwe	123.6	32	9.8	5%	1.0%	171.6	0.04	19.36
Ireland	119.3	173.2	31.2	63%	2.0%	12.6	0.46	0.58
Chile	112.2	15	7.4	20%	4.0%	15	0.23	3.98
Venezuela	103.8	11.8	4.3	38%	8.0%	8.6	0.13	1.64
Colombia	98.6	9.5	2.3	61%	4.0%	11.8	0.14	0.63
Portugal	94.4	102.7	9.4	4%	4.0%	8.9	0.85	23.07
Austria	91.5	111	11.3	3%	6.0%	4.8	1.57	31.04
Saudi Arabia	91.1	4.6	4.1	9%	13.0%	4.8	0.39	10.35
Bangladesh	88	65.7	0.6	85%	2.0%	18.1	0.13	0.18
Sweden	84.8	20.6	9.6	5%	16.0%	3.5	3	19.31
Kazakhstan	82.8	3.1	5.3	16%	6.0%	45.3	0.12	5.17
Philippines	80.6	27	1.1	19%	5.0%	10.6	1.04	4.34
Norway	68.3	22.2	15.3	33%	16.0%	4.1	1	2.04
Pakistan	65.9	8.5	0.5	17%	9.0%	10.3	0.42	4.89
New Zealand	62.2	23.2	16.4	63%	6.0%	12	0.26	0.58
Czech Republic	62	80.3	6.0	1%	9.0%	11.2	1.83	77.81
Switzerland	61	153.5	8.5	3%	9.0%	2.5	27.76	31.65
Greece	57.7	44.1	5.3	3%	8.0%	5.1	2.53	29.6
Papua New Guinea	57.1	12.6	10.7	71%	0.5%	167.1	0.31	0.4
Kenya	49.7	8.7	1.6	26%	1.0%	47.5	0.09	2.86

TABLE 3.2 *continued*

Selected indices from the National Environmental Accounting Database (NEAD).†

Country	U 22 sej/yr	U/A E11 sej/m²	U/P E16 sej/#	R/U %	Elec/U %	EMR E12 sej/$	EIR unitless	ELR unitless
Egypt	49.4	5	0.7	8%	14.0%	4.8	0.52	12.17
Nigeria	49.3	5.4	0.4	39%	3.0%	11.7	0.37	1.55
Finland	48.4	15.9	9.3	4%	16.0%	4	3.31	23.26
Denmark	48.1	113.4	9.0	4%	7.0%	3	5.7	21.83
Madagascar	44.1	7.6	2.8	84%	0.6%	113.6	0.03	0.19
Mozambique	43.7	5.6	2.4	93%	1.0%	118.7	0.03	0.07
Romania	39.4	17.1	1.8	14%	12.0%	10.6	0.94	6.4
Zambia	39.4	5.3	3.8	52%	1.0%	121.6	0.03	0.94
Vietnam	39.2	12	0.5	65%	6.0%	12.5	0.21	0.53
Morocco	37.1	8.3	1.3	19%	4.0%	11.1	0.77	4.25
Bolivia	37	3.4	4.4	62%	1.0%	44.1	0.17	0.62
Iceland	37	36.9	131.2	85%	2.0%	43.9	0.07	0.17
Hungary	36.9	40	3.7	2%	10.0%	7.9	4.69	49.53
Sudan	35.4	1.5	1.1	73%	1.0%	30.7	0.05	0.37
Israel	34.3	168.8	5.7	0%	11.0%	2.9	12.35	295.2
Ethiopia	33.4	3	0.5	83%	0.6%	55.5	0.05	0.2
Algeria	33	1.4	1.1	12%	7.0%	6.1	0.45	7.28
Bulgaria	32.3	29.2	4.0	6%	10.0%	25.6	0.53	15.55
Ecuador	31.2	11.3	2.5	61%	3.0%	19.6	0.15	0.65
Slovakia	28.8	59.1	5.3	3%	8.0%	14.2	2.2	38.1
Tanzania	28	3.2	0.8	78%	1.0%	30.8	0.07	0.28
Kuwait	24.9	139.5	11.1	1%	12.0%	6.9	0.32	82.1
Gabon	24.5	9.5	19.5	40%	0.4%	48.7	0.03	1.49
Belarus	24	11.5	2.4	6%	13.0%	23	6.31	14.95
Cameroon	22.9	4.9	1.5	73%	1.0%	24.7	0.08	0.38
Nepal	22.3	16.3	0.9	85%	1.0%	41.8	0.08	0.18
Uruguay	19.9	11.5	6.0	38%	4.0%	9.9	0.23	1.61
Ghana	19.9	8.6	1.0	31%	4.0%	40	0.36	2.25
Guatemala	19.7	18.2	1.7	37%	2.0%	10.4	0.4	1.67
Syria	18.7	10.2	1.1	6%	12.0%	7.6	0.17	15.71
Jordan	17.9	19.4	3.6	1%	4.0%	21.1	0.5	78.74
Tunisia	17.7	11.4	1.9	4%	5.0%	9.1	1.46	25.31
Serbia/Montenegro	16.5	16.1	1.6	13%	20.0%	15	0.47	6.55
Panama	16.2	21.4	5.5	61%	3.0%	16.2	0.28	0.64
Cote d'Ivoire	15.2	4.8	1.0	50%	2.0%	14.3	0.42	0.99
Libya	14.8	0.8	2.8	16%	13.0%	4.3	0.35	5.44
Armenia	14.1	49.6	4.5	3%	4.0%	73.7	0.09	38.54
Guyana	14	7.1	18.4	85%	1.0%	196.1	0.06	0.18
Slovenia	13.4	66.4	6.7	6%	8.0%	7.1	5.71	17
Cuba	12.8	11.5	1.1	19%	11.0%	4.6	1.25	4.33
Cent. African Rep.	12.7	2	3.4	94%	0.5%	139.6	0.01	0.06
Costa Rica	12.6	24.9	3.2	38%	5.0%	7.9	0.82	1.66
Suriname	12.4	7.7	29.2	84%	2.0%	159.1	0.08	0.2
Trinidad/Tobago	11.9	231.7	9.2	3%	4.0%	14.5	0.92	30.97
Namibia	11.8	1.4	6.2	46%	2.0%	34.1	0.3	1.19
Croatia	11.4	20.3	2.6	9%	12.0%	6.2	3.32	10.04

TABLE 3.2 *continued*

Selected indices from the National Environmental Accounting Database (NEAD).†

Country	U 22 sej/yr	U/A E11 sej/m^2	U/P E16 sej/#	R/U %	Elec/U %	EMR E12 sej/$	EIR unitless	ELR unitless
Mongolia	11.2	0.7	4.5	62%	3.0%	118.8	0.08	0.62
Jamaica	11.2	103.1	4.3	3%	5.0%	14.5	0.73	33.54
Oman	10.9	5.2	4.2	31%	7.0%	5.5	0.6	2.2
Guinea	10.8	4.4	1.3	60%	1.0%	35.4	0.08	0.67
Paraguay	10.8	2.7	2.0	72%	2.0%	14	0.25	0.39
Botswana	10.8	1.8	6.3	42%	2.0%	21.6	0.34	1.37
Turkmenistan	10.4	2.1	2.2	14%	7.0%	21.2	0.2	6.03
Nicaragua	10.3	8.6	2.0	56%	2.0%	26.2	0.23	0.79
Cambodia	10.1	5.7	0.8	78%	2.0%	30.1	0.16	0.29
Honduras	10	8.9	1.5	41%	4.0%	16.9	0.32	1.44
Lithuania	9.9	15.2	2.8	8%	10.0%	8.9	4.9	12.03
El Salvador	9.8	47.5	1.6	22%	4.0%	7.5	0.78	3.64
Congo	9.4	2.8	2.7	90%	1.0%	29.2	0.05	0.12
Mali	9.3	0.8	0.8	76%	0.5%	38	0.11	0.32
Azerbaijan	9.1	10.6	1.1	10%	19.0%	17.3	0.22	8.8
Uganda	9	4.5	0.4	65%	1.0%	15.7	0.13	0.54
Senegal	8.6	4.5	0.9	55%	2.0%	19.7	0.35	0.83
Yemen	8.5	1.6	0.5	37%	3.0%	10	0.37	1.68
Lebanon	8.3	81	2.4	4%	10.0%	5	20.55	23.69
Mauritania	6.8	0.7	2.6	79%	0.3%	75.1	0.13	0.27
Latvia	6.7	10.6	2.8	20%	9.0%	9.4	2.09	3.97
Estonia	6.6	15.3	4.8	10%	10.0%	12.8	5.21	8.97
Sierra Leone	6.1	8.5	1.4	57%	0.4%	96	0.52	0.77
Macedonia	5.9	23.7	2.9	4%	11.0%	16.4	0.69	23.02
Niger	5.8	0.5	0.5	74%	0.5%	32.5	0.1	0.35
Burkina Faso	4.9	1.8	0.4	63%	1.0%	22.5	0.2	0.59
Togo	4.8	8.7	1.1	22%	1.0%	35.8	0.26	3.57
Guinea-Bissau	4.6	16.3	3.4	97%	0.3%	202.7	0.02	0.03
Benin	4.2	3.8	0.7	45%	2.0%	18.8	0.39	1.23
Cyprus	4.1	44.6	5.2	2%	7.0%	4.7	10.82	59.14
Albania	4	14.7	1.3	22%	14.0%	10.5	1.25	3.56
Malawi	3.7	3.9	0.3	55%	3.0%	21.1	0.19	0.82
Eritrea	2.7	2.3	0.7	74%	1.0%	36.4	0.2	0.35
Belize	2.5	11.1	10.4	34%	0.7%	33.3	0.39	1.96
Moldova	2.4	7.2	0.6	10%	21.0%	18.7	5.17	8.78
Rwanda	1.9	7.7	0.2	36%	1.0%	11.1	0.21	1.75
Swaziland	1.4	8.4	1.3	21%	7.0%	10.4	3.27	3.76
Lesotho	1.4	4.6	0.8	53%	2.0%	16.2	0.74	0.88
Burundi	1.2	4.8	0.2	39%	1.0%	17.3	0.2	1.58
The Gambia	1.1	11.3	0.8	76%	1.0%	26.7	0.27	0.32
Djibouti	0.8	3.5	1.2	43%	2.0%	14.4	1.26	1.33
Average of Nations	120.2	42.7	2.8	34%	6.0%	27.9	1.58	15.2

U = total emergy use, U/A = use per area, U/P = use per person, R/U = % renewable, Elec/U = % electricity

EMR = Emergy Money Ratio in US$, EIR = Emergy Investment Ratio, ELR = Environmental Loading Ratio

† – The NEAD is available online at http://sahel.ees.ufl.edu

length in Chapter 6, varies between 2.0E+14 sej/$ (Guinea-Bissau) and 1.5E+12 sej/$ (Japan), a range of two orders of magnitude in the nominal resource purchasing power of money. Note some important surprises; use per capita, which integrates both non-renewable and renewable sources across a nation's population, suggests that Canada, Iceland, and Australia have among the highest values in the world system. Finally, Table 3.2 illustrates the uneven distribution of resource wealth; for example, the United States uses 1.8E+25 sej/yr, a value greater than the renewable flows of the entire biosphere, underscoring both the resource hegemony and unsustainability of that national system.

Resource use and resource partitioning

This first suite of indicators provides insight into the magnitude and character of each economic system. Among the most informative indices is the summation of all flows for a total use value (U – comprising free renewable flows, non-renewable flows from indigenous resource stocks and purchased imports crossing the national system boundary). A global map of national U values reveals substantial geographic variation (3 orders of magnitude), with larger, industrialized nations dominating (Figure 3.4). Africa in general has low total use values, and Sahelian nations in particular use much less emergy than the rest of the globe. Naturally, because U does not account for area or population, there are confounders to direct interpretation, but the general trends are largely as expected. Note (inset table in Figure 3.4) that the United States is the single largest user (1.8E25 sej/yr), equivalent to approximately 12.6% of total global use (area = 7.6%, population = 4.9%).

Total use is an aggregate of many types of resources; while environmental accounting makes their addition possible, the particular composition of the national resource basis is critically important. To provide further insight into patterns and composition of resource use, we look at particular resource partitions, such as fractions from renewable sources (%R), non-renewable sources (%N), and nonrenewable sources further divided into concentrated non-renewable use (%N1 – fuels, metals, minerals) and diffuse non-renewable use (%N0 – use rates exceeding replacement of wood, water, fish, and soil).

Renewable emergy use as a percent of total use (R/U) is shown in Figure 3.5. For all countries, the renewable flow component includes rainfall and river inputs, and tidal energy absorbed on the continental shelf; we avoid adding all renewable sources (e.g. sun + rainfall + wind) because these are produced in parallel, and their addition would count the solar energy required more than once. This logic has been described in detail previously (Odum, 1996).

Dryland countries rely significantly upon indigenous renewable flows. Mali, Mauritania and Niger obtain around 75% of their total emergy use from free environmental flows, while many western European nations derive less than 1% of their emergy use from these flows, operating instead primarily on imported emergy from outside the system. The fraction renewable (%R) is one of the most important indicators of long-term sustainability, and will be revisited later as a component of overall system well-being.

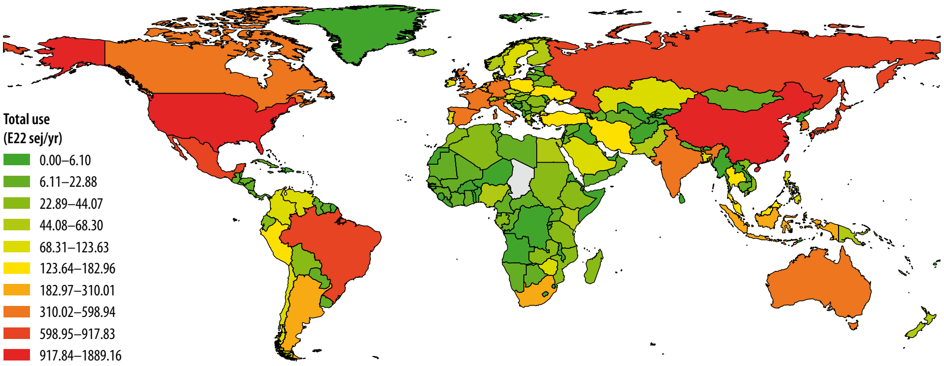
In addition to the fractional contribution of renewable resources, the density of renewable resources is a significant predictor of rural production potential in the absence of purchased or non-renewable subsidies. Figure 3.6 shows the renewable emergy density (sej/m^2/yr) on a national basis; clearly there is significant variability within nations (e.g. Eastern USA vs. Western USA), but this map underscores the critical rural resource limitations faced in sub-Saharan Africa.

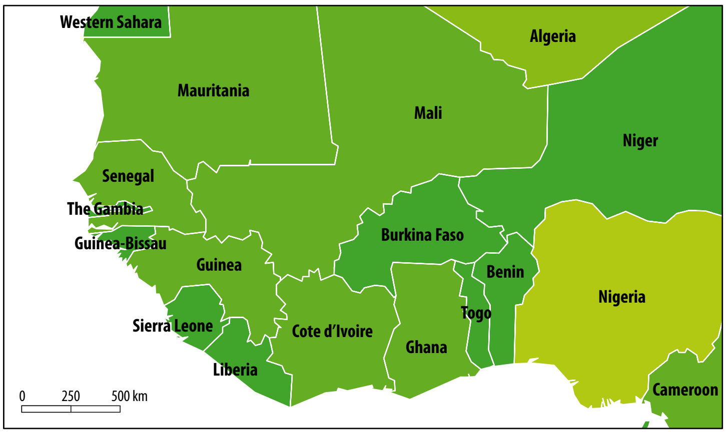
The fraction of use from diffuse natural capital (nonrenewable sources – N0) is shown in Figure 3.7. This includes extraction of water, forest, fish, and losses of soil organic matter, at rates faster than they can be replenished. The entire study area shows natural capital depletion fractions from 5–27%, and appears to be one of the global hotspots for potential shocks, due to simultaneous depletion of natural capital, while relying on natural capital flows for system operation. Notably, nations that rely on local depletion of natural capital tend to be countries classified as less developed. That most developed nations obtain a small fraction of their resources from depletion of natural capital suggests that they are better positioned to regulate excessive uses, and that they can export resource depletion to other parts of the world. A general trend of reliance on natural capital depletion and international trade is revisited later.

Electric power is the critical power source for information and industrial societies; the flexibility,

FIGURE 3.4

Global total emergy use (U). Values and global ranks (out of 134 nations) contain five focal Sahelian countries and nine other nations of varying size, location, and development status.

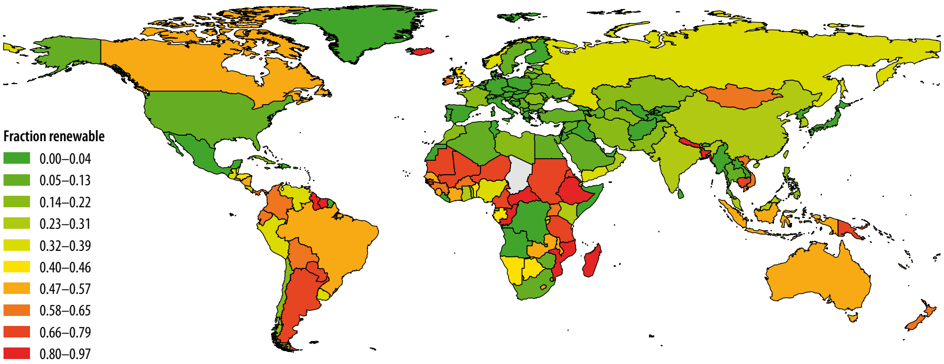


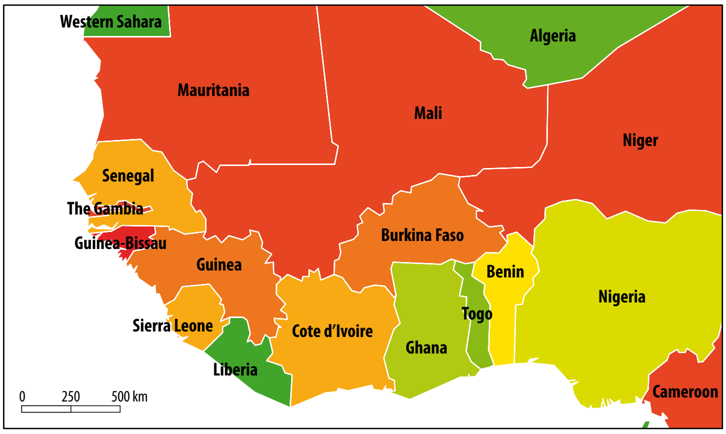


Country	Total use (E22 sej/yr)	Global rank
United States	1889.2	1
China	1285.6	2
Brazil	917.8	6
France	742.3	15
Indonesia	710.8	16
Saudi Arabia	707.7	35
Sweden	598.9	37
Kenya	545.1	47
Nicaragua	533.4	101
Mali	**525.3**	**107**
Senegal	**482.8**	**110**
Mauritania	**455.3**	**113**
Niger	**415.2**	**118**
Burkina Faso	**414**	**119**

FIGURE 3.5

Global map of indigenous renewable fraction of use (%R), with West Africa inset. The table of values and global ranks (out of 134 nations) contains the five focal Sahelian countries and nine other comparison nations of varying size, location, and level of development.

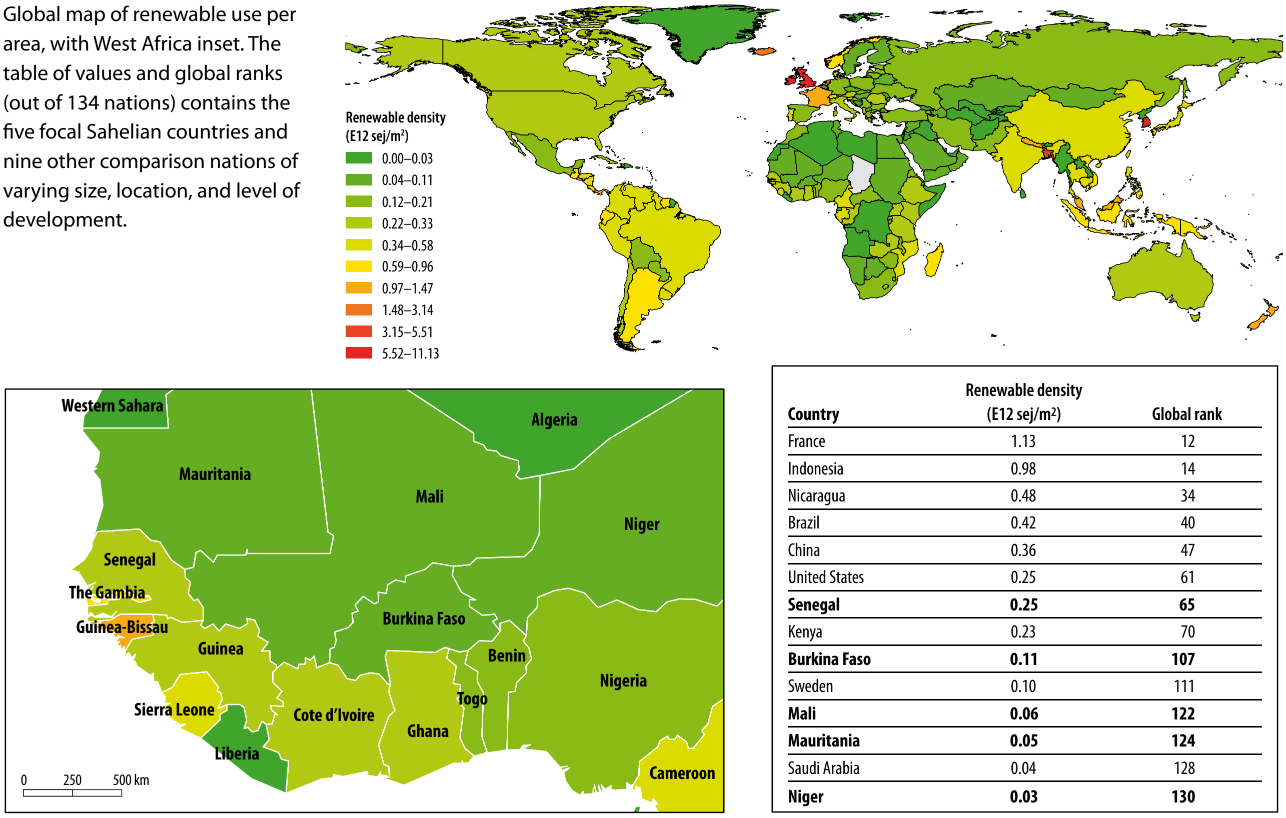




Country	Fraction renewable	Global rank
Mauritania	**0.79**	**12**
Mali	**0.76**	**16**
Niger	**0.74**	**18**
Burkina Faso	**0.63**	**26**
Indonesia	0.57	35
Nicaragua	0.56	37
Senegal	**0.55**	**38**
Brazil	0.5	43
China	0.26	69
Kenya	0.26	69
France	0.16	84
United States	0.12	90
Saudi Arabia	0.09	97
Sweden	0.05	107

FIGURE 3.6

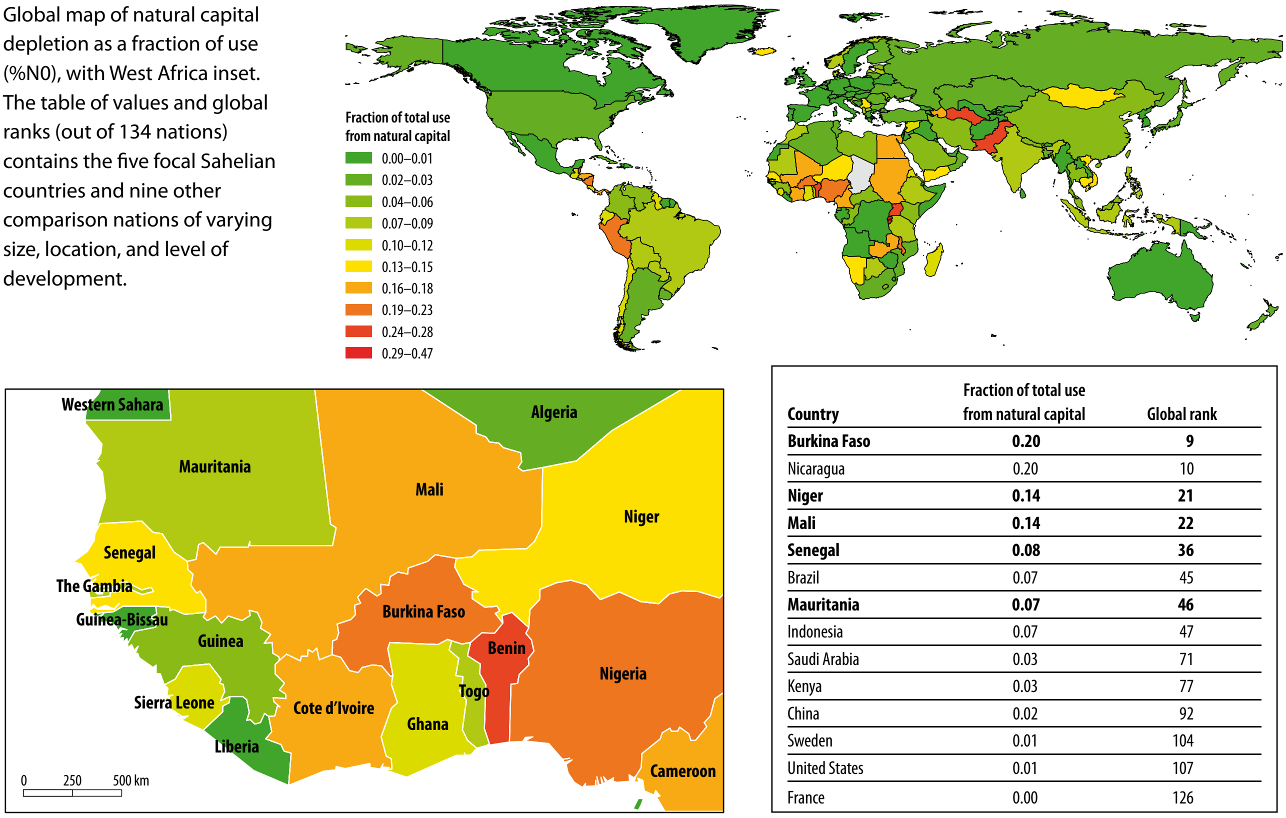
Global map of renewable use per area, with West Africa inset. The table of values and global ranks (out of 134 nations) contains the five focal Sahelian countries and nine other comparison nations of varying size, location, and level of development.



Country	Renewable density (E12 sej/m²)	Global rank
France	1.13	12
Indonesia	0.98	14
Nicaragua	0.48	34
Brazil	0.42	40
China	0.36	47
United States	0.25	61
Senegal	**0.25**	**65**
Kenya	0.23	70
Burkina Faso	**0.11**	**107**
Sweden	0.10	111
Mali	**0.06**	**122**
Mauritania	**0.05**	**124**
Saudi Arabia	0.04	128
Niger	**0.03**	**130**

FIGURE 3.7

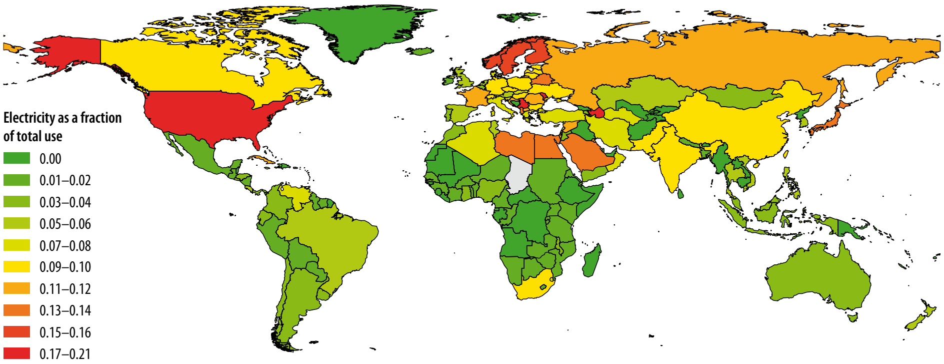
Global map of natural capital depletion as a fraction of use (%N0), with West Africa inset. The table of values and global ranks (out of 134 nations) contains the five focal Sahelian countries and nine other comparison nations of varying size, location, and level of development.

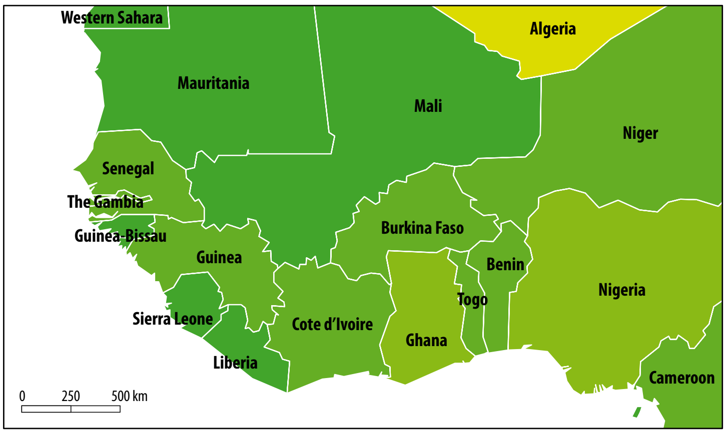


Country	Fraction of total use from natural capital	Global rank
Burkina Faso	**0.20**	**9**
Nicaragua	0.20	10
Niger	**0.14**	**21**
Mali	**0.14**	**22**
Senegal	**0.08**	**36**
Brazil	0.07	45
Mauritania	**0.07**	**46**
Indonesia	0.07	47
Saudi Arabia	0.03	71
Kenya	0.03	77
China	0.02	92
Sweden	0.01	104
United States	0.01	107
France	0.00	126

FIGURE 3.8

Global map of electricity consumption as a fraction of use, with West Africa inset.





Country	Electricity as a fraction of total use	Global rank
United States	0.2	2
Sweden	0.16	5
Saudi Arabia	0.13	10
France	0.11	18
China	0.1	23
Brazil	0.05	59
Indonesia	0.03	81
Nicaragua	0.02	89
Senegal	**0.02**	**89**
Kenya	0.01	104
Burkina Faso	**0.01**	**104**
Niger	**0.01**	**104**
Mali	**0.005**	**125**
Mauritania	**0.003**	**125**

transmissibility and generality of electricity as a flow of energy is the principal resource underlying technology and information. As such, the fraction of national resource use that occurs in the form of electricity is an excellent indicator of development status, and a useful benchmark for development trends over time. Electricity use as a fraction of total use (Figure 3.8) highlights areas with relatively low development, such as sub-Saharan Africa.

Metrics of use intensity

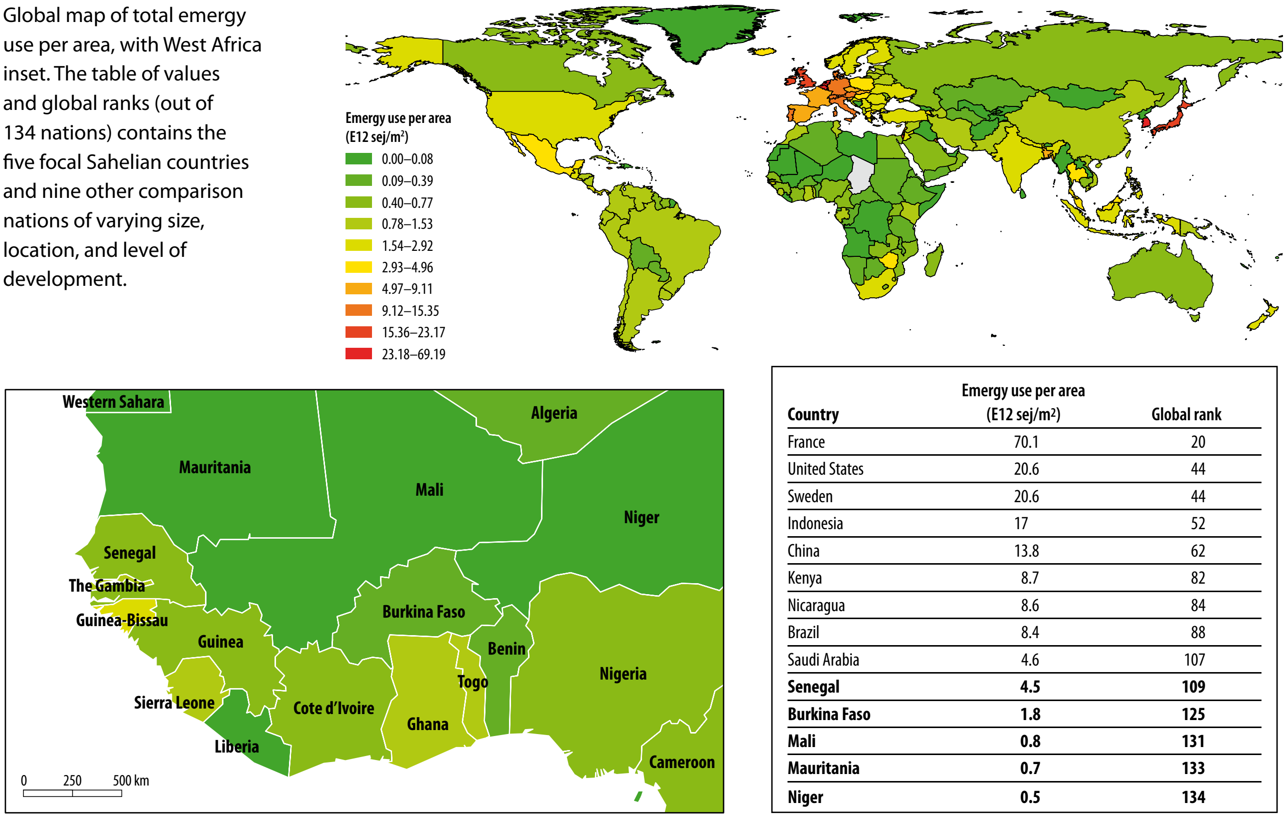
Because absolute emergy use values may correlate with the size of a nation, as is often the case with renewable flows, it is useful to consider these values with respect to area and population. Representing total emergy use, or any flow partition, per unit area or per capita provides a metric of intensity, or concentration of the emergy flow. Dividing a nation's total emergy use by its area gives the concentration of emergy use in space, or the empower density (Figure 3.9). Niger, Mauritania and Mali have three of the four lowest empower densities calculated for any nation. Small, highly industrialized nations, such as Japan, South Korea, and Western European nations, operate with intense spatial concentration of emergy flows.

Total emergy use per capita may provide insight into the general well-being of populations. A high emergy-per-person ratio suggests a high standard of living, given in more general terms than monetary income, which does not include the unpaid, direct wealth to people from the environment. All 12 West African countries fall below the global average of 2.8 x 10^{16} sej per capita, indicating a lower average well-being relative to other countries (Figure 3.10). Equity of use per capita within each country would provide additional insight into the distribution of resources and real wealth, as a person living a rural subsistence life may have a higher emergy use than a person with few resources and little buying power in an urban area.

It has been widely recognized that the use of fossil energy has been a catalyst for global and regional development. As such, national average fuel use is an important general indicator. Environmental accounting permits reporting of fuel use both as a comparative metric among nations, but also as a fraction of total resource consumption. Figure 3.11 shows the global distribution of fuel use per capita (sej/person/year), with greater than 2 orders of

FIGURE 3.9

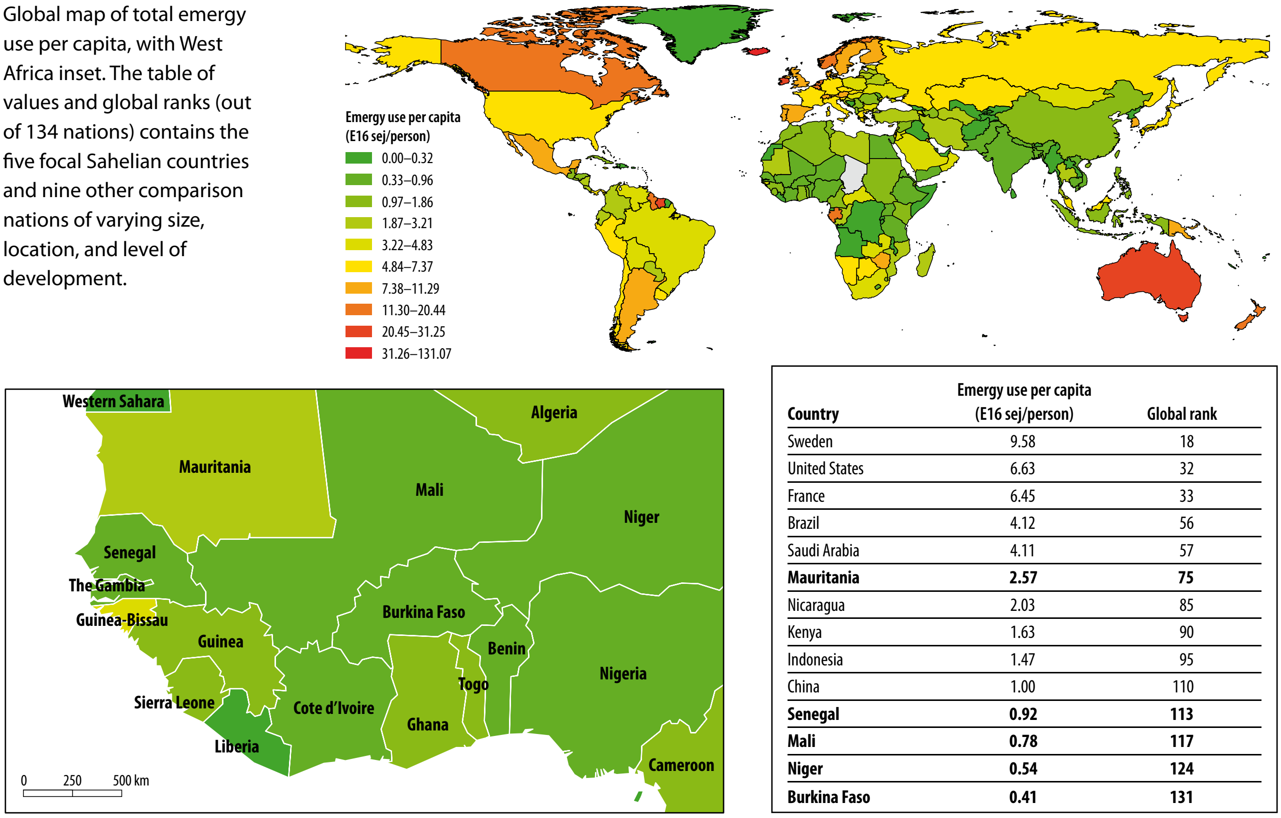
Global map of total emergy use per area, with West Africa inset. The table of values and global ranks (out of 134 nations) contains the five focal Sahelian countries and nine other comparison nations of varying size, location, and level of development.



Country	Emergy use per area (E12 sej/m²)	Global rank
France	70.1	20
United States	20.6	44
Sweden	20.6	44
Indonesia	17	52
China	13.8	62
Kenya	8.7	82
Nicaragua	8.6	84
Brazil	8.4	88
Saudi Arabia	4.6	107
Senegal	**4.5**	**109**
Burkina Faso	**1.8**	**125**
Mali	**0.8**	**131**
Mauritania	**0.7**	**133**
Niger	**0.5**	**134**

FIGURE 3.10

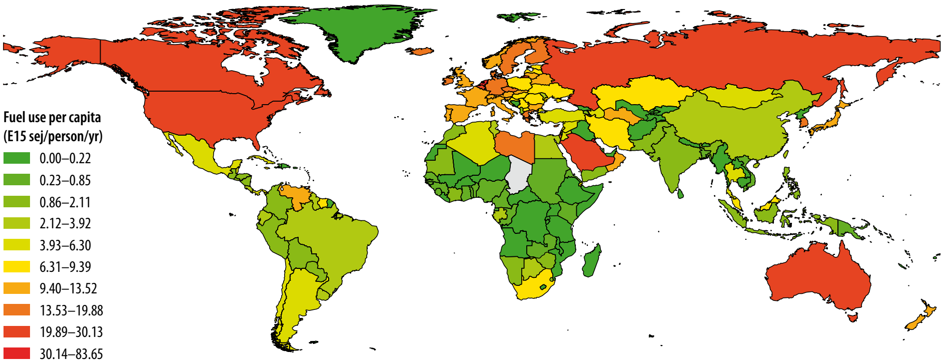
Global map of total emergy use per capita, with West Africa inset. The table of values and global ranks (out of 134 nations) contains the five focal Sahelian countries and nine other comparison nations of varying size, location, and level of development.

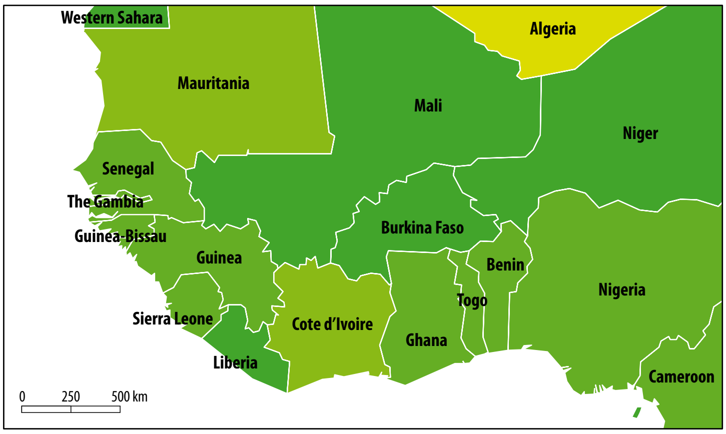


Country	Emergy use per capita (E16 sej/person)	Global rank
Sweden	9.58	18
United States	6.63	32
France	6.45	33
Brazil	4.12	56
Saudi Arabia	4.11	57
Mauritania	**2.57**	**75**
Nicaragua	2.03	85
Kenya	1.63	90
Indonesia	1.47	95
China	1.00	110
Senegal	**0.92**	**113**
Mali	**0.78**	**117**
Niger	**0.54**	**124**
Burkina Faso	**0.41**	**131**

FIGURE 3.11

Global map of fuel use per capita, with West Africa inset. Also given in the inset table is fuel use as a fraction of total use within the nation.

