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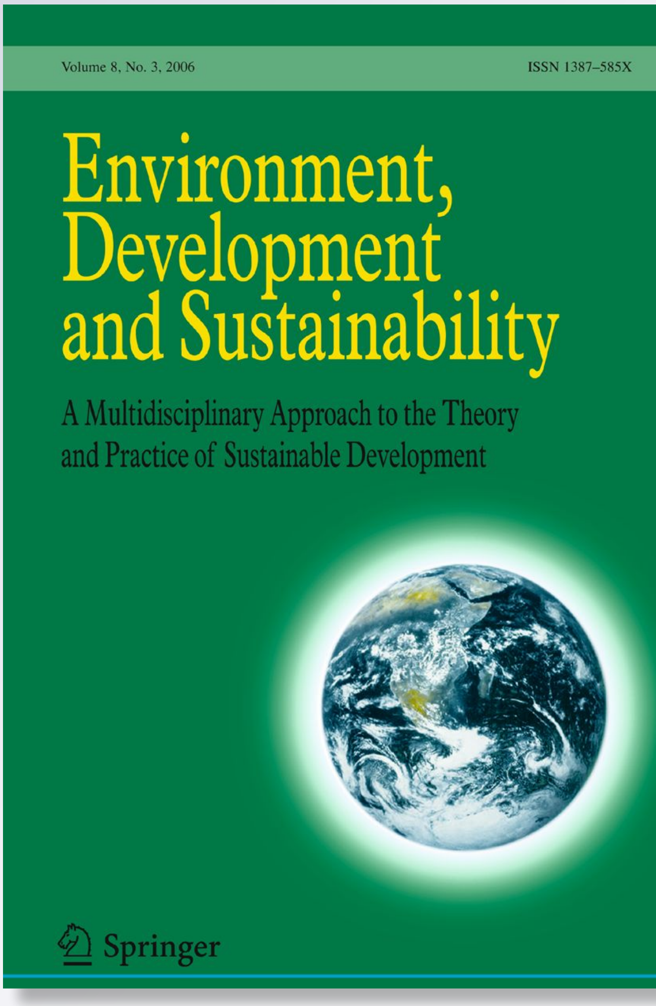

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Abstract The National Forests of the United States encompass 192.7 million acres (78 million hectares) of land, which is nearly five percent of the total land area of the nation. These lands are managed by the US Forest Service (USFS) for multiple uses, including extraction of timber, production of fossil fuels and minerals, public recreation, and the preservation of biodiversity, clean air, water, and soils. The USFS is interested in valuing the natural capital within, and the ecosystem services provided by, their lands. This is in part to justify expenditures in a time of limited resources. We used emergy and an environmental accounting approach, to quantify the ecosystem services, the exported environmental goods and information provided by National Forest System (NFS) lands, and the natural capital residing on those lands. Environmental accounting using emergy provides a method to value these flows of services and storages of capital using a common biophysical unit, the solar emjoule and its monetary equivalent the emdollar. We compare emdollar values to economic values gleaned from the literature. In 2005, the ecosystem services provided by USFS lands were equivalent to 197 billion emdollars, and the value of NFS natural capital was 24.3 trillion emdollars. Our evaluation suggests that the Federal Government budget allocation for the NFS ($5.55E+09 in 2005) was well spent, protecting 24.3 trillion emdollars in natural capital and insuring annual ecosystem services totaling 197 billion emdollars. Monetary values for some natural capital and ecosystem services are similar to emergy-derived values (resources like fish, wildlife, water, and firewood extracted from forests), and others are widely different (biodiversity, fossil, and mineral resources). There is large uncertainty associated with computing the environment's contributions to society whether using emergy or accepted economic techniques; yet, the magnitude of these emergy-derived estimates suggests that even with the uncertainty, the values are significant and monetary expenditures for the Forest Service are justified.

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1 Introduction

Increasingly government agencies like the United States Forest Service (USFS) are asked to provide documentation of the benefits to society derived from the expenditure of their annual monetary budgets. While it is relatively easy to account for monetary expenditures for goods and services in support of operations and the economic returns that result from them, such as the sale of timber or other material resources, it is more difficult to evaluate less tangible products such as the ecosystem services or the natural capital inherent in the forests and grasslands of the National Forest System (NFS). Because society benefits from ecosystem services and the natural capital from which they flow, and since to date the values of these resources within the NFS have not been well documented, it is most appropriate to answer the following question: "What is the value of the total assets (including both economic and natural capital) and ecosystem services provided by the US National Forest System?"

The US National Forests are coupled human and natural systems, thereby adding complexity to management strategies that must address multiple uses from timber extraction to the provision of recreational activities for people. Facing increased pressure to demonstrate a sound quantitative basis for management decisions, agencies of the government whose functions are environmental protection and preservation, as well as the wise use of resources requires methodologies that can account for both economic values and biophysical values within the same evaluative framework.

1.1 The United States Forest Service System

The United States Forest Service, part of the US Department of Agriculture, is responsible for 155 National Forests and 20 Grasslands totaling 192.7 million acres (78 million hectares) of public land in 44 states and Puerto Rico (USFS 2001). National forests cover about 5 % of the total area of the United States. In addition, they comprise roughly a quarter of all "natural" habitats in the United States and are vital for the survival of many endangered and threatened species. Virtually, every habitat type of the United States is contained within NFS lands, from the Redwoods of northern California to the prairie potholes of North Dakota. The NFS is organized into nine regions throughout the country, and these nine regions are further divided into 600 ranger districts. The emergy evaluation of the NFS was conducted by evaluating each region and then summing results to obtain overall values for the NFS as a whole.

1.2 Evaluation approach

In this study, we take a biocentric approach to valuation based on intrinsic ecological values. We use the emergy accounting framework and compare computed values of ecosystem services and natural capital in emergy with instrumental values derived from preference-based approaches, where appropriate. Emergy is the available energy (exergy) of one form required directly and indirectly to produce a good or service (Odum 1996).

The emergy accounting methodology uses the thermodynamic basis of all forms of energy and materials, but converts them into equivalents of one form of energy, usually sunlight (see Table 1 for definitions of other terminology). To compare emergy values with economic values, we express emergy in its monetary equivalent, the emdollar, since most people are familiar with money as a unit of accounts.

Recent discussions of the need for valuation methods highlight the debate in the conservation community regarding the complementarity or lack thereof of intrinsic versus instrumental values (TEEB 2010). Our purpose in this study is not to further the debate or to solve it, but rather to provide a detailed biophysical evaluation of ecosystem services and natural capital of the US Forest System as a case study and to address questions of the benefits derived from them compared to the economic costs of maintaining and managing them. In addition, we compare emergy-derived values with preference-based values, where these values exist, to highlight the potential complementarity of these two approaches not as a means of suggesting substitutability, since each approach evaluates very different facets of ecosystem services and natural capital. Preference-based values are instrumental values, derived from their usefulness in achieving a goal, whereas emergy focuses on valuation of the intrinsic properties of ecosystems that exist independently of any such contribution. Combined, both approaches provide complementary information, which may aid in policy formation and management.

1.3 Previous studies of Forest Systems

Krieger (2001) in a report to the Wilderness Society compiled over thirty economic studies valuing ecosystem services from forests. The methodologies used in these studies varied over the many accepted ways to indirectly measure society's willingness to pay for ecosystem services, resulting in a range of economic values for similar or even the same service, depending on the method used.

Other studies of forest systems using emergy synthesis have documented values of ecosystem services. Odum (1995) evaluated tropical forests at different scales, comparing

Table 1 Relevant terminology and definitions

Term	Definition
Ecosystem service	Benefit that people derive from nature, either passively or actively
Natural capital	A storage within the environment, provided by nature
Emergy	The available energy of one kind that is used up in transformations directly and indirectly to make a product or service
Solar emjoule (seJ)	The unit of emergy, a solar equivalent joule. Solar is the most diffuse energy, thus the logical base unit
Unit emergy value	The cumulative available energy (emergy) used to create one unit of matter, available energy, information, etc.
Empower	Emergy per unit time
Emergy intensity of currency (EIC)	Ratio of emergy supporting an economic system to the dollars circulating in the same economic system (units = seJ/$)
Emdollar (^{em}$)	The US dollar equivalent of emergy, computed by multiplying emergy by the EIC.

economic values to the intrinsic values using an emergy-based approach and suggested an optimum use level that balanced economic gain and the environmental values of the forest. Tilley and Swank (2003) used emergy synthesis to compare ecosystem services and economic outputs of the Wine Spring Creek watershed, a high-elevation (1,600 m), temperate forest located in the southern Appalachian Mountains of North Carolina, USA, revealing that the value of direct economic outputs was an order of magnitude less than both the ecological and social benefits. Doherty (1995) evaluated forests from several locations (Florida, Sweden, Puerto Rico, Thailand, and Papua New Guinea) and under varying uses with multiple outputs such as pulp and paper production, biomass for electricity production, fuel wood production, carbon sequestration, water supply, reforestation, and tourism.

2 Methods

In this study, the emergy accounting technique (Odum 1996; Brown and Ulgiati 2004) was used to quantitatively evaluate ecosystem services and capital assets of the NFS and to gain insight into the relative importance of the various components of services and assets. The storages (natural capital) and primary ecological processes (ecosystem services) of the entire NFS were evaluated. Because of the differences between regions in both driving inputs and natural capital, it was necessary to evaluate, separately, the individual regions and then sum across all regions to compute totals for the NFS.

2.1 Emergy evaluation of flows supporting the National Forest System

Spatial and temporal boundaries of the synthesis

The spatial boundaries were defined by the extent of NFS lands and the economic assets (roads, buildings, and machinery) and the natural capital (mineral resources, tree biomass, and miscellaneous natural resources) contained within them. Since we were evaluating the entire National Forest *System*, including its economic assets, the system boundary also included the Washington DC offices of the NFS. For the NFS lands that bordered an ocean, the boundary included the adjacent continental shelf area extending out 1 km from the shore. One kilometer was used as an estimate of the region of the continental shelf contributing to the onshore ecosystem. The vertical stratum of each system was 1,000 m above the highest ground elevation, and the depth included the mineral deposits and/or aquifers below the surface to a depth of 1 km.

To account for the wide regional diversity of climatic inputs and productivity as well as resource storages such as geological structures, soils, and biomass, we evaluated the nine individual region areas of the NFS and then sum across all regions to compute total emergy inputs, environmental services and natural capital to the entire NFS. Emergy evaluation tables were constructed for each region, and data were collected for each region from NFS regional databases. Details of data accusation and computations are given below.

Evaluation of flows

This evaluation of the NFS was conducted for the year 2005, the most recent year with nearly complete data records. In some cases, where data for 2005 were not available, data from an earlier year or a 10-year average were used and stated in the notes to emergy evaluation tables. The annual flows of energy, resources, and information supporting the NFS were those that crossed the system boundary (inputs) as well as resources that were extracted from and used within the NFS lands. The outputs from the NFS lands were also evaluated.

Tables of the actual flows of materials, labor, and energy supporting the NFS by region were constructed using an Energy Systems Language diagram of the system as a guide. Raw data for input flows (Joules, grams, dollars, or other units) were converted into emergy using unit emergy values (UEVs), and the emergy of the inputs was summed to obtain the total emergy supporting the system. Inputs that came from the same source were not added, to avoid double counting. Tables of flows were evaluated per unit time (per year). Reserve storages, that is, natural capital storages with turnover times longer than a year, were evaluated in a separate table from flows.

Unit emergy values (UEVs)

UEVs are conversion coefficients whose units are solar emjoules (seJ) per unit mass, or seJ/J, or seJ/$, depending on the units of the raw flow that is to be converted to emergy. Unit emergy values resulting from previous emergy evaluations were used in this study to convert raw units to emergy. In some cases, the UEVs are based on only one evaluation; in other cases, several evaluations have been done of the same material or energy, but from different sources or processes and possibly using different technology. Where there are numerous UEVs for the same material or energy, an average value was used. All UEVs are calculated for the 15.83E+24 seJ/year global renewable emergy baseline.

The conversion of dollars to emergy, which was necessary to capture emergy expenditures for services (explained below), was based on the ratio of emergy to dollar flows supporting the US economy in 2005 (termed the emergy intensity of currency, [EIC]). The EIC relates economic activity to the supporting emergy flows and was computed by dividing the total emergy flow supporting the US economy in 2005 (Sweeney et al. 2007) by the US gross domestic product (GDP) for that year. The EIC was used to convert dollar expenditures for human service to emergy by multiplying dollars by the EIC. The EIC was also used to convert emergy of ecosystem services and natural capital to dollar equivalents for comparison with economic values.

Input energy, material, and service flows

Environmental (renewable) Flows—The environmental flows supporting the NFS system that were evaluated included solar insolation, wind, the chemical and geopotential energy of rain, the chemical potential energy of transpiration, tidal energy, wave energy, and geothermal energy. Since the renewable environmental flows supporting the NFS are distributed in space, we used spatial data and GIS coverages to calculate annual average spatially weighted flows of the inputs. Data sources for the renewable inputs were as follows: rain (NOAA 2006); tides (NOAA 2006); solar radiation (NREL 2006); geothermal heat (International Heat Flow Commission (IHFC) 2006); and elevation changes (USGS 2006a). Annual average spatially weighted renewable flows for each region were calculated using ArcGIS software. Point measurements of average wave height and tidal range for 2005 were taken from NOAA weather stations located in the continental shelf area adjacent to National Forests (Regions 5, 6, and 10). Annual inputs of renewable energy were multiplied by their appropriate UEV to obtain emergy of each flow. In keeping with the methodology as outlined in Odum (1996), to avoid double counting of renewable emergy input to the NFS, the primary sources of sunlight, tidal, and geothermal emergy were summed and compared to the largest of the secondary sources and the largest of either the summed primary or the secondary was used as the renewable emergy absorbed (R_a).

Purchased (nonrenewable) Flows—The purchased inputs to the NFS included goods such as herbicides and pesticides, fuel, machinery, electricity, and seedlings. These data were obtained from unpublished and published NFS documents and databases (USFS 2003, 2004, 2005, 2006a). Quantities of purchased inputs were multiplied by appropriate UEVs to obtain emergy of each flow. Where data were given only in a monetary form (seedlings and miscellaneous expenditures), the dollar values were converted to a representative emergy value using the EIC for the United States in 2005.

Purchased Services and Labor—We differentiate between labor and services using the convention that services are background labor inputs to products (i.e., embodied labor), while labor is foreground inputs (i.e., direct input of labor to the evaluated process). The emergy of services was quantified through dollar flows, while labor inputs were quantified by hours worked. Data were yearly values found in NFS documents (USFS 2004, 2006a, and unpublished 2006b). Dollar values were converted to emergy using the EIC of the United States in 2005 (Sweeney et al. 2007). The emergy of labor performed by NFS employees was computed using an estimate for number of hours worked based on the number of full- and part-time employees in each region and in the Washington D.C. office. The work hours were then multiplied by an average UEV (seJ per J) for hourly work in the US economy based on the total emergy required to support labor, updated from Odum (1996).

Tourism—The annual emergy input from tourist visitors to the NFS was calculated by region using the Joules of tourist metabolic energy expended while visiting the forest multiplied by an average UEV for a Joule of human metabolic energy (updated from Odum 1996). The yearly number of hours of visitation to each region (USFS 2004) was multiplied by the average number of Joules used by human metabolic activity per hour to obtain the total number of Joules of tourist activity used in a region in the given year.