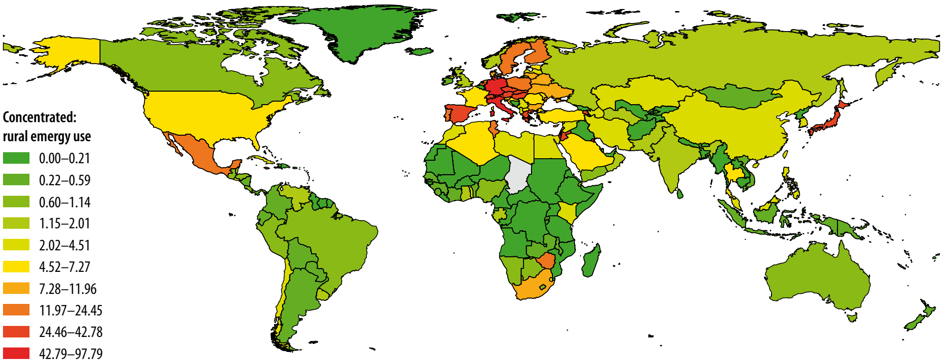


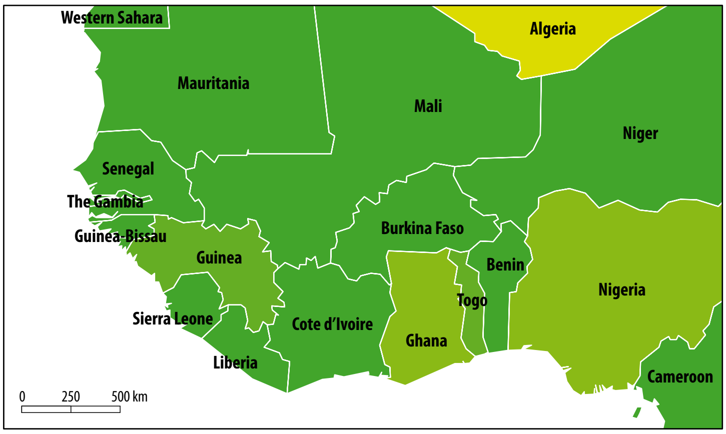


Country	Fuel use per capita (E15 sej/person/yr)	% of total	Global rank
United States	24.5	36.9%	5
Saudi Arabia	24.5	59.4%	6
Sweden	15.5	16.2%	19
France	11.5	17.8%	32
Brazil	3.0	7.2%	76
China	2.3	23.1%	80
Mauritania	**1.9**	**7.4%**	**82**
Indonesia	1.8	12.4%	84
Nicaragua	1.1	5.5%	99
Senegal	**0.8**	**8.8%**	**103**
Kenya	0.5	3.0%	111
Burkina Faso	**0.2**	**4.2%**	**124**
Niger	**0.2**	**2.9%**	**126**
Mali	**0.1**	**1.2%**	**133**

FIGURE 3.12

Ratio of concentrated to rural use on a national basis. Nations with the highest values globally are Belgium, Kuwait, Israel and Germany.





Country	Concentrated: rural emergy use	Global rank
Sweden	16.00	26
Saudi Arabia	7.27	35
United States	6.76	38
France	5.08	44
China	2.61	60
Kenya	2.49	62
Brazil	0.77	87
Senegal	**0.59**	**91**
Indonesia	0.56	93
Nicaragua	0.32	106
Burkina Faso	**0.20**	**115**
Mauritania	**0.17**	**118**
Niger	**0.13**	**122**
Mali	**0.11**	**124**

magnitude separating the largest from smallest values. Notably, northern European fuel use per capita, though markedly higher than the global average, is substantially lower than comparably developed nations. Fuel use as a fraction of total use is highest in Kuwait and Saudi Arabia (~60% of total use) and lowest in sub-Saharan Africa (~1–2%)

National-use intensity metrics describe aggregate resource consumption across rural and industrial sectors and regions. A useful metric of the intensity of resource use, and the degree to which resources are consumed in an urban or industrial manner (versus a rural or agrarian manner) is the ratio of concentrated to rural resources, defined as the sum of the local concentrated non-renewable flows and purchased non-renewable flows, divided by the sum of local dispersed non-renewable flows and renewable flows. This metric is summarized on a national basis in Figure 3.12. This metric is a useful indicator of industrial metabolism; nations with particularly high values tend to be highly industrial nations with limited land resources (Belgium, Japan, Germany). Nations with lower values occur in two clusters – large nations with an industrial base, and nations that have relatively little urban resource consumption (e.g. least developed nations).

Environmental load, economic attraction and sustainability

The Environmental Loading Ratio (ELR – Figure 3.13) relates non-renewable (both local and imported) to renewable use, reflecting pressure put upon local ecosystems to absorb impacts and process waste flows associated with resource use intensification; the formula for ELR is given in Table 3.1 and Figure A.1. ELR is frequently interpreted as a measure of environmental load; as local resource inputs from non-renewable resources increase, load on environmental systems increases. This metric does not integrate social investments in pollution control, and therefore is not a measure of environmental condition directly. Instead, it measures the potential load, and may provide a useful index of the need for pollution control; where that control is absent, environmental system decline is expected. Most of sub-Saharan Africa has comparatively low ELR values, with the exception of Botswana, South Africa and Kenya.

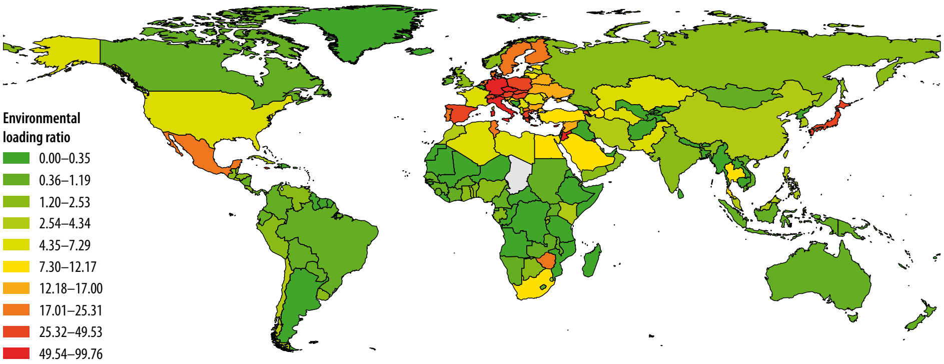
A second aggregate index, the emergy Investment Ratio (EIR), quantifies the degree to which a national economy is dependent on external investment for resources. It is ratio of imported emergy to indigenous sources, whether renewable or non-renewable; results of this metric are shown in Figure 3.14. In a sense, this metric measures participation in globalization and the degree to which locally available resources are sought by the global system. Notably, in sub-Saharan Africa only Nigeria, Benin, Cote D'Ivoire and Lesotho have values comparable with the global average. Nations with high values, which are those most strongly dependent on the global economy for resource acquisition, include Japan, Sweden, Switzerland, the Netherlands and Italy. This metric is useful as a gauge of development status, with the world's least developed nations (Nepal, Sudan, Madagascar, Bhutan) having low values, and nations in development transition exhibiting moderate values.

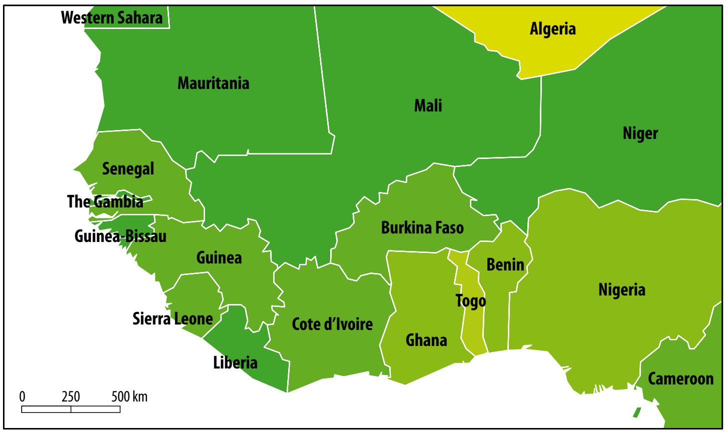
The Emergy Sustainability Index (ESI) measures two aspects of national economic sustainability; it is computed as the ratio of the Emergy Yield Ratio (EYR) and the Environmental Loading Ratio (ELR). If sustainability is viewed as the parallel process of minimizing environmental load (ELR) while encouraging development (i.e. maximizing EYR), sustainability can be quantified as the ratio of EYR to ELR. The resulting index (Figure 3.15) recognizes the multiple attributes of sustainability in the way that renewable fraction of use (Figure 3.5) cannot. That is, a nation may be considered sustainable only if it can simultaneously develop and reduce environmental degradation. There is no presumption of social sustainability in this metric; we discuss incorporation of such information below.

Nations with ESI values greater than 1 are considered comparatively sustainable, while nations with ESI values nearer 0.1 or below are profoundly reliant for their national production on resources that confer environmental load (either internally or elsewhere). Countries typically regarded as highly sustainable (e.g. Sweden) have very low ESI values, largely because they rely heavily on non-renewable energy resources. Mali, Mauritania, Niger and Cameroon, by contrast, have relatively high ESI values, primarily due to their comparative dependence on renewable use fractions. As non-renewable resources decline in importance (due to depletion or protection), economies with larger portions of their resource basis supported by indigenous resources, particularly renewable resources, are potentially less likely to exhibit serious shocks and dislocations of

FIGURE 3.13

Global map of Environmental Loading Ratio (ELR), an index of pollution potential.

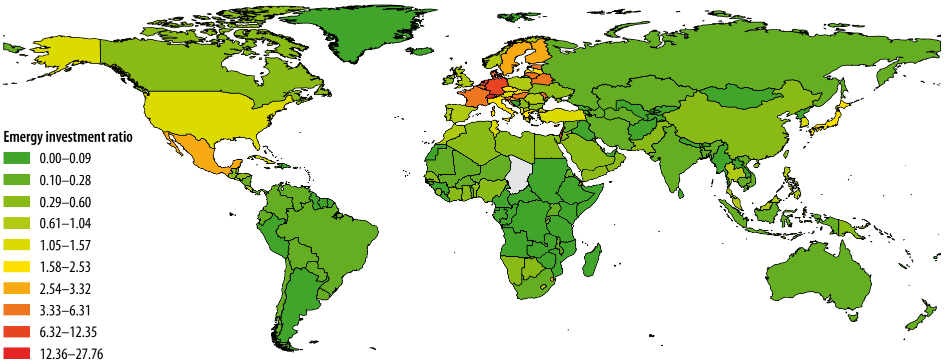


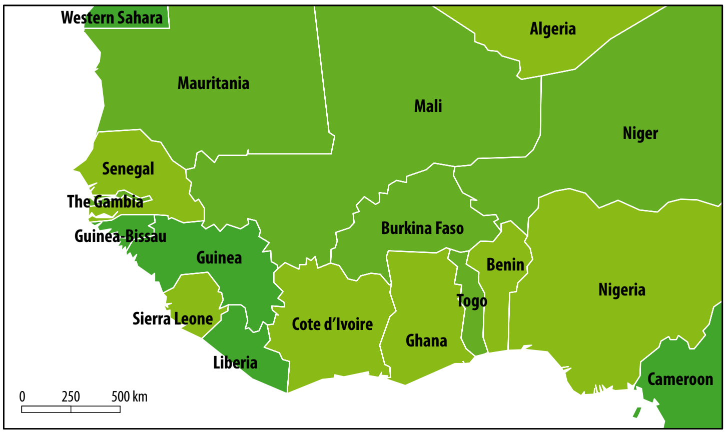


Country	Environmental loading ratio	Global rank
Sweden	19.31	29
Saudi Arabia	10.35	38
United States	7.29	45
France	5.19	51
Kenya	2.86	66
China	2.83	67
Brazil	1.00	91
Senegal	**0.83**	**96**
Nicaragua	0.79	98
Indonesia	0.74	100
Burkina Faso	**0.59**	**107**
Niger	**0.35**	**116**
Mali	**0.32**	**119**
Mauritania	**0.27**	**122**

FIGURE 3.14

Global map of the Emergy Investment Ratio (EIR).

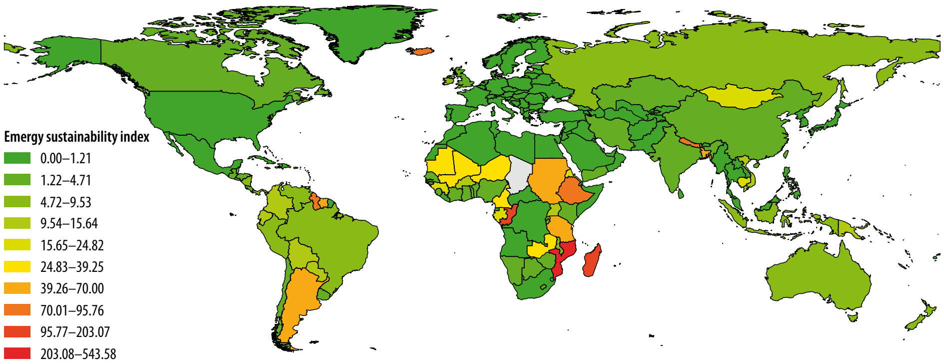


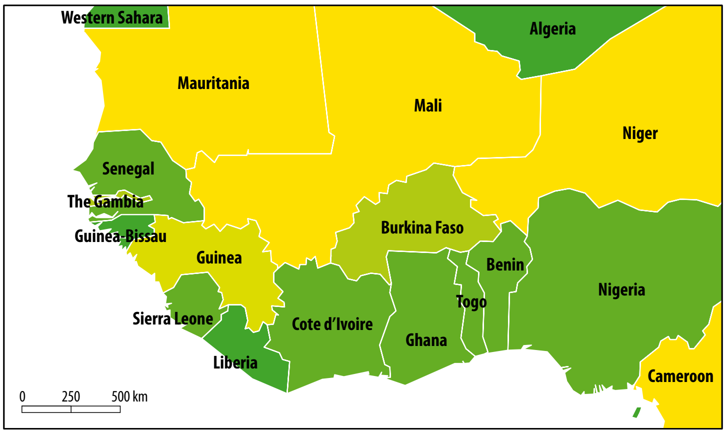


Country	Emergy investment ratio	Global rank
France	4.58	15
Sweden	3.00	20
United States	1.41	29
Saudi Arabia	0.39	65
Senegal	**0.35**	**70**
China	0.33	72
Nicaragua	0.23	83
Burkina Faso	**0.20**	**90**
Indonesia	0.19	94
Mauritania	**0.13**	**106**
Brazil	0.12	109
Mali	**0.11**	**110**
Niger	**0.10**	**111**
Kenya	0.09	113

FIGURE 3.15

Global map of the Emergy Sustainability Index (ESI).

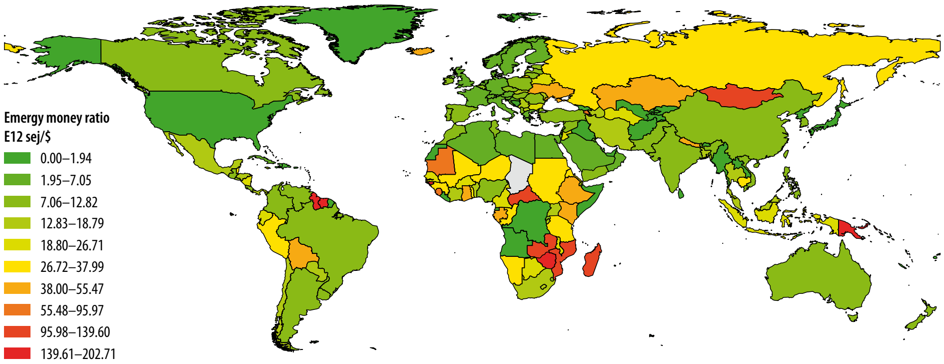


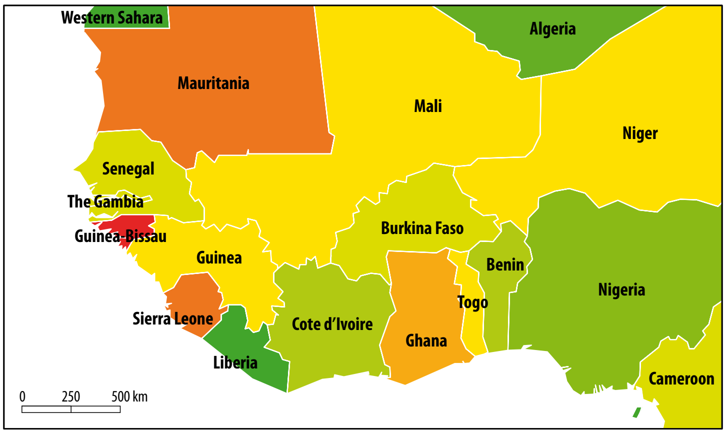


Country	Emergy sustainability index	Global rank
Mauritania	**31.22**	**17**
Niger	**31.04**	**18**
Mali	**30.92**	**19**
Burkina Faso	**10.02**	**33**
Brazil	9.53	34
Indonesia	8.64	36
Nicaragua	6.69	41
Senegal	**4.71**	**45**
Kenya	4.28	46
China	1.42	67
Saudi Arabia	0.35	92
France	0.23	98
United States	0.23	99
Sweden	0.07	111

FIGURE 3.16

Global map of the Emergy Money Ratio (EMR = Total Emergy Use/GDP).





Country	Emergy money ratio E12 sej/$	Global rank
Mauritania	**75.06**	**12**
Kenya	47.50	17
Mali	**37.99**	**23**
Niger	**32.45**	**29**
Nicaragua	26.18	37
Burkina Faso	**22.53**	**41**
Indonesia	20.64	46
Senegal	**19.69**	**47**
China	11.90	77
Brazil	11.76	79
Saudi Arabia	4.83	117
Sweden	3.54	127
France	2.92	129
United States	1.94	133

populations. While sub-Saharan Africa is not typically considered sustainable from the perspective of global human welfare, the globe's current reliance on emergy flows three times greater than the annual renewable supply (summarized in Figure 3.2) is profoundly unsustainable. In Chapter 7 we examine links between human welfare and resource consumption patterns that identify nations that provide for human development without relying excessively on non-renewable energy resources. Countries that meet that combined challenge all have high ESI values.

Emergy to Money Ratio (EMR)

The Emergy Money Ratio (EMR) relates the environmental resource basis of a nation to its economic productivity as measured by gross domestic product (GDP). While GDP is an imperfect measure of wealth and welfare, it is a useful measure of total transactions. The EMR quantifies the aggregate "price" of real wealth in the economy; that is, EMR is the unit price of emergy, and is computed as the total aggregate emergy use (U – Table 3.2) divided by the GDP in US dollars; EMR has units sej/$. This quantity has several important uses; first and foremost it permits reporting flows of environmental work in equivalent monetary units. That is, a flow for which no price exists (e.g., soil) but for which emergy flows are computed, can be reported in familiar money units by dividing the emergy flow by EMR [sej/(sej/$)].

The global map of national EMRs reveals that more industrialized countries tend to have lower EMRs (Figure 3.16). All 12 West African countries have considerably higher EMRs than the global average of 2.6 x 10^{12} sej per US$. While variation from the global average is a useful metric of development, it is even more useful as a metric of the structural inequities in trade amongst nations. We revisit this concept in detail in Chapter 6; briefly, a high EMR suggests the environmental resource basis necessary to generate a unit of currency ($) is large in comparison with nations with low EMR. When monetary trade equity is the objective, the result is that nations with high EMR mobilize and appropriate more environmental work to generate currency flow than do nations with low EMR. Because developing nations have high EMR and developed nations have low EMR, a structural inequity in the environmental resource basis of trade exists which favours developed nations. The need for global policy to rectify this inequity, particularly when considering international debt service, is an important finding of our analysis.

CHAPTER 4

Trends in emergy metrics for West African dryland nations

Time-series analysis of environmental accounting metrics uncovers trends that may be of significant predictive value, and allows estimation of the effects of the national development process on sustainability. Among the key findings in previous time-series environmental accounting is that total emergy use has grown by a factor of two between 1950 and 1998 (Brown and Ulgiati, 1999); renewable flows are largely constant, suggesting that non-renewable flows have grown by a factor of 4 over the same period, representing over 65% of the world system's total use in 1998. At the same time, gross world product has increased, but the ratio – the Emergy Money Ratio (EMR – sej/$) – has declined by 75%. Also, while total emergy use has grown, population has grown faster, so that by 1998 the emergy available per capita had declined 10–15% since 1950. Our objective in this section is to determine if similar trends hold for the five Sahelian nations (Figure 4.1) that have been undergoing economic development during that same time frame.

In the same manner used to compile data for the NEAD (Chapter 3), and using the same sources where possible, environmental accounting was done for each of the five nations. Data quality for periods prior to the 1990s is variable in completeness and quality. For some of the nations, and Mauritania in particular, the data that were available for some of the periods were judged sufficiently inadequate to exclude them from our analysis. We sought originally to track indices between 1950 and 2000 in five-year increments, but were forced to limit our analysis to the period after 1960, and to a variable interval due to data constraints. Detailed descriptions of methods and data gaps can be found in Cohen et al (2007a).

TIME SERIES FOR MALI

We first present data for Mali only to illustrate trends. Clear upward trends in total emergy use and imported emergy (Figure 4.2) suggest that development generally follows global trends of increasing resource appropriation. Imports track total use well, underscoring the parallel process of global market integration that accompanies development, but the fraction of total use from imports is clearly growing. It should be noted that imports are a comparatively small fraction of use, particularly *vis-à-vis* industrialized nations.

The observed global trends in the Emergy Money Ratio (EMR) and the total emergy per capita are evident in Mali (Figure 4.3). Observed declines in both are far more pronounced than for the globe as a whole; for example, emergy use per capita globally has declined less than 25% over the same period, while the same metric for Mali has fallen almost 60%. The causes for this more rapid decline are likely the combination of more rapid than average population growth and the comparatively small fraction of total use due to imported and non-renewable sources, which, though growing (Figure 4.2) is still small compared with the more constant flow of renewable emergy. Note also that the EMR is still very high compared with the global average of 2.6E12 sej/$ and the use per capita remains far below the global average of 7.8E16 sej/person. That the EMR declined and then stabilized in 1990 suggests that structural trade inequities (discussed in detail in Chapter 6) have not been rectified, and Malian trade on the international market may result in important negative externalities.

Gross domestic product (GDP) is a common metric of the magnitude of an economy, and evidence from Mali (Figure 4.4) is that this quantity was growing up to 1996. Moreover, as the economy grows, it has invested in resource use pathways more consistent with the modern global economy, as suggested by the similar growth in the fraction of total use as electricity. Note, however, that while electricity has grown in importance, the values are exceedingly small, even for Africa, where the average is nearly 2% of total use. As was noted in Table 3.2, most of the dryland nations in Africa exhibit the same behaviour, in contrast with other more humid nations in the region. Investment in electricity (production and distribution) is among the best indicators of development since, in many ways, electricity makes the modern world economic system possible. Growth in the fraction of total world system emergy use in the form of electricity has been steady, with current levels globally at 8.5%.

Trends in resource-use magnitude and composition are important, but they can be criticized for failing to account for concomitant changes in human welfare. Indeed, if the triple bottom line of environmental, economic and social welfare is to be part of sustainability assessment, considering only the resource basis can overlook important aspects of system maturation. While it is not the central objective of environmental accounting to make estimates of human welfare, it is important to consider how the biophysical basis of wealth

FIGURE 4.1

Five Sahelian focal nations (in red) for time-series analysis.

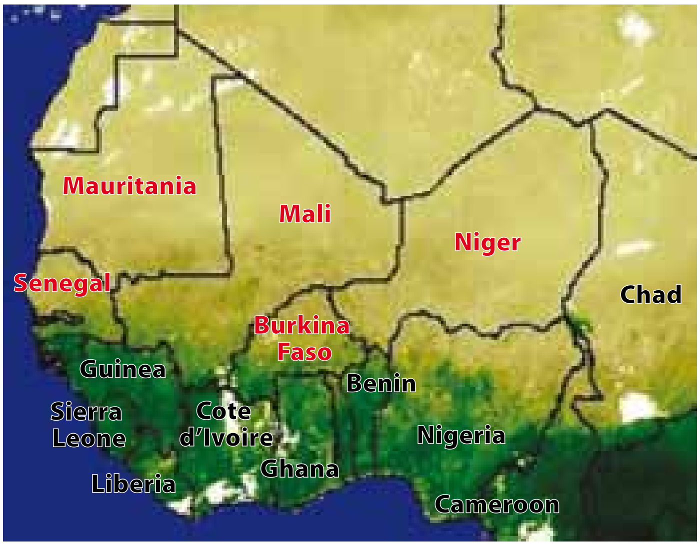


FIGURE 4.2

Time series of total emergy use and imported emergy for Mali between 1965 and 2001.

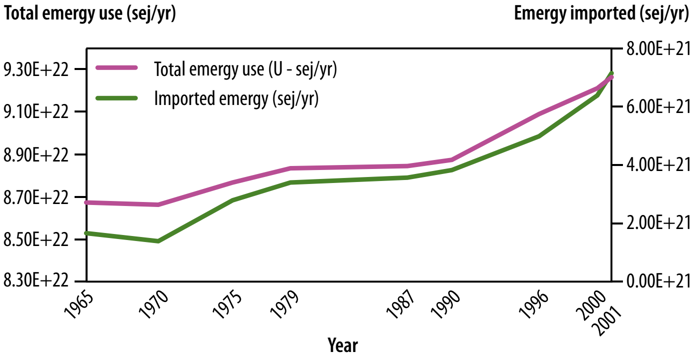


FIGURE 4.3

Time series of emergy use per capita (sej/#) and the Emergy Money Ratio (EMR – sej/$) for Mali between 1965 and 2000.

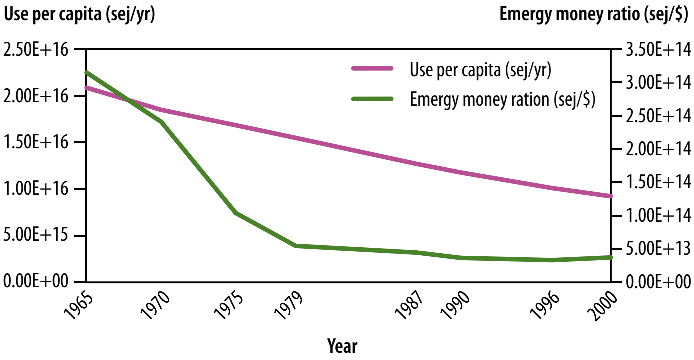


FIGURE 4.4

Time series of gross domestic product (GDP – $) and fraction of total use from electricity (%) for Mali between 1965 and 2001.

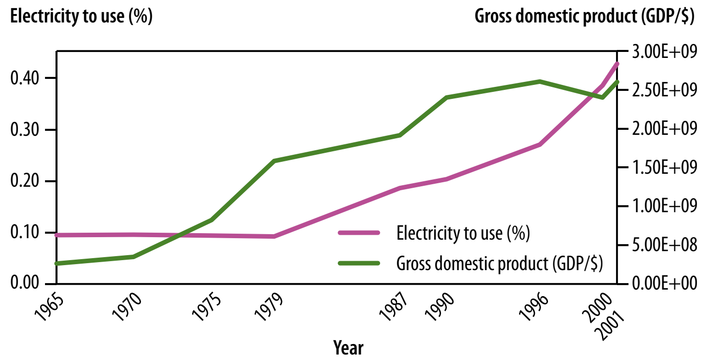
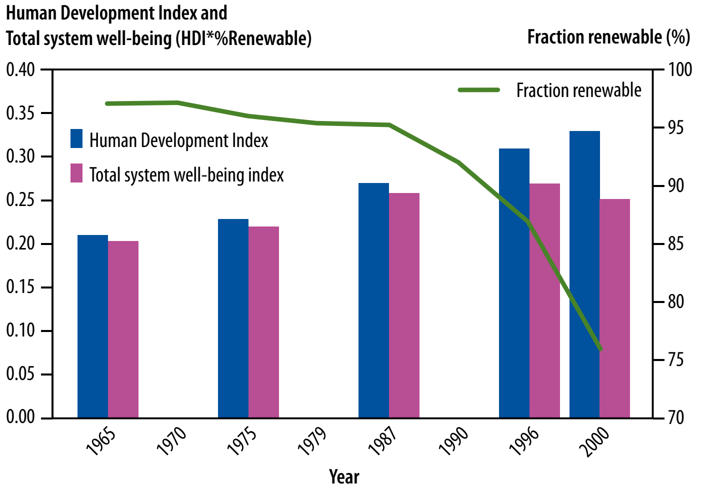


FIGURE 4.5

Time series of the UN's Human Development Index (HDI), fraction of total use from renewable sources (% R) and their product (referred to as the Total System Well-beingIndex) for Mali between 1962 and 2000. Note the right y-axis scale does not start at 0%.



translates into welfare. We consider this question in detail in Chapter 7, but provide a short discussion here because trends in human welfare over the period of our time-series record are available. We selected the UN's Human Development Index as a rough metric of human welfare; while there are compelling reasons to believe that HDI does not fully capture the essence of welfare, more complex metrics are often difficult to interpret and are rarely computed for all nations within the world system or over time. Moreover, the HDI has the property of varying, in principle, between 0 and 1, with higher values suggestive of greater average human welfare. Actual HDI values for 2000 were available for 124 nations, and these ranged from a low of 0.277 (in Niger) to a high of 0.942 (Norway); to ensure that both %R and HDI varied across the full range of scores, we scaled the reported values to a range from 0 to 1. We developed a new metric of sustainability that links biophysical resources with welfare by computing the product of the HDI and the fraction renewable, a metric that also varies between 0 and 1, where higher values indicate a higher reliance on locally renewable resources. This index, which we call the Total System Well-beingIndex (TSWI), increases as nations achieve two aspects of sustainability. That is, high values of TSWI can be observed only when both HDI and %R are high; nations where either one is low will, because the values are multiplied together, also be low. Analysis of this metric across all 134 nations evaluated as part of the NEAD is presented later. Here (Figure 4.5) we present the progress of HDI and TSWI between 1965 and 2000 for Mali.

HDI is systematically increasing, suggesting that, on average, Mali's national system is generating greater welfare. At the same time that HDI has been increasing, the fraction of total use from renewable resources has been declining, associated with increasing appropriation of non-renewable resources within the Malian economy, and the greater integration with the world economy. The rate at which non-renewable resources increase (i.e., %R declines) in the Malian economy is clearly increasing since the late 1980s. As a metric of future dependence of external or locally-depleting sources of real wealth, this is amongst the most important indices within a national environmental accounting frame.

TSWI is, again, the product of HDI and %R, so that value is sensitive to the rate of decline in %R in comparison to the rate of increase in HDI. What we observe is that TSWI increases through 1996, but then declines to 2000. That is, the rate of non-renewable use from both within and outside the country grew faster over the last decade than HDI. We note that the TSWI values for Mali are moderate; many nations are lower either because they depend to a greater extent on non-renewable resources, or because they fail to use the resources they do have for increasing human welfare.

TIME SERIES FOR FIVE SAHELIAN NATIONS

Analyses of the five focal nations over time are summarized together to compare trends observed for Mali with trends observed in the West African

Sahel region. Total use trends globally have been increasing, with use in 2000 roughly twice use in 1965. Similar but less rapid trends are observed for the Sahelian nations (Figure 4.5). Trends in all nations except Mauritania are upwards, but notably faster in Senegal than the rest. The rate of increase appears relatively constant, through slower growth in total use was observed throughout the region in the 1980s and early 1990s, again with the exception of in Senegal. It is also important to note that the area of each nation is different (which has direct bearing on the total emergy use); Burkina Faso and Senegal are far smaller (2.3E+11 and 1.9E+11 m^2, respectively) than the others. A more realistic comparison of growth in economic intensity is emergy density (sej/m^2) (Figure 4.7).

The trends in use per area (emergy density) illustrate the comparative development distinction between Senegal and the others, with values there nearly three times higher than any of the other four countries. Global comparison (see Figure 3.9) indicates that these are the lowest emergy densities observed within the world economic system. Niger in particular has very low density, principally due to the large areas of that country that are effectively uninhabited.

As with emergy use per area, scaling total use to population provides useful insight. Since population is growing where land area is not, the relative dynamics of population growth versus resource use change the characteristics of the time-series trends (Figure 4.8). In particular, despite systematic increases in the resource use within the region, the resource use per capita is declining. This parallels trends observed globally (Brown and Ulgiati, 1999), but at more precipitous rates (15% globally, 35% for Senegal and Burkina Faso and 55–60% for Mali, Niger and Mauritania). Since the resource endowment per capita in these nations is currently already far lower than the rest of the world system (world average ~2.8E+16 sej/capita/year), the more rapid than average downward trend is a first-order policy challenge.

While resource use has increased, and use per capita decreased, the composition of that use has also changed relatively uniformly amongst the five nations. In particular, aggregating resource inputs according to whether they are from renewable or non-renewable flows provides insight into patterns of economic development, and provides a useful benchmark for measuring biophysical sustainability (Figure 4.9).

FIGURE 4.6

Trends in total emergy use for five Sahelian nations, 1965–2000.

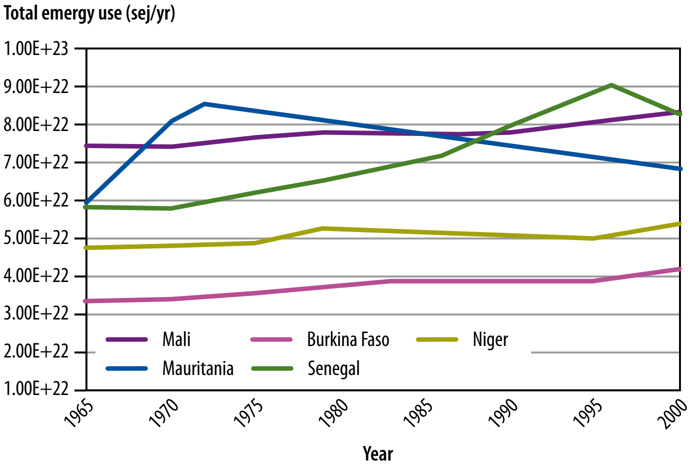


FIGURE 4.7

Trends in total emergy use per area for five Sahelian nations, 1965–2000.

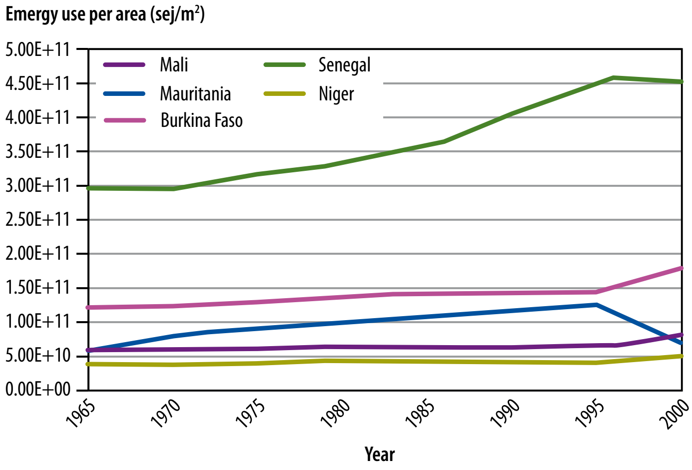


FIGURE 4.8

Trends in total emergy use per capita for five Sahelian nations, 1965–2000.

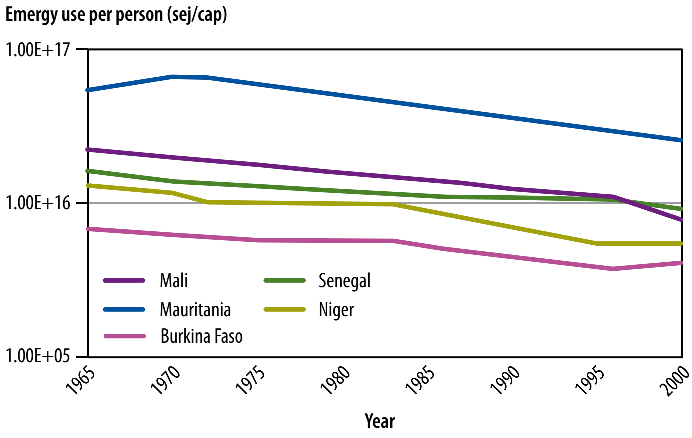


FIGURE 4.9

Trends in the fraction of emergy use from renewable sources for five Sahelian nations, 1965–2000.

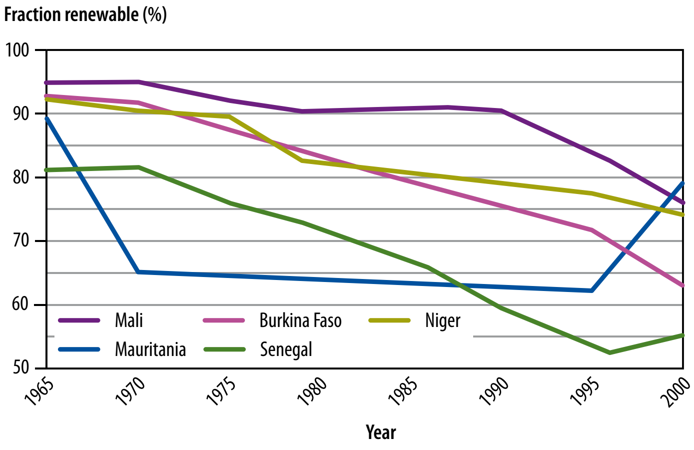


FIGURE 4.10

Trends in the Environmental Loading Ratio for five Sahelian nations, 1965–2000.

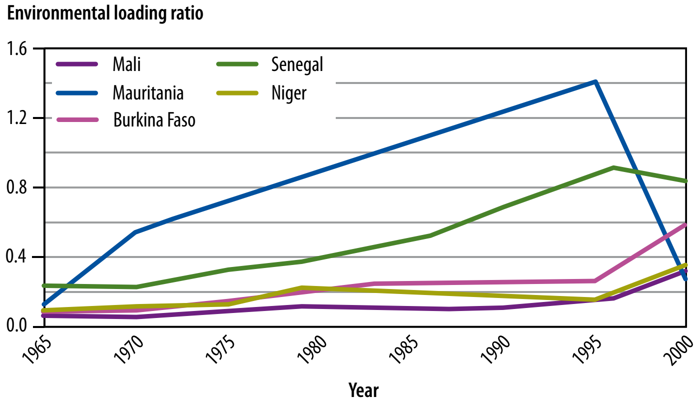
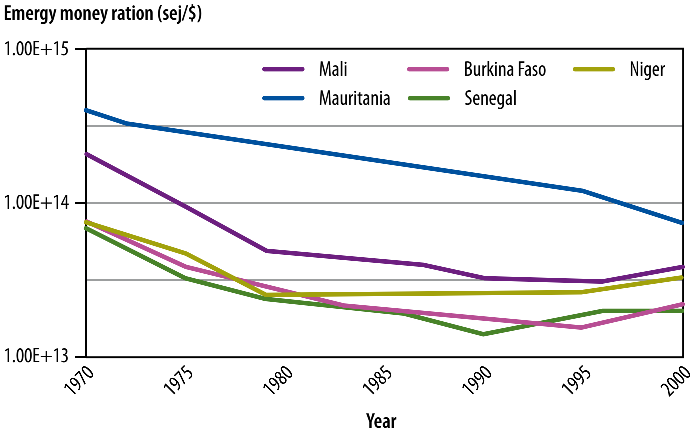


FIGURE 4.11

Trends in the Emergy Money Ratio (EMR) for five Sahelian nations, 1965–2000.



The trends are uniformly downwards for all nations except Mauritania, which exhibits a recent surge in %R because an increasing fraction of the non-renewable resources that are extracted are not used within the nation (hence they are not part of use). The global trend is also downwards, with non-renewable stocks currently providing nearly 67% of the total emergy use in the world system; that is, %R hovers around 35% for the globe, underscoring the relatively high dependence on renewable sources in the Sahelian nations.

It is also evident that, as was the case for Mali, the rates of transitions from economies dependent wholly on renewable resources to ones dependent on local and external sources of non-renewable emergy are increasing. That rapid transition appears to have occurred in Senegal in the 1970s and 1980s, in Burkina Faso in the 1980s and in Mali in 1990s.

As would be expected, as the fraction renewable declines, the Environmental Loading Ratio (ELR) increases (Figure 4.10). The ELR has been interpreted as a metric of pollution production potential; values range globally from 0.03 (Guinea-Bissau) to over 300 (Belgium), suggesting that levels in the Sahelian nations, though clearly increasing, are still comparatively low. Values were increasing more rapidly in Senegal than in the other nations until the most recent observation (2000), where marked increases in ELR were observed for Niger, Mali and Burkina Faso.

Finally, we examine patterns of the emergy-money ratio (EMR) over time (Figure 4.11). Mirroring the trends observed globally, there is a decline in the EMR; declines observed here are far larger than the average, but the EMR values are still roughly an order of magnitude higher than the global system (EMR_{global} ~2.6E+12sej/$). This suggests that the structural inequities embedded in the global system of trade, an issue discussed at length in Chapter 6, have been improving; however, these five nations still suffer great disadvantage when trading on the global marketplace. The trends are also interesting in that the reductions in trade inequity were principally realized during the 1970s and 1980s, and have since been exacerbated, with EMR values actually increasing slightly between 1995 and 2000 for Mali, Niger and Burkina Faso, and between 1990 and 1995 for Senegal.