Exports from NFS lands

The outputs from the NFS system were first expressed as emergy and then converted to emdollars (using the 2005 EIC) for comparison with economic values determined either directly from market prices or imputed from stated or revealed preference approaches. Economic value of recreation and timber was obtained directly from NFS documents. The economic value of minerals, fossil fuels, water, and peat was determined using market prices, while the economic value of hunting/fishing was estimated using non-market valuation methods. The emdollar values of outputs were calculated by multiplying their emergy value by the US 2005 EIC. Data sources and emergy evaluation of outputs were as follows:

Extracted Firewood and Timber—The mass of firewood estimated from unpublished NFS data. Harvested timber sales data quantified total harvest biomass, converted to dry weight and to emergy based on average for softwood.

Chemical and Geopotential Energy of Water—Computed from total volume of water leaving the National Forest System (Sedell et al. 2000) average elevation estimated from GIS topographic coverages and assumed 50 ppm dissolved solids in river discharge water.

Minerals and Fossil Fuels—Published data on extraction of minerals (USFS 2003) and fossil fuels (USFS 2005).

Harvested Wildlife and Fish—Wildlife hunting and fish harvest (total take) were computed by estimating the animals taken using data on the number of hours spent hunting or fishing on NFS lands and data on the average success rate per hour (USDI 2002).
Information (Research)—The estimate of exported information research was based on the number of NFS employees engaged in research (USFS 2006b) multiplied by the amount of time an employee works in a given year.

2.2 Emergy evaluation of the assets of the National Forest System

Both the natural capital and the economic fixed assets of the NFS were evaluated as follows:

Natural capital

Shrub and Herbaceous Biomass—COLE (Carbon On-Line Estimator) (NCASI 2006) was used to obtain an estimate for the mass of shrubs and herbaceous vegetation, as well as the mass of soil organic matter, in each of the forest types that occur in the 9 NFS regions. The carbon mass was converted to biomass based on carbon content of 45 % (Goodale 2002).
Surface Water—Surface water volume on NFS lands was from Sedell et al. 2000.
Land Area—Land area of NFS (Sedell et al. 2000)
Ground Water—Estimate of the water stored in aquifers under NFS lands was made using the online USGS Groundwater Atlas (USGS 2005) and gross estimates of aquifer characteristics.
Fish and Wildlife—Estimates of the biomass of fish and wildlife on NFS lands (by region) were made using carbon flux and turnover time of trophic levels. A trophic network analysis of a representative trophic chain from primary producers through top carnivores was constructed (EcoNetwrk 2006), and using an estimate of primary production, by region, with typical transfer efficiencies between trophic levels, carbon flux was computed. Transfer efficiencies were as follows: 3 % energy transfer from primary producers to herbivores and primary consumers (insects) and 10 % energy transfer for each trophic level thereafter. We estimated turnover times for each trophic level based on a review of the literature.
Soil—The emergy of soils was computed using US coverage of soil organic matter from NCASI (2006) intersected with data layer of NFS boundaries. Soil organic matter based on soil type was multiplied by area of each soil type in each region to compute total soil organic matter by region for the System. The UEV of soil organic matter was a globally weighted average UEV taken from Brown and Ulgiati (2011).
Tree Biomass—The storage of timber in each of the regions was obtained from the RPA Data Wiz (Pugh 2004), a compilation of forest inventory data compiled by the NFS including biomass per hectare of each tree species. A weighted average UEV for soft- and hard wood was used to compute emergy of tree biomass.
Water Stored in Glaciers—The ice stored in glaciers on NFS lands was estimated from USGS and NFS data (USGS 2006b, USFS 2006b). Total volume is based on an estimate of average depth of the glaciers and area determined from GIS measurements of the extent of the glaciers within the boundaries of the National Forests.
Fossil Fuels and Minerals—Since data on mineral and fossil fuel reserves on NFS land were not available, we assumed that total storages were proportional to the percentage of the United States that was NFS land (approximately 5 %). The UEV used for mineral

storages was a weighted average of the UEVs of the most abundant minerals (gold, lead, silver, and copper) that are mined on NFS lands. While there may be reserves of other metals within the NFS, we used only those metals that are actively mined, as computed from total annual production of minerals (USGS 2006c).

Biodiversity—Biodiversity emergy is the emergy required to *maintain* biodiversity. We computed 5,970 species of higher plant and animal taxa within the National Forests, based on data for North America (NA) (Szaro 1992) and percent of NA within the NFS (3.16 %). The emergy per species was computed for average species in NA within 9 taxa including flowering plants, gymnosperms, ferns, insects, mammals, birds, reptiles, amphibians, and fish (fresh & saltwater). The UEVs were computed following a method first proposed by Odum (1996) using average turnover times for each taxa multiplied by the emergy supporting the region (in this case NA), then dividing by the number of species in each taxa.

Economic assets

Roads, Building, and Equipment—The extent and characteristics of roads, buildings, and machinery on NFS lands were unpublished, but it was recorded in internal NFS databases, made available by NFS. Road characteristics were determined by class, and these class specifications were found through personal correspondence (USFS 2006b). The amount of office equipment was estimated from the average mass of office equipment, 15 kg, per m^2 of office given in Means (2006). Average building mass was calculated using area of buildings and average mass per unit area (Buranakarn 1998).

Knowledge—The storage of knowledge within the NFS system was computed using the emergy of the workforce educational level and job experience, as proposed by Odum (1996) and updated by Campbell and Lu (2009) using the educational level, average age, and annual US emergy support per capita.

2.3 Ecosystem services of USF System

The NFS ecosystem services were summarized from the overall emergy evaluation of the National Forest System. First, they were expressed as emergy and then converted to emdollars (using the 2005 EIC) for comparison with economic values determined either directly from market prices or imputed from stated or revealed preference approaches. In general, economic value of products sold (e.g., hydroelectricity, timber) was obtained directly from NFS documents. Economic value of recreation was computed from average travel costs. The economic value of minerals, fossil fuels, water, and peat were determined using market prices, while the economic value of hunting/fishing was estimated using the number of hunters and fishers and expenditures per capita from USDI (2002).

We used the ecosystem service categories as suggested in Millennium Ecosystem Assessment (2005) to organize services derived from the NFS. Data for evaluations were taken primarily from NFS publications as follows:

Provisioning services

- *Wildlife harvested*—Based on published data (USDI 2002 and Aiken 2005) for counts of large and small game and migratory birds harvested within the USA, and estimates of average dry weights of species. Quantity harvested from NFS lands assumed to be equal to 3.7 % of total USA land area within the NFS.

- *Fish harvested*— Based on published data (USDI 2002) for estimates of number of fish caught and estimates of average dry weight biomass. Quantity harvested from NFS lands assumed to be equal to 3.7 % of total USA land area within the NFS.
- *Water supply*—Based on the chemical potential of all stream flow leaving Forest Service lands (Sedell et al. 2000).
- *Hydroelectricity produced*—based on published data (USFS 2005).
- *Fossil Fuels extracted*—based on published data (USFS 2005).
- *Minerals extracted*—based on published data (USFS 2005).
- *Timber harvested*—based on published data (USFS 2005).
- *Fuel wood extracted*—based on published data (USFS 2005).

Regulating services

- *Carbon sequestration*—based on 6 MT/ha and 7.80E+07 ha of land within the NFS.
- *Water purification*—total annual rainfall on Forest Service lands.
- *Air purification*—based on estimate of airborne particulate deposition (Tilley and Swank 2003).

Supporting services

- *Gross primary production*—estimate of gross primary production based on estimates of standing biomass (Pugh 2004).

Cultural services

- *Organized recreation*—based on visitor use data (USFS 2004).
- *Information produced*—based on the total number of NFS employees engaged in research (unpub. USFS 2006b) and the emergy of their salary.

3 Results

3.1 Description of the NFS System

Figure 1 is a systems diagram of the US Forest System showing the environmental driving energies, purchased resources, components and processes, as well as exports. The environmental sources on the left drive environmental subsystems and develop storages of vegetation, surface water, geologic structure, and soil. These environmental subsystems and storages contribute to the image of the NFS lands, which serves to draw in tourists from outside the system, (see the top right box), who in turn bring emergy and money into the system, as well as remove some emergy in the form of harvested fish and wildlife. The non-renewable sources such as fuels and electricity drive the human-dominated subsystems that include visitors and the NFS facilities (Assets, Fig. 1). The NFS assets are purchased machinery and goods used in the production of information and management of resources. The assets of the NFS contribute to the management of fire (see divisor symbol on the interaction symbol in the middle of the diagram). The fire interaction draws down the vegetation storages. The probability of fire is increased by lightning from outside the

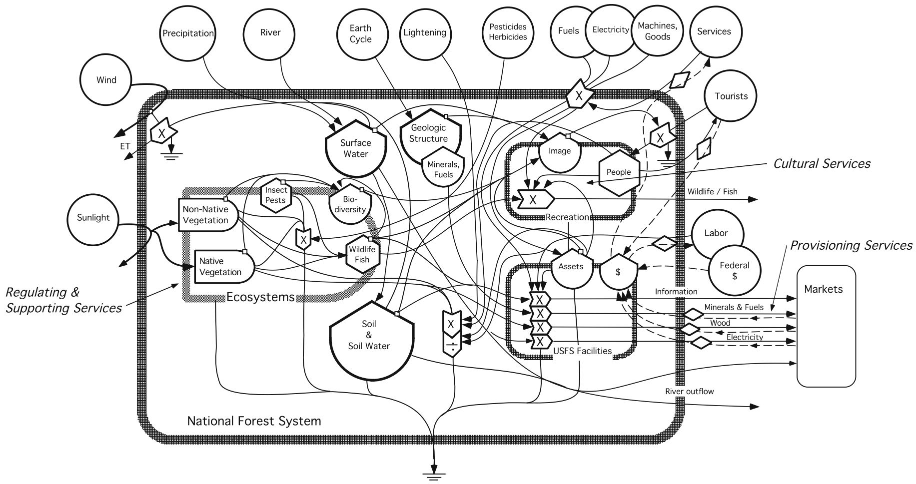

Fig. 1 Systems diagram of the USFS system (after Brown and Campbell 2007) showing the interplay of ecosystems, facilities and recreation in providing ecosystem services

system as well as by tourists in the system. The flows exiting the system to the right are exports.

Also indicated on the diagram are the various ecosystem services provided by the NFS System. Provisional services exit the system to the right where there are markets, which exchange money for the commodities. In some cases, the NFS receive these funds (dashed lines inflowing to facilities; the diamond symbol represents exchange price). In other cases, such as the water used by society, the NFS system is not paid directly. Cultural services are shown being generated mostly within the recreational functions box, while regulating and supporting services are generated within the ecosystems.

3.2 Emergy flows supporting the NFS System

Table 2 summarizes the emergy evaluation of the NFS, listing the driving energies, monetary inflows and outflows, and exports of the system. Footnotes that detail data, sources, and calculations can be found in Appendix 1.

Referring to Table 2, the renewable emergy (sum of sunlight, tides, and geothermal) supporting the US National Forests in 2005 was 19.9.5E+21 seJ year^{-1}, equivalent to ^{em}\$10.5 billion. The non-renewable inputs (the sum of indigenous and purchased) total 17.8E+21 seJ year^{-1} (^{em}\$9.3 billion), which is about 47 % of the total emergy driving the NFS. The largest purchased input to the system is services, which accounted for about 93 % of the total purchased and indigenous inputs.

The emergy value of visitors and recreationists using the National Forests is an important line item (line 17). The emergy value of visitors is equivalent to about ^{em}\$13.3 billion, reflecting the importance and impact of human use of the Forests.

The emergy of exports from the NFS totaled 402.9E+21 seJ in 2005 with an emdollar value of ^{em}\$ 212 billion. The largest exports were fossil fuels and minerals exported from the NFS followed by the emergy in information and the geopotential energy in water.

Table 2 Emergy evaluation of the flows supporting US National Forest System

Note[a]	Item	Units	Quantity	Emergy intensity (seJ/unit)	Solar emergy (×10^{18} seJ)	EmDollars (×10^6 ^{Em}\$)
Renewable resources						
1	Sunlight	J	4.37E+21	1.00E+00	4,371.0	2,300.5
2	Rain chemical potential	J	2.62E+18	6.36E+03	16,637.8	8,756.7
3	Transpiration	J	1.18E+18	6.36E+03	7,506.8	3,950.9
4	Rain geopotential	J	1.08E+18	1.10E+04	11,844.7	6,234.0
5	Wind kinetic	J	3.40E+18	1.58E+03	5,362.9	2,822.6
6	Hurricanes	J	3.38E+17	6.49E+03	2,193.6	1,154.5
7	Waves	J	6.11E+17	2.22E+04	13,544.0	7,128.4
8	Tides	J	1.96E+17	7.24E+04	14,170.3	7,458.0
9	Geothermal energy	J	6.87E+16	2.03E+04	1,394.3	733.8
Total renewable[b]					19,935.5	10,492.4
Indigenous non-renewable resources						
10	Soil loss (harvesting)	g	9.73E+10	1.68E+09	163.5	86.1
10a	Soil OM loss (harvesting)	J	8.04E+13	1.18E+04	0.9	0.5
11	Miscellaneous products (plants)	J	2.50E+13	5.04E+04	1.3	0.7
Total and non-renewable					165.7	87.2
Purchased inputs						
12	Petroleum products	J	4.04E+15	1.87E+05	756.0	397.9
13	Machinery, equipment	g	4.95E+09	1.13E+10	55.8	29.4
14	Misc. goods	g	7.22E+07	2.49E+10	1.79	0.9
15	Electricity	J	1.17E+15	2.92E+05	341.8	179.9
16	Services (incl Labor)	\$	8.66E+09	1.90E+12	16,454.0	8,660.0
Total imports					17,609.4	9,268.1
17	Visitors' time	J	1.60E+15	1.50E+07	23,995.7	12,629.3
Exports						
18	Extracted firewood	J	1.17E+16	3.06E+04	358.9	188.9
19	Harvested wood	J	1.02E+17	5.04E+04	5,158.3	2,714.9
20	Water, chemical potential	J	1.26E+18	1.08E+04	13,566.5	7,140.2
21	Water, geopotential	J	2.01E+18	1.10E+04	22,144.8	11,655.1
22	Minerals	g	4.16E+12	1.46E+10	60,691.1	31,942.7
23	Fossil fuels	J	1.52E+18	1.31E+05	198,798.7	104,630.9
24	Harvested wildlife	J	5.50E+14	9.46E+05	520.6	274.0
25	Harvested fish	J	9.96E+13	2.10E+06	209.2	110.1
26	Information	Hrs	1.94E+07	2.35E+14	4,562.9	2,401.5
Total exports					306,011.0	161,058.4
Economic payments received						
27	US Gov't budget allocation	\$	5.55E+09			
28	Payment for timber	\$	2.24E+08			
29	Payments for minerals/fuels extracted	\$	2.84E+09			

Table 2 continued

Note[a]	Item	Units	Quantity	Emergy intensity (seJ/unit)	Solar emergy ($\times 10^{18}$ seJ)	EmDollars ($\times 10^{6}$ ^{Em}\$)
30	Fee payments[2.]	\$	5.05E+07			
Total payments received			8.66E+09			

[a] Foot notes to Table 2 can be found in Appendix 1

[b] To avoid double counting, renewable emergy is the sum of sunlight, tides, and earth cycle

Economic income of the NFS totaled \$8.66 billion, of which the NFS annual budget allocation from US Government in 2005 was about \$5.55 billion (USDA 2006). The next largest payment was from the sale of minerals and fuels (\$2.8 billion), while the sale of timber resulted in payments of \$224 million, or about 2.5 % of total dollar income.

3.3 Natural and economic capital of the NFS System

Table 3 lists the natural and economic capital of the National Forest System. We have arranged the table in an ascending order from lowest to highest emergy. Footnotes that detail data, sources, and calculations can be found in Appendix 2.