CHAPTER 5

The global value of natural capital: soil, water, fish and forests

VALUING THE GLOBAL DEPLETION OF NATURAL CAPITAL

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 by human activities through time. As these stocks degrade, often precipitously, quantification of their value becomes a central means to direct policy towards their protection. The National Environmental Accounting Database we developed (Chapter 1) 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 (i.e. inverted U-shape) may have significant implications for both the interpretation of ESI and broader macro-scale policy.

Global declines in stocks of stored ecological work are well documented; topsoils erode many times faster than ecosystems can replenish them; rivers and aquifers are exploited beyond their capacity to recharge; fish stocks are depleted by excessive extractive effort, resulting in severe changes in populations and ecosystem structure; deforestation accelerates as the human agricultural footprint expands. All of these stocks are sources of wealth or capital similar to the stocks of financial capital. To demonstrate their value, both intrinsically and as the raw materials of economic processes, they are increasingly referred to as natural capital.

Because the stocks of natural capital that are being depleted are effectively free to humans (that is, the costs of their extraction are borne by society, now or in the future, and not by individual extractors) there is a strong price incentive to over-exploit them. Environmental accounting offers one way to place the depletion of natural capital stocks in the perspective of national and international accounts, thereby providing an estimate of their value for use in designing and calibrating regulatory or incentive-based interventions.

The database of national environmental accounts, described previously, tabulates estimated losses of natural capital to the extent that extraction exceeds the rate of renewal. That is, only non-renewable or unsustainable uses are integrated into the calculations of the resource basis of nations. The rationale for this distinction is that the renewable resources (sunlight, rainfall, geologic work, tides, etc.) available within a nation are able to support in perpetuity some level of extractive use. When human users extract natural capital at rates faster than this sustainable threshold they are using historical environmental work. An example would be a regional aquifer system. Water that human users extract at or below a rate that can be compensated for by natural recharge rates would be considered part of the renewable flows available to that system; when water extraction rates exceed recharge rates, as is happening in many aquifer systems in arid areas, or where irrigation demand is high, the water extracted represents historical flows (sometimes referred to as fossil water). It is use of natural capital stocks beyond their capacity for replacement that represents a consumption of an historical endowment, and is treated as non-renewable in the calculus of environmental accounting.

Using existing data sets on the depletion of soil, water, fish and forests, described in detail in the sections that follow, and estimating the environmental work required to generate each of these flows, we estimate several key indicators for each country. First, we estimate the fraction of total resource use accruing from each of these sources separately and combined; natural capital depletion is often diffuse (i.e., spread widely across the landscape) and external (i.e., not reflected in market prices), so quantifying the relative magnitude of each flow is critical for the purposes of scaling national and international responses. Second, we determine the equivalent monetary value for each flow as a way of placing them in familiar currency units. Finally, we explore the relationships between a nation's dependence on natural capital depletion and other aspects of resource sustainability.

For each natural capital stock described, a common set of measurement processes was required. As with all environmental accounting, two quantities are necessary to place flows in comparative context: the physical flows (e.g., grams of soil loss per year) and the transformity (e.g., sej per gram of soil). The following sub-sections describe the process of obtaining these two quantities for each of the four natural capital stocks (soil, water, fish and forests) for each country in the national environmental accounting database (NEAD).

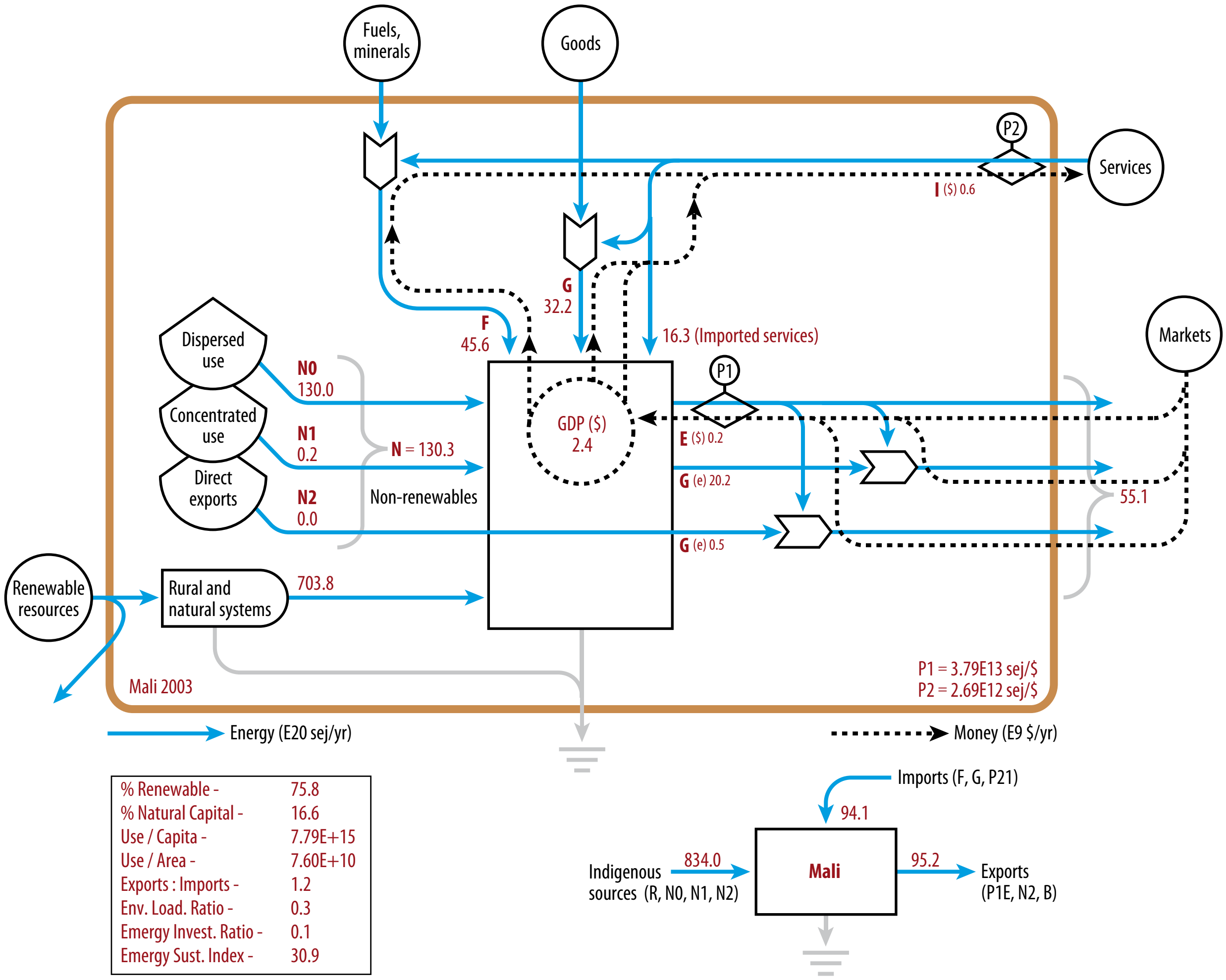
We define natural capital as the accumulated stores of material, energy and information in the biosphere, and argue that it is the resource foundation of economic production. From mined materials and fuels to soil and forests and biodiversity, natural capital represents the embodied work of nature that 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 ecosystem services are well documented (e.g. Costanza et al, 1998).

Because free market prices do not reflect the work required 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 our 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 dialogue. 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 (Chapter 1; 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, residual heat, 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 labour) 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 syntheses.

Natural capital is effectively non-renewable. Whether such stocks accrue over millions of years (e.g. geologic sources such as minerals, fossil fuels) or hundreds of years (e.g., slowly renewable sources such as top soils, forests, groundwater, fish stocks) is of limited importance when the rates of exhaustion can be measured in years or decades. However,

FIGURE 5.1

Summary diagram (after Odum, 1996) of the resource basis of a national economy (Mali, 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 nation and globe, respectively.



in an effort to delineate geological storages from those that are more dynamic, we divide natural capital into dispersed and concentrated uses (Figure 5.1). 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 (past environmental work required) and related to economic measures of costs using standard protocols of national environmental accounting (Odum, 1996; Doherty et al, 2002).

METHODS FOR ACCOUNTING FOR NATURAL CAPITAL DEPLETION

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).

TABLE 5.1.

Sources of data for analysis of the global costs of natural capital depletion.

Variable	Dataset	Accessed via…	URL for dataset
Rainfall	Wilmott grid V.2.01	Center for Climatic Research	http://climate.geog.udel.edu/~climate/html_pages/download.html
Evapotranspiration	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	http://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	http://faostat.fao.org/
Wood biomass per area	IPCC report, Table 3A.1.4	Intergovernmental Panel on Climate Change	http://www.ipcc-nggip.iges.or.jp/lulucf/cop9/Chp3/Chp3_8_1_Annex_3A_1_COP9.pdf
Annual forest extent lost	Global Forest Resources Assessment 2000	UNEP, GEO-3 Data Compendium, 1.1	http://geocompendium.grid.unep.ch/data_sets/forests/nat_forest_ds
Water extraction	AQUASTAT database	Food and Agriculture Organization	http://www.fao.org/nr/water/aquastat/main/index.stm
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.grid.unep.ch/data/grid/soils.html http://gov/epubs/ndp/ndp081/ndp081.html
Soil degradation	GLASOD database	ISRIC	http://www-cger.nies.go.ip/grid-e/gridtxt/grid15.html

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 (Table 5.1).

Soil loss

Soil losses are typically evaluated based on soil organic matter (SOM) lost (via erosion by wind or water, oxidation after tillage). While SOM stocks globally are relatively well known (Figure 5.2A), 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 5.3) 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 5.4):

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

FIGURE 5.2

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}

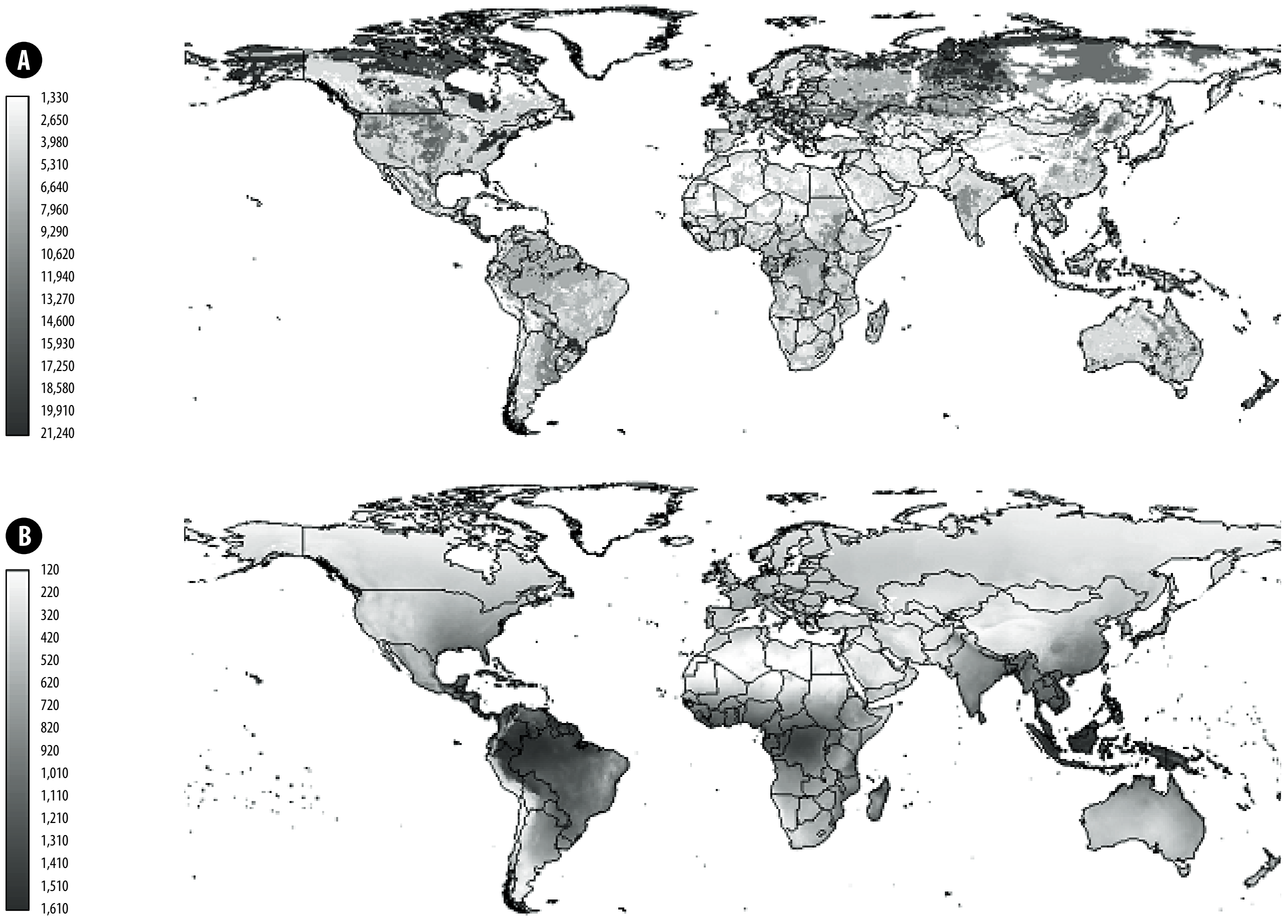
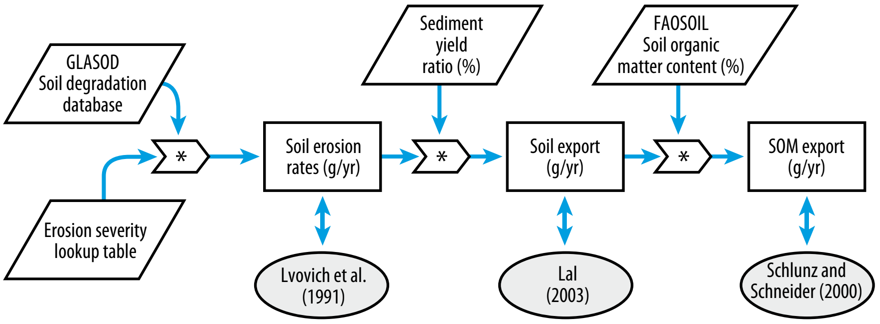


FIGURE 5.3

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

FIGURE 5.4

Analytical scheme for extracting soil erosion from global maps. The erosion severity look-up table (Table 5.2) 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.



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 5.2). The resulting product is a raster map (cell size = 0.5º) with soil-loss rates per unit area, as well as a global estimate of total soil erosion that can be compared with previous literature estimates (Lvovich et al, 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 5.2A) was obtained from the FAO/UNESCO Digital Soil Map of the World CD-ROM.

TABLE 5.2

Erosion severity lookup table for GLASOD soil degradation map.

GLASOD soil degradation mechanism	GLASOD soil degradation type	Soil erosion rate (g/m²/yr)	Literature range (g/m²/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.

TABLE 5.3

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%
South 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%

4) We assumed that only 10% of eroded material is ultimately exported (sediment yield ratio – Figure 5.4). 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 (i.e., is carried away 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).

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) has 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 5.5); 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 5.3. Notably, the fraction of total fish harvest that is deemed unsustainable ranges from a low of 12% (India) to a high of over 93% (Peru). This follows from Figure 5.5, 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

FIGURE 5.5

Summary of fish stock exploitation by region; pie size corresponds to the number of stocks, not total catch (from Marine Fisheries Service, FAO, 2005).

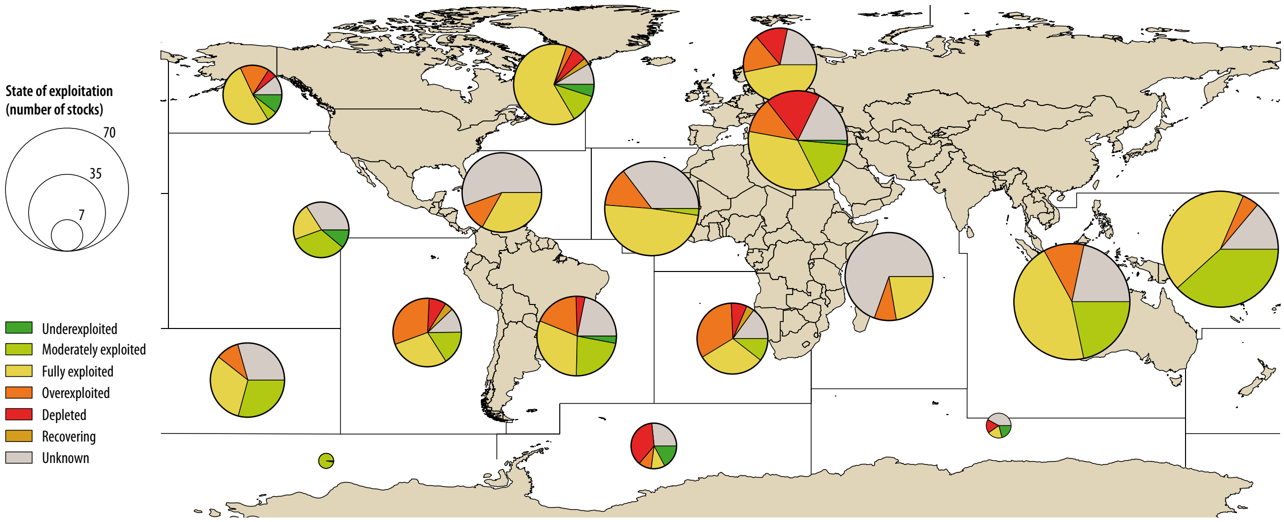
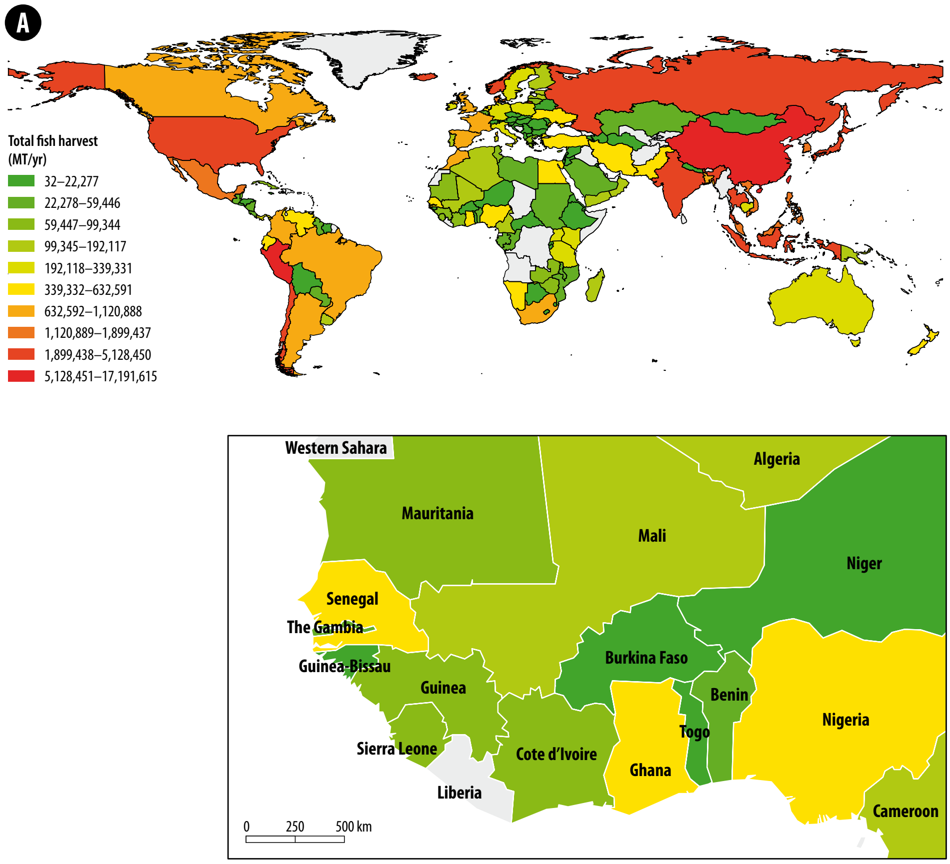
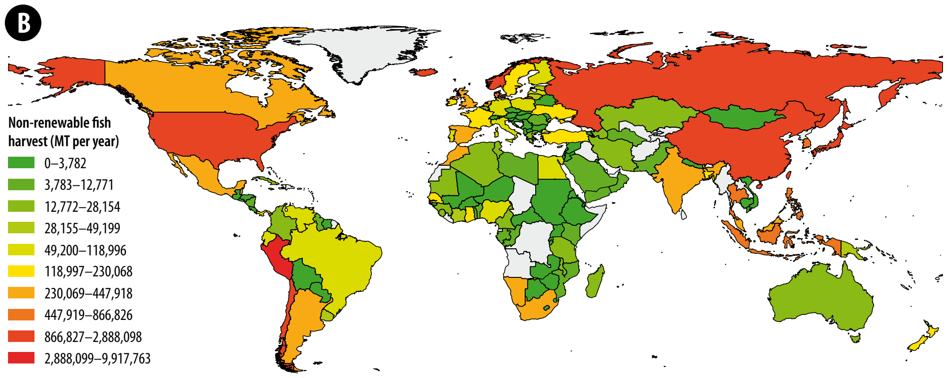


FIGURE 5.6

A) Total fish and
B) Non-renewable fish
catch by country in
metric tons for 2000.





Country	Non-renewable fish harvest (MT/yr)	Global rank
China	2,582,065	3
United States	1,834,566	4
Indonesia	866,826	9
France	230,039	25
Sweden	181,392	27
Brazil	156,836	30
Mauritania	**60,652**	**44**
Nicaragua	23,304	56
Saudi Arabia	12,771	69
Kenya	**6,262**	**84**
Mali	**0**	**127**
Burkina Faso	**0**	**129**
Niger	**0**	**132**

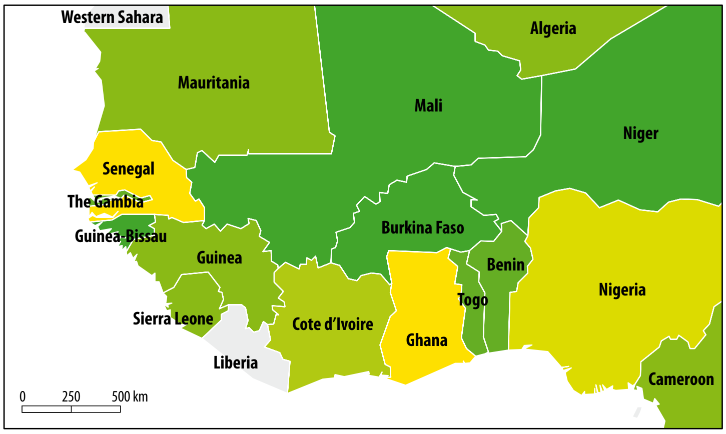
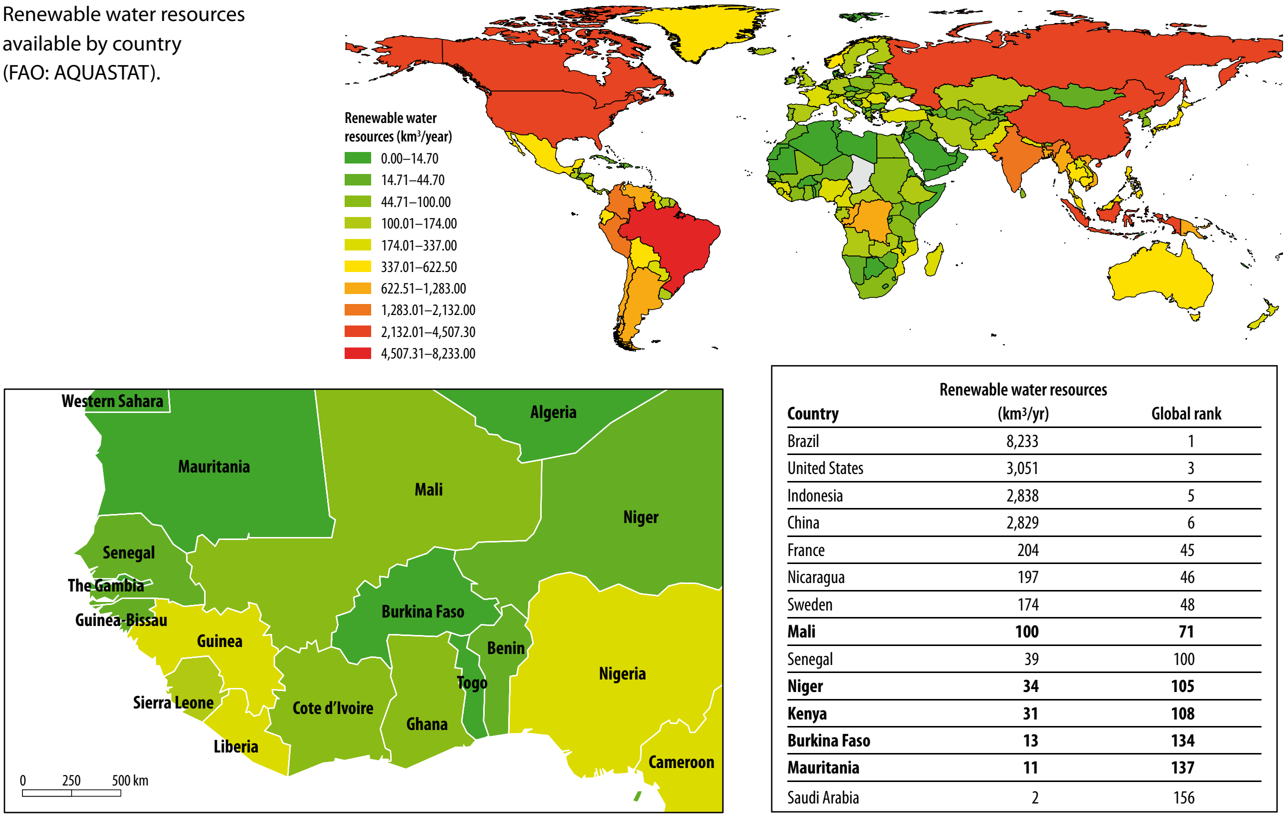


FIGURE 5.7

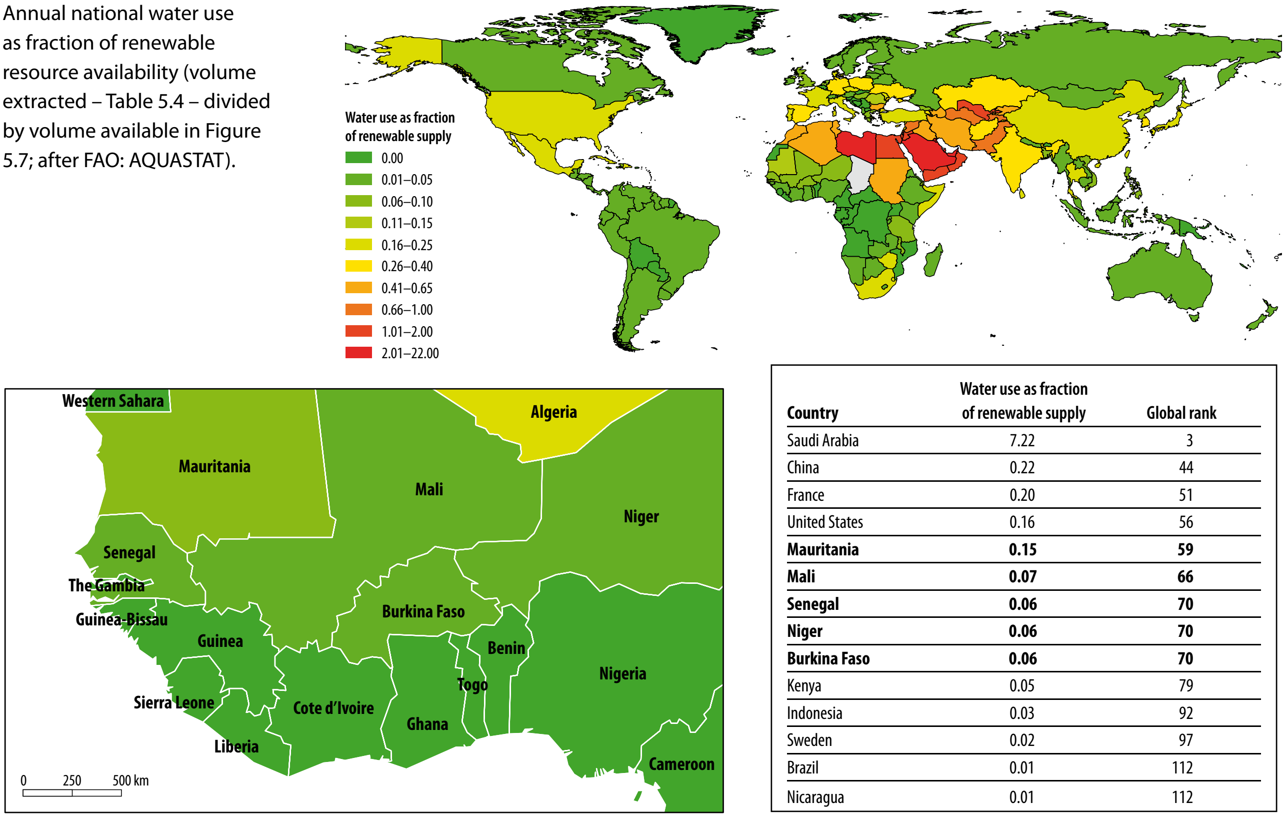
Renewable water resources available by country (FAO: AQUASTAT).



Country	Renewable water resources (km³/yr)	Global rank
Brazil	8,233	1
United States	3,051	3
Indonesia	2,838	5
China	2,829	6
France	204	45
Nicaragua	197	46
Sweden	174	48
Mali	**100**	**71**
Senegal	39	100
Niger	**34**	**105**
Kenya	**31**	**108**
Burkina Faso	**13**	**134**
Mauritania	**11**	**137**
Saudi Arabia	2	156

FIGURE 5.8

Annual national water use as fraction of renewable resource availability (volume extracted – Table 5.4 – divided by volume available in Figure 5.7; after FAO: AQUASTAT).



Country	Water use as fraction of renewable supply	Global rank
Saudi Arabia	7.22	3
China	0.22	44
France	0.20	51
United States	0.16	56
Mauritania	**0.15**	**59**
Mali	**0.07**	**66**
Senegal	**0.06**	**70**
Niger	**0.06**	**70**
Burkina Faso	**0.06**	**70**
Kenya	0.05	79
Indonesia	0.03	92
Sweden	0.02	97
Brazil	0.01	112
Nicaragua	0.01	112

Ocean. The final map of over-fishing in mass units (Figure 5.6) can be multiplied by the UEV for fish to arrive at the emergy costs.

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 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 define both national water resource availability and use, but also to provide guidance on quantities of water use considered unsustainable (http://www.fao.org/waicent/faoinfo/agricult/agl/aglw/aquastat/dbase/index.stm) (Figure 5.7). 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 (Figure 5.8). 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 5.4 summarizes water availability, use and sustainability

TABLE 5.4

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	1,896.7	645.8	171.7
Pakistan	222.7	169.4	113.7
Egypt	58.3	68.3	53.7
Uzbekistan	50.4	58.3	45.7
Iran	137.5	72.9	38.5
Iraq	75.4	42.7	23.8
Sudan	64.5	37.3	21.2
Turkmenistan	24.7	24.7	18.5
Saudi Arabia	2.4	17.3	16.7
Syria	26.3	20.0	13.4
Azerbaijan	30.3	17.3	9.7
Germany	154.0	47.1	8.6
Tajikistan	16.0	12.0	8.0
Spain	111.5	35.6	7.8
Kazakhstan	109.6	35.0	7.6
Afghanistan	65.0	23.3	7.0
China	2,829.0	630.3	0.0
USA	3,051.0	479.3	0.0
Japan	430.0	88.4	0.0
Indonesia	409.9	87.1	0.0
Bangladesh	2,838.0	82.8	0.0
Mexico	1,210.6	79.4	0.0
Russian Fed.	457.2	78.2	0.0
Brazil	4,507.3	76.7	0.0
Canada	891.2	71.4	0.0

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. Forest biomass stocks for each nation are shown in Figure 5.9. Annual deforestation rates by nation (Figure 5.10) are published by the Global Forest Resource Assessment. 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

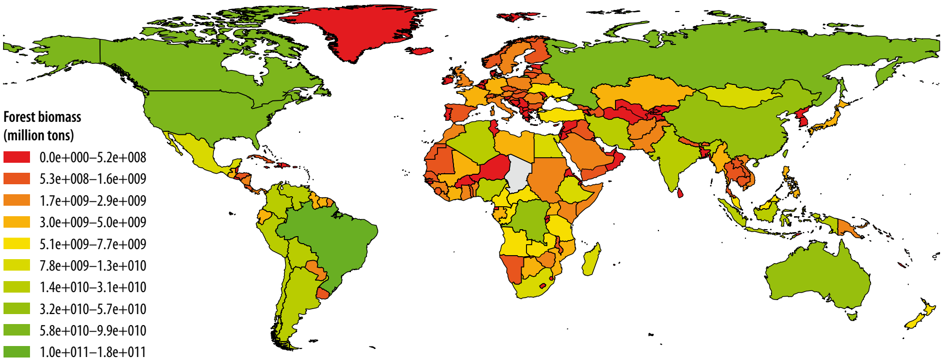
TABLE 5.5

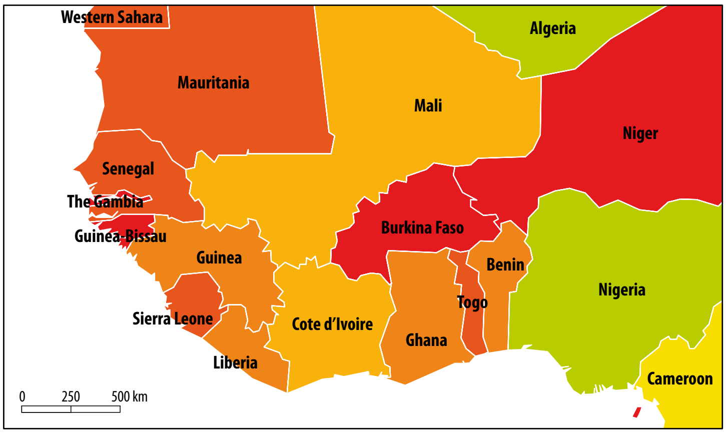
Summary of annual forest loss (or gain) and the associated change in biomass for select countries.

Country	Annual change (1,000 ha)	Biomass (tons/ha)	Biomass change (tons)
China	1,806	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	-1,312	1.36E+02	-1.78E+08
Brazil	-2,309	2.09E+02	-4.83E+08

FIGURE 5.9

Forest biomass in million tons by nation (UNEP GeoCompendium).

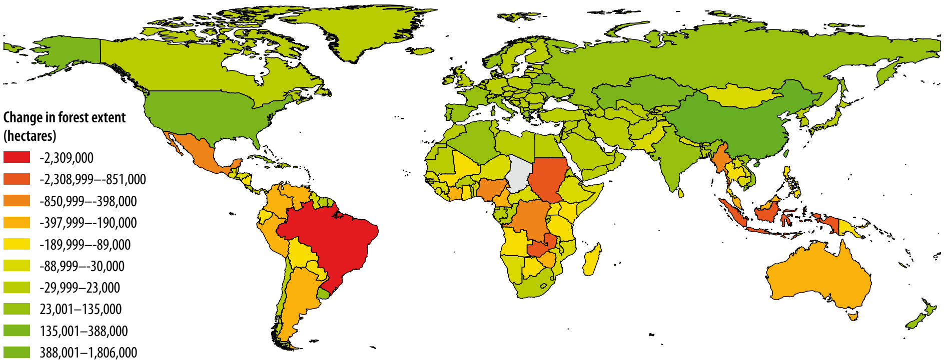


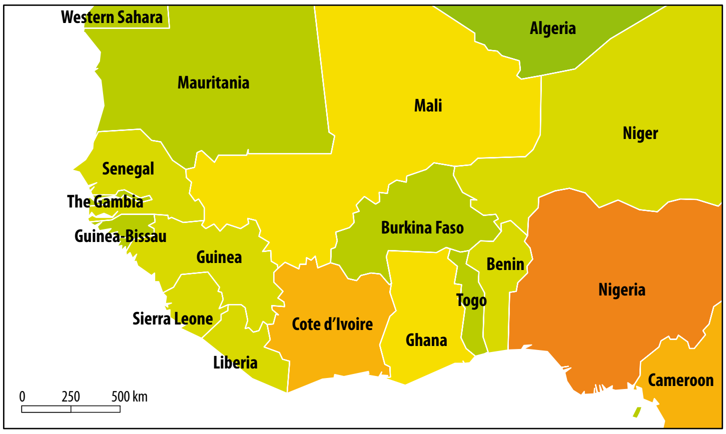


Country	Forest biomass (million tons)	Global rank
Brazil	1.8E+11	1
United States	9.9E+10	2
China	5.7E+10	5
Indonesia	2.5E+10	9
France	5.0E+09	35
Mali	**3.8E+09**	**44**
Kenya	2.7E+09	56
Sweden	2.6E+09	58
Saudi Arabia	2.4E+09	60
Nicaragua	1.9E+09	71
Mauritania	**6.2E+08**	**106**
Senegal	**5.8E+08**	**109**
Niger	**5.1E+08**	**112**
Burkina Faso	**4.4E+08**	**117**

FIGURE 5.10

Annual change in forest cover in 1,000 hectares per year between 1950–2000.





Country	Change in forest extent (hectares)	Global rank
China	1,806,000	1
United States	388,000	2
France	62000	7
Sweden	1,000	50
Saudi Arabia	0	59
Mauritania	**-10,000**	**128**
Burkina Faso	**-15,000**	**131**
Senegal	**-45,000**	**146**
Niger	**-62,000**	**154**
Kenya	-93,000	166
Mali	**-99,000**	**167**
Nicaragua	-117,000	170
Indonesia	-1,312,000	193
Brazil	-2,309,000	194

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 provides 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 basis) across all forest systems. A summary of the data showing forest loss rates and an estimate of forest biomass per unit area is given in Table 5.5; note that countries with positive annual change have reported afforestation over the 10-year period between 1990 and 2000.

DEVELOPMENT OF UNIT EMERGY VALUES FOR NATURAL CAPITAL STOCKS

For fish, forests and water, we used existing UEVs from recent sources; all values were either reported using the 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}).

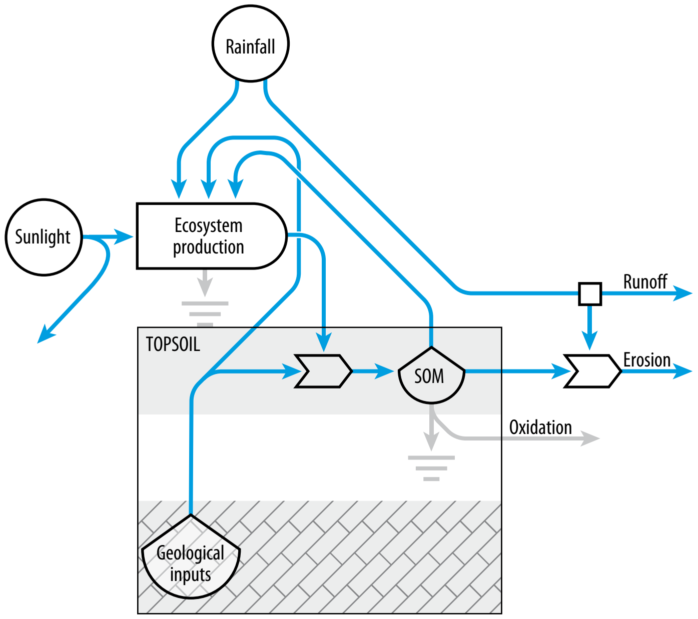
Soil

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 5.11, 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 5.12 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). The source of rainfall chemical potential is from the UNEP GRID database (see Appendix

FIGURE 5.11

Systems schematic of soil genesis showing the interaction of ecosystem and geological inputs to produce topsoil.



A); Figure 5.13A shows the product of the UEV for rainfall and the rainfall quantity over a global raster map with cell resolution of 0.5º.

The other sources of data for the UEV computation are SOM stocks (Figure 5.2A) from the Digital Soil Map of the World v. 3.6 (FAO, 2003), and respiration data derived from Raich et al (2002) (Figure 5.2B), based on average values between 1980 and 1994. From these maps, we derived a map of SOM turnover times (Figure 5.13B – 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 0.5˚ 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.

Fish

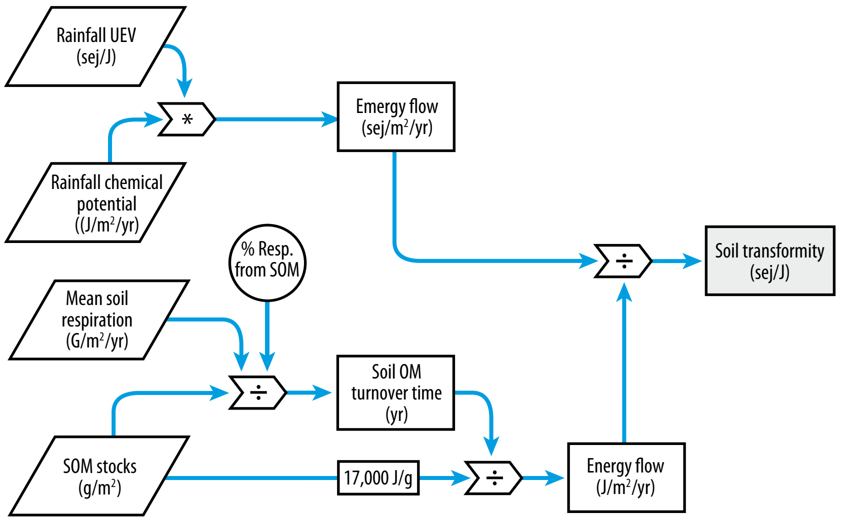
The UEV for fish is the most complex of the four natural capital flows; fish harvested for human consumption may be obtained from multiple trophic levels, be of profoundly variable size, and be from dramatically different ecosystems. As such, specifying a global UEV estimate is challenging. We took the 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.