We have separated natural capital stocks from economic capital to highlight their differences, both in function and magnitude. Ecosystem services are generated from natural capital, while economic capital is used by humans to manage, harvest, and appreciate (as in recreation) ecosystems. By far, the natural capital of the NFS exceeds economic capital by almost 57–1. The total emergy of natural capital was 46.2E+24 seJ translating into about ^{em}\$24.3 trillion, whereas the total emergy of economic capital in 2005 was 5.7E+23 seJ or about ^{em}\$301 billion. The largest natural capital stocks were biodiversity representing about 37 % of the total, and the potential fossil fuel and mineral reserves (combined accounting for 38 %).

3.4 Emergy and economic values of ecosystem services

Table 4 lists some of the ecosystem services provided by the NFS based on categories suggested by the Millennium Ecosystem Assessment (2005). For comparison, we have listed computed economic values. Few ecosystem services have clearly established monetary values (Krieger 2001). Emergy-derived values for most of the provisional services were taken directly from Table 1 (Exports). Of the provisioning services, fossil fuels and minerals extracted had the largest emergy values, combined totaling about 93 % of the provisioning services or ^{em}\$136 billion, while their economic value totaled \$2.8 billion. In several cases (fish and wildlife harvest and water supply), the computed economic value of the service exceeded the emdollar value.

Of the regulating services, the emergy value of the ecosystem services required to generate clean water was the greatest (19.9E+21 seJ or ^{em}\$10.5 billion). The emergy value of ecosystem services required to sequester carbon was 6.6E+21 seJ (^{em}\$3.5 billion) and for regulating clean air was 23.7E+21 seJ (^{em}\$12.5 billion). Thus, the total emdollar value of regulating services was ^{em}\$26.4 billion, while the computed monetary values totaled \$4.7 billion, the largest of which was clean air (\$3.3 billion).

Table 3 Emergy in natural and economic capital of US National Forest System

Note[a]	Item	Units	Quantity	Emergy intensities (seJ/unit)	Solar emergy ($\times 10^{21}$ seJ)	EmDollars ($\times 10^{9}$ Em$)
Natural capital						
1	Herb./shrub biomass	J	6.91E+18	9.79E+03	67.7	35.6
2	Surface water	J	1.57E+18	5.04E+04	79.0	41.6
3	Land area	ha	7.80E+07	1.05E+15	81.9	43.1
4	Ground water	J	2.80E+18	1.91E+05	535.0	281.6
5	Fauna	g	6.02E+13	1.72E+10	1,037.9	546.3
6	Soil OM	J	1.50E+20	1.18E+04	1,771.1	932.2
7	Tree biomass	J	7.71E+19	5.04E+04	3,885.8	2,045.2
8	Glaciers	g	6.23E+17	6.40E+06	3,986.2	2,098.0
9	Minerals (possible reserve)	g	2.20E+13	3.75E+11	8,243.2	4,338.5
10	Fossil fuels (possible reserve)	J	9.74E+19	9.76E+04	9,506.1	5,003.2
11	Biodiversity	# of spp,	5.97E+03	2.85E+21	16,984.9	8,939.4
Total natural capital					46,178.8	24,304.6
Economic capital						
12	Office equipment	g	3.84E+10	1.13E+10	0.4	0.2
13	Machinery & tools	g	9.91E+10	1.13E+10	1.1	0.6
14	Buildings	g	1.02E+12	6.50E+09	6.6	3.5
15	Roads (paved)	g	4.81E+12	2.77E+09	13.3	7.0
16	Roads (dirt)	$	3.14E+10	1.90E+12	59.7	31.4
17	Roads (gravel)	g	7.15E+13	1.68E+09	120.1	63.2
18	Knowledge	# emp	3.15E+04	1.18E+19	370.6	195.0
Total economic capital					571.9	301.0

[a] Notes to Table 3 can be found in Appendix 2

Gross primary production (GPP) was the only supporting service we evaluated, the emergy value of which was 16.6E+21 seJ (^{em}\$8.7 billion). In this case, the best estimate of a monetary value for gross primary production was the estimated value of nutrient cycling in forests (Krieger 2001), which resulted in a value roughly 4 times that of the computed emdollar value.

Cultural services evaluated included the emergy of recreation based on the emergy value of visitors to the Forest System (24.0E+21 seJ or ^{em}\$12.6 billion) and the information generated by FS staff (4.6E+21 seJ or ^{em}\$2.4 billion). The computed monetary values were lower for both organized recreation ($9.2 billion, computed using estimated travel costs) and the production of information ($0.2 billion, computed using the payments for NFS staff).

The total computed emdollar value of ecosystem services was ^{em}\$196.9 billion compared to a computed economic value of $70.7 billion or roughly 2.8 times as large. There

Table 4 Emergy, emdollar, and economic value of services of the National Forest System (2005)

Note[a]	Parameter	Emergy value (10^{21} seJ/year)	Emdollars[b] (10^9 Em$/year)	Economic value (10^9 $/year)
Provisioning services				
1	Fish harvest	0.2	0.1	1.3
2	Extracted firewood	0.4	0.2	0.1
3	Wildlife harvest	0.5	0.3	2.9
4	Harvested timber	5.2	2.7	0.2
5	Water supply	13.6	7.2	12.4
6	Minerals extracted	60.7	31.9	1.1
7	Fossil fuels extracted	198.1	104.3	1.7
Regulating services				
8	Carbon sink	6.6	3.5	0.4
9	Clean air	23.7	12.5	3.3
10	Clean water	19.9	10.5	1.0
Supporting services				
11	Gross primary productivity	16.6	8.7	36.8
Cultural services				
12	Organized recreation	24.0	12.6	9.2
13	Information produced	4.6	2.4	0.2
Total ecosystem services/year			196.9	70.7

[a] Notes to Table 4 can be found in Appendix 3

[b] Emdollars are calculated by dividing emergy in column 3 by 1.9E+12 seJ/$, the average ratio of emergy to money in the USA economy in 2005

does not appear to be any clear trend regarding the relationship between the computed use values and the emergy-derived emdollar values. However, where monetary values were computed using gross expenditures (fish and wildlife harvesting), the monetary values exceeded the emdollar values.

Figure 2 summarizes the driving energy and resource input and outputs expressed as ecosystem services. Included are the renewable inputs (19.9E+21 seJ/year), the purchased economic inputs (17.6E+21 seJ/year), the emergy value of Forest System visitors (24.0E21 seJ/year), and the computed emergy value of the ecosystem services by category. The total dollar income to the Forest Service System is shown as the dashed lines equaling $8.7 billion, which flows through the system and then is used to purchase the economic inputs.

4 Discussion

4.1 Flows and storages of the NFS

Table 2 lists the main driving energies of the NFS and their emergy and emdollar equivalents. The NFS is dominated by its renewable emergy base and by inputs of employees (labor) and the emergy of services embodied in purchased inputs (line 16).

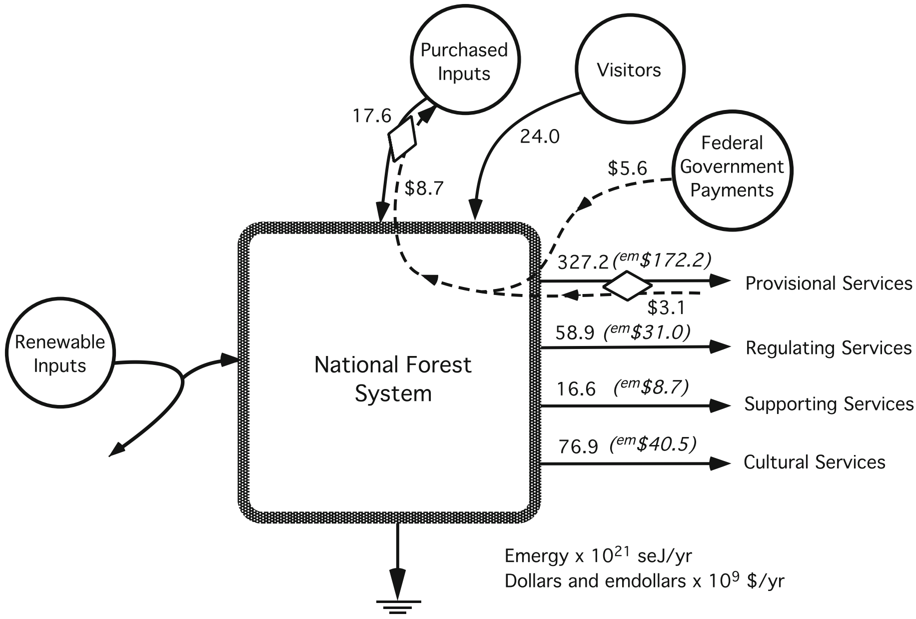

Fig. 2 Summary diagram of the USFS system showing the driving emergy from renewable and purchased inputs, emergy in annual visitors, Federal Government budget allocation, and money received from sales. The ecosystems service outflowing to the right are evaluated in emergy and (emdollars)