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 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

FIGURE 5.12

Analysis flow chart used to compute UEVs for soils globally.



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 in the Southeastern United States, which is among the most transmissive in the world and consequently expected to be of lower UEV, we suggest that our computed water capital depletion costs are significant underestimates.

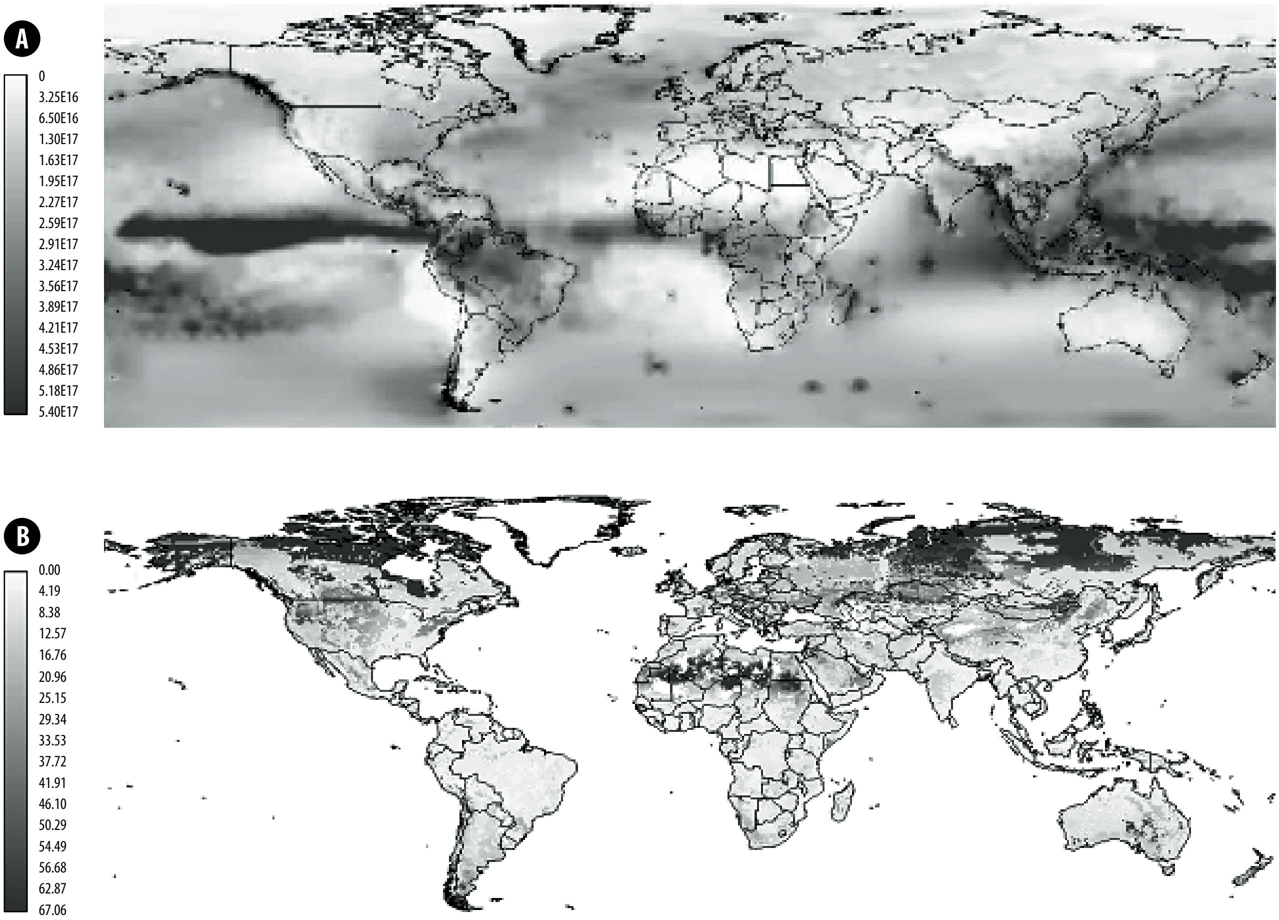
Figure 5.14 shows the total water extraction by nation assuming that the UEV of water is as above. Note, however, that these are not the final natural capital costs, because much of this water, and for some nations all of the water, is within the estimates of renewable supply. This distinction (water use vs. sustainable water use) is useful overall, but may mask significant water over-use because of aggregation at the national scale. For example, while water use in the United States is, overall, sustainable, water use in the southwestern part of the country is not. The methods in this work are constrained by the scale at which data on sustainable use are reported; future work on water use sustainability within the context of environmental accounting will need to consider local-scale issues more as data become available.

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

FIGURE 5.13

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).



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+4 sej/J for temperate hardwood biomass. While lower UEVs exist in the emergy literature (Doherty, 1995, reports boreal spruce (*Picea aibes*) = 1.7E+04 sej/J, slash pine (*Pinus elliotti*) = 3.3E+04 sej/J, and loblolly pine (*Pinus taeda*) = 1.9E+04 sej/J), these are typically for production forest operations, and not mature ecosystems. We consider the selected UEV to be conservative.

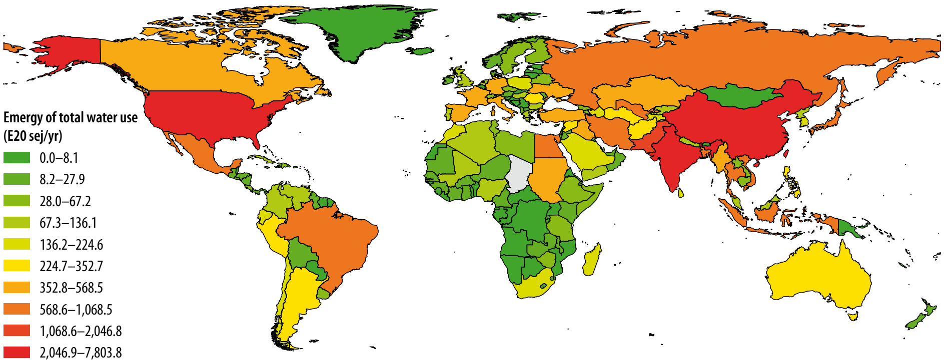
Resource flows in context – integration in the NEAD

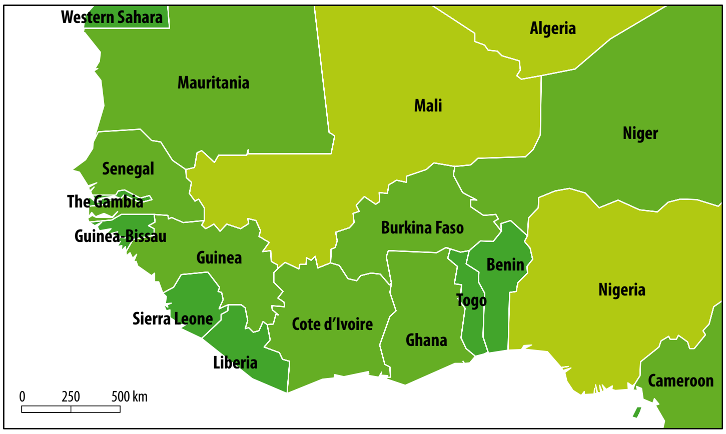
We used the NEAD to scale the magnitude of natural capital flows to national and global accounting. We report several indices to facilitate comparative inference:

1) Total Natural Capital – natural capital depletion in emergy units
2) % Natural Capital – natural capital emergy divided by total 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 – relationships between 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).

FIGURE 5.14

Emergy value of total water use. The fraction of water use that is considered unsustainable varies dramatically between countries, so our estimate of natural capital depletion is not the same as water use.





Country	**Emergy of total water use (E20 sej/yr)**	**Global rank**
China	7,615.9	2
United States	5,791.4	3
Indonesia	1,000.3	7
Brazil	716.5	14
France	482.8	20
Saudi Arabia	209.3	36
Mali	**79.1**	**62**
Sweden	35.8	74
Senegal	**26.8**	**84**
Niger	**26.3**	**86**
Mauritania	**20.5**	**93**
Kenya	19.1	95
Nicaragua	15.7	100
Burkina Faso	**9.7**	**113**

RESULTS OF NATURAL CAPITAL ACCOUNTING

We first present the results of a new computation of the Unit Emergy Value of soil organic matter. Figure 5.15A provides a map of UEVs globally; the median value globally is 1.34E5 sej/J, which coincides 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 3.2E4–3.3E5 sej/J.

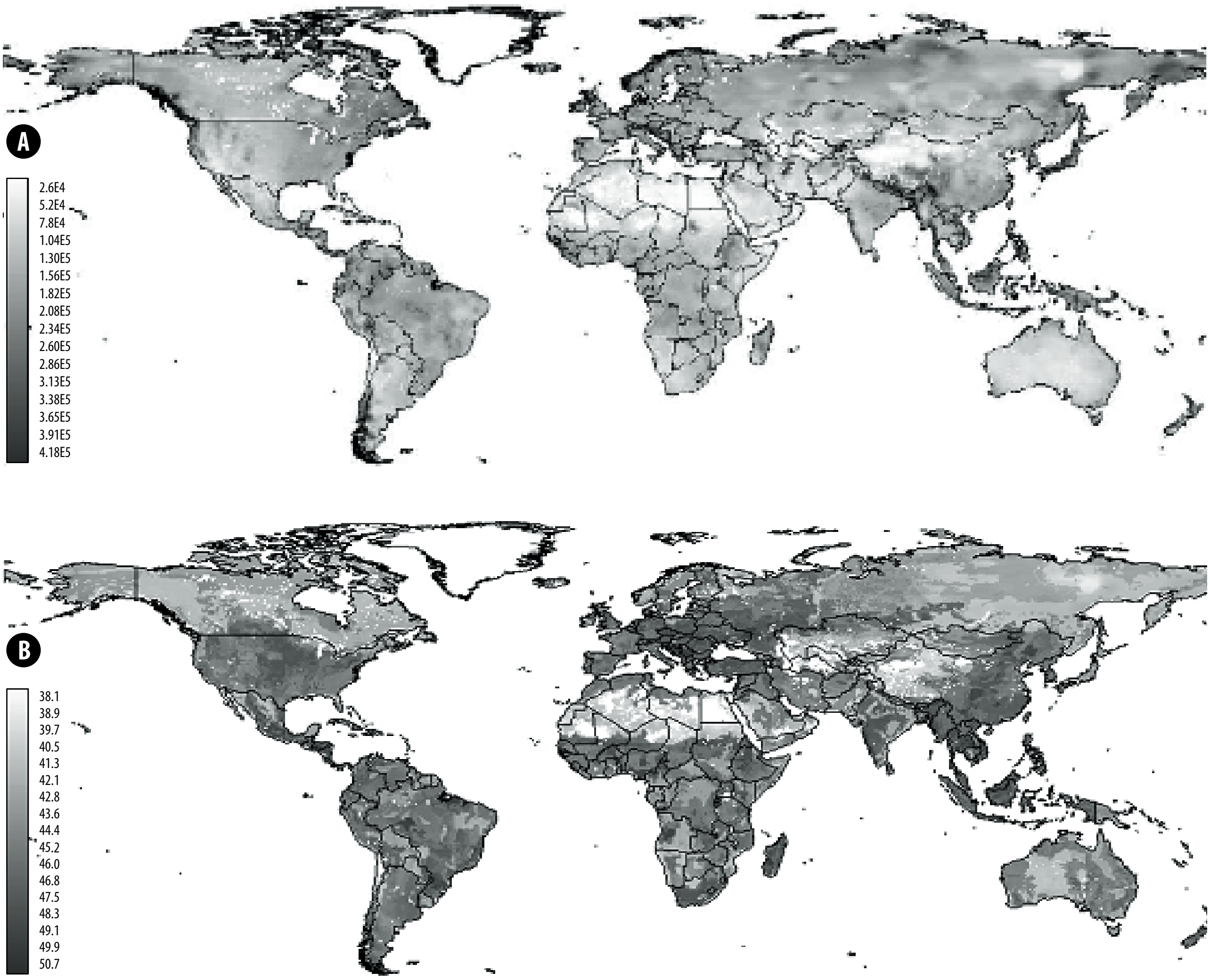
Multiplying the UEV by SOM export (derived by multiplying the erosion rate by the SOM fraction and a sediment yield ratio of 10%) yields the total emergy loss. This quantity, shown in Figure 5.15B (natural log transformed for map clarity) was parsed by country boundaries to yield a total annual emergy cost.

Using the estimated rates of soil loss and associated Unit Emergy Values, an estimate of the total emergy in soil erosion on an annual basis was computed (Figure 5.16). Note that global hotspots for erosion (SE China, Central American, East Africa) are clearer on the disaggregated map (Figure 5.15B) than at the scale of nations because of the large differences in the sizes of countries. However, aggregating flows based on national boundaries permits them to be interpreted in the same units as other flows more evident in the national system (e.g., imports or electricity production) and from this get a better sense of the magnitude of the external costs that erosion carries.

Despite substantial deforestation over the last 300 years, there remain large stocks of biomass

FIGURE 5.15

Maps of A) soil Unit Emergy Value (UEV – sej J^{-1}), and B) natural-log emergy of soil loss (sej km^{-2} yr^{-1}).



in forests. Figure 5.17 illustrates the magnitude of these stocks in emergy units on a national basis. As can be seen, the highest stock is in Brazil, with an estimated emergy value of 7.7E25 sej. To put this stock in perspective, the total emergy inputs (from sunlight, earth heat and tidal momentum) to the globe on an annual basis are less than 20% of this value. The sum of stocks across all the nations for which data were available (n = 177) is 4.99E27 sej, or 330 times the global emergy input. While the value is implicitly uncertain, this value underscores the remarkable magnitude of the shared global inheritance that forests represent. The rate of depletion of this stock is the short-term spending of this inherited resource, a process that should be controlled via policy before it is controlled due to scarcity.

A summary of deforestation costs on a national basis was estimated to determine the costs of depleting this enormous global stock (Figure 5.18). As before, large countries have higher values, simply because of their size. However, what Figure 5.18 shows clearly is that Brazil has the largest costs by far. On a national basis, costs of deforestation are particularly large, both in magnitude and national fraction of resource use, in the humid tropics.

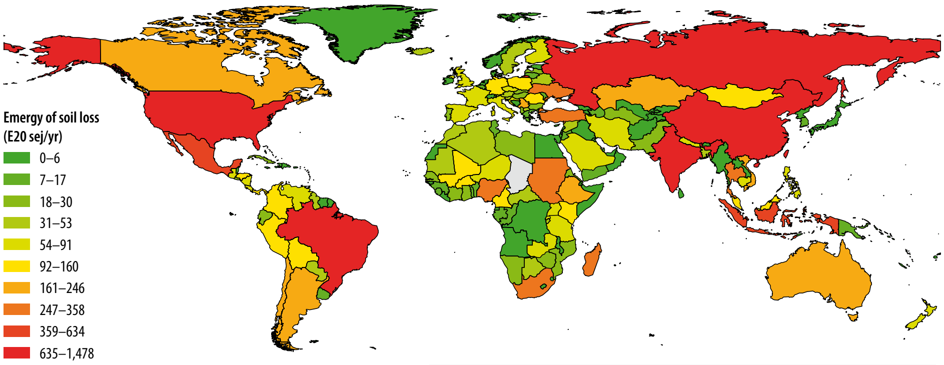
Finally, it is possible to estimate the emergy costs associated with the depletion of fish stocks; this estimate includes both freshwater and marine species, but the magnitude of marine fishing overwhelms the fish caught from freshwater. While China harvests the greatest mass of fish, Peru is the nation for which the largest amount of their catch is considered non-renewable (Figure 5.19).

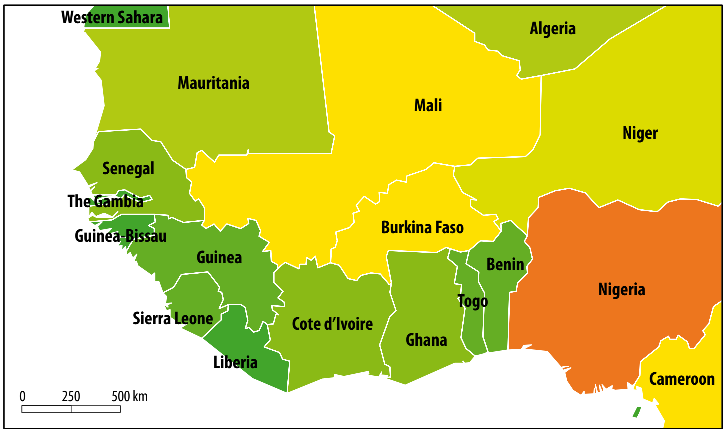
Tabular and map summaries of the global estimates of natural capital losses (Figure 5.20 A through D) illustrate the extent and severity of natural capital depletion globally, by specific natural capital source. We report the total emergy flow, which tends to highlight large countries because natural capital depletion is an extensive process. Mapping based on fraction of total use (%) is represented across all sources of natural capital in Figure 5.21.

Table 5.6 presents information on emergy flows and imputed macroeconomic value based on the global EMR (2.64E12 sej/$ – Sweeney et al, 2007). We

FIGURE 5.16

Maps of total emergy in soil loss by nation.

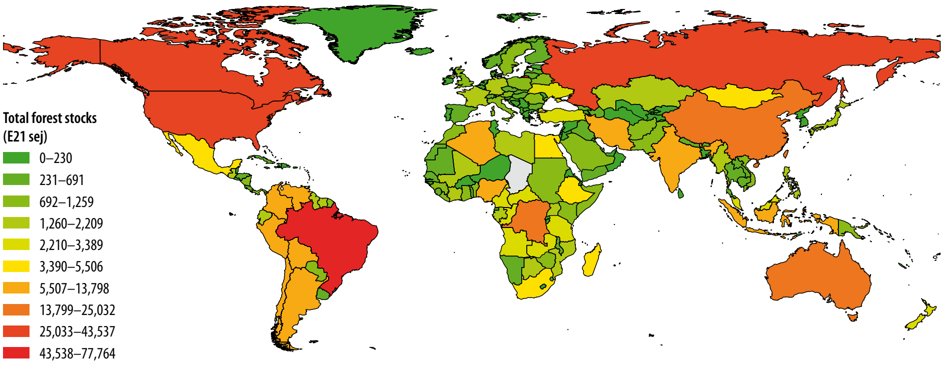


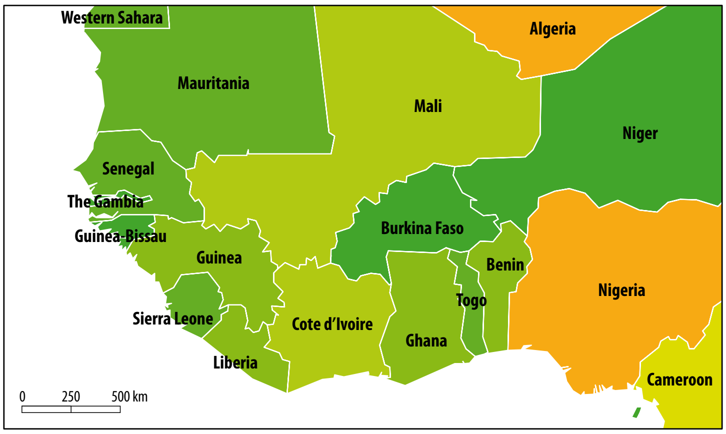


Country	Emergy of soil loss (E20 sej/yr)	Global rank
China	1,478.2	1
Brazil	1,429.9	2
United States	1,158.3	4
Indonesia	634.3	6
Mali	**108.9**	**33**
Kenya	102.4	35
Burkina Faso	**99.1**	**36**
Niger	**82.7**	**38**
Nicaragua	74.5	45
Saudi Arabia	63.2	51
France	62.9	52
Sweden	41.8	63
Mauritania	**39.7**	**65**
Senegal	**27.1**	**81**

FIGURE 5.17

Maps of emergy in the global forest stock in 2000. For comparison, note that the total annual emergy use for the world system is ~4.5E+25 sej/yr and the renewable flows are ~1.5E+25 sej/yr; the emergy value of forest stocks in Brazil (highest globally) is 7.8E+25 sej.

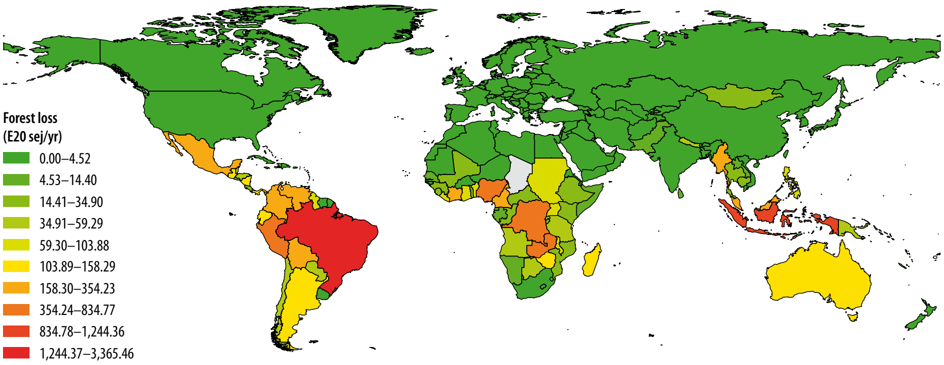


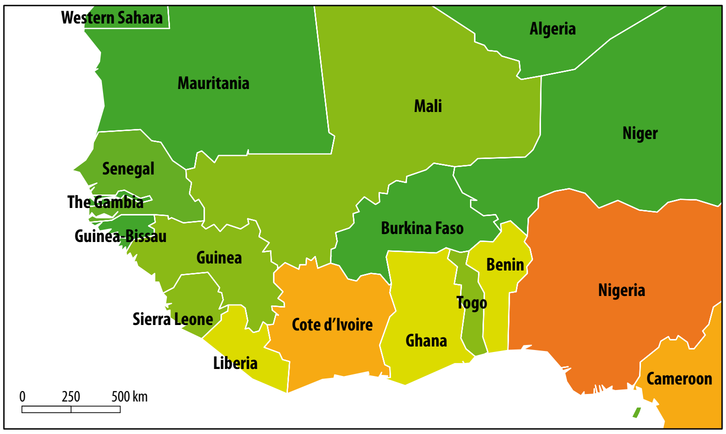


Country	Total forest stocks (E21 sej)	Global rank
Brazil	7.78E+04	1
United States	4.35E+04	2
China	2.50E+04	5
Indonesia	1.09E+04	9
France	2.21E+03	35
Mali	**1.66E+03**	**44**
Kenya	1.20E+03	56
Sweden	1.14E+03	58
Saudi Arabia	1.04E+03	60
Nicaragua	8.52E+02	71
Mauritania	**2.72E+02**	**106**
Senegal	**2.53E+0**	**109**
Niger	**2.23E+02**	**112**
Burkina Faso	**1.93E+02**	**117**

FIGURE 5.18

Non-renewable forest loss in emergy units for 2000.





Country	Forest loss (E20 sej/yr)	Global rank
Brazil	3.37E+23	1
Indonesia	1.24E+23	2
Nicaragua	1.31E+22	19
Kenya	3.11E+21	42
Mali	**2.14E+21**	**52**
Senegal	**9.41E+20**	**61**
Niger	**1.73E+20**	**71**
Burkina Faso	**1.67E+20**	**72**
Mauritania	**4.18E+19**	**80**
United States	0.00E+00	82
China	0.00E+00	82
France	0.00E+00	82
Sweden	0.00E+00	82
Saudi Arabia	0.00E+00	82

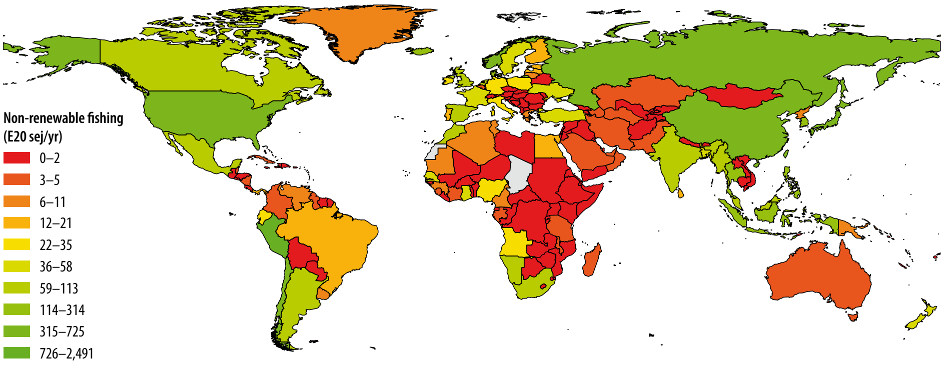
elected to use the global EMR and not the national EMR because we were interested in global costs; imputed macro-economic costs by country can be obtained using appropriate national EMR. Nations in Table 5.6A/B were chosen based on total emergy in each category, biasing towards larger countries.

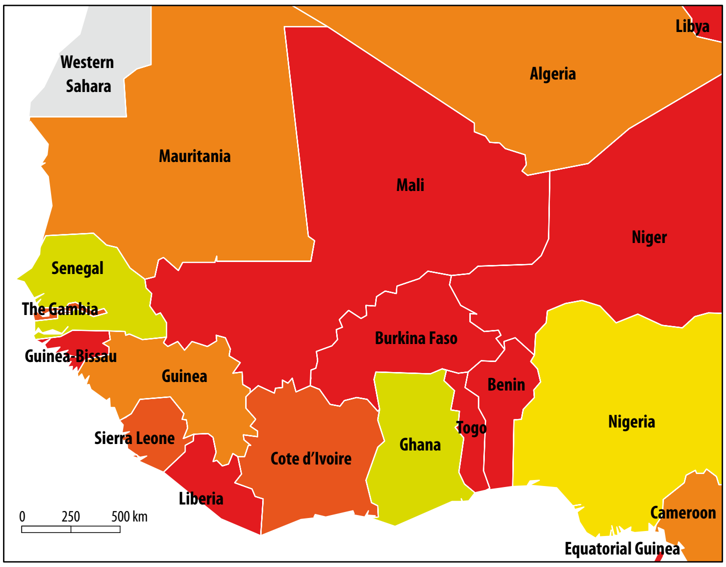
The annual global costs of natural capital depletion, compiled from the cost estimate for full list of 134 nations, are summarized for each category in Figure 5.22. The largest annual cost is soil erosion ($610 billion annually), but all flows are of approximately equal magnitude. The sum of costs, which can be added because flows are independent, is $1.5 trillion annually.

Finally, Figure 5.23 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. In that same range of ESI (0.1–10.0), there are 43 countries with high natural-capital reliance (>5%). They 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%).

FIGURE 5.19

Non-renewable over-fishing losses in emergy units for 2000.





Country	Non-renewable fishing (E20 sej/yr)	Global rank
China	648.51	3
United States	460.77	4
Indonesia	217.71	9
France	57.78	28
Sweden	45.56	30
Senegal	39.39	33
Brazil	15.23	48
Mauritania	**5.85**	**64**
Nicaragua	3.21	80
Saudi Arabia	2.36	90
Kenya	**1.57**	**98**
Mali	**0**	**132**
Niger	**0**	**132**
Burkina Faso	**0**	**132**

TABLE 5.6A

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	1,478.2	1.10%	$5.60E+10	India	2,393.3	4.50%	$9.07E+10
Brazil	1,429.9	2.00%	$5.42E+10	Pakistan	1,585.4	24.10%	$6.01E+10
Russia	1,343.1	1.80%	$5.09E+10	Egypt	749	15.20%	$2.84E+10
USA	1,158.3	0.60%	$4.39E+10	Iran	536.8	3.30%	$2.03E+10
India	1,010.9	1.90%	$3.83E+10	Sudan	295.5	8.30%	$1.12E+10
Indonesia	634.3	2.00%	$2.40E+10	Turkmenistan	257.5	24.60%	$9.75E+09
Mexico	535	0.60%	$2.03E+10	Saudi Arabia	233.1	2.60%	$8.83E+09
Ukraine	357.8	2.20%	$1.36E+10	Syria	186.6	10.00%	$7.07E+09
Nigeria	332.9	6.80%	$1.26E+10	Azerbaijan	135	14.80%	$5.11E+09
Turkey	332.8	2.20%	$1.26E+10	Germany	119.2	0.20%	$4.51E+09
Thailand	330.9	1.80%	$1.25E+10	Spain	108.1	0.20%	$4.10E+09
Sudan	300.1	8.50%	$1.14E+10	Kazakhstan	105.9	1.30%	$4.01E+09
South Africa	299	1.40%	$1.13E+10	Yemen	78.1	9.20%	$2.96E+09
Madagascar	290.5	6.60%	$1.10E+10	Morocco	74.6	2.00%	$2.83E+09
Ethiopia	246.2	7.40%	$9.32E+09	Bulgaria	72.1	2.20%	$2.73E+09
Australia	235.2	0.50%	$8.91E+09	Libya	57.4	3.90%	$2.17E+09
Serbia	220	13.40%	$8.33E+09	Ukraine	36.8	0.20%	$1.40E+09
Vietnam	218.5	5.60%	$8.28E+09	Algeria	34.7	1.10%	$1.31E+09
Mali	**108.9**	**11.7%**	**$2.87E+08**	**Mali**	**0**	**0.0%**	**$0.00E+00**
Burkina Faso	**99.1**	**20.1%**	**$4.40E+08**	**Burkina Faso**	**0**	**0.0%**	**$0.00E+00**
Niger	**82.7**	**14.2%**	**$2.55E+08**	**Niger**	**0**	**0.0%**	**$0.00E+00**
Mauritania	**39.7**	**5.9%**	**$5.29E+07**	**Mauritania**	**0**	**0.0%**	**$0.00E+00**
Senegal	**27.1**	**3.1%**	**$1.38E+08**	**Senegal**	**0**	**0.0%**	**$0.00E+00**

PLACING COSTS OF NATURAL CAPITAL DEPLETION IN CONTEXT

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, depletion of slowly renewable stocks represents a significant and unsustainable source of national wealth.

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 an economic value of lost ecosystem stocks, we can also infer that natural capital depletion represents an annual cost to global society of over $1.5 trillion; as before, this cost estimate is for loss of stocks only, not the total service provided. Moreover, this cost is for 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

TABLE 5.6B

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

	Overfishing				Deforestation		
Country	Emergy (E20 sej)	%U	Costs (Em$)	Country	Emergy (E20 sej)	%U	Costs (Em$)
China	3,754.6	2.90%	$3.16E+10	Brazil	3,326	4.70%	$1.26E+11
Peru	2,328.1	15.60%	$8.30E+09	Indonesia	1,229.8	4.00%	$4.66E+10
Japan	1,119	1.60%	$7.50E+10	Zambia	610	15.50%	$2.31E+10
USA	1,094.9	0.60%	$5.66E+10	Nigeria	504.7	10.20%	$1.91E+10
Chile	993.1	8.90%	$6.63E+09	Peru	454.2	3.10%	$1.72E+10
Indonesia	911.7	2.90%	$4.42E+09	Venezuela	350.1	3.40%	$1.33E+10
Russia	882.6	1.20%	$3.09E+09	Malaysia	334.9	2.10%	$1.27E+10
$India	813.9	1.50%	$7.14E+09	Colombia	256.7	2.60%	$9.72E+09
T$hailand	655.7	3.60%	$4.39E+09	Cote d'Ivoire	237.4	15.60%	$8.99E+09
Norway	633.7	9.30%	$1.55E+10	Mexico	234.8	0.30%	$8.90E+09
Philippines	414.8	5.10%	$3.91E+09	Bolivia	203.1	5.50%	$7.69E+09
South Korea	401.7	1.00%	$4.46E+09	Cameroon	200.4	8.80%	$7.59E+09
Denmark	335.1	7.00%	$1.10E+10	Madagascar	156.4	3.50%	$5.93E+09
Vietnam	316.8	8.10%	$2.53E+09	Ecuador	142.6	4.60%	$5.40E+09
Mexico	295	0.30%	$1.87E+09	Guatemala	138.1	7.00%	$5.23E+09
Spain	231.6	0.50%	$2.86E+09	Argentina	133.6	0.50%	$5.06E+09
Canada	227.8	0.40%	$2.71E+09	Nicaragua	129.8	12.50%	$4.92E+09
Argentina	200.1	0.70%	$1.95E+09	Zimbabwe	123.5	1.00%	$4.68E+09
UK	163.3	0.30%	$4.31E+09	Panama	115.4	7.10%	$4.37E+09
Senegal	**87.85**	**10.20%**	**$4.46E+08**	Uganda	102.2	11.40%	$3.87E+09
Sweden	73.9	0.90%	$2.09E+09	**Mali**	**21.2**	**2.30%**	**$5.57E+07**
Mali	**24**	**0.026%**	**$6.32E+07**	**Senegal**	**9.3**	**1.10%**	**$4.73E+07**
Mauritania	**17.66**	**0.026%**	**$2.35E+07**	**Burkina Faso**	**1.7**	**0.30%**	**$7.34E+06**
Niger	**3.55**	**0.006%**	**$1.09E+07**	**Niger**	**1.7**	**0.30%**	**$5.27E+06**
Burkina Faso	**1.86**	**0.004%**	**$8.24E+06**	**Mauritania**	**0.4**	**0.10%**	**$5.51E+05**

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 maps employed in our UEV estimation procedure, we estimate the total value of global stocks of soil organic matter (across the 134 nations of NEAD) to be 2.4E27 sej, which corresponds to an imputed economic value of $904 trillion (for 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

FIGURE 5.20

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

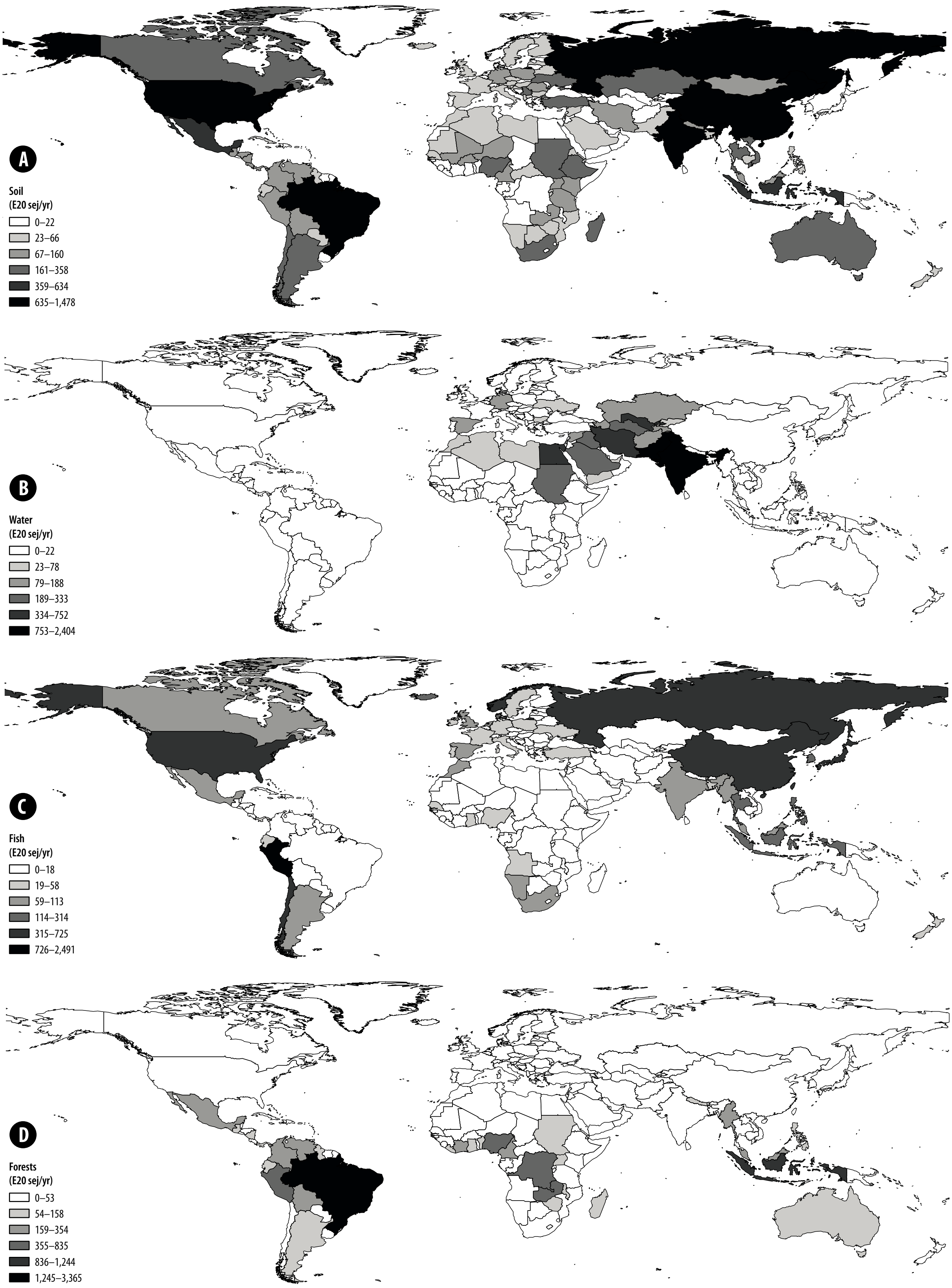
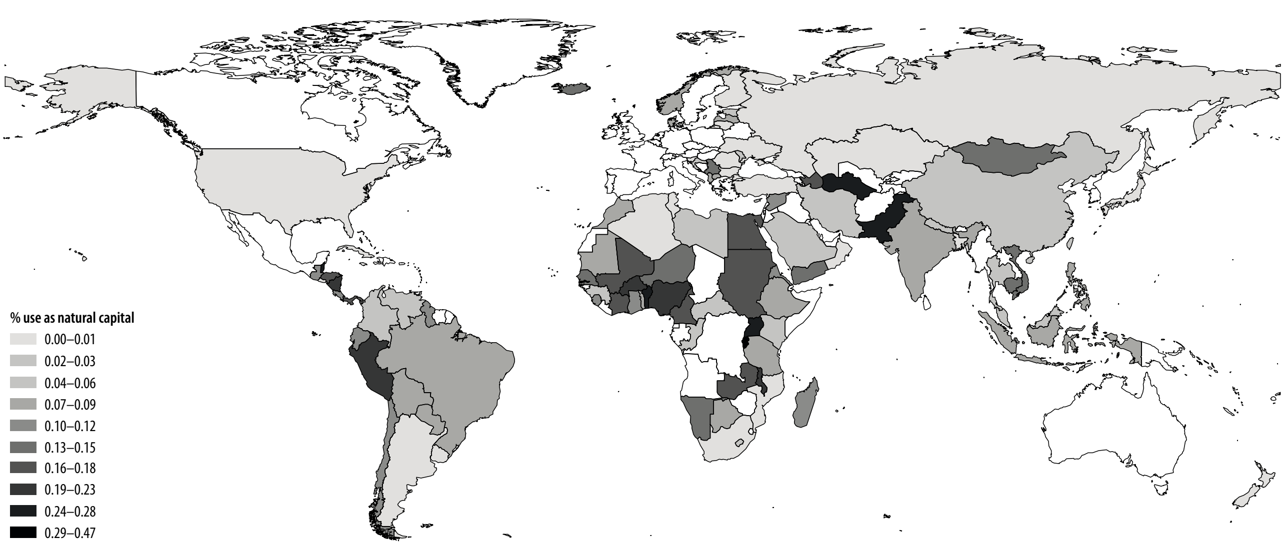


FIGURE 5.21

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



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 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 endeavoured 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.

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 is also 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 capacities that are 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

FIGURE 5.22

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

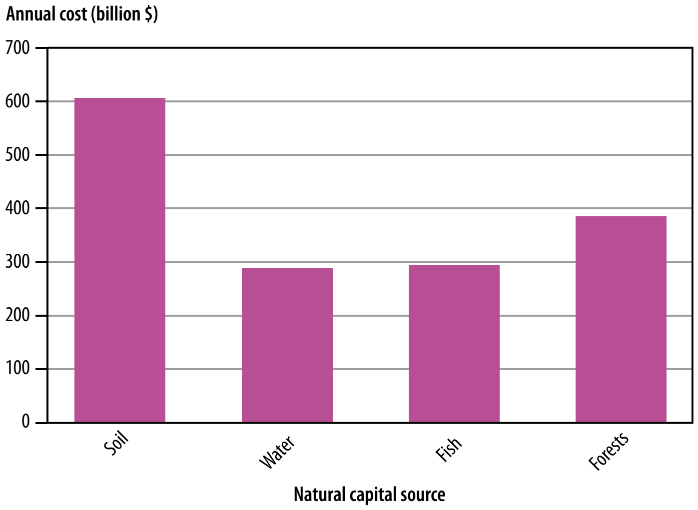


FIGURE 5.23

National-scale natural capital depletion as A) % of total use and B) total emergy flow vs. the Emergy Sustainability Index (ESI).

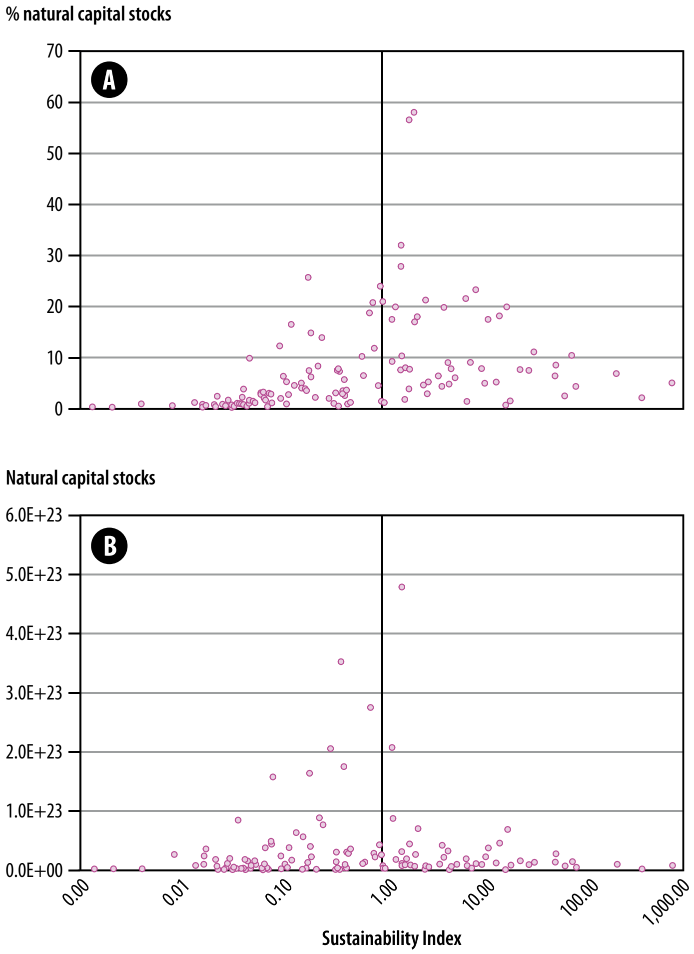
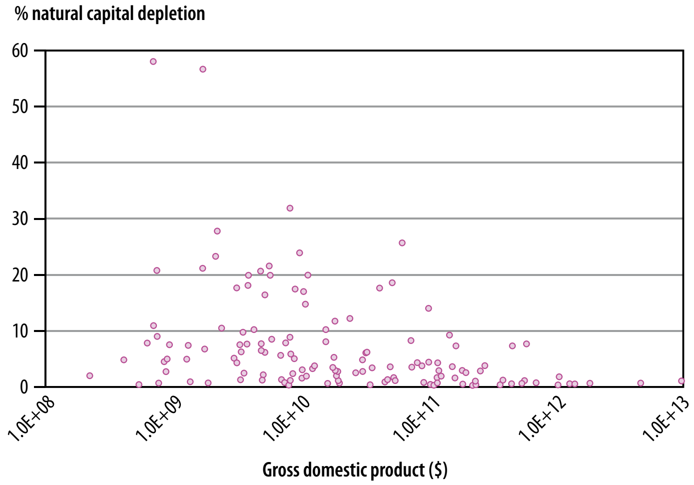


FIGURE 5.24

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



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 investment in environmental protections with increasing social wealth, and also export of environmental destruction outside of national boundaries as countries develop increasingly stringent 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 Figure 5.24, which shows the relationship between GDP and natural capital depletion. Both demonstrate that wealthy countries have largely weaned themselves from a reliance on depleting natural capital (possibly in favour 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 5.24).

CHAPTER 6

Environmental accounting of international trade and debt

ENVIRONMENTAL TRADE EQUITY

Increasing global integration of economic production has clear advantages; via trade the means of production are decentralized and made efficient via comparative advantage. While trade is clearly capable of mutually increasing wealth for trading partners, economies produce services and commodities under vastly different conditions. Given the growing interest in global sustainability, it is reasonable to ask whether these different conditions lead to variable accrual of negative externalities between trading partners. More specifically, does the equitability of finances between trading partners belie inequities in environmental costs. This question is uniquely suited to environmental accounting because the singular numeraire afforded by emergy can be compared across trading partners in much the same way that financial flows can. The principal question that this chapter focuses on is whether trading partners with equitable money flows also exhibit equitable flows of emergy.

Our principal tool in an evaluation of trade equity amongst trading partners, or more commonly a nation trading on the global marketplace, is the Emergy Money Ratio (EMR). This index describes the broad association between the environmental resource basis of a nation (measured in emergy) and the domestic economic production (gross domestic product, usually reported in US$). The primary use of the EMR in environmental accounting is to impute the macroeconomic value of environmental work. As has been presented previously, money pays only for human service, so the work of nature is free. However, to conclude that environmental services and stocks do not have value leads inexorably towards resource misuse. Emergy can account for value across market and non-market commodities, but offers that quantification in units that are broadly unfamiliar to policy makers (i.e., solar emjoules). To provide a more familiar scale for considerations of value, the EMR can facilitate placement of emergy values into a dollar-equivalent scale called emergy$. We reiterate that this is principally an interpretive aid useful for understanding the value of non-market goods and services. In a previous chapter, this was used to place the flow of depleted natural capital (e.g., soil erosion, deforestation) into units that underscore the magnitude of such negative externalities.

An additional insight made possible with EMR is the environmental resource equity of international transactions. The schematic of trade shown in Figure 6.1 identifies the structural issues present when nations trade. In this case, the nation of Niger is shown trading with the global economy; the specific commodities traded are aggregated into total resource flows imported and exported. Naturally, Niger trades particular commodities with particular countries, but for illustrative purposes we simplify the situation. For each unit of equivalent currency (US$) circulating in Niger, nearly 3.25E13 sej are traded. Within the global economy as a whole, the emergy transacted for a single dollar is

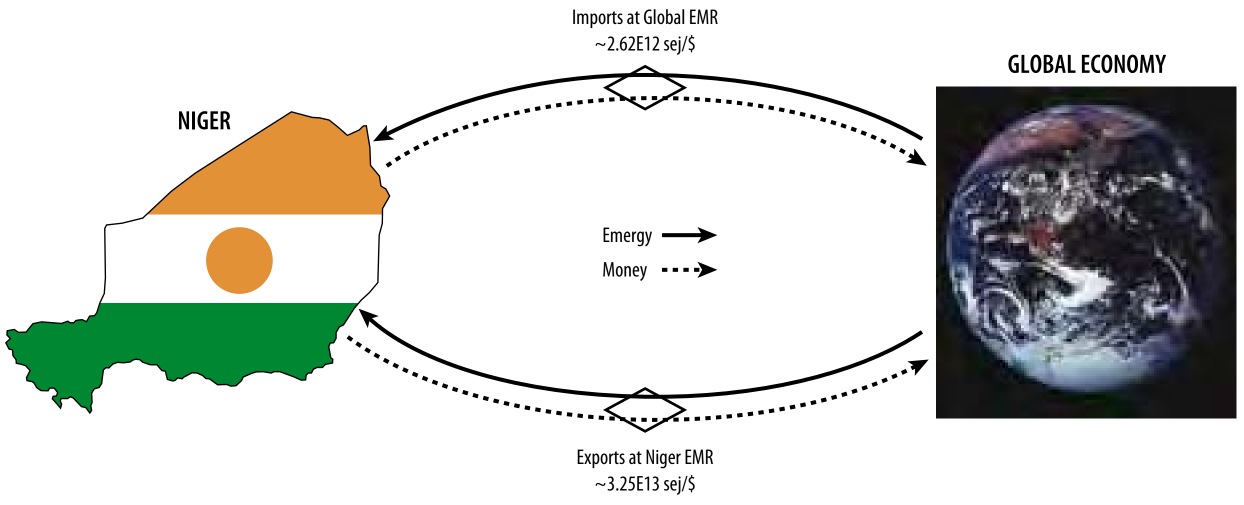
TABLE 6.1

Trade equity matrix for select nations. Equity is measured for column nations trading with row nations (i.e., the US enjoys a structural trade benefit in trade with all other selected nations).

	United States	France	Sweden	Saudi Arabia	Brazil	China	**Senegal**	Indonesia	**Burkina Faso**	Nicaragua	**Niger**	**Mali**	Kenya	**Mauritania**
USA	-	0.66	0.55	0.40	0.16	0.16	**0.10**	0.09	**0.09**	0.07	**0.06**	**0.05**	0.04	**0.03**
France	1.51	-	0.83	0.60	0.25	0.25	**0.15**	0.14	**0.13**	0.11	**0.09**	**0.08**	0.06	**0.04**
Sweden	1.83	1.21	-	0.73	0.30	0.30	**0.18**	0.17	**0.16**	0.14	**0.11**	**0.09**	0.07	**0.05**
Saudi Arabia	2.50	1.65	1.37	-	0.41	0.41	**0.25**	0.23	**0.21**	0.18	**0.15**	**0.13**	0.10	**0.06**
Brazil	6.08	4.03	3.32	2.43	-	0.99	**0.60**	0.57	**0.52**	0.45	**0.36**	**0.31**	0.25	**0.16**
China	6.15	4.07	3.36	2.46	1.01	-	**0.60**	0.58	**0.53**	0.45	**0.37**	**0.31**	0.25	**0.16**
Senegal	**10.17**	**6.74**	**5.56**	**4.08**	**1.67**	**1.65**	**-**	**0.95**	**0.87**	**0.75**	**0.61**	**0.52**	**0.41**	**0.26**
Indonesia	10.67	7.07	5.83	4.27	1.75	1.73	**1.05**	-	**0.92**	0.79	**0.64**	**0.54**	0.43	**0.27**
Burkina Faso	**11.64**	**7.71**	**6.37**	**4.66**	**1.92**	**1.89**	**1.14**	**1.09**	**-**	**0.86**	**0.69**	**0.59**	**0.47**	**0.30**
Nicaragua	13.53	8.96	7.40	5.42	2.23	2.20	**1.33**	1.27	**1.16**	-	**0.81**	**0.69**	0.55	**0.35**
Niger	**16.77**	**11.11**	**9.17**	**6.72**	**2.76**	**2.73**	**1.65**	**1.57**	**1.44**	**1.24**	**-**	**0.85**	**0.68**	**0.43**
Mali	**19.63**	**13.00**	**10.74**	**7.87**	**3.23**	**3.19**	**1.93**	**1.84**	**1.69**	**1.45**	**1.17**	**-**	**0.80**	**0.51**
Kenya	24.54	16.26	13.42	9.83	4.04	3.99	**2.41**	2.30	**2.11**	1.81	**1.46**	**1.25**	-	**0.63**
Mauritania	**38.79**	**25.69**	**21.21**	**15.54**	**6.38**	**6.31**	**3.81**	**3.64**	**3.33**	**2.87**	**2.31**	**1.98**	**1.58**	**-**

FIGURE 6.1

Schematic of international trade equity showing aggregated parameters of trade between Niger and global economy. The Emergy Money Ratio (EMR) uncovers structural inequities that make this trading relationship disadvantageous to Niger.



2.62E12 sej. These values differ by over an order of magnitude (EMR_{Niger} ~10 x EMR_{global}).

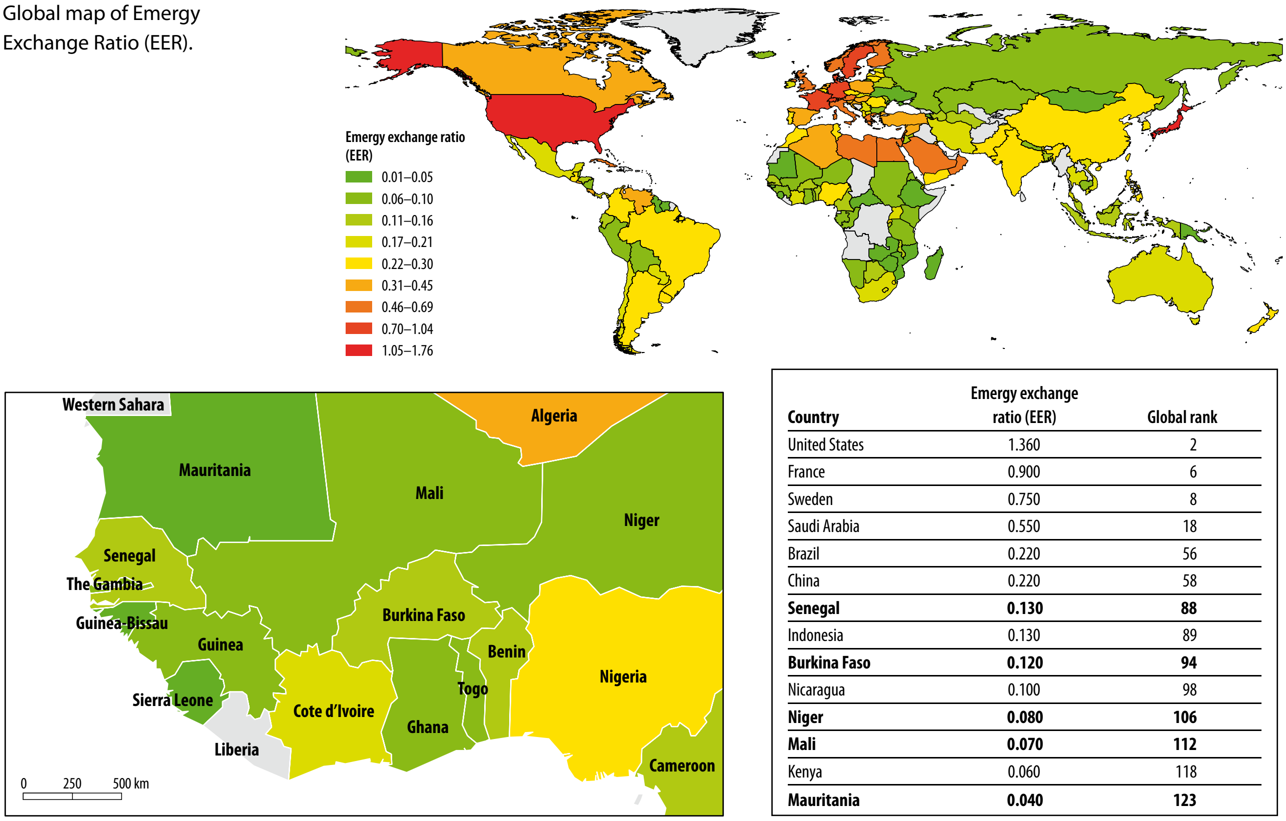
When Niger trades with the global economy, it exchanges internal financial resources for physical resources, receiving 2.62E12 sej per dollar. Given money flows that are balanced (i.e. imports ≈ exports), that same currency is used by the global economy to acquire physical resources from Niger. However, for this transaction, over 10 times more emergy is removed from Niger. In short, Niger is structurally disadvantaged when trading with the global economy because the resources necessary to generate revenue are 10-fold higher than the resources it receives in return.

A metric measuring this inequity is called the Emergy Exchange Ratio (EER), which compares the resource purchasing power of a standard unit of currency between two nations. The EER is the ratio of EMR values; for example the EER value for Niger trading with the global economy is 0.08 (EMR_{globe}/EMR_{Niger}). Countries with high EMR values (typical of developing nations – Figure 6.2) trading with low EMR countries (developed nations) have low EER values, indicating resource inequity. The EER can be computed as a global average (~2.6E+12 sej/$) or between two particular trading partners. Among the most disadvantaged nations in this regard are those in sub-Saharan Africa; the United States, Switzerland and Japan are among the main beneficiaries of this structural trade inequity.

One intriguing implication of the map of EER (Figure 6.2) is that a far greater number of countries, and indeed citizens, fall below the 1:1 trade equity threshold than above it. The countries with the highest EER values are Japan and USA, collectively responsible for roughly half of world economic product (~$15 trillion annually). However, it is worth pointing out that nations do not trade with the global market, they trade bilaterally or as part of trading blocs. As such, another meaningful, though more disaggregated, measure of trade equity is shown in a trade equity matrix wherein the cells of the matrix are the EER between the row and column countries (Table 6.1). By way of example for why this is an important refinement, we consider the situation in Mali, where the EER_{global} is 0.07. Based on this implied inequity,

FIGURE 6.2

Global map of Emergy Exchange Ratio (EER).



Country	Emergy exchange ratio (EER)	Global rank
United States	1.360	2
France	0.900	6
Sweden	0.750	8
Saudi Arabia	0.550	18
Brazil	0.220	56
China	0.220	58
Senegal	**0.130**	**88**
Indonesia	0.130	89
Burkina Faso	**0.120**	**94**
Nicaragua	0.100	98
Niger	**0.080**	**106**
Mali	**0.070**	**112**
Kenya	0.060	118
Mauritania	**0.040**	**123**

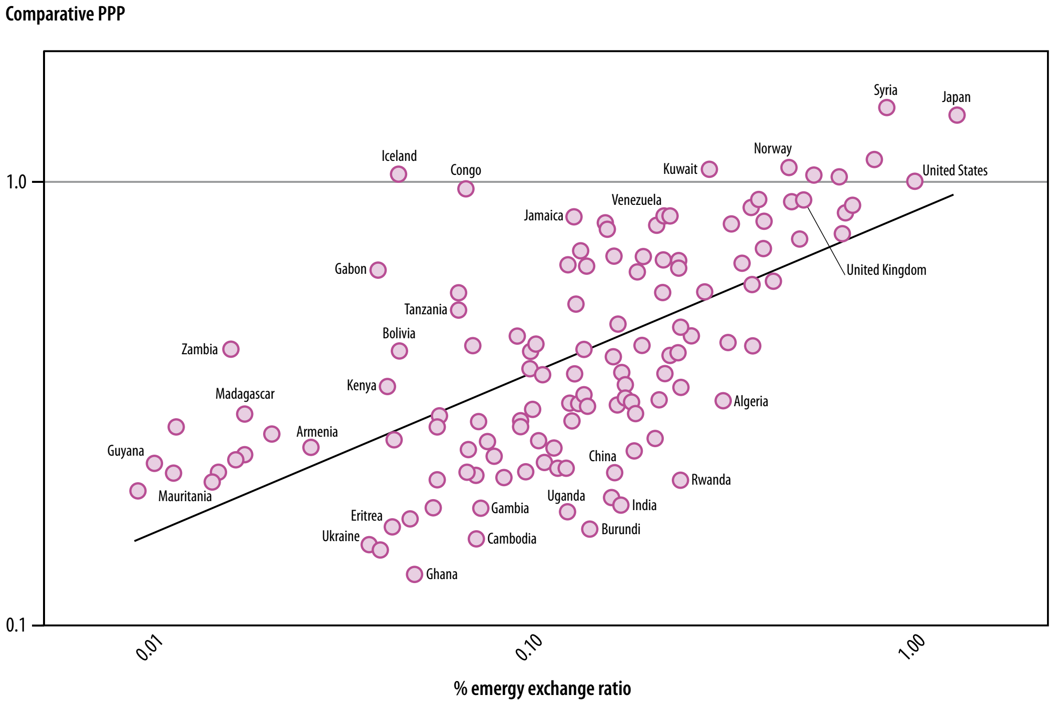
exported emergy should greatly exceed imported emergy. Comparing imports and exports reveals, perhaps surprisingly, that Mali's international trade is nearly in balance. The reason is that most of Mali's trade is amongst ECOWAS (a West African trading bloc) nations where Mali is far less disadvantaged. Moreover, particular commodities exchanged are not "average" commodities in the sense of conforming to the broad national EMR. Nations may choose to export goods and services with low EMR rather than unprocessed goods that generally have high EMR. As such, use of EER for policy decisions is not warranted; it is, however, illustrative of the prevailing structures embedded, perhaps unwittingly, in the world trade system.

The structural conditions that lead to inequity in trade (when trade is based on monetary balance) are frequently assessed in economics using a measure called Purchasing Power Parity (PPP). The financial resources necessary to acquire a standard basket of goods is compared amongst nations, and the typical result is that the same resources can be purchased for less capital in developing nations than in developed nations. The ratio of PPP for one country to the PPP for another is termed the comparative PPP. Similarities in this conceptual framework led to the hypothesis that the comparative PPP for a given nation *vis-à-vis* the USA should correlate with the EER value, again computed for nations in comparison with the USA. The strong association between the values (Figure 6.3) suggests that variability in PPP is at least in part due the comparative resource basis of money among nations.

As discussed above, trade does not take place between nations and the global market, but between particular nations. Countries are in a position to decide to trade with nations with relatively similar EMR values, minimizing any structural inequities; similarly, nations may decided to export only certain products which reduce any trade equity gap. For example, nations that export primarily raw resources (fuels, agricultural commodities, mined materials) have high trade inequity values (exports/imports – Figure 6.4). Other nations, even those with high EMR values that would ordinarily lead to inequitable trade, may manage trade (partners and commodities)

FIGURE 6.3

Comparison of the Emergy Exchange Ratio (EER), which quantifies resource inequity for trade between nations, with national PPP values. Both indices are unitless, and both measure the comparative buying power of currency within different national economies, with reference to the US dollar.



in a manner to minimize this effect; Brown et al (2003) explore this for the nations at the southern tip of South America (the MERCOSUR trading bloc), and the fact that similar trading partnerships have emerged around the world may be, in part, evidence that the trade inequities embedded in global trade are observable even in the short term. In general, however, less developed countries tend to be resource exporters, while highly developed nations tend to be resource importers (Figure 6.4), which serves to widen the gap in resource endowment, despite the myriad benefits that international trade confers. One implication is that trade agreements should be made more consistent with the real wealth that traded commodities represent, and compensation to resource-exporting countries be made accurately to reflect the value of the exported goods.

INTERNATIONAL DEBT

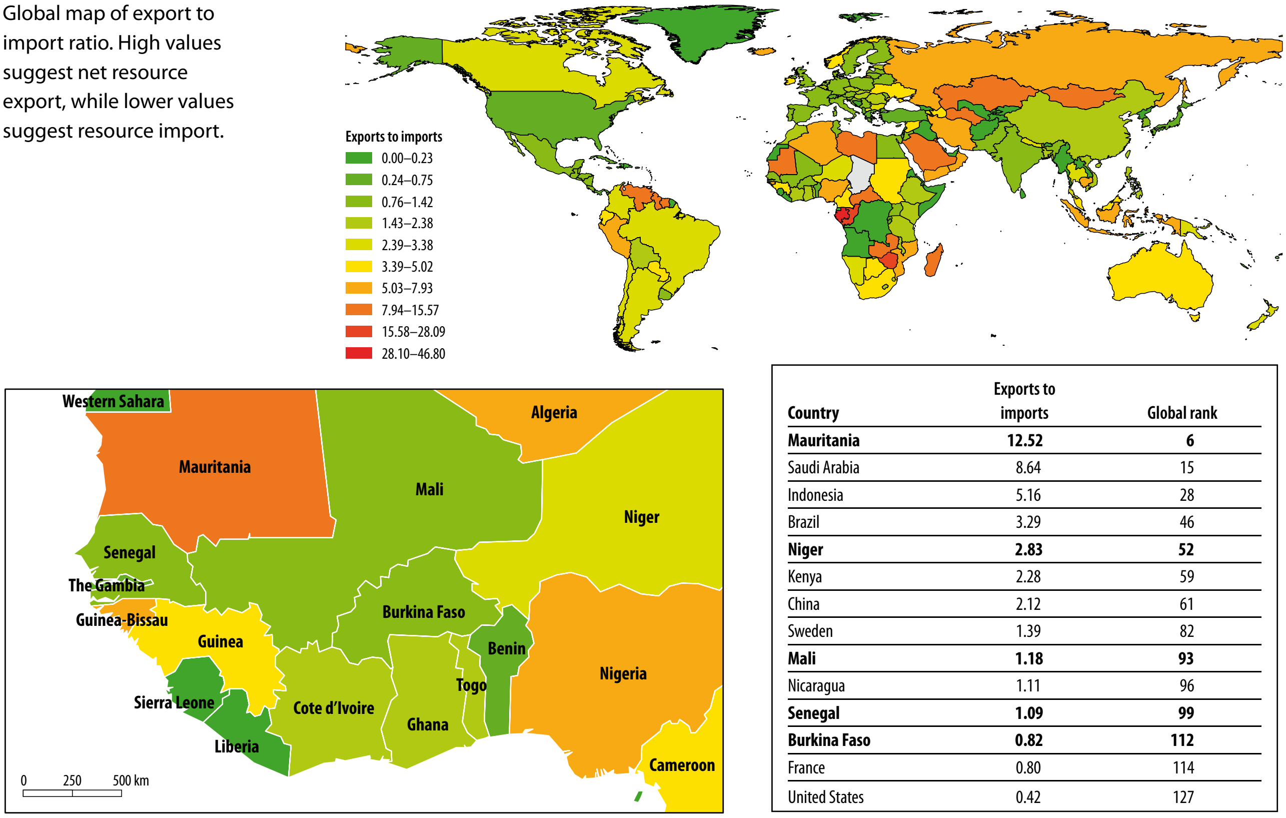
The concept of trade equity (EER) can be applied to international loans. Every dollar Niger receives in international loans from global lenders represents purchasing power for Niger in the global market. Where loans are used to purchase goods and services, the buying power that Niger receives is equivalent to 2.62E12 sej of environmental work (Figure 6.1).

In order to service international loans, Niger exports local resources (renewable and non-renewable) to generate international revenue. As with trade equity, the process of generating a unit of revenue in dollars requires that consumers from the global market purchase Niger's products, which are sold at the Niger EMR of 3.25E13 sej/$. Therefore, each unit of currency borrowed requires approximately 12 times the environmental resource be extracted from Niger for repayment. Loan interest serves only to exacerbate the problem.

The situation is depicted schematically in Figure 6.5; starting with some initial debt, a nation makes payments to creditors to reduce that debt. The influx of funds from incurring the debt is used to purchase goods and services from the global market, and the mechanism of generating currency to make payments is the export of resources (emergy). For nations with low EER (i.e., structural disadvantages when trading in money is balanced), servicing the

FIGURE 6.4

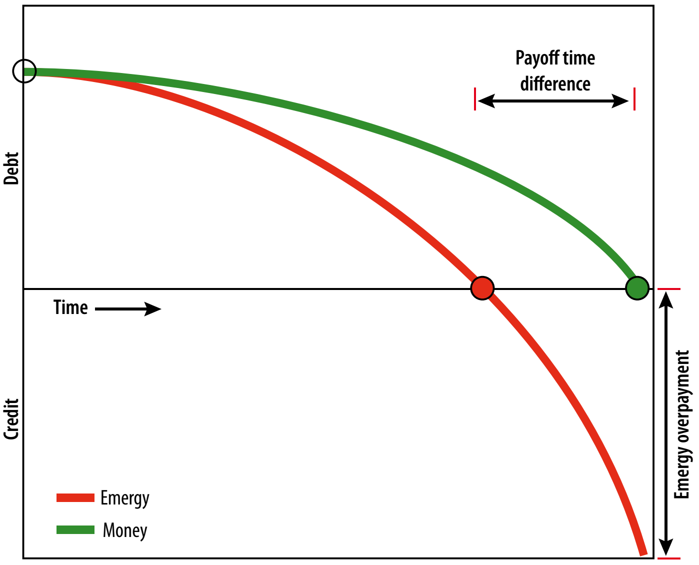
Global map of export to import ratio. High values suggest net resource export, while lower values suggest resource import.



Country	Exports to imports	Global rank
Mauritania	**12.52**	**6**
Saudi Arabia	8.64	15
Indonesia	5.16	28
Brazil	3.29	46
Niger	**2.83**	**52**
Kenya	2.28	59
China	2.12	61
Sweden	1.39	82
Mali	**1.18**	**93**
Nicaragua	1.11	96
Senegal	**1.09**	**99**
Burkina Faso	**0.82**	**112**
France	0.80	114
United States	0.42	127

FIGURE 6.5

Schematic of debt payments in money and emergy. Initial debt is paid off in money payments that represent real wealth (emergy). Where a structural inequity in the Emergy Exchange Ratio (EER) exists between payer and payee, the date at which debt is repaid in emergy can be different from the date for financial repayment. Debt-repaying nations faced with this structural inequity may become emergy creditors despite remaining in financial debt.



debt requires appropriation of local emergy. Since the money represents greatly different quantities of emergy when used to purchase goods within and outside the nation, the effect is that, over time, the emergy in debt repayments can exceed the emergy in the original loan. In some cases where EER is particularly disadvantageous to the borrower, the nation may end up becoming an emergy creditor despite needing to continue to service high levels of monetary debt.

Recently, there have significant efforts to forgive much of Africa's debt. As countries struggle to make loan service payments and simultaneously fall further behind global development, there are important ethical reasons to consider this scenario, even from a strictly monetary perspective. However, when the loans and debt service are put in units of environmental work, the need for debt relief becomes greatly amplified.

We offer as an example the international debt and loan service payments from five West African nations: Mali, Senegal, Niger, Burkina Faso and

FIGURE 6.6

Official debt (in US$) and emergy debt (also in US$ adjusted by EMR). Official US dollar long-term external debt (LDOD) data from the World Bank (GDF Online, 2005).

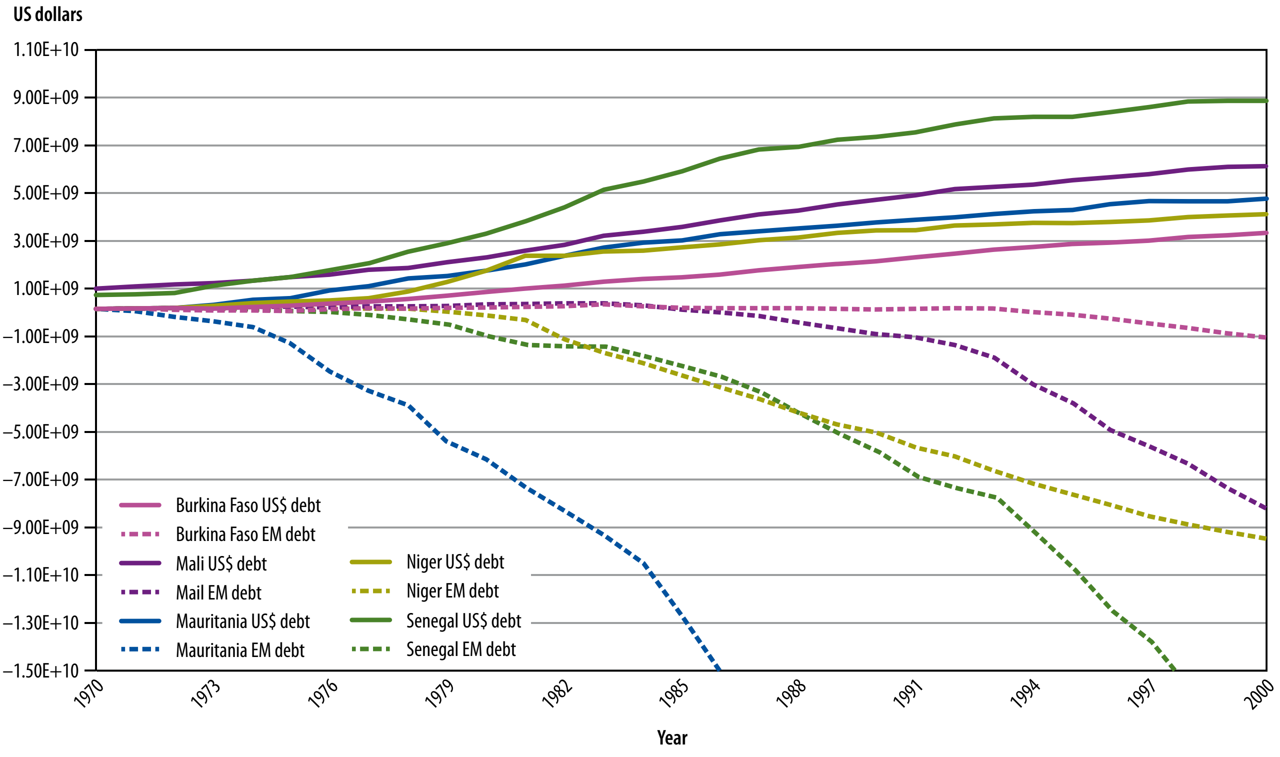


TABLE 6.2

Summary of long-term financial debts, emergy indebtedness and year of emergy repayment for five West African nations.

Nation	2000 official debt outstanding balance (World Bank 2005)	2000 EMdebt balance	Year of repayment for EMdebt
Burkina Faso	-3.31E+09	1.11E+09	1994
Mali	-6.16E+09	8.22E+09	1986
Mauritania	-4.77E+09	7.65E+10	1971
Niger	-4.10E+09	9.46E+09	1979
Senegal	-8.86E+09	1.83E+10	1975

Mauritania. Each has substantial international indebtedness (Table 6.2). In order to generate international currency to make their debt payments, they export large quantities of local environmental capital, in the form of mined resources, agricultural commodities or other raw goods.

To evaluate the current indebtedness of each focal nation, we compiled information on current debt and repayments over 30 years (starting in 1970). Each year, the EMR was computed to put debt service payments in emergy units; similarly emergy values of the original loans were evaluated using the global average EMR for the disbursement year. The balance of payments in money and emergy is summarized in Figure 6.6; when the debt repayments are compared in emergy units, all five nations have repaid their loans, and have become emergy creditors. This is most pronounced for Mauritania and Senegal, who officially owe $4.8 and $8.9 billion, respectively, but have over paid by $77 and $18 billion respectively if flows are examined in emergy units. This conclusion supports recent debt relief efforts for these nations; the general framework for assessing inequity is expected to yield the same conclusion for all of sub-Saharan Africa. Ferreyra and Brown (2006) reach an identical conclusion for Argentina.

CHAPTER 7

The resource basis of human development and system sustainability

Social equality, economic stability, environmental conservation and global carrying capacity are all part of the broader concept of sustainable development (Munasinghe and McNeely, 1995), and have become familiar issues in contemporary society. Researchers monitor various indicators of ecological, economic and social condition in order to compare well-being and progress towards sustainability between nations. Examples of these include international debt, Gross Domestic Product (GDP) and carbon dioxide emission rates, as well as popular aggregated indices such as Yale's Environmental Sustainability Index (YESI) and the United Nations Development Programme's Human Development Index (HDI). However, there is no single index that serves as a universally accepted measure of sustainability (Kaufmann and Cleveland, 1995; Hanley, 2000). Indicators such as GDP are criticized for being one-dimensional and therefore inadequate predictors of total well-being (Steer and Lutz, 1993), though Ko and Hall (2003) report a particularly strong biophysical basis for GDP inferred from correlations with fossil fuel consumption. Likewise, many researchers are unsatisfied by popular aggregated indices. The YESI is criticized for its subjective methodology and for combining too many disparate variables (The Ecologist, 2001; Morse, 2004; Morse and Frasier, 2005), masking more relationships than it reveals. HDI is criticized for its inclusion of GDP as a component of well-being and for not including a measure of happiness or sustainability (Van Den Berg, 2002; Morse, 2004; for suggested modifications see Ivanova et al, 1998; Noorbakhsh, 1998; Anad and Sen, 2000; Lind, 2004; Morse, 2003). Despite advances in sustainability and well-being research, there is a great need to quantify links between environmental sustainability, human well-being, and non-economic resource flows. We offer the caveat to our analyses that they rely heavily on HDI as a useful measure of human condition; insofar as that metric is flawed, our inferences will be equally flawed. We anticipate that a more effective integration of the three pillars of sustainability (economy, society, environment) will eventually be accomplished with better measures of social well-being. Our analyses here simply reflect an attempt to cast a wide net around the sustainability question, such that there is some explicit recognition that the three pillars are not interchangeable. Emergy is most well suited for environmental and economic assessment, and attempts to link the social elements of sustainability are only as effective as the accepted measures of those elements.

This chapter in the report addresses these issues using environmental accounting (EA), also known as emergy synthesis. Environmental contributions to economies or individuals are not adequately captured in monetary terms (Odum, 1996). By expressing both economic and environmental flows in common units, environmental accounting permits meaningful comparison of resource requirements for national economic processes, and consequently a means to monitor and compare sustainability. Ecosystem services at the national level were evaluated using environmental accounting and synthesized into indices of sustainability and environmental contributions in the National Environmental Accounting Database (NEAD, previously described). To better understand indices of well-being which are commonly used by researchers and their relationship to quantitative measures of resource use, several indices of well-being were compared with each other and with these EA indices for 134 nations.

EMERGY INDICES

National-level emergy flows and aggregate indices were calculated for 134 nations for the year 2000 within the NEAD. Due to the large number of emergy indices, correlations were calculated for normalized emergy indices to eliminate redundancy. If two indices were correlated with an R of 0.8 or above (significant at .01 level, 2-tailed), the one less commonly used in interpretation or less insightful for national comparisons was dropped from the analysis. Exceptions were made for emergy indices which, although highly correlated with other indices, have individual importance in interpreting results of an emergy analysis. Additional methodological details can be found in King et al (2007).

Well-being and sustainability indices

Composite indices of human, economic and environmental sustainability, as well as many social, economic, governmental and environmental indicators which are either common in the literature or are currently receiving much global media attention (Flanders and Ross-Larson, 2002; Cheru, 2002; Poku, 2002; York et al, 2003) were compared with each other and emergy indices. The comparison of well-being and sustainability indicators was carried out on seven overall groups of indicators (see Table 7.1), which were selected as follows.

Group 1: Aggregate indices, so termed because they are each composed of several metrics, were chosen because they have become popular in the literature for describing and comparing nations. These include the ecological footprint (EF), Yale Environmental Sustainability Index (YESI), the United Nations Development Programme's Human Development Index (HDI), and Well-being Index (WI), Ecosystem Well-being Index (EWI) and Human Well-being Index (HWI). Definitions and sources for these indices can be found in Appendix E. Some indices, such as the Genuine Progress Indicator (GPI) and Gross National Happiness (GNH) could not be analyzed because they have not been computed for a sufficient number of countries.

Groups 2–5: To select a manageable set of society, economy, government and environment indicators from a population of over 1,200 indicators with global data coverage, a process of eliminating obscure or redundant indicators was conducted. First, roughly 50 indicators were selected based on their frequency of citation in the literature and the degree of global media attention they are receiving (Flanders and Ross-Larson, 2002; Cheru, 2002; Poku, 2002; York et al, 2003). Then this first group of 50 indicators was correlated (Pearson method) against the entire population of 1,200 indicators. Any indicator from the population that was not correlated with the original 50 with an R of 0.8 (significant at .01 level, 2-tailed) or above was also selected. All analyses were performed in Statistica v. 7.0 (StatSoft, Inc., Tulsa, OK)

Groups 6 and 7: Metrics within the YESI and HDI were selected for evaluation in order to clarify apparent discrepancies between sustainability indices and explore criticisms of these indices. Most importantly, we note that neither of these indices has as its primary objective the evaluation of biophysical or resource sustainability. As such, comparison between emergy metrics and these may be muted by attention to other aspects of sustainability. We therefore decompose the metrics into their constituent parts to determine if facets of their aggregate value are more closely coincident with environmental accounting metrics.

A complete list of indices, their definitions and sources can be found in Appendix E.. This final list was then organized into the thematic groups and sub-groups found in Table 7.1 to simplify interpretation of the analysis. To prepare them for analysis, all indices and indicators were evaluated for normality and transformed where appropriate.

To elucidate overlap and inconsistencies between the various indices and to provide insight regarding which countries are providing for the well-being of their population and environment, Pearson correlations between all indicators and emergy indices were conducted.

A regression analysis was performed to identify those countries whose human well-being, as measured by the HDI, was higher or lower than would be predicted based on their non-renewable emergy use per capita. A new indicator of total well-being was derived, based on the premise that environmental sustainability can be defined as minimizing the percentage of resource use that comes from non-renewable resources, and human sustainability can be defined as maximizing human well-being as measured by the HDI. The formula for this new indicator, the emergy-based Total System Well-being Index (TSWI) is

$$\mathbf{TSWI_i = HDI_i * \%R_i}$$

TABLE 7.1

Indicator groups.

Group #	Group	Sub-groups	# of indicators
1	Aggregate indices		6
2	Social well-being indicators	Quality of life and health, education, labour, demographics	20
3	Govt. & political indicators	Economic freedom, civil freedom, quality of governance, risk to finance & investment	24
4	Economic indicators	Income, use of money, military, tourism, technology, debt, aid	18
5	Environmental indicators	Land use, fertilizer use, deforestation, water quality, air quality, energy	13
6	YESI component indices		26
7	HDI component indices		3

TABLE 7.2

Correlation matrix of aggregate indices.

Index	EF	YESI	HDI	WI	HWI	EWI
Ecological footprint (EF)	1					
Yale Environmental Sustainability Index (YESI)	0.408(**)	1				
Human Development Index (HDI)	0.855(**)	0.417(**)	1			
Wellbeing Index (WI)	0.630(**)	0.723(**)	0.644(**)	1		
Human Wellbeing Index (HWI)	0.880(**)	0.519(**)	0.931(**)	0.795(**)	1	
Ecosystem Wellbeing Index (EWI)	-0.600(**)	0.140	-0.645(**)	0.067	-0.552(**)	1

** Correlation is significant at 0.01 level. * Correlation is significant at 0.05 level

TABLE 7.3

Correlation matrix of aggregate indices and key emergy indices.

	Ecological footprint	YESI	HDI	WI	HWI	EWI
% Renewable	-0.567(**)	0.089	-0.612(**)	-0.163	-0.530(**)	0.648(**)
Use per area	0.560(**)	0.081	0.689(**)	0.426(**)	0.712(**)	-0.586(**)
Use per capita	0.768(**)	0.539(**)	0.748(**)	0.676(**)	0.768(**)	-0.333(**)
Non-renewable use per capita	0.554(**)	0.220(*)	0.593(**)	0.331(**)	0.511(**)	-0.387(**)
Emergy Investment Ratio	0.555(**)	0.124	0.577(**)	0.360(**)	0.585(**)	-0.467(**)
Emergy Sustainability Index	-0.589(**)	0.082	-0.628(**)	-0.200(*)	-0.559(**)	0.644(**)

** Correlation is significant at 0.01 level. * Correlation is significant at 0.05 level.

YESI – Yale Environmental Sustainability Index; HDI – Human Development Index; WI – Well-being Index; HWI – Human Well-Being Index; EWI – Ecosystem Well-Being Index where i denotes analysis on a national basis, HDI is the Human Development Index, and %R is the percent of a nation's total emergy use which comes from renewable sources. To determine its utility as a well-being indicator, TSWI was correlated to aggregate indices. Note that we scaled the published HDI values (which range from 0.227 to 0.942) so that the nation with the lowest HDI (Niger) was given a score of 0 and other nations scaled equivalently. This ensured that the two metrics (HDI and %R) exert equal control over TWSI; with a reduced HDI range, %R becomes dominant (range is from 0.003 to 0.965). Our interest was in countries that simultaneously achieved both high HDI and high %R, with equal leverage given to each.