Within the NFS, there are significant storages of fossil fuels and minerals (Table 3), which result in large export flows of fossil fuels and minerals (comprising 85 % of total exports from the system). Water is the next most important export from the NFS in both its chemical potential and its geopotential totaling about 12 % of total exports. Surprisingly, wood extracted from the NFS accounts for only about 2 % of total exports. While there are a large number of scientists and professionals engaged in the generation of information within the NFS, its emergy value represents only about 1.5 % of total exports. The fact that such a large percentage of exports are from minerals and fossil fuels is in line with the multiple uses of NFS lands and a significant component of the resources that the Forest Service manages.

Natural capital resources of the NFS are explored in Table 3, where it is obvious that mineral fossil fuel resources dominate. Like most estimates of reserves of natural resources, these data are subject to fairly large uncertainty, yet the very magnitude of the potential reserves suggests that the National Forests are well endowed, accounting for as much as 38 % of total assets. Of particular interest is biodiversity, which is evaluated based on weighted UEVs within nine taxa. Biodiversity represents the largest of the natural capital assets, accounting for about 37 % of total assets. While it may appear that the inclusion of biodiversity, herbaceous and shrub biomass, tree biomass, and faunal biomass is in some way double counting, it should be pointed out that these are very different aspects of the same resources. While, indeed, biodiversity is composed of plants and animals, it represents the information content of the ecosystem as reflected in the diversity of species present.

4.2 Ecosystem services

The National Forest System provides a wide array of ecosystem services (Table 4 and Fig. 2), the largest of which are provisional services (especially the value of extracted minerals and fossil fuels, ^{em}\$ 146.6 billion). Regulating, supporting and cultural services combined amount to about ^{em}\$ 50 billion. When compared to the Federal Government monetary support of the NFS (\$5.6 billion), the combined output of services (^{em}\$ 196.7 billion) is about 35 times the government funding.

4.3 Comparison of donor and receiver values

Ecosystem services and natural capital are variously defined in the literature, but in general, they usually refer to resources and processes that have value to humans, in a user (or utility) framework. There is no question that humans benefit from ecosystem services and capitalize on natural capital. Within an anthropocentric framework, valuing resources and natural processes using willingness-to-pay (WTP) might be a reasonable approach, which we term a receiver value system. Yet, as shown in this evaluation of the National Forests, there are numerous capital assets and services that provide important functions, which may or may not be understood within a utility framework. The use of emergy accounting to evaluate the flows of energy, materials, and information supporting the NFS provides a second approach to valuing that captures services and assets that lay outside the WTP frame of reference. We term this framework a donor value system.

This study highlights two approaches to valuing natural capital and ecosystem services. The emergy method can be thought of as describing intrinsic values as compared to the utilitarian or user values of economic evaluation. The definition of emergy is "the available energy of one kind that is used up in transformations directly and indirectly to make a product or service" (Odum 1996). In other words, it is a measure of the investment of resources necessary to produce a product or service. In this study, we computed the emergy value of natural capital and ecosystem services as the available energy (converted to emergy) required to make them. We then used the monetary equivalent of emergy, the emdollar, to express emergy within a value scale more familiar to most people. This does not change the underlying donor side valuation approach, but does result in dollar-equivalent values that represent the biosphere's investment in the natural capital and ecosystem service.

It should be pointed out that direct comparison between these two value systems is not the intention of this research, but rather we seek a clearer understanding of how the values from either perspective relate across the boundary between donor and receiver. In general, the values of ecosystem services are somewhat comparable, resulting in total values in the range of \$71 (monetary) to ^{em}\$197 billion (emergy). While we did not compute the economic value of biodiversity (Table 3), Krieger (2001) summarized studies for US forests concluding that biodiversity was valued at between \$4 and \$54 billion annually for the entire United States. Pimentel et al. (1997), using a variety of valuation techniques, estimated the annual economic and environmental benefits of biodiversity in the United States to be \$319 billion. Our computed emdollar value of biodiversity assets (Table 3) for only the US Forest Service system was considerably higher (^{em}\$2.1 trillion). The values Krieger and Pimentel reported were for annual benefits derived from biodiversity (i.e., a receiver or use value), while our approach computes the emergy required to generate the storage of biodiversity (its intrinsic value).

There are no clear trends in the differences between monetary and emdollar values shown in Table 4. It is apparent from our analysis in general, however, that those natural capital assets and ecosystem services that exist far from anything resembling a market (i.e., biodiversity) result in greater divergence between monetary and emergy values. Where there are functioning markets (e.g., fish, firewood, timber, and water), the emergy-derived values and monetary values are more closely aligned. In general, monetary values and emergy values for provisioning services were within an order of magnitude of the emdollar values. The big exception was the monetary value of minerals and fossil fuels compared to their emdollar values. The computed emdollar value of minerals was 30 times that of the monetary value, and that for fossil fuels was 60 times the monetary value. The large differences reflect the very large benefit society receives from underpriced minerals and fuels.

It is interesting to compare these two approaches and the computed values that result. In the economic valuation given here, we used prices where there were obvious markets (water, timber, fuels etc.), and where there were no reliable markets (e.g., gross primary production), we relied on published estimates from the literature. We were not exhaustive in our search for prices or published estimates, as economic valuation was not the main point of our research, and there are many studies using different economic methods (e.g., see Krieger 2001).

4.4 Limitations

The uncertainty inherent in estimating several parameters in this study stems from two different sources. On the one hand, there is the uncertainty in the data, for instance, the accuracy of the mapping and generation of spatial data for computing the renewable inputs of sunlight, rain, winds, etc. Then there is the uncertainty related to the assumptions employed where no data existed, for instance, the estimates of mineral and fossil fuel reserves within the NFS, or the number of species within taxa found in the NFS. Where no data existed, we used ratios of the NFS to either the USA or North America and assumed like densities or linear relationships. More refined data could obviously change the results, but even if our estimates are 100 % off, the macro trend is still evident. So while there is uncertainty and values might change with better data, the fact that the emergy values of biodiversity or fossil fuels are so large, by orders of magnitude, suggests that even with refinement, they are still extremely important resources within the National Forest System.