Comparative analysis of aggregate indices

Table 7.2 is a correlation matrix showing the relationships between the aggregate indices of environmental and/or human well-being. Notably, the Yale Environmental Sustainability Index (YESI) is significantly positively correlated with the ecological footprint. The YESI is also strongly correlated with measures of human wellbeing, such as the Human Development Index (HDI) and Human Well-being Index (HWI), as well as the Well-being Index (WI), which is an average of the Ecosystem Well-being Index (EWI) and HWI. Conversely, relationships between the other indicators suggest that as measures of environmental well-being increase, measures of human well-being decrease. For example, the HDI and HWI are both positively correlated with the EF and negatively correlated with the EWI.

Table 7.3 shows the strongest correlations between the aggregate indices and the emergy indices and demonstrates the following relationships:

1. As resource-based measures of sustainability increase (percent renewable and the Emergy Sustainability Index), environmental well-being as indicated by the EF and EWI increases and human well-being as indicated by the HDI and HWI decreases.
2. As resource-use intensity increases (emergy/area, emergy/capita, non-renewable emergy use/capita and the Emergy Investment Ratio), environmental well-being, as indicated by the EF and EWI, decreases and human well-being, as indicated by the HDI and HWI, increases.

However, relationships between emergy indices and environmental well-being were not observed for YESI. Of all aggregate indices tested, the YESI had the lowest correlations with emergy indices. This suggests that the YESI measures different metrics of sustainability than does environmental accounting, perhaps indicating a potential synergy between them. That is, if the two methods provide non-redundant information, use in concert may provide a more complete picture of policy priorities than either alone.

Comparative analysis of well-being indicators

Complete results of individual social, political, economic and environmental well-being indicators analyzed in this study can be found in DeVincenzo King (2006). Figure 7.1 summarizes the strongest relationships found between these various components of human well-being and emergy indices. As environmental sustainability (measured by % renewable) increases, social well-being, economic well-being, and governmental well-being decrease. Inversely, as economic development increases (as measured by magnitude of the economy), social well-being, economic well-being and governmental well-being increase. This apparent trade-off between environmental sustainability and human well-being is discussed later.

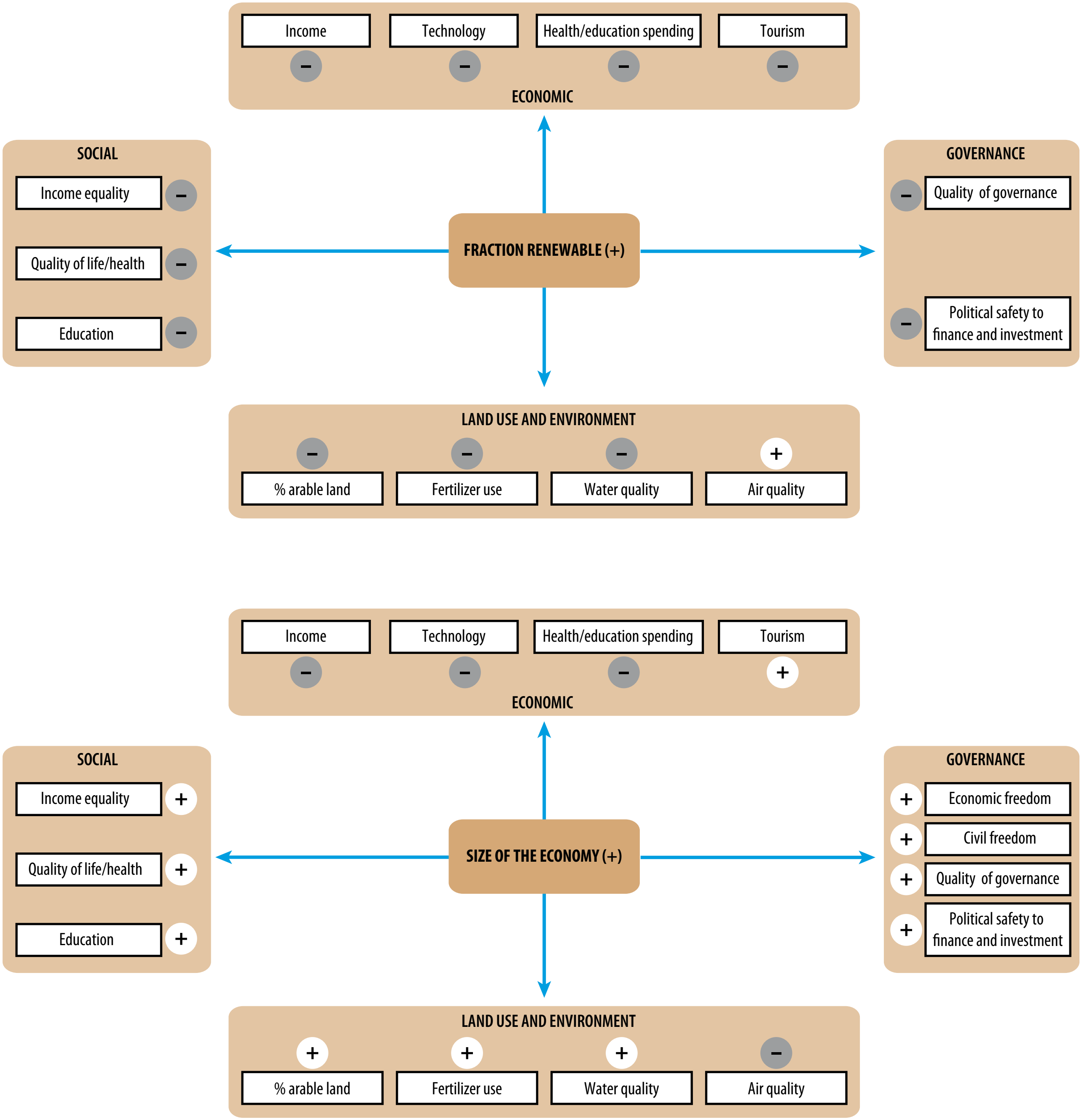
Comparative analysis of aggregate index components

Yale Environmental Sustainability Index (YESI): A correlation analysis of the components of the YESI suggests that Reducing Environmental Stresses (RES) is negatively correlated with EF and positively correlated with the EWI (as would be expected of an environmental well-being indicator), whereas the Reducing Human Vulnerability (RHV) and Social and Institutional Capacity (SIC) components are strongly positively correlated with HDI, HWI, GDP and the GDP Index (GDP Index is the United Nations Development Programme's adjusted GDP per capita). These two components are also negatively correlated with EWI and positively correlated with EF. This suggests that these two components, which make up one-third of the quantification of the overall YESI, may be better indicators of human well-being than environmental well-being.

As illustrated by Figure 7.2, YESI shows no relationship to the fraction of emergy from renewable sources, a simple biophysical measure of environmental sustainability. Table 7.3 suggests the strongest correlations between the emergy

FIGURE 7.1

Summary diagrams of the relationships between well-being and percent renewable (a) and magnitude of the economy (b).

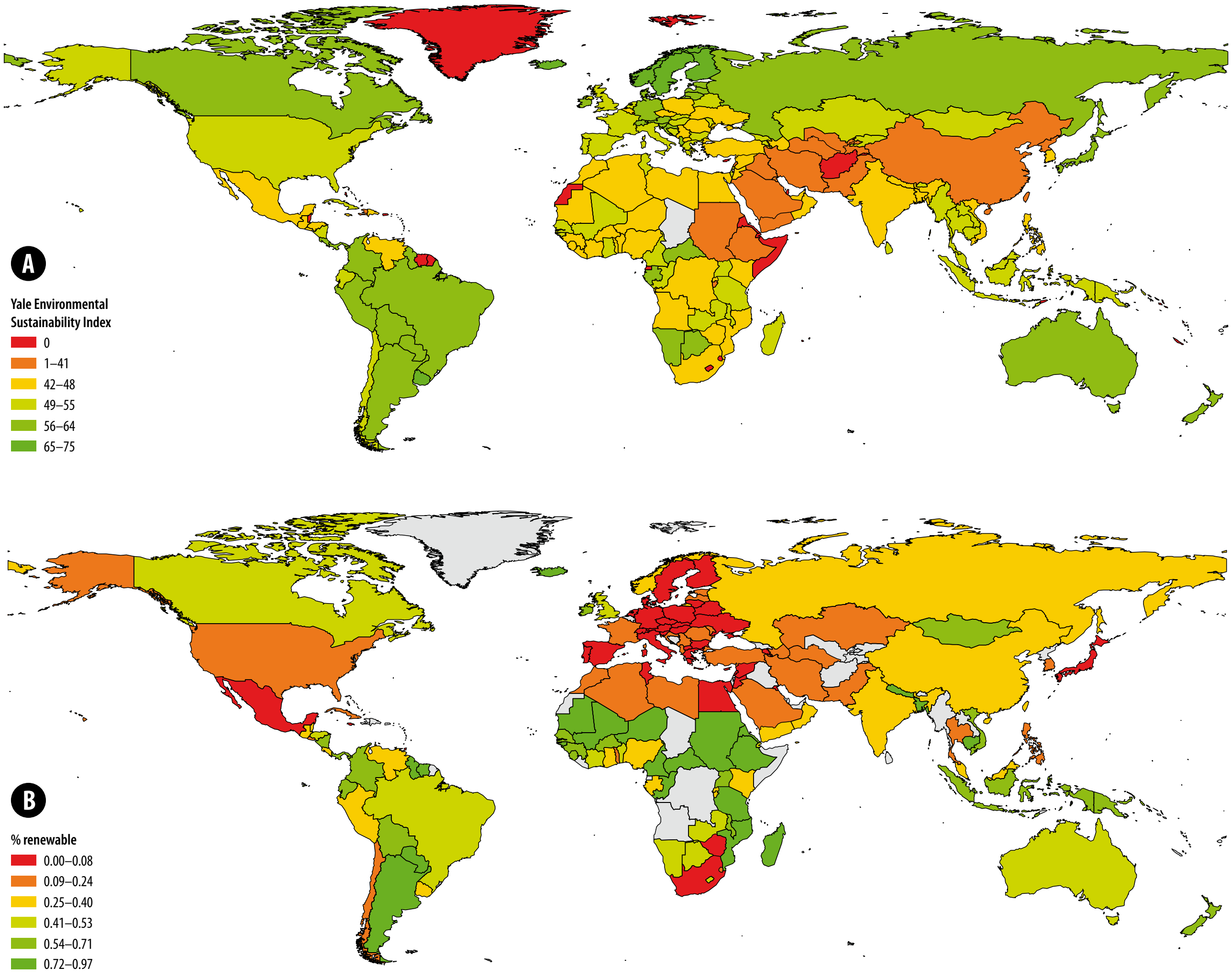


indices and YESI components. Ten of the 21 YESI indicators are uncorrelated or significantly negatively correlated with percent renewable (R/U). The difference between the YESI and percent renewable is particularly interesting in the sub-Saharan African nations in Figure 7.2 below. While the YESI defines these nations as unsustainable, by emergy measures they have relatively low non-renewable emergy use per capita and a large percent of their total emergy use comes from renewable sources.

Sixteen of 21 indicators comprising YESI have a strong and significant positive correlation to magnitude of the economy (Figure 7.1). This suggests that the YESI is principally a measure of economic

FIGURE 7.2

Maps of sustainability indices (A) Map of the Yale Environmental Sustainability Index. Data from Esty et al, 2005 (B) Map of emergy percent renewable.



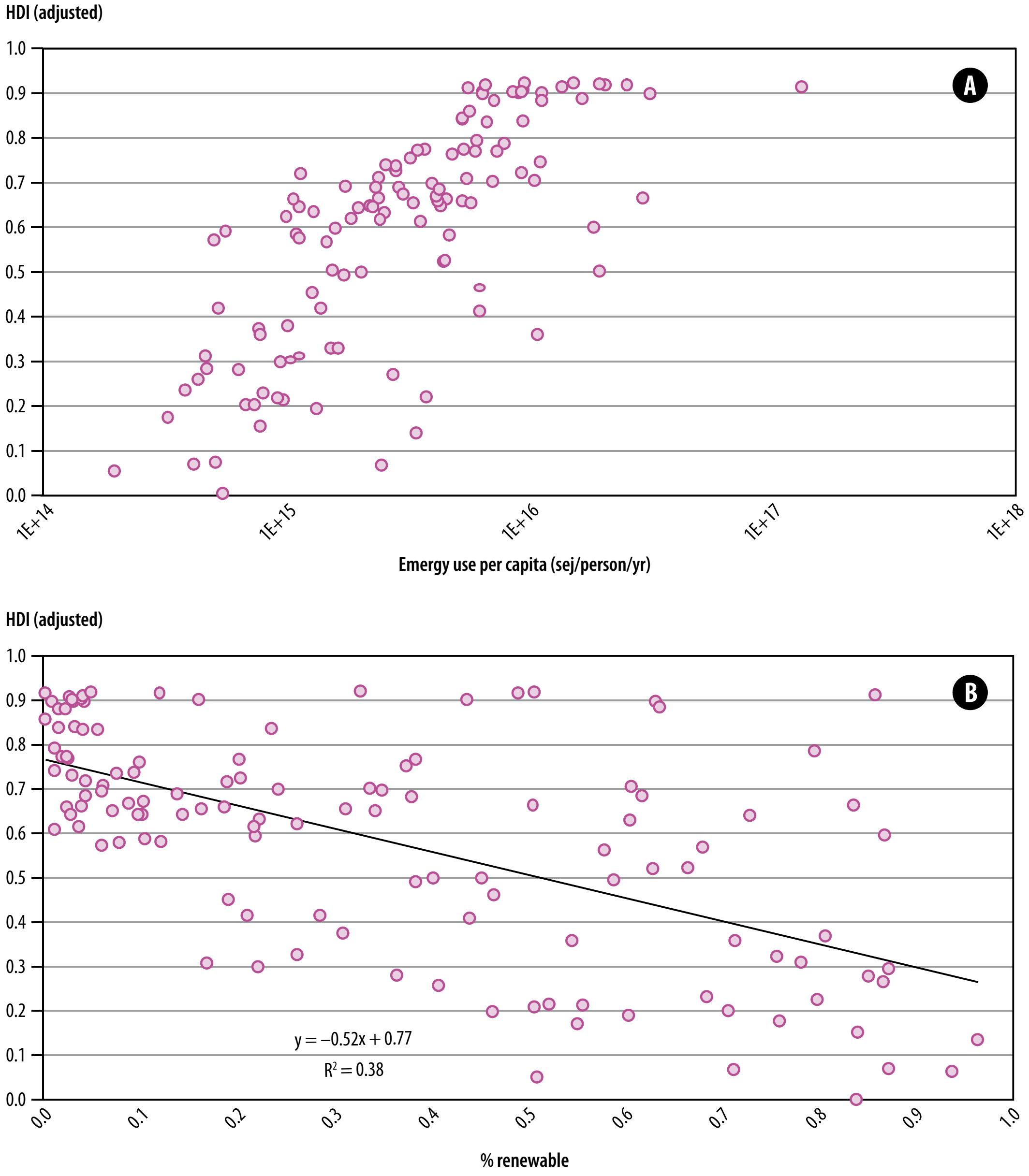
development and may be less useful as a measure of environmental conditions. For example, the YESI is significantly positively correlated to total non-renewable resource use per capita (r = 0.54) and, though not shown, fossil fuel use per capita (r = 0.23). It is debatable whether sustainability metrics should decline with increasing dependence on non-renewable resources, particularly given the positive relationships between non-renewable use and human well-being (see below). However, national systems that are not simultaneously striving to maximize human well-being and minimize environmental impact are risking both.

Human Development Index (HDI): Results show that the Human Development Index (HDI) is significantly positively correlated with total emergy use per capita (r = 0.75) and negatively correlated with the fraction of total use from renewable sources (%R; r = 0.62) (Figure 7.3). Significant scatter suggests that resource use alone does not fully explain human welfare.

Nations that lie above the best fit line (% renewable – Figure 7.3B)) are evidently producing human welfare more effectively than would be expected from knowledge of resource use alone. The residuals of the predicted regression between human development and the fraction of resource use from renewable resources gives a clearer idea of which nations fall into that category. As a policy objective, metrics of human welfare conditioned on resource use provide a highly quantitative benchmark against which to judge development.

FIGURE 7.3

HDI scatter plots (A) vs. non-renewable emergy use per capita. (B) vs. fraction total use from renewable resources.



Countries with large positive residuals (Figure 7.4), including Iceland, New Zealand, Ireland, Canada and Argentina, have better human welfare (as measured by HDI) than would be predicted based on how dependent their national economy is on renewable resources. In other words, these nations achieve a high standard of living without implicit dependence on non-renewable resources. Countries with high negative residuals, including most African nations, have lower human welfare than would be predicted based on the fraction of resource use from renewable resources.

HDI has been criticized as a human well-being indicator because it is partially composed of GDP per capita (Steer and Lutz, 1993). However, relationships were also observed between individual components of the HDI (Table 7.4). This suggests that despite inclusion of GDP per capita, HDI captures at least some of the important elements of human well-being as measured by its other two components (life expectancy and education). Moreover, while there is a proliferation of alternative indices, none are as widely used as HDI, nor computed from as many nations. We acknowledge that any intrinsic

FIGURE 7.4

Graph of regression residuals of % renewable vs. prediction of HDI based on % renewable. Nations above the 0.0 residual produce higher human development than would be predicted based on their renewable resource consumption; nations below the line produce less human development than would be expected. The TWSI captures this residual.

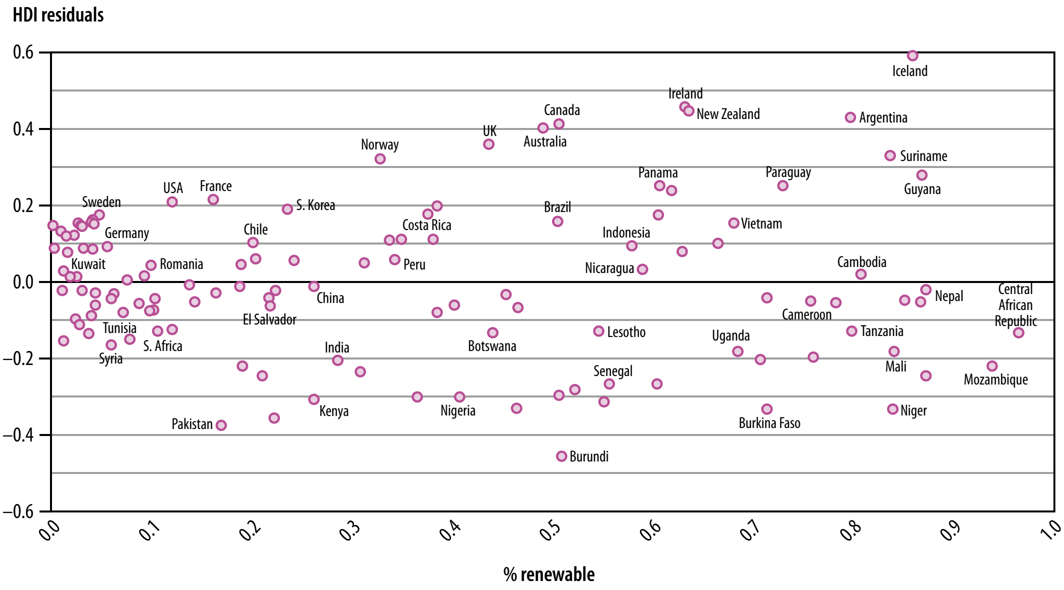


TABLE 7.4

Correlation matrix of HDI components and emergy indices. **

	HDI	Life Expectancy Index	Education Index	GDP Index	Emergy use/ capita	Non-renewable use /capita
HDI	1					
Life Expectancy Index in HDI	0.93	1				
Education Index in HDI	0.93	0.77	1			
GDP Index in HDI	0.94	0.81	0.80	1		
Emergy use/capita	0.75	0.61	0.70	0.79	1	
Non-renewable use/capita	0.59	0.51	0.55	0.59	0.71	1
% renewable emergy use	-0.61	-0.55	-0.60	-0.63		

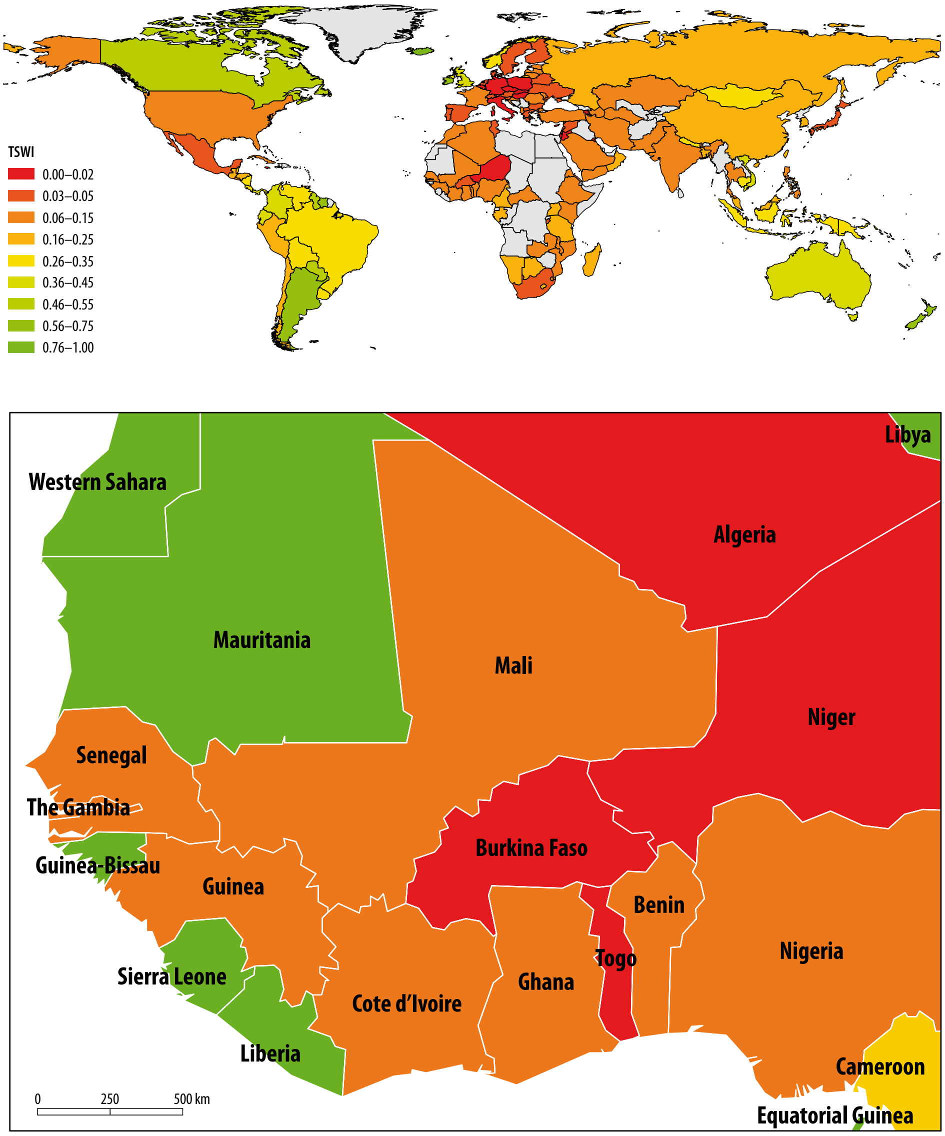
** All correlations were significant at the 0.01 level.

biases embedded within HDI (e.g., overemphasis on economic over social development) will be retained in any analyses in which HDI is used.

Total System Well-being Index (TSWI): Based on the above analysis of HDI, the TSWI (the product of HDI and emergy percent renewable) captures both human development and resource-use aspects of sustainability. Figure 7.5 shows the global distribution of TSWI, with national rankings (Table 7.5) also presented. Both HDI and the percent of emergy use from renewable resources are on 0–1 scales, so their product has a maximum of 1 and a minimum of 0. We note that the total range of HDI in 2000 was 0.27–1.0; to ensure that HDI and %Renewable are weighted equally in the index, we scaled the measured values to range between 0 and 1 in order to ensure that both %R and HDI have equal leverage on the resulting product. Countries with a high TSWI have high HDI (human welfare) given their

FIGURE 7.5

Map of the total system wellbeing index ($HDI_{adjusted}$ * %R).



fractional use of renewable resources (environmental sustainability). It is worth reiterating that high TWSI values can be achieved at both ends of the development spectrum.

Table 7.5 shows the correlations between the TSWI and the aggregate indices. Interestingly, the TSWI is not correlated with the WI, which should also be a measure of total well-being. Also, while the TSWI is positively correlated with measures of environmental well-being, it is negatively correlated with measures of human well-being such as the HDI and HWI.

The correlations between aggregate indices in Table 7.3 and Table 7.4 suggest that overall, and within the time domain of available energy resource subsidies from fossil fuel stores, human well-being and environmental well-being have an inverse relationship. Relationships between well-being indicators and emergy indices reinforce this finding. The only well-being indicator that increases with environmental sustainability and decreases with economic development is air quality (see Figure 7.1). From a resource-use perspective (Table 7.5), nations that maximize the magnitude of their economy and their per capita emergy intensity have higher human well-being and lower environmental well-being. Those nations with high raw resource exports appear to have low human well-being and environmental well-being.

TABLE 7.5

National rankings and values for the Total System Well-beingIndex (TSWI = HDI * %R).

Rank	Nation	TSWI
1	Iceland	0.784
2	Argentina	0.625
3	Ireland	0.567
4	New Zealand	0.564
5	Suriname	0.555
6	Guyana	0.518
7	Paraguay	0.468
8	Canada	0.465
9	Australia	0.450
10	Panama	0.428
11	Colombia	0.424
12	United Kingdom	0.394
13	Vietnam	0.388
14	Ecuador	0.381
15	Mongolia	0.348
16	Brazil	0.336
17	Bolivia	0.328
18	Indonesia	0.326
19	Norway	0.302
20	Cambodia	0.297
21	Uruguay	0.295
22	Nicaragua	0.292
23	Costa Rica	0.282
24	Venezuela	0.260
25	Nepal	0.257
26	Papua New Guinea	0.255
27	Cameroon	0.246
28	Russian Federation	0.244
29	Sudan	0.241
30	Belize	0.237
31	Bangladesh	0.237
32	Madagascar	0.231
33	Honduras	0.227
34	Peru	0.223
35	Namibia	0.215
36	Oman	0.205
37	Gabon	0.201
38	South Korea	0.197
39	Lesotho	0.195
40	Guatemala	0.189
41	Botswana	0.180
42	Tanzania	0.180
43	Malaysia	0.170
44	China	0.163
45	Uganda	0.158
46	Chile	0.155
47	Latvia	0.148
48	France	0.146
49	Albania	0.142
50	Eritrea	0.141
51	Cuba	0.136
52	Gambia	0.135
53	Iran	0.134
54	Central African Republic	0.131
55	El Salvador	0.130
56	Mali	0.127
57	Philippines	0.124
58	India	0.119
59	Senegal	0.119
60	Ghana	0.116
61	Guinea	0.115
62	Zambia	0.113
63	United States	0.111
64	Kazakhstan	0.108
65	Cote dIvoire	0.106
66	Nigeria	0.104
67	Yemen	0.102
68	Romania	0.095
69	Malawi	0.094
70	Turkmenistan	0.092
71	Benin	0.092
72	Swaziland	0.088
73	Morocco	0.086
74	Kenya	0.086
75	Estonia	0.076
76	Algeria	0.071
77	Thailand	0.070
78	Croatia	0.069
79	Togo	0.067
80	Azerbaijan	0.066
81	Turkey	0.063
82	Moldova	0.062
83	Ethiopia	0.060
84	Saudi Arabia	0.059
85	Mozambique	0.058
86	Lithuania	0.057
87	Pakistan	0.052
88	Burkina Faso	0.047
89	Slovenia	0.047
90	Ukraine	0.047
91	South Africa	0.046
92	Sweden	0.045
93	Belarus	0.044
94	Bulgaria	0.042
95	Denmark	0.039
96	Netherlands	0.038
97	Finland	0.037
98	Syria	0.035
99	Portugal	0.035
100	Mexico	0.032
101	Macedonia	0.031
102	Austria	0.028
103	Switzerland	0.028
104	Greece	0.028
105	Lebanon	0.027
106	Burundi	0.025
107	Japan	0.025
108	Tunisia	0.023
109	Trinidad and Tobago	0.023
110	Spain	0.021
111	Poland	0.020
112	Slovakia	0.020
113	Jamaica	0.019
114	Armenia	0.017
115	Hungary	0.015
116	Italy	0.014
117	Cyprus	0.014
118	Czech Republic	0.010
119	Kuwait	0.009
120	Germany	0.009
121	Jordan	0.008
122	Israel	0.003
123	Belgium	0.003
124	Niger	0.000

TABLE 7.6

Correlations between TSWI and aggregate indices.

Metric	TSWI
EF	-0.305(**)
ESI	0.304(**)
HDI	-0.217(*)
WI	0.086
HWI	-0.203(*)
EWI	0.451(**)

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

If one accepts the premise that HDI accurately reflects human well-being, the regression graph in Figure 7.4 and the proposed TSWI provide a measure of efficiency of resource use. Nations that have a high TSWI score (which include Iceland, Argentina, Suriname, Guyana and Ireland) are generating human welfare predicated on more renewable resource basis.

Interestingly, the TSWI is not correlated with the Well-being Index (WI)(Table 7.6), although both combine human well-being and environmental well-being, and therefore should be measures of total well-being. This is especially surprising since individual components of the WI appear to be adequate measures of human and environmental well-being, respectively (see Table 7.3 and Table 7.4). The Human Well-being Index (WI) is significantly positively correlated with HDI and the Ecosystem Well-being Index (EWI) is significantly negatively correlated with ecological footprint (EF). One explanation for this discrepancy is that WI is an average of human and environmental well-being, whereas the TSWI is a product of the two, making it more sensitive to extreme values. This may make the TSWI more useful than the WI for identifying nations with high total well-being, as nations must score high in both components to receive a high total score, whereas an average may mask a deficiency in one category.

CHAPTER 8

Conclusions

Environmental accounting offers insight into the source of wealth that complements traditional economic analyses. The main strength of this approach is that the natural resources that are the fundament of a robust and sustainable economy are largely neglected in traditional economics. The value of these stocks and services is clearly too high to be overlooked, and progress towards sustainability requires benchmarks against which their status can be formally integrated. While there are numerous options for such an analysis, we argue here that the thermodynamic basis of environmental accounting lends a level of cross-flow integration that is unique. And though there are strong reasons to expect, and indeed we observe, consistency in the various metrics of resource sustainability (e.g., ecological footprint analysis) environmental accounting with emergy has systems-level advantages when considering the myriad flows that constitute the resource basis of a nation or regional system.

There are five principal findings of this work. Many are confirmations of previous statements. For example, our observation regarding our collective dependence on non-renewable stocks for creating contemporary wealth is not new. However, the values we report underscore the magnitude of the problem, and provide a global benchmark against which future efforts to improve world system sustainability can be compared. Other conclusions are likely to be less obvious. We report on the structural inequities that are built into the global trade system; while solutions to this inequity may challenge fundamental notions of economic fairness, we argue that resource fairness is a far more compelling rationale for a global system. Moreover, our observation of a strong relationship between the Emergy Money Ratio and the economic measure of Purchasing Power Parity suggests that considerations of the resource basis of equitable trade have direct links with existing economic theory. Finally, some of our findings are suggestive of further work. We developed a new metric of total system sustainability, reasoning that nations that can simultaneously achieve high levels of human development (measured using the human development index) and do so relying principally on renewable resource flows, are those most likely to succeed in a lower-energy global system. The nations that succeed in this regard need to be carefully considered by other nations seeking to set policies that will improve their overall sustainability. Our principal findings are:

1. The non-renewable basis of national economic systems in West Africa is growing, and development appears to be, in part, moving away from economic reliance on renewable resources, and towards reliance on non-renewable and often external resources. This finding echoes those of Brown and Ulgiati (1999) for a more aggregated analysis of the global economy.
2. Sahelian dryland national economies are amongst the lowest globally with respect to the magnitude and intensity of emergy use (per area, per capita, fraction electricity). They are among the highest in the world in the fraction of total emergy support derived from renewable resources.
3. Temporal trends in the Sahelian nations are towards greater reliance on non-renewable stocks (both internal and external), but more rapid increases in human development have resulted in improvement in the Total System Well-beingIndex.
4. Natural capital depletion is a problem of enormous and under-appreciated magnitude. The global annual imputed costs, on relatively conservative estimates of natural capital depletion, appear to be in excess of $1.5 trillion (summed across soil erosion, deforestation, overfishing and overuse of water resources). Protection of these resources represents a first-order policy challenge because these costs are diffuse, incremental and distributed across numerous stakeholders. These challenges are amplified for dryland nations due to convergence of fragile environmental resources and strong reliance on dispersed (as opposed to mineral) natural capital.
5. The relationship between emergy and money yields insights into structural inequities built into the international trade system. Of particular importance amongst our findings are that a) developing nations export far more emergy than they import overall, and b) that, when measured in emergy units, African nations have generally repaid their international debts, sometimes many times over.

Human well-being and environmental resource use are inversely correlated, but with significant residual variation. Nations that produce welfare with low resource throughput or while retaining reliance on renewable resources are model systems for national sustainability planning. We propose a metric of sustainability that couples the UN Human Development Index and the fraction of national resources from renewable emergy (%R). This Total System Well-beingIndex (TSWI) yields significant quantitative insight into the status and trends of national sustainability around the globe.

CHAPTER 9

Policy recommendations

This study was intended to present a broad overview of the kinds of analyses possible at the national scale using environmental accounting. While the technique is comparatively new, and requires several important assumptions (Campbell et al, 2005), the findings illustrate the suite of problems that face societies around the world in managing the interface between people and nature. It would be naïve to presume that, armed with technical findings, large changes in policy are possible: the political process (Bryant, 1991) is an important constraint on environmental policy. However, the strictly technical findings of this report do point towards several key areas of policy advancement. This section summarizes these findings and sets out three main areas of policy reform.

Our principal finding, which echoes numerous authors that have studied the same issues, is that the current human system depends to an alarming degree on non-renewable resources. We calculated, for example, that the entire supply of renewable exogenous energy that drives the earth system is only roughly half the non-renewable resource use (15e+24 sej/yr of renewable emergy vs. 30E+24 sej/yr of non-renewable). It follows that maintaining the same resource basis of the global economy on renewable sources alone would require three global systems. Similarly, we observe that most of the developed nations of the world rely even more dramatically on non-renewable resources: the northern European economies in particular rely on non-renewable sources for between 90 and 99% of their total resource consumption. The staggering degree to which this is unsustainable should be clear, and policy actions to reduce this dependence to the maximum extent possible are urgently needed.

We also observed that global system is strongly dependent on, or at least leads to, the depletion of natural capital; the global losses (i.e., consumption in excess of replacement) of forests, water, fish and soil exceed a total annual cost of $1.6 trillion, a cost that is hidden from contemporary ledgers by the fact that these stocks built up over long periods of time prior to the emergence of the modern economic system. It should be self-evident, however, that these costs cannot be borne indefinitely, and that those most likely to incur the full implications of these dramatic rates of depletion in our shared global inheritance are future generations. For reasons of inter-generational equity, this depletion needs to be reversed.

We observed that the relationship between real wealth (the goods and services that are bought and sold, in emergy units) and money creates strongly asymmetric trade between nations. It is a common observation that money buys different amounts of goods in different areas; the Emergy Exchange Ratio, which was shown to be closely related to Purchasing Power Parity between nations, captures this inequity. Specifically, this metric suggests that less developed nations, which have high emergy-to-money ratios (EMR), are at a competitive disadvantage when trading with more developed nations, which characteristically have lower EMR values. These asymmetric trading relationships exacerbate existing development inequities, and inexorably favour most developed nations. Exploring the fairness of trade using emergy could allow policy makers to discern the magnitude of trade inequity, correct inequities in the market-place, and understand the status and trends of national trading relationships.

This trade inequity has implications for national indebtedness. We showed that African nations in particular, because they are at such a stark trade disadvantage *vis-à-vis* the main global economy, have more than paid off their international debts, when the value of those debts is evaluated in units of resources rather than money. That is, the often crushing burden of international debt that African nations have had to deal with is unfounded: the export of real material wealth to the global economy from Africa, and indeed other less developed nations, means that they frequently paid off their loans many decades ago. Debt relief for Africa is one clear policy avenue that should continue to be supported in light of these findings.

Finally, we observed that the relationship between resource and use and human welfare is unequivocal; that is, more resource use, particularly non-renewable resource use, leads to higher human development index scores. That said, there is some important variability in the ways that national systems create human welfare from their resource base. Sustainability has three facets – environmental welfare, economic development and social justice. Our analyses here say very little about the third, and profoundly important, aspect of sustainability, and future work should explore further the links between the biophysical basis of nations and their social equity and quality of governance. However, insofar as the UN's Human Development Index captures something useful about human well-being, a national system might be viewed through the lens of its ability to produce high levels of human welfare while relying principally on the renewable resources available. Indeed, total system well-being requires attention to both. We observed that some nations that produce more human welfare than would be predicted given their fractional reliance on renewable energy. That is, nations such as Iceland, Ireland, New Zealand, Argentina and Canada (among several others) may be model systems for how renewable resources can be put to use in generating human welfare. Indeed, the entire continent of South America appears to generally lead the world in this regard. At the same time, almost the entire continent of Africa (with the exception of Egypt) produces less human welfare for their particular dependence of non-renewable resources. It is not hard to connect this finding with previous findings that assert a systemic trade inequity for less developed nations. However, there may be substantial policy comparisons that can be made between systems with high total system well-being and those with low, that point to strategies to improve human welfare while maintaining or improving environmental sustainability that may be internationally portable. This detailed policy analysis is beyond the scope of the current work, but the results of our total system well-being evaluation may provide a useful starting point for that more detailed analysis.

Finally, focusing in on the nations of West Africa, critically imperilled because of their reliance on a fragile environmental system and because of many of the colonial and contemporary trade inequities that were mentioned above, we observe that the development process has been slow and, in some key ways, unsustainable. While it is clear that human development has risen, along with GDP and GDP per capita, the process has largely been fuelled by an increasing reliance within the national economy on non-renewable resources. Indeed, we observe that the total system well-being, which rises with HDI, but falls as more and more of the resources are derived from non-renewable sources, has actually been falling. That is, improvements in human welfare have occurred more slowly than increases in non-renewable resource use. While it is clearly ethically problematic to consider the rise in human development status, though modest, as counter-productive, in the long run, the development process should be focused on increasing HDI more quickly than contemporaneous increases in non-renewable resource use. In other words, the development process might best be strategized as skipping the phase of over-reliance on non-renewable resources that was part of the trajectory in the developed world, and evaluate development projects both on their capacity to create human well-being AND remain principally dependent on local renewable resources. In the long term, over-emphasis on one aspect of sustainability to the exclusion of the others is deleterious.

The integration of this worldview, wherein resources and ecosystems have intrinsic value that may be different from the price attached to them, into national and international policy is a clear challenge. One avenue for integration is to begin to track the data on environmental trade and resource use in emergy units so that, over time, the trends and comparisons suggested in this report will become clearer. For example, recent policies in the USA and Europe that are directed at reducing dependence on fossil energy sources should, if successful, incrementally change the structure of those economies in ways that improve the emergy metrics of sustainability. A comprehensive assessment of the biophysical resource basis of national systems can be tracked with the same level of rigour and detail as has been the case for economic performance; as such a national environmental accounting tracking system emerges, it can continue to leverage the massive improvements in whole-earth surveillance technologies that can help parameterize and refine the simple models used in this study. We propose that the UN Environment Programme be tasked with the creation and maintenance of the international capacity to track the environmental performance of nations in biophysically meaningful units. As environmental and economic performance continue to diverge, as Cobb and Daly (1989) assert they have, the time series of data that would allow direct links between policy decisions and/or changes in national economic structures would finally be available. Information is the key to setting good policy, and while the results of this work suggest that policy changes are needed, the particulars of those changes will require more detailed data.

Another policy arena that is considerable long-term importance for the rural poor is an emphasis on development programs that simultaneously address the obvious improvements in health, education, market access, and food production and the less obvious needs to maintain the environmental system upon which local human systems depend. Protecting the soil, sustainable harvesting of forests and fish, and the careful use of water for domestic, agricultural and industrial uses should be overt and fully integrated priorities of development activities. Given the need to move the global system towards one that creates human welfare without inexorably reducing environmental conditions, development projects should be envisioned that have suitably dualistic goals. One example of how this might work is to evaluate various development project alternatives using the typical economic assessments, but also add environmental accounting to the list of indicators. A project might be judged useful if, in addition to conventional project criteria, it also relies principally on renewable resources, or makes a substantial effort to avert the external costs of natural capital depletion. Environmental accounting, among several tools, has the ability to offer insight on development projects; indeed, Odum (1996) spends considerable time exploring the ways in which alternative developments might be contrasted using emergy.

This kind of integrated thinking – economy, society, environment – when implemented on a project-by-project and policy-by-policy basis, and evaluated at the national scale via high quality standardized data, could be used to effectively judge development strategies and learn efficiently from successes and failures. Since the stakes are high, and the challenge presented by our contemporary global reliance on non-renewable energy is so vast, immediate attention to even incremental progress is essential.

References

Anad, S., and A. Sen, 2000. The Income Component of the Human Development Index. Journal of Human Development, 1(1): 83–106.

Brown, M.T and S. Ulgiati. 1999. Emergy Evaluation of the Biosphere and Natural Capital. Ambio 28:486–493

Brown, M.T. 2003. Resource imperialism: emergy perspectives on sustainability, international trade, and balancing the welfare of nations. Advances in Energy Studies, 3rd Biennial International Workshop, Servizi Grafici Editoriali, Padova, Italy.

Brown, M.T., C. Ferreyra and E. Bardi. 2003. Emergy evaluation of a common market economy: MERCOSUR sustainability. Proceedings of the Second Biennial Emergy Research Conference. The Center for Environmental Policy, University of Florida, Gainesville, FL, USA.

Buenfil, A. 2001. Emergy analysis of water. PhD. Dissertation, University of Florida, Gainesville, FL, USA.

Campbell, D.E. 2000. A revised solar transformity for tidal energy received by the earth and dissipated globally: implication for emergy analysis. Proceedings of the First Biennial Emergy Analysis Research Conference. The Center for Environmental Policy, University of Florida, Gainesville, FL, USA.

Campbell, D.E., S.L. Brandt-Williams and T. Cai. 2005. Current technical problems in emergy analysis. Proceedings of the Third Biennial Emergy Research Conference. The Center for Environmental Policy, University of Florida, Gainesville, FL, USA.

Cheru, F., 2002. Debt, Adjustment and the Politics of Effective Response to HIV/AIDS in Africa. Third World Quarterly, 23(2): 299–312.

Cohen, M.J. 2003. Systems Evaluation of Erosion and Erosion Control in a Tropical Watersheds. Ph.D. Dissertation, University of Florida, Gainesville, FL, USA

Cohen, M.J., K.D. Shepherd and M.T. Brown. 2006. Estimating the environmental costs of soil erosion at multiple scales in Kenya using emergy synthesis. Agriculture Ecosystems and Environment 114:249–269

Cohen, M.J., S. Sweeney and M. Brown. 2007a. Comparative assessment of emergy time series for the Sahel. Proceedings of the 4th Biennial Emergy Conference. The Center for Environmental Policy, University of Florida, Gainesville, FL, USA.

Cohen, M.J., S. Sweeney, and M.T. Brown. 2007b. Computing the Unit Emergy Value of Crustal Elements. Proceedings of the 4th Biennial Emergy Research Conference. Gainesville, FL, USA

Cohen, M.J., S. Sweeney, M.T. Brown and D. King. 2007d. Soil, water, fish and forests: natural capital in the wealth of nations. Proceedings of the 4th Biennial Emergy Conference. The Center for Environmental Policy, University of Florida, Gainesville, FL, USA.

Costanza, R., R. D'Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R.V. O'Neill, J. Paruelo, R.G. Raskin, P. Sutton, and M. van den Belt. 1997. The value of the world's ecosystems and natural capital. Nature 387:253–260

Daly, H. and J. Cobb. 1989. For the Common Good. Beacon Press, Boston, MA, USA

DeVincenzo King, D. M. 2006. Emergy Accounting of the Resource Basis of Nations, Human Well-being and International Debt. University of Florida Masters Thesis.

Doherty, S. J., M.T. Brown, R.C. Murphy, H.T. Odum, and G.A. Smith. 1993. EMERGY Synthesis Perspectives, Sustainable Development, and Public Policy Options for Papua New Guinea. Center for Wetlands and Water Resources, UF.

Doherty, S.J., 1995. Emergy evaluations and limits to forest production. PhD. Dissertation, Dept. of Environmental Engineering Sciences, Univ. of Florida, Gainesville, FL, USA.

Doherty, S.J., P.O. Nilsson, and H.T. Odum. 2002. Emergy evaluation of forest production and industries in Sweden. Department of Bioenergy, Swedish University of Agricultural Sciences, Report No. 1.

Esty, D.C., M. Levy, T. Srebotnjak, and A. de Sherbinin. 2005. 2005 Environmental Sustainability Index: Benchmarking National Environmental Stewardship. Yale Center for Environmental Law and Policy, New Haven, CT, USA. Available online at www.yale.edu/esi Accessed April 20, 2005.

FAO. 2003. Digital Soil Map of the World and Derived Soil Properties. [CD-ROM]. FAO/UNESCO Land and Water Digital media Series

FAO. 2005. Review of the State of World Marine Fishery Resources. FAO Fisheries Technical Paper #457. Rome, Italy.

Ferreyra, C. and M.T. Brown. 2007. Emergy perspectives on the Argentine economy during the 20th century: a tale of natural resources, exports and external debt. International Journal of Environment and Sustainable Development 6:17–35

Flanders, S., and B. Ross-Larson, eds., 2002. The Human Development Report 2002. Oxford University Press, Inc., New York, NY, USA.

Hanley, N., 2000. Macroeconomic Measures of 'Sustainability'. Journal of Economic Surveys, 14(1): 1–30.

Ivanova, I., F.J. Arcelus, and G. Srinivasan, 1998. An Assessment of the Measurement Properties of the Human Development Index. Social Indicators Research, 46: 157–179.

Kaufmann, R.K. and C.J. Cleveland, 1995. Measuring Sustainability: Needed – An Interdisciplinary Approach to an Interdisciplinary Concept. Ecological Economics, 15: 109–112.

King, D., M.J. Cohen, S. Sweeney and M.T. Brown. 2007. The resource basis of human welfare. Proceedings of the 4th Biennial Emergy Conference. The Center for Environmental Policy, University of Florida, Gainesville, FL, USA.

Ko, J. and C.A.S. Hall, 2003. The correlation between GDP and both energy use and emergy use. Proceedings of the Second Biennial Emergy Research Conference. The Center for Environmental Policy, University of Florida, Gainesville, FL, USA.

Lal, R. 2003. Soil erosion and the global carbon budget. Environment International 29:437–450

Lind, N., 2004. Values Reflected in the Human Development Index. Social Indicators Research, 66: 283–293.

Loh, J., and M. Wackernagel, 2004. Living Planet Report 2004. World Wide Fund for Nature, Gland, CH. Available online at www.panda.org Accessed April 20, 2005.

Lvovich MI, Karasik GY, Bratseva NL, Medvedeva GP, Maleshko AV. Contemporary intensity of the world land intercontinentl erosion. Moscow: USSR Academy of Sciences; 1991.

Morse, S., 2003. For Better or for Worse, Till the Human Development Index Do Us Part? Ecological Economics, 45: 281–296.

Morse, S., 2004. Indices and Indicators in Development: An Unhealthy Obsession with Numbers. Earthscan Publications, Sterling, VA, USA.

Morse, Stephen, and Evan D.G. Frasier, 2005. Making 'Dirty' Nations Look Clean? The Nation State and the Problem of Selecting and Weighting Indices as Tools for Measuring Progress towards Sustainability. Geoforum, Vol. 36: 625–640.

Munasinghe, Mohan, and Jeffrey McNeely, 1995. Key Concepts and Terminology of Sustainable Development. In: Munasinghe, M. and W. Shearer, (Eds.). Defining and Measuring Sustainability: The Biogeophysical Foundations. The World Bank, Washington, D.C.

Noorbakhsh, F., 1998. A Modified Human Development Index. World Development, 26(3): 517–528.

Odum, H.T. 2000. Folio #2: Emergy of Global Processes. Handbook of Emergy Evaluation. Center for Environmental Policy, University of Florida, Gainesville, FL, USA.

Odum, H.T. 2000. Emergy of Global Processes. Handbook of Emergy Evaluation, Folio 2. Center for Environmental Policy, University of Florida, Gainesville, FL, USA.

Odum, H.T., 1996. Environmental Accounting. Emergy and Environmental Decision Making. John Wiley & Sons, NY, USA.

Odum, H.T., E.C. Odum, R. King, and R. Richardson. 1987. Ecology and Economy: Emergy Analysis and Public Policy in Texas. Energy Systems in Texas and the United States, Policy Research Project

Odum, H.T., S.J. Doherty, F.N. Scatena and P.A. Kharecha. 2000. Emergy evaluations of reforestation alternatives in Puerto Rico. Forest Science 46:521–530

Odum, H.T., M.T. Brown and S. Brandt-Williams. 2001. Introduction and Global Budget. Handbook of Emergy Evaluation, Folio 2. Center for Environmental Policy, University of Florida, Gainesville, FL, USA.

Odum. H.T. 1988. Self-Organization, Transformity, and Information. Science 242:1132–1138

Pimentel, D., C. Harvey, P. Resosudarmo, K. Sinclair, D. Murz, M. McNair, S. Crist, L. Shpritz, L. Fitton, R. Saffouri and R. Blair. 1995. Environmental and economic costs of soil erosion and conservation benefits. Science 267:1117–1122

Poku, N., 2002. Poverty, Debt and Africa's HIV/AIDS Crisis. International Affairs, 78(3):531–536.

Prescott-Allen, R., 2001. The Wellbeing of Nations: A Country-by-Country Index of Quality of Life and the Environment. Island Press, Washington, DC.

Raich, J.W., C.S.Potter, and D. Bhagawati. 2002. Interannual variability in global soil respiration, 1980–1994. Global Change Biology 8:800–812

Stachetti-Rodrigues, G., M.T. Brown and H.T. Odum. 2003. SAMeFrame – Sustainability Assessment Methodology Framework. Advances in Energy Studies, 3rd Biennial International Workshop, Servizi Grafici Editoriali, Padova, Italy.

StatSoft, Inc. 2004. STATISTICA (data analysis software system), version 6. www.statsoft.com.

Steer, A., and E. Lutz, 1993. Measuring Environmentally Sustainable Development. Finance & Development, 30(4): 20–23.

Sweeney, S., M.J. Cohen, D.M. King and M.T. Brown. 2007. Creation of a Global Emergy Database for Standardized National Emergy Synthesis. Proceedings of the 4th Biennial Emergy Research Conference. Gainesville, FL, USA

The Ecologist (Eds.), 2001. Keeping Score. The Ecologist, 31(3): 44–47.

Tilley, D.R. and W.T. Swank. 2003. EMERGY-based environmental systems assessment of a multi-purpose temperate mixed-forest watershed of the southern Appalachian Mountains, USA. Journal of Environmental Management 69:213–227

Ulgiati, S., H.T. Odum and S. Bastianoni. 1994. Emergy Use, Environmental Loading and Sustainability: An Emergy Analysis of Italy. Ecological Modelling 73:215–68.

Ulgiati, S.M. and M.T. Brown. 1998. Monitoring patterns of sustainability of natural and man-made ecosystems. Ecological Modelling 108:23–36

Van Den Berg, H., 2002. Does Annual Real Gross Domestic Product per Capita Overstate or Understate the Growth of Individual Welfare over the Past Two Centuries? The Independent Review, 7(2):181–196.

World Bank Group. 2005. Global Development Finance (GDF) Online Database. www.worldbank.ogr/data/onlinedatabases/onlinedatabases.html Accessed July 8, 2005.

World Commission on Environment and Development. 1987. Our Common Future. Oxford University Press, Oxford, UK.

York, R., E.A. Rosa, and T. Dietz, 2003. STIRPAT, IPAT and ImPACT: Analytic Tools for Unpacking the Driving Forces of Environmental Impacts. Ecological Economics, 46: 351–365

Appendices

APPENDIX A: Datasets used in the global emergy database

The development of a standardized database for 134 national economies globally required identification of datasets with global coverage. These datasets are not uniform, nor are they compiled centrally. This appendix summarizes the sources of data used for all analyses presented in this report.

APPENDIX B: Energy Systems Language and national systems diagrams

Diagrams are an integral part of understanding the workings of systems in general, and national economies in particular. The systems language provides a visual tool for holistic depiction of processes – symbol definitions are provided here. Also in this appendix are diagrams of five focal dryland nations in West Africa (Mali, Niger, Senegal, Burkina Faso and Mauritania). Detailed diagrams of major flows, stocks, transformations, imports and exports are aggregated into a standardized national diagram for comparison among nations.

APPENDIX C: National environmental accounting table

Detailed accounting tables for each country synthesize the physical flows (mass and energy) for each of the major inputs (flows across the national boundary, stocks used within the national boundary) for a given year. These tables aggregate information from multiple sources, and permit conversion of input flows in physical units to emergy units. Each table is constructed of a [1] note number, [2] line item, [3] physical flow annually, [4] units (J, grams, $), [5] Unit Emergy Values (quantity), [6] UEV units (sej per unit), [7] emergy (sej), and [8] equivalent macroeconomic value ($). For each note number [1], detailed footnotes are provided for the source of physical flows and any necessary conversions, and information on the citation for each UEV.

APPENDIX D: Summary flows and indices for 12 West African economies

Each national analysis results in a set of diagnostic indicators of the economic resource basis. Many of these indicators were previously described. These indices summarize the national resource basis for international comparison. This index provides the actual values for 12 West African nations, computed ca. 2000.

APPENDIX E: Definitions of Indicators

Appendix A

Datasets used in the global emergy database

Variable	Dataset	Source	Accessed through…	URL for dataset
Land area	The World Factbook	CIA, 2005	Central Intelligence Agency	www.cia.gov/cia/publications/factbook/
Net solar radiation	Earth Radiation Budget Experiment	ERBE	Digital Atlas of the World Water Balance	www.ce.utexas.edu/prof/maidment/gishyd97/atlas/atlas.htm
Continental shelf area	Global Maritime Boundaries Database	Pruett & Cimino 2000	UNEP, GEO-3 Data Compendium, 1.1	geocompendium.grid.unep.ch/
Tidal range	Typology Data Set	Davies, 1980	Land-Ocean Interactions in the Coastal Zone	www.loicz.org
Number of tides	Typology Data Set	Snead, 1980	Land-Ocean Interactions in the Coastal Zone	www.loicz.org
Rainfall	Wilmott grid V.2.01	Wilmott et al, 1998	Center for Climatic Research	climate.geog.udel.edu/~climate/html_pages/download.html
Evapotranspiration	Ahn and Tateishi, AET grid	Ahn & Tateishi, 1994	UNEP, GEO Data Portal, GNV183	www.grid.unep.ch/data/data.php?category=atmosphere
Elevation	ETOPO5	NOAA, 1988	National Geophysical Data Center	www.ngdc.noaa.gov/mgg/global/etopo5.HTML
Rain runoff volume	UNH/GRDC Composite Runoff Fields	Fekete et al, 2000	Water Systems Analysis Group, UNH	www.grdc.sr.unh.edu/index.html
River flow at border	GRDC discharge database	GRDC, 2005	Global Runoff Data Center	grdc.bafg.de/servlet/is/1035/?lang=en
Wind speed	Climate Research Unit CL 1.0	New et al, 2002	Climate Research Unit	www.cru.uea.ac.uk/~timm/grid/CRU_CL_1_0.html
Coastline length	The World Factbook	CIA, 2005	Central Intelligence Agency	www.cia.gov/cia/publications/factbook/
Wave height	Typology Data Set	Times, 1983	Land-Ocean Interactions in the Coastal Zone	www.nioz.nl/loicz/welcome.html
Heat flow	Global Heat Flow Database	Pollack et al, 1993	International Heat Flow Commission	www.heatflow.und.edu/index2.html
Ag. & livestock production	FAOSTAT	FAO, 2005	Food and Agriculture Organization	faostat.fao.org/
Fishery extraction	FIGIS	FAO, 2005	Food and Agriculture Organization	faostat.fao.org/
Nonrenewable fisheries	FAO Fisheries Technical Paper 457	FAO, 2005	Food and Agriculture Organization	ftp://ftp.fao.org/docrep/fao/007/y5852e/y5852e00.pdf
Wood extraction	FAOSTAT	FAO, 2005	Food and Agriculture Organization	faostat.fao.org/
Wood biomass per area	IPCC report, Table 3A.1.4	Penman et al,2003	Intergovernmental Panel on Climate Change	www.ipcc-nggip.iges.or.jp/public/gpglulucf/
Annual forest extent lost	Global Forest Resources Assessment 2000	FAO, 2001	UNEP, GEO-3 Data Compendium, 1.1	geocompendium.grid.unep.ch/data_sets/forests/nat_forest_ds.htm
Water extraction	AQUASTAT database	FAO, 2005	Food and Agriculture Organization	http://www.fao.org/ag/agl/aglw/aquastat/main/index.htm
Hydroelectricity production	International Energy Annual 2004	EIA, 2004	Energy Information Administration	http://www.eia.doe.gov/iea/

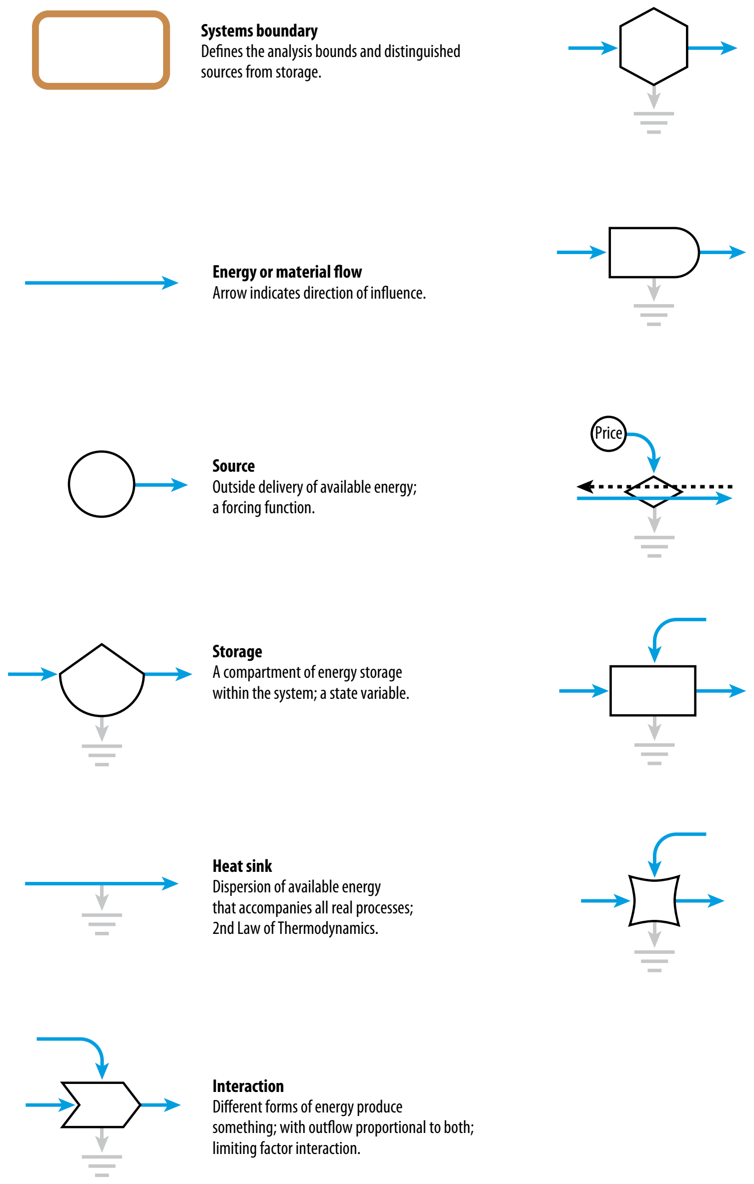
Variable	Dataset	Source	Accessed through…	URL for dataset
Electricity consumption	International Energy Annual 2004	EIA, 2004	Energy Information Administration	http://www.eia.doe.gov/iea/
Gas, coal, oil production	International Energy Annual 2004	EIA, 2004	Energy Information Administration	http://www.eia.doe.gov/iea/
Metal , mineral production	World Mineral Production, 1999–2003	Taylor et al, 2005	British Geological Survey	
Soil organic matter content	(get from Matt)			
Soil degradation	GLASOD database	ISRIC, 1990	ISRIC	www.grid.unep.ch/data/grid/soils.html
Gas, coal, oil, elec. trade	World Energy Database	EIA, 2001	EIA, International Energy Annual 2001	www.eia.doe.gov/emeu/world/main1.html
All other trade	COMTRADE	UN	United Nations Statistics Division	unstats.un.org/unsd/comtrade/default.aspx
GDP	UNCDB	UN		
Tourism expenditure	UNCDB	UN		

Appendix B

Energy Systems Language and national systems diagrams

FIGURE B.1

Definition of systems symbols.



Systems boundary
Defines the analysis bounds and distinguished sources from storage.

Energy or material flow
Arrow indicates direction of influence.

Source
Outside delivery of available energy; a forcing function.

Storage
A compartment of energy storage within the system; a state variable.

Heat sink
Dispersion of available energy that accompanies all real processes; 2nd Law of Thermodynamics.

Interaction
Different forms of energy produce something; with outflow proportional to both; limiting factor interaction.

Consumer unit
Unit that transforms and stores energy and feeds back control autocatalytically.

Producer unit
Collects, concentrates and stores low-quality energy (photosynthesis, chemosynthesis).

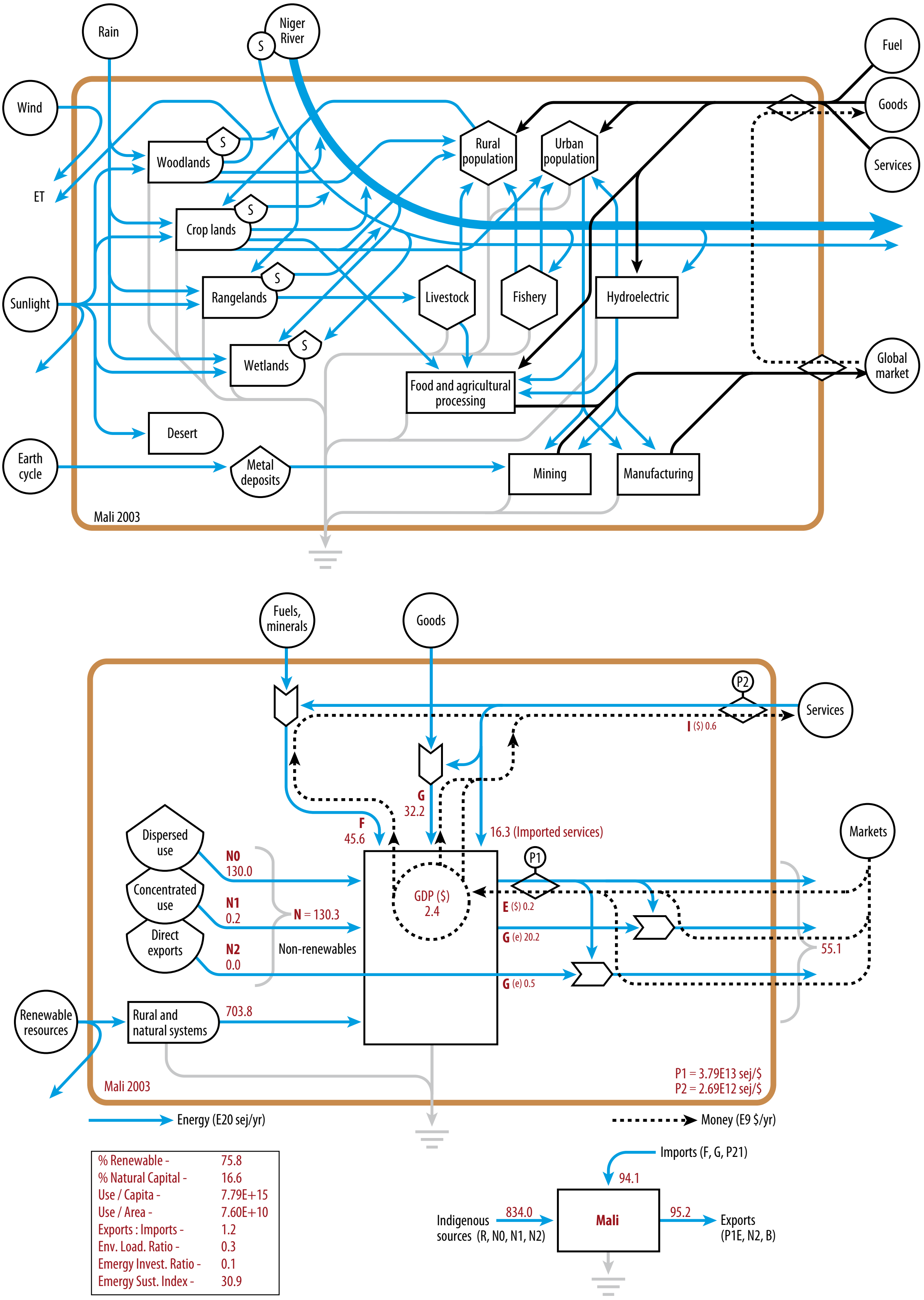
Market transaction
Depicts sale of goods, services (solid) in exchange for currency (dashed) according to marketplace.

Miscellaneous box
Depicts production/consumption units that do not have specific symbols.

Switching function
Indicates flow contingent of specific criteria; threshold function.

FIGURE B.2

Systems diagrams of Mali showing multiple levels of aggregation.



% Renewable -	75.8
% Natural Capital -	16.6
Use / Capita -	7.79E+15
Use / Area -	7.60E+10
Exports : Imports -	1.2
Env. Load. Ratio -	0.3
Emergy Invest. Ratio -	0.1
Emergy Sust. Index -	30.9

Appendix C

National environmental accounting table

TABLE C.1

Emergy account line items.

Country: **Mali** Year: 2000

#	Line item	Flow	Flow units	UEV	UEV units	Emergy E20 sej/yr	Em$ E6 $/yr
RENEWABLE FLOWS:							
1	Sunlight	3.2E+21	J	1.0E+00	sej/J	32.2	94.0
2	Deep heat	na	J	5.8E+04	sej/J	--	--
3	Tide	0.0E+00	J	7.4E+04	sej/J	0.0	0.0
4	Wind	3.3E+18	J	2.5E+03	sej/J	79.8	232.8
5	Total water	see notes	J	varies	sej/J	703.8	2054.6
6	Waves	0.0E+00	J	5.1E+04	sej/J	0.0	0.0
INTERNAL TRANSFORMATIONS (ECONOMIC):							
7	Agriculture production	4.9E+16	J	varies	sej/J	92.6	270.3
8	Livestock production	3.4E+15	J	varies	sej/J	110.9	323.9
9	Fisheries production	2.9E+14	J	8.4E+06	sej/J	24.0	70.1
10	Fuelwood production	3.0E+16	J	varies	sej/J	11.2	32.7
11	Industrial roundwood production	2.6E+15	J	varies	sej/J	2.4	7.1
12	Water extraction	3.2E+16	J	2.4E+05	sej/J	79.1	230.9
13	Hydroelectricity	9.4E+14	J	2.8E+05	sej/J	2.6	7.6
14	Total Electricity	1.5E+15	J	2.9E+05	sej/J	4.4	12.9
INDIGENOUS NONRENEWABLE EXTRACTION:							
19	Forestry	5.5E+16	J	3.8E+04	sej/J	21.2	61.8
20	Fisheries	0.0E+00	J	8.4E+06	sej/J	0.0	0.0
21	Water	0.0E+00	J	2.8E+05	sej/J	0.0	0.0
22	Topsoil losses, organic matter	-	J	varies	sej/J	17.6	51.4
23	Coal	0.0E+00	J	6.6E+04	sej/J	0.0	0.0
24	Natural gas	0.0E+00	J	6.8E+04	sej/J	0.0	0.0
25	Oil	0.0E+00	J	9.4E+04	sej/J	0.0	0.0
26	Minerals	6.5E+09	g	varies	sej/g	0.1	0.3
27	Metals	2.9E+07	g	varies	sej/g	0.1	0.4
IMPORTS:							
28	Fuels	see notes	mixed	varies	sej/J	10.7	31.1
29	Metals	see notes	mixed	varies	sej/g	16.7	48.7
30	Minerals	see notes	mixed	varies	sej/g	18.3	53.3
31	Food & agriculture products	see notes	mixed	varies	sej/J	7.3	21.2
32	Livestock, meat, fish	see notes	mixed	varies	varies	2.2	6.5
33	Plastics & synthetic rubber	see notes	mixed	varies	sej/g	2.6	7.7
34	Chemicals	see notes	mixed	varies	varies	10.4	30.4
35	Finished products	see notes	mixed	varies	varies	3.5	10.3
36	Mach. & trans. equip.	2.0E+08	$	2.6E+12	sej/$	5.3	15.5

TABLE C.1 *continued*

Emergy account line items.

						Country: **Mali** Year: 2000	
#	Line item	Flow	Flow units	UEV	UEV units	Emergy E20 sej/yr	Em$ E6 $/yr
37	Other refined goods	3.2E+07	$	2.6E+12	sej/$	0.8	2.4
38	Electricity	0.0E+00	J	2.9E+05	sej/J	0.0	0.0
39	Service in imports	6.2E+08	$	2.6E+12	sej/$	16.3	47.7
EXPORTS:							
40	Tourism	4.1E+07	$	3.4E+13	sej/$	14.0	41.0
41	Food & agriculture products	see notes	mixed	varies	sej/J	11.8	34.3
42	Livestock, meat, fish	see notes	mixed	varies	varies	0.9	2.5
43	Finished products	see notes	mixed	varies	varies	1.6	4.8
44	Fuels	see notes	mixed	varies	sej/J	0.0	0.0
45	Metals	see notes	mixed	varies	sej/g	0.5	1.5
46	Minerals	see notes	mixed	varies	sej/g	0.0	0.0
47	Plastics & synthetic rubber	see notes	mixed	varies	sej/g	0.0	0.1
48	Chemicals	see notes	mixed	varies	varies	0.1	0.3
49	Mach. & trans. equip.	1.3E+07	$	3.4E+13	sej/$	4.5	13.3
50	Other refined goods	3.8E+06	$	3.4E+13	sej/$	1.3	3.8
51	Electricity	0.0E+00	J	2.9E+05	sej/J	0.0	0.0
52	Service in exports	2.0E+08	$	3.4E+13	sej/$	67.1	196.0

See notes section for details on line item calculations.

			Country ISO3 code
		MLI Mali	Country
Emergy Table Notes		2000	Year
# Variable	Value	Units	Source
RENEWABLE FLOWS:			
1 Sunlight			
Land area =	1.2E+12	m^2	CIA, 2005
Cont. shelf area =	0.0E+00	m^2	CIA, 2005
Net radiation =	82.4	W/m^2	ERBE grid, from Maidement, 1997 (1983–1991 average)
Energy =	3.2E+21	J/yr	Total area * radiation * 3.154e7 sec/yr
Transformity =	1	sej/J	Odum, 1996
2 Deep heat			
Land area =	1.2E+12	m^2	CIA, 2005
Heat flow =	--	mW/m^2	Pollack et al, 1993, Global Heat Flow Database (lack of data)
Energy =	--	J/yr	Area * (heat flow/1000) * 3.154e7 sec/yr
Transformity =	5.8E+04	sej/J	Odum, 2000, Folio2
3 Tide			
Cont. shelf area =	0.0E+00	m^2	CIA, 2005
Avg. tidal range =	0.00	m	LOICZ Typology Data Set, 1998 (version 3)
Number of tides =	0.00	#/day	LOICZ Typology Data Set, 1998 (version 3)
Seawater density =	1.0E+03	kg/m^3	
Energy =	0.0E+00	J/yr	shelf area*0.5*#tide/yr*tiderange^2*1025kg/m^3*9.8 m/sec^2*0.5
Transformity =	7.4E+04	sej/J	Odum et al, 2000, Folio1

				Country ISO3 code
			MLI Mali	Country
Emergy Table Notes			2000	Year
#	Variable	Value	Units	Source
4	Wind			
	Avg. surf. windspeed =	2.4E+00	m/sec	New et al, 1999, CRU CL 1.0 grid (1961–1990 average)
	Avg.geostrophic speed =	4.1E+00	m/sec	assume surface winds are 0.6*geostrophic
	Air density =	1.23	kg/m^3	Odum, 1996, p.294
	Drag coefficient =	0.001	na	
	Energy =	3.3E+18	J/yr	total area * 1.23 * 0.001 * geostrophic speed^3 * 3.154e7 s/yr
	Transformity =	2.5E+03	sej/J	Odum et al, 2000, Folio1
5	Total water			
	Total inland area =	1.2E+12	m^2	CIA, 2005
	Land area =	1.2E+12	m^2	CIA, 2005
	Continental shelf area =	0.0E+00	m^2	Pruett and Cimino, 2000, Global Maritime Boundaries Database
	Avg. rain on land =	0.39	m/yr	Wilmott et al, 1998, Precipitation grid V.2.01 (1920–1980 avg.)
	Avg. rain on shelf =	0.00	m/yr	Wilmott et al, 1998, Precipitation grid V.2.01 (1920–1980 avg.)
	AET estimate =	0.33	m/yr	Ahn and Tateishi, 1994, grid (1920–1980 avg.)
	Runoff estimate =	0.02	m/yr	Fekete et al, 2000, UNH/GRDC Composite Runoff Fields V.1.0
	Elevation =	varies	m	ETOPO5 DEM
	River inflow =	4.5E+10	m^3/yr	GRDC, 2005, Global Runoff Data Centre gauge data
	River outflow =	5.6E+10	m^3/yr	GRDC, 2005, Global Runoff Data Centre gauge data
	Rain chem. potential (land) =	2.4E+18	J/yr	Land area * rain on land *1000kg/m^3 * 4940J/kg
	Rain chem.pot. TRF (land) =	3.1E+04	sej/J	Odum et al, 2000, Folio1
	Rain chem. potential (shelf) =	0.0E+00	J/yr	shelf area * rain on shelf *1000kg/m^3 * 4940J/kg
	Rain chem.pot. TRF (shelf) =	7.0E+03	sej/J	Baseline (sej)/Global rain on shelf (J) from Wilmott et al, 1998
	Evapotransp. chem. potential =	2.0E+18	J/yr	Inland area * AET * 1000kg/m^3 * 4940J/kg
	Evapotransp. chem.pot. TRF =	3.1E+04	sej/J	Odum et al, 2000, Folio1
	Rain, runoff geopotential =	1.1E+17	J/yr	GIS cellcalc: <runoff>*<cell elev>* 1000 kg/m^3* 9.8 m/sec^2
	River inflow geopotential =	1.6E+17	J/yr	SUM (river IN(m^3)*elev at border(m)*1000kg/m^3*9.8m/sec^2)
	River outflow geopotential =	7.7E+16	J/yr	SUM (river OUT(m^3)*elev at border(m)*1000kg/m^3*9.8m/sec^2)
	Net total runoff geopotial =	2.0E+17	J/yr	Rain runoff geopot. + River inflow geopot. - River outflow geopot.
	Water runoff geopotential TRF =	4.7E+04	sej/J	Odum et al, 2000, Folio1
	Rain runoff, chem. potential =	1.5E+17	J/yr	Land area(m^2) * Runoff(m^3) * 1000kg/m^3 * 4940J/kg
	Rain RO, chem. potential TRF =	3.1E+04	sej/J	Odum et al, 2000, Folio1
	Riverin, chem. potential =	2.2E+17	J/yr	River IN(m^3/sec)*3.154e7sec/yr*1000kg/m^3*4940J/kg
	Riverout, chem. potential =	2.8E+17	J/yr	River OUT(m^3/sec)*3.154e7sec/yr*1000kg/m^3*4940J/kg
	Net river chem. potential =	-5.4E+16	J/yr	River IN chemical potential - River OUT chemical potential
	River chem. potential TRF =	8.1E+04	sej/J	Odum et al, 2000, Folio1
TOTAL WATER EMERGY DETERMINATION:				
	Location =	L	---	CIA, 2005; C = coastal, L = landlocked
	Rain, chemical potential =	7.3E+22	sej/yr	(Land chem. J * land rain trf)+(Shelf chem. J * shelf rain trf)
	AET, chemical potential =	6.1E+22	sej/yr	AET chem. potential J * land rain chem. potential trf
	Rain, land, chemical potential =	7.3E+22	sej/yr	Rain on land chemical pot. J * land rain chem. potential trf
	Rain, shelf, chemical potential =	0.0E+00	sej/yr	Rain on shelf chemical pot. J * shelf rain chem. potential trf
	Water runoff, geopotential =	9.2E+21	sej/yr	Net total water runoff geopotential J * Runoff geopotential trf
	Water runoff, chemical potential =	Not appl.	sej/yr	If coastal, (Rain runoff chem. J * rain trf)+(Net river chem. J * river trf)
	Total water, chemical potential =	Not appl.	sej/yr	if coastal, [Rain chem. (sej)] + [Net river chem. J * river chem. trf]
	AET chem. pot. + RO geopot. =	7.0E+22	sej/yr	AET chem. potential sej + RO geopotential sej
	Largest water =	7.0E+22	sej/yr	Total water chem. potential OR AET chem. potential +RO geopot.