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Appendix 1

Notes to Table 2. Emergy evaluation of the flows supporting US National Forest System

Renewable resources		
Solar insolation		
Land area	7.80E+11 m^2	
Insolation	6.83E+09 J/m^2/year	NREL (2006)
Albedo	1.80E−01 (% given as a decimal)	Estimate
Energy	(area) × (avg. insolation) × (1 − albedo)	
	4.37E+21 J	
UEV	1.00E+00 seJ/J	Odum (2000)
Rain—*chemical potential*		
Land area	7.80E+11 m^2	
Rain	0.68 m/year	NOAA (2006)
Total volume rain	5.30E+11 m^3	
Chemical potential energy of rain water	4.94 J/g	Odum (1996)
Energy	(volume) × (1,000 kg/m^3) × (4,940 J/kg)	
	2.62E+18 J/year	
UEV	6.36E+03 seJ/J	Brown and Ulgiati (2011)
Transpiration		
Land area	7.80E+11 m^2	
Transpiration rate	3.10E−01 m/year	Average of regions
Total transpiration	2.38E+11 m^3	
Chemical potential energy of rain water	4.94 J/g	Odum (1996)
Energy	(volume) × (1,000 kg/m^3) × (4,940 J/kg)	
	1.18E+18 J/year	
UEV	6.36E+03 seJ/J	Brown and Ulgiati (2011)
Rain geopotential		
Run-off	0.37 m/year	NOAA (2006)
Mean elevation change	3.78E+02 m	
Land area	7.80E+11 m^2	
Energy	(area)(rainfall)(avg change in elevation)(density)(gravity)	
	1.07E+18 J	
UEV	1.10E+04 seJ/J	Brown and Ulgiati (2011)
Wind, kinetic		
Area	7.80E+11	
Air density	1.30E+00 kg/m^3	
Avg. annual wind velocity	4.21E+00 mps	NOAA (2006)
Geostrophic wind	7.02E+00 (observed winds are about 0.6 of geostrophic wind)	
Drag coeff.	1.60E−03	
Energy	(area) × (density) × (drag coefficient) × (geostrophic wind—gradient velocity)^3 × (31,500,000 s/year)	

	3.40E+18	
UEV	1.58E+03 seJ/J	Brown and Ulgiati (2011)
Hurricanes		
Avg. energy/storm	5.00E+05 kcal/m^2/day	Odum et al. (1986)
Avg. hurricane freq	1.00E−01 /year	
Percent energy that is kinetic	3.0 %	
Percent of energy dispersed to land	10 %	
Avg. residence time	1.00E+00 day/year	
Area	1.03E+11 m^2	
Energy	(0.1/year) × (1 year/365 days) × (5E+05 kcal/m^2/day) × (.003 × area in m^2) × (4,186 J/kcal)	
	1.77E+14 J/year	
UEV	6.49E+03 seJ/J	Odum (2000)
Wave		
Shore length	1.14E+06 m	
Wave height	1.75E+00 m	
Energy	(shore length)(1/8)(density)(gravity)(wave height^2)(velocity)	
	6.12E+17 J/year	
UEV	2.22E+04 seJ/J	Brown and Ulgiati (2011)
Tidal		
Continental shelf area	5.16E+09 m^2	
Avg. tide range	3.27E+00 m	
Density	1.03E+03 kg/m^3	
Tides/year	7.06E+02 (number of tides in 365 days)	
Energy (J)	(shelf)(0.5)(tides/year)(mean tidal range)^2	
	(density of seawater)(gravity)	
	1.96E+17 J/year	
UEV	7.24E+04 seJ/J	Brown and Ulgiati (2011)
Geothermal energy		
Heat flow	1.85E+06	IHFC (2006)
Area	7.80E+11 m^2	
Carnot efficiency	4.76E−02 (315–300 K)/315 K	
Energy (J)	(area)(heat flow)(Carnot efficiency)	
	6.87E+16 J/m^2	
UEV	2.03E+04 seJ/J	Brown and Ulgiati (2011)
Indigenous non-renewable resources		
Soil loss	9.73E+10 g/year	USFS (2005)

UEV	1.68E+09	Brown and Ulgiati (2011)
Organic matter in top soil (3.5 % of soil loss)	3.41E+09 g/year	
Energy (J)	(g of C) × (5.4 kcal/g) × (4,187 J/cal)	
	7.32E+13 J	
UEV	1.18E+04 seJ/J	Brown and Ulgiati (2011)
Miscellaneous products (plants)	1.40E+09 g/year	USFS (2005)
Energy (J)	(g) × (3.5 kcal/g) × (4,186 J/Cal)	
	2.05E+13 J	
UEV	1.80E+04 seJ/J	Average goods—Odum (2000)
Dollar value misc. prod	3.08E+06 $/year	
Purchased inputs		
Petroleum products		
Forest service use	1.65E+07 gal/year	USFS (2005)
Energy (J)	(gal) × (13e7 J/gal)	
	2.14E+15 J/year	
FS building use	3.00E+07 sq ft	Estimate
Intensity	6.00E+04 BTU/sq ft/year	EIA (1998)
Energy use	(BTU/sq ft/year) × (sq ft) × (1,055 J/BTU)	
	1.90E+15 J/year	
Total fuel use	4.04E+15 J/year	
UEV	1.87E+05 seJ/J	Brown and Ulgiati (2011)
Machinery, equipment		
USFS vehicle mass	1.01E+11 g	Estimate
Avg. vehicle lifespan	2.00E+01 years	Estimate
Annual use	(vehicles) × (g/vehicle) × (1/avg. life of vehicle)	
	5.06E+09 g	
UEV	1.13E+10 seJ/g	CEP (2006)
Goods (pesticides, herbicides, misc. goods)		
Quantity	7.22E+07 g/year	USFS (2003)
UEV	2.49E+10 seJ/g	CEP(2006)
Emergy	1.79E+18 seJ/year	
Electricity		
Building area	30,011,200 sq ft	USFS (2005)
Energy intensity	37,000 BTU/ft^2/year	EIA (1998)
Energy (J)	(area) × (BTU/year) × 1,055 J/BTU)	
	1.17E+15 J	
UEV	2.92E+05 seJ/J	Odum (1996)
Total USFS budget	4.88E+09 $/year	
Services including labor	8.66E+09 $/year	USFS (2005)

Unit emergy value	1.90E+12 seJ/$	CEP (2006)
Emergy (seJ)	1.65E+22 seJ/year	
Visitors		
Visitors	2.05E+08 people/year	USFS (2004)
Average stay	1.80E+01 h	USFS (2004)
Total hours of stay	3.69E+09 h/year	
Hourly metabolism	1.04E+02 kcal/h	
Energy expenditure (J)	(kcal/h) × (h) × (4,186 J/Cal)	
Energy (J)	1.60E+15 J/year	
UEV	1.50E+07 seJ/J	Odum (1996)
Exports		
Extracted firewood		
Mass	7.82E+08 kg	USFS (2006)
Energy (J)	(mass) × (1,000 g/kg) × (15,000 J/g)	
	1.17E+16 J/year	
UEV	3.06E+04 seJ/J	Brown and Bardi (2001)
Harvested wood		
Sum of the regions	6.82E+12 g/year	USFS (2005)
Energy (J)	(g) × (15,000 J/g)	
	1.02E+17 J/year	
UEV	5.04E+04 seJ/g	Brown and Bardi (2001)
Water, chemical potential		
Stream discharge	2.54E+11 m^3/year	USFS (2000)
Chemical potential	(m^3/year) × (1,000 kg/m^3) × (4,940 J/kg)	
Joules	1.25E+18 J/year	
UEV	1.08E+04 seJ/J	Brown and Ulgiati (2011)
Water, geopotential energy		
Stream discharge	2.54E+11 m^3/year	
Avg. elevation above NGVD	8.00E+02 m	
Geopotential (J)	(discharge) × (avg elevation) × (density) × (gravity)	
	1.99E+18 J	
UEV	1.10E+04 seJ/J	Brown and Ulgiati (2011)
Minerals		
Minerals excavated	4.16E+12 g/year	USFS (2003)
Avg. UEV	1.46E+10 seJ/g	
Emergy	6.06E+22 seJ/year	
Minerals ($ value)	2.01E+09 $/year	USFS (2003)
Fossil fuels		
Oil	9.42E+17 J/year	USFS (2005)