				Country ISO3 code
			MLI Mali	Country
Emergy Table Notes			2000	Year
#	Variable	Value	Units	Source
6	Waves			
	Coastline length =	0.0E+00	m	CIA, 2005
	Average wave height =	--	m	still trying to identify a good dataset
	Average wave speed =	4.40	m/s	= SQRT(9.8*depth of ht. meas.) = 4.4 if at 2m
	Waves =	--	J/yr	coastlength(m)*1/8*1025kg/m^3 *height^2 *speed(m/s)* 3.154e7 s/yr
LARGEST RENEWABLE FLOW:				
	Largest Renew =	7.0E+22	sej/yr	largest land renew + tide if coastal country
				(Deep heat and wave not considered as of now due to sparse data)
INTERNAL TRANSFORMATIONS:				
7	Agriculture production			
	Agriculture production =	3.7E+06	MT/yr	FAOSTAT, 2005
	Agriculture production =	4.9E+16	J/yr	indv.items * 1e6 g/MT * energy conversion (J/g)
	Agriculture TRF =	varies	sej/J	multiple transformities for various FAO commodities
8	Livestock production			
	Livestock production =	7.4E+05	MT/yr	FAOSTAT, 2005
	Livestock production =	3.4E+15	J/yr	indv.items * 1e6 g/MT * energy conversion (J/g)
	Livestock TRF =	varies	sej/J	multiple transformities for various FAO commodities
9	Fisheries production			
	Fisheries production =	1.1E+05	MT/yr	FAOSTAT, 2005
	Fisheries production =	2.9E+14	J/yr	indv.items * 1e6 g/MT * energy conversion (J/g)
	Fisheries TRF =	8.4E+06	sej/J	Brown et al, 1993
10	Fuelwood production			
	Fuelwood production =	3.0E+06	MT/yr	FAOSTAT, 2005
	Fuelwood production =	3.0E+16	J/yr	indv.items * 1e6 g/MT * energy conversion (J/g)
	Fuelwood TRF =	varies	sej/J	multiple transformities for various FAO commodities
11	Industrial roundwood production			
	Industrial roundwood =	2.6E+05	MT/yr	FAOSTAT, 2005
	Indistrial roundwood =	3.0E+16	J/yr	indv.items * 1e6 g/MT * energy conversion (J/g)
	Industial roundwood TRF =	varies	sej/J	multiple transformities for various FAO commodities
12	Water extraction			
	Water extraction =	6.5E+09	m^3/yr	AQUASTAT, 2005
	Water extraction =	2.6E+15	J/yr	extraction(m^3/yr)* 1000 kg/m^3 * 4940 J/kg
	Water extraction TRF =	2.4E+05	sej/J	Buenfil, 2001, average Florida groundwater
13	Hydroelectricity production			
	Hydroelectricity production =	2.6E+08	kwh/yr	EIA, International Energy Annual 2002
	Hydroelectricity production =	3.2E+16	J/yr	production(kwh/yr) * 3.6e6 J/kwh
	Hydroelectricity TRF =	2.8E+05	sej/J	Odum, 1996, Brazilian hydroelectricity
14	Total electricity use			
	Total Electricity Use =	4.3E+08	kwh/yr	EIA, International Energy Annual 2002
	Hydroelectricity Production =	9.4E+14	J/yr	Use(kwh/yr) * 3.6e6 J/kwh
	Electricity TRF =	2.9E+05	sej/J	Odum, 1996, average from several types of power plants

			Country ISO3 code
		MLI Mali	Country
Emergy Table Notes		2000	Year
# Variable	Value	Units	Source
NONRENEW EXTRACTION:			
19 Forestry			
Forestry, NR use =	3.1E+06	MT/yr	Biomass density(MT/ha)*Extent change (ha), if less than zero
Biomass density =	3.1E+01	MT/ha	IPCC report, Table 3A.1.4
Avg. forest extent change =	-9.9E+04	ha/yr	GRID-GENEVA GEO-3 (get orig. ref)
Forestry, NR use =	5.5E+16	J/yr	Forestry use (MT) * 1.8e10 J/MT
Forestry TRF =	3.8E+04	sej/J	Avg. of 4 TRFs used for wood products (see FAO subtable)
20 Fisheries			
Fisheries, net loss =	0.0E+00	MT/yr	FAO Fisheries Technical Paper 457, amounts over MSY
Fisheries, net loss =	0.0E+00	J/yr	Loss (MT) * 1e6 g/MT * 2600 J/g
Fisheries TRF =	8.4E+06	sej/J	Brown et al, 1993
21 Water			
Water, NR extraction =	0.0E+00	m^3/yr	AQUASTAT
Water, NR extraction =	0.0E+00	J/yr	Extraction (m^3) * 1000 kg/m^3 * 4940 J/kg
Water TRF =	2.8E+05	sej/J	Buenfil, 2001 (Floridan aquifer)
22 Topsoil losses, organic matter			
Topsoil losses =	2.9E+14	g/yr	Cohen, in prep (model based on GLASOD, xxxx data)
Avg. organic matter content =	3.4E-01	%	FAO Global Soils Database
Organic matter losses =	2.2E+16	J/yr	Assume 4.5 kcal/g SOM
Topsoil losses, org. matter TRF =	varies	sej/J	Cohen et al 2007c
23 Coal			
Coal production =	0.0E+00	MT/yr	EIA, online tables
Forestry, NR use =	0.0E+00	J/yr	Poduction (MT) * 2.45e10 J/MT
Coal TRF =	6.6E+04	sej/J	Odum, 1996, p.308
24 Natural gas			
Natural gas production (dry) =	0.0E+00	m^3/yr	EIA, online tables
Forestry, NR use =	0.0E+00	J/yr	Production (m^3) * 3.82e7 J/m^3
Natural Gas TRF =	6.8E+04	sej/J	Bastianoni et al, 2005
25 Oil			
Oil production =	0.0E+00	bbl/yr	EIA, online tables
Forestry, NR use =	0.0E+00	J/yr	Production (bbl) * 6.12e9 J/bbl
Oil TRF =	9.4E+04	sej/J	Bastianoni et al, 2005
26 Minerals			
Mineral production =	6.5E+03	MT/yr	British and US Geological Surveys
Mineral production =	6.5E+09	g/yr	Production (MT) * 1e6 g/MT
Minerals TRF =	varies	sej/g	individual TRFs assigned to each mineral; Cohen, 2006
27 Metals			
Metal production =	2.9E+01	MT/yr	British and US Geological Surveys
Metal production =	2.9E+07	g/yr	Production (MT) * 1e6 g/MT
Metals TRF =	varies	sej/g	individual TRFs assigned to each metal; Cohen, 2006

				Country ISO3 code
			MLI Mali	Country
Emergy Table Notes			2000	Year
#	Variable	Value	Units	Source
IMPORTS:				
28	Fuels			
	Crude oil =	0.0E+00	bbl/yr	EIA, 2003, World Energy Database
	Crude oil =	0.0E+00	J/yr	Crude import (bbl) * 5.85E9 J/bbl
	Crude oil TRF =	9.4E+04	sej/J	Bastianoni et al, 2005
	Refined oil (gasoline, etc) =	1.4E+06	bbl/yr	EIA, 2003, World Energy Database
	Refined oil =	8.2E+15	J/yr	Refined oil (bbl) * 6.2E9 J/bbl
	Refined oil TRF =	1.3E+05	sej/J	Odum et al, 1995, Alaskan refined products
	Coal (hard, lignite) =	0.0E+00	MT/yr	EIA, 2003, World Energy Database
	Coal (hard, lignite) =	0.0E+00	J/yr	Coal (MT) * 2.97e4 J/g
	Coal TRF =	5.7E+04	sej/J	Odum, 1996
	Coal (coke) =	0.0E+00	MT/yr	EIA, 2003, World Energy Database
	Coal (coke) =	0.0E+00	J/yr	Coke (MT) * 2.88e4 J/g
	Coal TRF =	5.7E+04	sej/J	Odum, 1996
	Natural gas =	0.0E+00	ft^3/yr	EIA, 2003, World Energy Database
	Natural gas =	0.0E+00	J/yr	Natural gas(ft^3) * 0.028317 m^3/ft^3 * 3.82e7 J/m^3
	Natural gas TRF =	6.8E+04	sej/J	Bastianoni et al, 2005
29	Metals			
	Metals =	1.2E+11	g/yr	UN, COMTRADE, commodities reported in weight
	Metals =	0.0E+00	$/yr	UN, COMTRADE, commodities reported only in $
	Metals TRF =	varies	varies	indvidual TRFs assigned to each SITC1 code, 4-digit level
30	Minerals			
	Minerals =	5.7E+11	g/yr	UN, COMTRADE, commodities reported in weight
	Minerals =	6.1E+03	$/yr	UN, COMTRADE, commodities reported only in $
	Minerals TRF =	varies	varies	indvidual TRFs assigned to each SITC1 code, 4-digit level
31	Food & ag. products			
	Food and ag. products =	4.4E+15	J/yr	UN, COMTRADE, commodities with TRFs in units of sej/J
	Food and ag. products =	0.0E+00	g/yr	UN, COMTRADE, commodities with TRFs in units of sej/g
	Food and ag. products TRF =	varies	varies	indvidual TRFs assigned to each SITC1 code, 4-digit level
32	Livestock, meat, fish			
	Meat products =	1.7E+14	J/yr	UN, COMTRADE, commodities reported in weight
	Meat products =	1.4E+02	$/yr	UN, COMTRADE, commodities reported only in $
	Meat products TRF =	varies	varies	indvidual TRFs assigned to each SITC1 code, 4-digit level
33	Plastics & synthetic rubber			
	Plastics =	1.9E+10	g/yr	UN, COMTRADE
	Plastics TRF =	varies	varies	indvidual TRFs assigned to each SITC1 code, 4-digit level
34	Chemicals			
	Chemicals =	4.3E+13	J/yr	UN, COMTRADE, commodities with TRFs in units of sej/J
	Chemicals =	2.1E+11	g/yr	UN, COMTRADE, commodities with TRFs in units of sej/g
	Chemicals =	0.0E+00	$/yr	UN, COMTRADE, commodities reported only in $
	Chemicals TRF =	varies	varies	indvidual TRFs assigned to each SITC1 code, 4-digit level
35	Finished products			
	Finished products =	5.3E+14	J/yr	UN, COMTRADE, commodities with TRFs in units of sej/J
	Finished products =	8.3E+09	g/yr	UN, COMTRADE, commodities with TRFs in units of sej/g
	Finished products TRF =	varies	varies	indvidual TRFs assigned to each SITC1 code, 4-digit level

			Country ISO3 code
		MLI Mali	Country
Emergy Table Notes		2000	Year
# Variable	Value	Units	Source
36 Mach. & trans. equip.			
Machinery =	2.0E+08	$/yr	UN, COMTRADE, using $ value
World sej/$ used as TRF =	2.6E+12	sej/$	Sweeney et al, 2006
37 Other refined goods			
Other refined goods =	3.2E+07	$/yr	UN, COMTRADE, using $ value
World sej/$ used as TRF =	2.6E+12	sej/$	Sweeney et al, 2006
38 Electricity			
Electricity imports =	0.0E+00	kwh/yr	EIA, International Energy Annual 2002
Electricity imports =	0.0E+00	J/yr	Use(kwh/yr) * 3.6e6 J/kwh
Electricity TRF =	2.9E+05	sej/J	Odum, 1996, average from several types of power plants
39 Service in imports			
Dollar value of all imports =	6.2E+08	$/yr	UN, COMTRADE
World sej/$ used as TRF =	2.6E+12	sej/$	Sweeney et al, 2006
EXPORTS:			
40 Tourism			
Tourist expenditures =	4.1E+07	$/yr	UNCDB, 2005
World sej/$ used as TRF =	2.6E+12	sej/$	Sweeney et al,2006
41 Food & ag. products			
Food and ag. products =	3.7E+15	J/yr	UN, COMTRADE, commodities with TRFs in units of sej/J
Food and ag. products =	0.0E+00	g/yr	UN, COMTRADE, commodities with TRFs in units of sej/g
Food and ag. products TRF =	varies	varies	indvidual TRFs assigned to each SITC1 code, 4-digit level
42 Livestock, meat, fish			
Meat products =	1.3E+13	J/yr	UN, COMTRADE, commodities reported in weight
Meat products =	4.9E+03	$/yr	UN, COMTRADE, commodities reported only in $
Meat products TRF =	varies	varies	indvidual TRFs assigned to each SITC1 code, 4-digit level
43 Finished products			
Finished products =	2.5E+13	J/yr	UN, COMTRADE, commodities with TRFs in units of sej/J
Finished products =	2.0E+08	g/yr	UN, COMTRADE, commodities with TRFs in units of sej/g
Finished products TRF =	varies	varies	indvidual TRFs assigned to each SITC1 code, 4-digit level
44 Fuels			
Crude oil =	0.0E+00	bbl/yr	EIA, 2003, World Energy Database
Crude oil =	0.0E+00	J/yr	Crude import (bbl) * 5.85E9 J/bbl
Crude oil TRF =	9.4E+04	sej/J	Bastianoni et al, 2005
Refined oil (gasoline, etc) =	0.0E+00	bbl/yr	EIA, 2003, World Energy Database
Refined oil =	0.0E+00	J/yr	Refined oil (bbl) * 6.2E9 J/bbl
Refined oil TRF =	1.3E+05	sej/J	Odum et al, 1995, Alaskan refined products
Coal (hard, lignite) =	0.0E+00	MT/yr	EIA, 2003, World Energy Database
Coal (hard, lignite) =	0.0E+00	J/yr	Coal (MT) * 2.97e4 J/g
Coal TRF =	5.7E+04	sej/J	Odum, 1996
Coal (coke) =	0.0E+00	bbl/yr	EIA, 2003, World Energy Database
Coal (coke) =	0.0E+00	J/yr	Coke (MT) * 2.88e4 J/g
Coal TRF =	5.7E+04	sej/J	Odum, 1996
Natural gas =	0.0E+00	ft^3/yr	EIA, 2003, World Energy Database
Natural gas =	0.0E+00	J/yr	Natural gas(ft^3) * 0.028317 m^3/ft^3 * 3.82e7 J/m^3
Natural gas TRF =	6.8E+04	sej/J	Bastianoni et al, 2005

#	Variable	Value	Units	Source
				Country ISO3 code
			MLI Mali	Country
Emergy Table Notes			2000	Year
#	Variable	Value	Units	Source
45	Metals			
	Metals =	8.2E+09	g/yr	UN, COMTRADE, commodities reported in weight
	Metals =	0.0E+00	$/yr	UN, COMTRADE, commodities reported only in $
	Metals TRF =	varies	varies	indvidual TRFs assigned to each SITC1 code, 4-digit level
46	Minerals			
	Minerals =	1.7E+08	g/yr	UN, COMTRADE, commodities reported in weight
	Minerals =	0.0E+00	$/yr	UN, COMTRADE, commodities reported only in $
	Minerals TRF =	varies	varies	indvidual TRFs assigned to each SITC1 code, 4-digit level
47	Plastics & synthetic rubber			
	Plastics =	3.8E+08	g/yr	UN, COMTRADE
	Plastics TRF =	varies	varies	indvidual TRFs assigned to each SITC1 code, 4-digit level
48	Chemicals			
	Chemicals =	8.8E+12	J/yr	UN, COMTRADE, commodities with TRFs in units of sej/J
	Chemicals =	9.1E+08	g/yr	UN, COMTRADE, commodities with TRFs in units of sej/g
	Chemicals =	0.0E+00	$/yr	UN, COMTRADE, commodities reported only in $
	Chemicals TRF =	varies	varies	indvidual TRFs assigned to each SITC1 code, 4-digit level
49	Mach. & trans. equip.			
	Machinery =	1.3E+07	$/yr	UN, COMTRADE, using $ value
	Country sej/$ used as TRF =	3.4E+13	sej/$	Sweeney et al, 2006
50	Other refined goods			
	Other refined goods =	3.8E+06	$/yr	UN, COMTRADE, using $ value
	Country sej/$ used as TRF =	3.4E+13	sej/$	Sweeney et al, 2006
51	Electricity			
	Electricity imports =	0.0E+00	kwh/yr	EIA, International Energy Annual 2002
	Electricity imports =	0.0E+00	J/yr	Use(kwh/yr) * 3.6e6 J/kwh
	Electricity TRF =	2.9E+05	sej/J	Odum, 1996, average from several types of power plants
52	Service in exports			
	Dollar value of all imports =	2.0E+08	$/yr	UN, COMTRADE
	Country sej/$ used as TRF =	3.4E+13	sej/$	Sweeney et al, 2006

Appendix D

Summary flows and indices for 12 West African economies

TABLE D.1

Summary flows and indices for 12 West African economies (c.a. 2000).

		Focal nations					West African nations less reliant on drylands resources						
Code	Summary flows	Burkina Faso	Mali	Mauritania	Niger	Senegal	Benin	Cameroon	Cote d'Ivoire	Ghana	Guinea	Nigeria	Sierra Leone
R	Renewable flow, E20 sej/yr	309.6	703.8	530.9	432.0	471.8	189.9	1,661.3	765.7	611.1	650.1	1,935.7	345.5
N	Nonrenewable indigenous, E20 sej/yr	101.2	130.3	694.8	98.1	197.1	115.0	569.6	326.0	1,328.8	523.9	6,156.8	56.8
N0	Dispersed nonrenewable, E20 sej/yr	100.7	130.0	45.2	84.4	70.6	112.9	365.9	259.1	127.0	48.8	857.5	54.6
N1	Concentrtated nonrenew use, E20 sej/yr	0.5	0.2	19.9	13.5	97.0	2.1	87.9	49.1	726.4	306.0	796.8	2.3
N2	Nonrenew export without use, E20 sej/yr	0.0	0.0	629.7	0.1	29.5	0.0	115.7	17.8	475.4	169.1	4,502.4	0.0
F(i)	Imported fuel, mineral, metal, E20 sej/yr	41.5	45.6	58.9	20.1	118.4	64.0	51.7	234.9	192.7	42.0	683.5	105.0
G(i)	Imported goods (incl. elec), E20 sej/yr	26.9	32.2	11.1	23.3	63.4	42.4	82.5	150.1	260.5	25.1	504.2	97.3
I	Dollars paid for Imports, E6 $/yr	548.4	618.9	359.9	384.6	1,511.8	467.3	1,468.6	2,481.9	2,695.5	460.9	5,749.2	2,13.5
P2I	Emergy of services in Imports, E20 sej/yr	14.5	16.3	9.5	10.2	39.9	12.3	38.8	65.5	71.2	12.2	151.8	5.6
F(e)	Exported fuel, mineral, metal, E20 sej/yr	0.9	0.5	629.8	0.5	42.4	4.2	165.1	158.2	505.8	169.6	4563.8	0.5
G(e)	Exported goods, E20 sej/yr	20.6	20.2	21.1	38.9	68.2	29.6	18.4	169.2	85.4	30.1	19.3	3.2
E	Dollars received for exports, E6 $/yr	174.5	196.0	403.1	330.4	613.7	182.6	1,722.8	3,593.2	997.7	425.9	27,079.2	41.4
P1E	Emergy of services in exports, E20 sej/yr	39.3	74.4	302.6	107.2	120.8	34.3	425.1	512.8	398.6	150.7	3,159.8	39.8

TABLE D.1 *continued*

Summary flows and indices for 12 West African economies (c.a. 2000).

		Focal nations					West African nations less reliant on drylands resources						
Code	Summary flows	Burkina Faso	Mali	Mauritania	Niger	Senegal	Benin	Cameroon	Cote d'Ivoire	Ghana	Guinea	Nigeria	Sierra Leone
X	GDP, E6 $/yr	2,191.9	2,443.2	899.9	1,798.4	4,373.7	2,255.0	9,273.5	10,681.5	4,977.6	3,063.5	42,245.7	635.9
P2	World emergy/$ ratio, E12 sej/$	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
P1	Country emergy/$ ratio, E12 sej/$	22.5	38.0	75.1	32.5	19.7	18.8	24.7	14.3	40.0	35.4	11.7	96.0

		Focal nations					West African nations less reliant on drylands resources						
Code	Indices	Burkina Faso	Mali	Mauritania	Niger	Senegal	Benin	Cameroon	Cote d'Ivoire	Ghana	Guinea	Nigeria	Sierra Leone
IMP	Flow of imported emergy, E20 sej/yr	83	94	79	54	222	119	173	451	524	79	1,339	208
U	Total emergy use, U, E20 sej/yr	494	928	675	584	861	424	2,288	1,524	1,989	1,084	4,930	610
EXP	Total exported emergy, E20 sej/yr	68	111	995	152	242	70	635	867	1,030	354	7,828	47
%indg	Fraction of use from indigenous source	0.83	0.90	0.88	0.91	0.74	0.72	0.92	0.70	0.74	0.93	0.73	0.66
EXP: IMP	Export to imports	0.82	1.18	12.52	2.83	1.09	0.59	3.67	1.93	1.96	4.46	5.84	0.23
%R	Fraction of use, locally renewable	0.63	0.76	0.79	0.74	0.55	0.45	0.73	0.50	0.31	0.60	0.39	0.57
%free	Fraction of use that is free	0.83	0.90	0.85	0.88	0.63	0.71	0.89	0.67	0.37	0.64	0.57	0.66
Conc: rural	Ratio of concentrated to rural	0.20	0.11	0.17	0.13	0.59	0.40	0.13	0.49	1.69	0.55	0.76	0.53
U/area	Use per area, empower density, E9 sej/m^2	180	76	66	46	448	383	487	479	861	441	541	852
R/area	Renew per area, renew density, E9 sej/m^2	113	58	52	34	246	172	354	241	265	264	213	482
U/cap	Use per person, E9 sej/capita	4.1	7.8	25.5	5.4	9.2	6.8	15.1	9.6	10.2	13.4	4.3	13.8
CC	Renew carry capacity,present living std., E6#	7.5	9.0	2.1	8.0	5.1	2.8	11.0	7.9	6.0	4.9	45.1	2.5
%elec	Ratio of electricity to use	0.02	0.09	0.03	0.05	0.03	0.00	0.01	0.01	0.01	0.02	0.02	0.01

		Focal nations					West African nations less reliant on drylands resources						
Code	Indices	Burkina Faso	Mali	Mauritania	Niger	Senegal	Benin	Cameroon	Cote d'Ivoire	Ghana	Guinea	Nigeria	Sierra Leone
fuel/cap	Fuel use per person, E12 sej/capita	174	90	1,884	155	805	517	483	1,197	516	281	674	324
EIR	Investment Ratio, imports/indigenous	0.20	0.11	0.13	0.10	0.35	0.39	0.08	0.42	0.36	0.08	0.37	0.52
ELR	Environmental loading ratio, (NR use)/R	0.59	0.32	0.27	0.35	0.83	1.23	0.38	0.99	2.25	0.67	1.55	0.77
EYR	Yield ratio, total use / nonrenew use	2.68	4.14	4.67	3.85	2.21	1.81	3.65	2.01	1.44	2.50	1.65	2.30
ESI	ESI, Emergy Sustainability Index	4.51	12.97	17.16	10.98	2.68	1.47	9.68	2.03	0.64	3.74	1.06	3.01
%soil	Fraction of use that is soil loss	0.20	0.12	0.06	0.14	0.03	0.04	0.07	0.01	0.01	0.01	0.07	0.03
ABR	Agriculture benefit ratio	1.65	1.87	1.09	1.82	10.18	4.95	0.65	12.71	7.89	6.73	5.12	1.59

Appendix E

Definitions of Indicators[3]

AGGREGATE INDICES

1. **Ecological footprint** The ecological footprint (EF) is a national index of natural resource consumption reported in the number of global hectares (a hectare with the average biological productivity for a hectare on Earth) it would take to support one person from that nation. The Total EF includes the amount of built-up land, the amount of water withdrawn, and the area required to provide and absorb the waste from food, timber and energy consumption. For example, the EF for a country includes the biocapacity needed to sequester the carbon produced by that country from the burning of fossil fuels. The EF does not include waste flows for which there is no limit considered sustainable (e.g. heavy metals, plutonium, CFCs, dioxins) or for which there is currently no reliable data on the wastes impact (e.g. acid rain). A higher EF corresponds to a higher consumption of resources per person (Loh and Wackernagel, 2004). This index and its component indicators were calculated using data from the year 2001.
2. **Ecosystem Well-being Index** See description of the Well-being Index.
3. **Human Development Index** The Human Development Index (HDI) is a measure of a country's average achievement in human development based upon a long and healthy life (life expectancy at birth), knowledge (adult literacy rate and gross enrolment ratio) and standard of living (Gross Domestic Product per capita). Each indicator's range is transformed to a scale from zero to one, with zero being the minimum value and one being the maximum value for each indicator for a specific year. Countries are given a score in each of the three categories (Life Expectancy Index, Education Index and GDP Index). These scores are then averaged to determine the HDI. The higher a country's HDI, the higher its level of human development. Countries are also ranked and classified by their HDI as countries of "high" (reclassified as 3), "medium" (reclassified as 2) or "low" (reclassified as 1) human development (Flanders and Ross-Larson, 2002). This index and its component indicators were calculated using data from the year 2000.
4. **Human Well-being Index** See description of the Well-being Index.
5. **Well-being Index** The Well-being Index (WI) is similar to the ESI. It is based on the concept that ecosystem well-being and human well-being should be measured separately, then equally weighted and considered together. Countries are given performance scores from zero to 100 for both aspects of well-being. These performance scores are separately called the Human Well-being Index (HWI) and Ecosystem Well-being Index (EWI). The HWI is a composite of indicators in the five categories of health and population, wealth, knowledge and culture, community and equity. The EWI is composed of indicators in the five categories of land, water, air, species and genes and resource use. HWI and EWI are then averaged to determine a country's WI. A high WI corresponds to a high total well-being (Prescott-Allen, 2001). These indices were calculated using data from the most recent year available.
6. **Yale Environmental Sustainability Index** The Yale Environmental Sustainability Index (YESI) is a measure of a country's environmental health and history, resource use and institutional mechanisms to change society's environmental and resource use trajectory. The index is based on five components (state of environmental systems, stress on those systems, human vulnerability to environmental change, social and institutional capacity to cope with stresses, and contribution to global stewardship) derived from 21 indicators considered fundamental to

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[3] The following definitions are taken directly from their respective sources and computed using data from the year 2000 unless otherwise noted

sustainability (e.g. water quality, reducing air pollution, basic human sustenance, science and technology). Seventy-six variables are transformed to comparable scales, then aggregated and used to score countries in these 21 indicator categories. The 21 indicators are weighted equally and then averaged to determine a country's ESI. The ESI score is meant to quantify a country's ability to avoid environmental deterioration. The higher a country's ESI score, the more likely it is to maintain environmental health and resources in the future (Esty et al, 2005). This index and its component indicators were calculated using data from the most recent year available.

SOCIAL, ECONOMIC, GOVERNMENTAL AND ENVIRONMENTAL INDICATORS

1. **Adult literacy rate (% age 15 yrs and above)** The percentage of people aged 15 and above who can, with understanding, both read and write a short, simple statement on their everyday life (Flanders and Ross-Larson, 2002).
2. **Age dependency ratio (dependents to working-age population)** Age dependency ratio is the ratio of dependents – people younger than 15 and older than 64 – to the working-age population – those ages 15–64. For example, 0.7 means there are 7 dependents for every 10 working-age people (The World Bank Group, WDI Online, 2005).
3. **Agriculture, value added (% of GDP)** Agriculture corresponds to ISIC divisions 1–5 and includes forestry, hunting, and fishing, as well as cultivation of crops and livestock production. Value added is the net output of a sector after adding up all outputs and subtracting intermediate inputs. It is calculated without making deductions for depreciation of fabricated assets or depletion and degradation of natural resources. The origin of value added is determined by the International Standard Industrial Classification (ISIC), revision 3 (The World Bank Group, WDI Online, 2005).
4. **Aid per capita (current US$)** Aid per capita includes both official development assistance (ODA) and official aid, and is calculated by dividing total aid by the midyear population estimate (The World Bank Group, WDI Online, 2005).
5. **Arms exports (constant 1990 US$)** Arms transfers cover the supply of military weapons through sales, aid, gifts, and those made through manufacturing licenses. Data cover major conventional weapons such as aircraft, armored vehicles, artillery, radar systems, missiles, and ships designed for military use. Excluded are transfers of other military equipment such as small arms and light weapons, trucks, small artillery, ammunition, support equipment, technology transfers, and other services (The World Bank Group, WDI Online, 2005).
6. **Arms imports (constant 1990 US$)** Arms transfers cover the supply of military weapons through sales, aid, gifts, and those made through manufacturing licenses. Data cover major conventional weapons such as aircraft, armored vehicles, artillery, radar systems, missiles, and ships designed for military use. Excluded are transfers of other military equipment such as small arms and light weapons, trucks, small artillery, ammunition, support equipment, technology transfers, and other services (The World Bank Group, WDI Online, 2005).
7. **Average interest (%)** Interest represents the average interest rate on all new public and publicly guaranteed loans contracted during the year. To obtain the average, the interest rates for all public and publicly guaranteed loans have been weighted by the amounts of the loans. Public debt is an external obligation of a public debtor, including the national government, a political subdivision (or an agency of either), and autonomous public bodies. Publicly guaranteed debt is an external obligation of a private debtor that is guaranteed for repayment by a public entity (The World Bank Group, GDF Online, 2005).
8. **CO_2 emissions (metric tons per capita)** Carbon dioxide emissions are those stemming from the burning of fossil fuels and the manufacture of cement. They include contributions to the carbon dioxide produced during consumption of solid, liquid, and gas fuels and gas flaring (The World Bank Group, WDI Online, 2005).
9. **Combined primary, secondary and tertiary gross enrollment ratio (%)** The gross enrollment ratio is the number of students enrolled in a level of education, regardless of age, as a percentage of the population of official school age for that level (Flanders and Ross-Larson, 2002). Data for this indicator is from the year 1999.
10. **Combustible renewables and waste (% of total energy)** Combustible renewables and waste comprise solid biomass, liquid biomass,

biogas, industrial waste, and municipal waste, measured as a percentage of total energy use (The World Bank Group, WDI Online, 2005).

11. **Current account balance (% of GDP)** Current account balance is the sum of net exports of goods, services, net income, and net current transfers (The World Bank Group, WDI Online, 2005).
12. **Debt outstanding (LDOD), total long-term (US$)** Long-term debt outstanding and disbursed (LDOD) is the total outstanding long-term debt at year end. Long-term external debt is defined as debt that has an original or extended maturity of more than one year and that is owed to nonresidents and repayable in foreign currency, goods, or services. Long-term debt has three components: public debt, which is an external obligation of a public debtor, including the national government, a political subdivision (or an agency of either), and autonomous public bodies; publicly guaranteed debt, which is an external obligation of a private debtor that is guaranteed for repayment by a public entity; private nonguaranteed external debt, which is an external obligation of a private debtor that is not guaranteed for repayment by a public entity. Public and publicly guaranteed long-term debt are aggregated (The World Bank Group, GDF Online, 2005).
13. **Debt service (LTDS), total long-term (US$)** Long-term debt service payments (LTDS) are the sum of principal repayments and interest payments in the year specified. Long-term external debt is defined as debt that has an original or extended maturity of more than one year and that is owed to nonresidents and repayable in foreign currency, goods, or services (The World Bank Group, GDF Online, 2005).
14. **Disbursements, total long-term (DIS, US$)** Disbursements on long-term debt are drawings on loan commitments during the year specified. Long-term external debt is defined as debt that has an original or extended maturity of more than one year and that is owed to non-residents and repayable in foreign currency, goods, or services (The World Bank Group, GDF Online, 2005).
15. **Electric power consumption (kwh per capita)** Electric power consumption measures the production of power plants and combined heat and power plants, less distribution losses, and own use by heat and power plants (The World Bank Group, WDI Online, 2005).
16. **Electricity production from coal sources (% of total)** Sources of electricity refer to the inputs used to generate electricity. This indicator refers to the percentage generated from coal (The World Bank Group, WDI Online, 2005).
17. **Electricity production from oil sources (% of total)** Sources of electricity refer to the inputs used to generate electricity. Oil refers to crude oil and petroleum products (The World Bank Group, WDI Online, 2005).
18. **Employment in agriculture (% of total employment)** Employment in agriculture is the proportion of total employment recorded as working in the agricultural sector. Employees are people who work for a public or private employer and receive remuneration in wages, salary, commission, tips, piece rates, or pay in kind. Agriculture includes hunting, forestry, and fishing, corresponding to major division 1 (ISIC revision 2) or tabulation categories A and B (ISIC revision 3) (The World Bank Group, WDI Online, 2005).
19. **Employment in industry (% of total employment)** Employment in industry is the proportion of total employment recorded as working in the industrial sector. Employees are people who work for a public or private employer and receive remuneration in wages, salary, commission, tips, piece rates, or pay in kind. Industry includes mining and quarrying (including oil production), manufacturing, electricity, gas and water, and construction, corresponding to major divisions 2–5 (ISIC revision 2) or tabulation categories C–F (ISIC revision 3) (The World Bank Group, WDI Online, 2005).
20. **Employment in services (% of total employment)** Employment in services is the proportion of total employment recorded as working in the services sector. Employees are people who work for a public or private employer and receive remuneration in wages, salary, commission, tips, piece rates, or pay in kind. Services include wholesale and retail trade and restaurants and hotels; transport, storage, and communications; financing, insurance, real estate, and business services; and community, social, and personal services, corresponding to divisions 6–9 (ISIC revision 2) or tabulation categories G–P (ISIC revision 3) (The World Bank Group, WDI Online, 2005).
21. **Expenditure per student, primary (% of GDP per capita) Public expenditure per student**

(primary) is the public current spending on education divided by the total number of students by level, as a percentage of GDP per capita (The World Bank Group, WDI Online, 2005).

22. **Fertilizer consumption (100 grams per hectare of arable land)** Fertilizer consumption (100 grams per hectare of arable land) measures the quantity of plant nutrients used per unit of arable land. Fertilizer products cover nitrogenous, potash, and phosphate fertilizers (including ground rock phosphate). The time reference for fertilizer consumption is the crop year (July through June). Arable land includes land defined by the FAO as land under temporary crops (double-cropped areas are counted once), temporary meadows for mowing or for pasture, land under market or kitchen gardens, and land temporarily fallow. Land abandoned as a result of shifting cultivation is excluded (The World Bank Group, WDI Online, 2005).
23. **Food production index (1999–2001 = 100)** Food production index covers food crops that are considered edible and that contain nutrients. Coffee and tea are excluded because, although edible, they have no nutritive value (The World Bank Group, WDI Online, 2005).
24. **Forest area (% of land area)** Forest area is land under natural or planted stands of trees, whether productive or not (The World Bank Group, WDI Online, 2005).
25. **GDP per capita (constant 2000 US$)** GDP per capita is gross domestic product divided by midyear population. GDP is the sum of gross value added by all resident producers in the economy plus any product taxes and minus any subsidies not included in the value of the products. It is calculated without making deductions for depreciation of fabricated assets or for depletion and degradation of natural resources. Data are in constant U.S. dollars (The World Bank Group, WDI Online, 2005).
26. **GDP per capita (PPP US$)** GDP is the total output of goods and services for final use produced by an economy, by both residents and non-residents, regardless of the allocation to domestic and foreign claims. It does not include deductions for depreciation of physical capital or depletion and degradation of natural resources. PPP (Purchasing Power Parity) is a rate of exchange that accounts for price differences across countries, allowing international comparisons of real output and incomes. At the PPP US$ rate (as used in this Report), PPP US$1 has the same purchasing power in the domestic economy as $1 has in the United States (Flanders and Ross-Larson, 2002).
27. **GDP per capita rank minus HDI rank** See description of HDI in Appendix A (Flanders and Ross-Larson, 2002).
28. **GNI per capita, Atlas method (current US$)** GNI per capita (formerly GNP per capita) is the gross national income, converted to U.S. dollars using the World Bank Atlas method, divided by the midyear population. GNI is the sum of value added by all resident producers plus any product taxes (less subsidies) not included in the valuation of output plus net receipts of primary income (compensation of employees and property income) from abroad. GNI, calculated in national currency, is usually converted to U.S. dollars at official exchange rates for comparisons across economies, although an alternative rate is used when the official exchange rate is judged to diverge by an exceptionally large margin from the rate actually applied in international transactions. To smooth fluctuations in prices and exchange rates, a special Atlas method of conversion is used by the World Bank. This applies a conversion factor that averages the exchange rate for a given year and the two preceding years, adjusted for differences in rates of inflation between the country, and through 2000, the G-5 countries (France, Germany, Japan, the United Kingdom, and the United States) (The World Bank Group, WDI Online, 2005).
29. **Health expenditure per capita (current US$)** Total health expenditure is the sum of public and private health expenditures as a ratio of total population. It covers the provision of health services (preventive and curative), family planning activities, nutrition activities, and emergency aid designated for health but does not include provision of water and sanitation. Data are in current U.S. dollars (The World Bank Group, WDI Online, 2005).
30. **Hospital beds (per 1,000 people)** Hospital beds include in-patient beds available in public, private, general, and specialized hospitals and rehabilitation centers. In most cases beds for both acute and chronic care are included (The World Bank Group, WDI Online, 2005).
31. **Household final consumption expenditure per capita (constant 2000 US$)** Household final consumption expenditure per capita (private consumption per capita) is calculated using private consumption in constant 2000

prices and World Bank population estimates. Household final consumption expenditure is the market value of all goods and services, including durable products (such as cars, washing machines, and home computers), purchased by households. It excludes purchases of dwellings but includes imputed rent for owner-occupied dwellings. It also includes payments and fees to governments to obtain permits and licenses. Here, household consumption expenditure includes the expenditures of nonprofit institutions serving households, even when reported separately by the country. Data are in constant 2000 U.S. dollars (The World Bank Group, WDI Online, 2005).

32. **International migration stock (% of population)** Migration stock is the number of people born in a country other than that in which they live. It also includes refugees (The World Bank Group, WDI Online, 2005).
33. **Internet users (per 1,000 people)** Internet users are people with access to the worldwide network (The World Bank Group, WDI Online, 2005).
34. **Land use, arable land (% of land area)** Arable land includes land defined by the FAO as land under temporary crops (double-cropped areas are counted once), temporary meadows for mowing or for pasture, land under market or kitchen gardens, and land temporarily fallow. Land abandoned as a result of shifting cultivation is excluded (The World Bank Group, WDI Online, 2005).
35. **Land use, arable land (hectares per person)** Arable land (hectares per person) includes land defined by the FAO as land under temporary crops (double-cropped areas are counted once), temporary meadows for mowing or for pasture, land under market or kitchen gardens, and land temporarily fallow. Land abandoned as a result of shifting cultivation is excluded (The World Bank Group, WDI Online, 2005).
36. **Land use, irrigated land (% of cropland)** Irrigated land refers to areas purposely provided with water, including land irrigated by controlled flooding. Cropland refers to arable land and land used for permanent crops (The World Bank Group, WDI Online, 2005).
37. **Life expectancy at birth (years)** The number of years a newborn infant would live if prevailing patterns of age-specific mortality rates at the time of birth were to stay the same throughout the child's life (Flanders and Ross-Larson, 2002).
38. **Military expenditure (% of GDP)** Military expenditures are based on the NATO definition, which includes all current and capital expenditures on the armed forces, including peacekeeping forces; defence ministries and other government agencies engaged in defence projects; paramilitary forces, if these are judged to be trained and equipped for military operations; and military space activities. Such expenditures include military and civil personnel, including retirement pensions of military personnel and social services for personnel; operation and maintenance; procurement; military research and development; and military aid (in the military expenditures of the donor country). Excluded are civil defense and current expenditures for previous military activities, such as for veterans' benefits, demobilization, conversion, and destruction of weapons. This definition cannot be applied for all countries, however, since that would require much more detailed information than is available about what is included in military budgets and off-budget military expenditure items (The World Bank Group, WDI Online, 2005).
39. **Organic water pollutant (BOD) emissions (kg per day per worker)** Emissions per worker are total emissions of organic water pollutants divided by the number of industrial workers. Organic water pollutants are measured by biochemical oxygen demand, which refers to the amount of oxygen that bacteria in water will consume in breaking down waste. This is a standard water-treatment test for the presence of organic pollutants (The World Bank Group, WDI Online, 2005).
40. **Out-of-pocket health expenditure (% of private expenditure on health)** Out-of-pocket expenditure is any direct outlay by households, including gratuities and in-kind payments, to health practitioners and suppliers of pharmaceuticals, therapeutic appliances, and other goods and services whose primary intent is to contribute to the restoration or enhancement of the health status of individuals or population groups. It is a part of private health expenditure (The World Bank Group, WDI Online, 2005).
41. **Percent of population living with HIV/AIDS in 2001** The estimated number of people living with HIV/AIDS at the end of the year specified (United Nations Program on HIV/AIDS 2004). Data for this indicator is from the year 2001.

42. **Permanent pasture (% of land area)** Permanent pasture is land used for five or more years for forage crops, either cultivated or growing wild. Total land area is a country's total area, excluding area under inland water bodies. In most cases the definition of inland water bodies includes major rivers and lakes (The World Bank Group, WDI Online, 2005).
43. **Population ages 0–14 (% of total)** Population ages 0–14 is the percentage of the total population that is in the age group 0–14 (The World Bank Group, WDI Online, 2005).
44. **Population ages 15–64 (% of total)** Population ages 15–64 is the percentage of the total population that is in the age group 15–64 (The World Bank Group, WDI Online, 2005).
45. **Population ages 65 and above (% of total)** Population ages 65 and above is the percentage of the total population that is 65 or older (The World Bank Group, WDI Online, 2005).
46. **Population below income poverty line (%) $1/day (1993 PPP US$) 1983–2000** The percentage of the population living below $1 a day – at 1985 international prices (equivalent to $1.08 at 1993 international prices), adjusted for Purchasing Power Parity (Flanders and Ross-Larson, 2002). Data for this indicator is from the years 1983–2000.
47. **Population below income poverty line (%) $2/day (1993 PPP US$) 1983–2000** The percentage of the population living below $2 a day – at 1985 international prices (equivalent to $2.16 at 1993 international prices), adjusted for Purchasing Power Parity (Flanders and Ross-Larson, 2002). Data for this indicator is from the years 1983–2000.
48. **Population not using improved water sources (%)** The proportion of the population not using any of the following types of water supply for drinking: piped water, a public tap, a borehole with a pump, a protected well, a protected spring or rainwater (Flanders and Ross-Larson, 2002).
49. **PPP conversion factor to official exchange rate ratio** Purchasing power parity conversion factor is the number of units of a country's currency required to buy the same amount of goods and services in the domestic market as a U.S. dollar would buy in the United States. Official exchange rate refers to the exchange rate determined by national authorities or to the rate determined in the legally sanctioned exchange market. It is calculated as an annual average based on monthly averages (local currency units relative to the U.S. dollar) (The World Bank Group, WDI Online, 2005).
50. **Ratio of girls to boys in primary and secondary education (%)** Ratio of girls to boys in primary and secondary education is the percentage of girls to boys enrolled at primary and secondary levels in public and private schools (The World Bank Group, WDI Online, 2005).
51. **Refugee population by country or territory of asylum per capita** Refugees are people who are recognized as refugees under the 1951 Convention Relating to the Status of Refugees or its 1967 Protocol, the 1969 Organization of African Unity Convention Governing the Specific Aspects of Refugee Problems in Africa, people recognized as refugees in accordance with the UNHCR statute, people granted a refugee-like humanitarian status, and people provided with temporary protection. Asylum seekers are people who have applied for asylum or refugee status and who have not yet received a decision or who are otherwise registered as asylum seekers. Country of asylum is the country where an asylum claim was filed (The World Bank Group, WDI Online, 2005). Refugees were divided by population to acquire refugees per capita.
52. **Refugee population by country or territory of origin per capita** Refugees are people who are recognized as refugees under the 1951 Convention Relating to the Status of Refugees or its 1967 Protocol, the 1969 Organization of African Unity Convention Governing the Specific Aspects of Refugee Problems in Africa, people recognized as refugees in accordance with the UNHCR statute, people granted a refugee-like humanitarian status, and people provided with temporary protection. Asylum seekers are people who have applied for asylum or refugee status and who have not yet received a decision or who are otherwise registered as asylum seekers. Country of origin generally refers to the nationality or country of citizenship of a claimant (The World Bank Group, WDI Online, 2005). Refugees were divided by population to acquire refugees per capita.
53. **Rural population (% of total population)** Rural population is calculated as the difference between the total population and the urban population (The World Bank Group, WDI Online, 2005).
54. **Tax revenue (% of GDP)** Tax revenue refers to compulsory transfers to the central government for public purposes. Certain compulsory transfers

such as fines, penalties, and most social security contributions are excluded. Refunds and corrections of erroneously collected tax revenue are treated as negative revenue (The World Bank Group, WDI Online, 2005).

55. **Telephone average cost of call to US (US$ per three minutes)** Cost of international call to U.S. is the cost of a three-minute, peak rate, fixed line call from the country to the United States (The World Bank Group, WDI Online, 2005).
56. **Total debt (EDT)/GNI (%)** Total external debt to gross national product (The World Bank Group, GDF Online, 2005).
57. **Total debt stocks per capita (EDT/capita)** Total debt stocks (EDT) consists of public and publicly guaranteed long-term debt, private nonguaranteed long-term debt (whether reported or estimated by the staff of the World Bank), the use of IMF credit, and estimated short-term debt (The World Bank Group, GDF Online, 2005). EDT was divided by population to acquire EDT/capita.
58. **Underweight children under age five (%)** 1995–2000 Includes moderate and severe underweight, which is defined as below two standard deviations from the median weight for age of the reference population (Flanders and Ross-Larson, 2002). Data for this indicator is from 1995–2000.
59. **Unemployment, total (% of total labour force)** Unemployment refers to the share of the labour force that is without work but available for and seeking employment. Definitions of labour force and unemployment differ by country (The World Bank Group, WDI Online, 2005).

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Over the past several decades, increasing human population, economic development, and emergence of global markets, have resulted in immense pressures on natural resources, and these pressures are expected to intensify further over the next few decades. It is essential for sustainable policy that the costs of degradation of ecosystem services associated with development be incorporated into decision making and are not considered to be free. There is a growing need to include natural capital and ecosystem services in national accounting.

This report presents an environmental accounting framework based on a biophysical approach to quantifying values of ecosystem services. The foundation of the method (emergy analysis) is based on our understanding of energy and material flow through systems. Accounting for basic physical flows of energy and materials transformed in both environmental and economic processes permits a direct linkage with monetary valuation of environmental services and natural capital.

Detailed environmental accounting of 134 national economies is presented, with a strong emphasis on the dryland countries of West Africa, where the rural poor are especially dependent on environmental resources. Environmental accounting is used for: (i) understanding the comparative resource basis of nations, (ii) determining the value of global losses of natural capital, (iii) quantifying links between a nation's resource basis and indicators of human welfare, and (iv) examining implications of biophysical valuation on international trade and debt.

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