UEV	1.48E+05 seJ/J	Brown et al. (2010b)
Natural gas	5.58E+16 J/year	USFS (2005)
UEV	1.48E+05 seJ/J	Brown et al. (2010b)
Coal	5.20E+17 J/year	USFS (2005)
UEV	9.71E+04 seJ/J	Brown et al. (2010b)
Total fossil fuel emergy	1.98E+23 seJ	
Weighted UEV for fuels	1.31E+5 seJ/J	
Hunting		
% Dry weight for wildlife	2.50E−01 %	
Big game extracted	1.30E+06 Big game/years	USFWS (2002)
Avg. mass	5.68E+04 g/game	
Energy content	2.65E+04 J/g	
Energy (J)	#Game/year × avg mass × (% dry weight) × J/g	
	4.88E+14 J/year	
UEV	9.90E+05 seJ/J	Brown et al. (2006)
Emergy	4.83E+20 seJ	
Small game extracted	4.92E+06 Small game/year	USFWS (2002)
Avg. mass	3.30E+03 g/animal	
Energy content	6.37E+03 J/g	
Energy (J)	#× avg mass × (percent dry weight)J/g	
	2.58E+13 J/year	
UEV	1.20E+05 seJ/J	Brown et al. (2006)
Emergy	3.10E+18 seJ	
Migratory birds extracted	1.14E+07 #/year	USFWS (2002)
Avg. mass	1.30E+03 g/bird	
Energy content	8.83E+03 J/g	
Energy (J)	#× avg mass × (percent dry weight)J/g	
	3.26E+13 J/year	
UEV	1.01E+05 seJ/J	Brown et al. (2006)
Emergy	3.29E+18 seJ	
Other species extracted	4.32E+05 #/year	USFWS (2002)
Avg. mass	6.35E+03 g	
Energy content	6.37E+03 J/g	
Energy (J)	#× avg mass × (percent dry weight)J/g	
	4.36E+12 J/year	
UEV	1.50E+05 seJ/J	Brown et al. (2006)
Emergy	6.54E+17 seJ	

Sum of Emergy from game	4.90E+20 seJ	
Weighted UEV for game	9.46E+05 seJ/J	
Fishing	5.84E+07 (fish caught)	USFS (2004)
Avg. mass	4.54E+02 g/fish	Assume avg. weight = 1 lb
% dry weight	20 %	
Energy content	1.88E+04 J/g	(4.5 Cal/G × 4,187 J/cal)
Energy (J)	#× avg mass × (percent dry weight) × J/g	
	9.96E+13 J	
UEV	2.10E+06 seJ/J	CEP (2006)
Information produced		
Emergy value of information produced = scientific and information staff, hours worked		
Public information	2.30E+03 (individuals)	USDA-FS (2010)
Washington office	3.40E+03 (individuals)	USDA-FS (2010)
Research information	4.00E+03 (individuals)	USDA-FS (2010)
Annual work	2.00E+03 h/person	
Total hours	1.94E+07 h/year	
Transformity	2.35E+14 seJ/h	Odum (1996)
Emergy of information	4.56E+21 seJ	
Economic payments received		
US government budget allocation		
2005 Budget	5.55E+09 $	USDA (2006)
Payment received for timber		
2005 Payments received	2.24E+08 $/year	USFS (2006)
Payments for extracted minerals		
2005 Payments received	2.84E+09 $/years	USFS (2006)
Fee payments received		
2005 Payments received	5.05E+07 $/year	USFS (2006)

Emergy evaluation of the flows supporting US National Forest System

Appendix 2

Notes to Table 3. Emergy in Natural and Economic Capital of US National Forest System

Herb./shrub biomass		
Understory biomass	6.91E+18 g	NCASI (2006)
UEV	9.79E+03	Brown and Bardi (2001)
Surface water		
Volume	3.22E+11 m^3	Sedell et al. (2000)
Density	1.0E+06 g/m^3	
Concentration lake	500 ppb = 999,500 ppb water	
Concentration sea water	35 ppt = 965,000 ppb water	
R	8.33 J/mol/degree	
T	300 °K	Odum (2000)
w	18 g/mol	
Gibbs free energy		
Energy in water (J)	1.0 m^3 × 1.0E+06 g/m^3 × 4.87 J/g × volume	
	1.57E+18 J	
UEV	5.04E+04	(Odum 2000)
Land area		
USFS system area	7.80E+07	USFS (2001)
UEV	1.05E+15 seJ/ha	Odum (1996)
Ground water		
Volume	5.7E+11 m^3	USGS (2005)
Density	1.0E+06 g/m^3	
Concentration ground water	10 ppb = 999,900 ppb water	
Concentration sea water	35 ppt = 965,000 ppb water	
R	8.33 J/mol/degree	
T	300 °K	
w	18 g/mol	
Gibbs free energy		
Energy in ground water (J)	1.0 m^3 × 1.0E+06 g/m^3 × 4.94 J/g × volume	
	2.80E+18	
UEV	1.91E+05	Brown et al. (2010b)
Fauna (data and calculations for biomass and UEVs from Brown and Campbell (2007))		

Fauna	Biomass (g)	UEV (seJ/g)	Emergy (seJ)
Primary consumer	1.30E+13	6.34E+09	8.24E+22
Herbivores	2.60E+13	8.30E+09	2.16E+23
Omnivores	1.40E+13	1.15E+10	1.61E+23
Carnivores	4.20E+12	5.85E+10	2.46E+23

Fauna	Biomass (g)	UEV (seJ/g)	Emergy (seJ)
Top carnivores	3.00E+12	1.11E+11	3.33E+23
Total biomass	6.02E+13		
Weighted UEV		1.72E+10	
Total emergy			1.04E+24

Soil OM		
Mass OM	6.64E+09 mt	USGS (2006a, b, c)
	6.64E+15 g	
Energy (J)	MassOM × 5.4 kcal/g of OM × 4,186 J/kcal	
	1.50E+20 J	
UEV	1.18E+04 seJ/J	Brown and Ulgiati (2011)
Tree biomass		
Tree biomass	9.75E+09 m^3	USFS (2005)
	5.40E+02 kg/m^3	
Mass	m^3 × kg/m^3 × 1,000 g/kg	
	5.26E+15 g	
	3.50E+00 kcal/g of tree biomass	
Energy (J)	g × 4.5 kcal/g × 4,186 J/kcal	
	7.71E+19 J	
UEV	5.04E+04 seJ/J	Brown and Bardi (2001)
Glaciers		
Volume	6.77E+11 m^3	USGS (2005)
Density	9.20E+05 g/m^3	
Mass	6.23E+17 g	
Specific emergy	6.40E+06 seJ/g	Odum (2000)
Minerals		
Gold	1.17E+09 g	Estimate based on 5 % of total US Reserves
UEV	5.22E+11 seJ/g	Brown and Ulgiati (2011)
Lead	1.51E+13 g	Estimate based on 5 % of total US Reserves
UEV	4.97E+11 seJ/g	Brown and Ulgiati (2011)
Silver	9.33E+10 g	Estimate based on 5 % of total US Reserves
UEV	4.64E+11 seJ/g	Brown and Ulgiati (2011)
Copper	6.81E+12 g	Estimate based on 5 % of total US Reserves
UEV	1.02E+11 seJ/g	Brown and Ulgiati (2011)
Total mass	2.20E+13 g	
Weighted UEV	3.75E+11 seJ/g	
Total emergy	8.24E+24 seJ	SumProduct of minerals and UEVs
Fossil fuels		
Oil	1.03959E+18 J	USGS (2005)
UEV	1.48E+05 seJ/J	Brown et al. (2010a, b)

Natural gas	3.70233E+15 J	USGS (2005)
UEV	1.71E+05 seJ/J	Brown et al. (2010a, b)
Coal	4.59E+09 kg	EIA (1999)
Available energy (J)	(kg coal) × (2.1E+10 J/kg)	
	9.63E+19 J	
UEV	9.71E+04 seJ/J	Brown et al. (2010a, b)
Total available energy	9.74E+19	
Weighted UEV	9.76E+04	
Total Fossil fuel storage	9.51E+24 seJ	
Biodiversity		
Average unit emergy values for taxa		

Taxa	# species in North America[a]	Renewable emergy[b] (E+24 seJ/year)	Turnover time[c] (avg TT of organisms)	Emergy/Taxa[d] (E+24 seJ/taxa)	UEV[e] (seJ/species)
Flowering plants	18,956	9.40	10	94	4.96E+21
Gymnosperms	113	9.40	15	141	1.25E+24
Ferns	404	9.40	4	37.6	9.31E+22
Insects	164,000	9.40	2	18.8	1.15E+20
Mammals	466	9.40	10	94	2.02E+23
Birds	1,090	9.40	6	56.4	5.17E+22
Reptiles	368	9.40	4	37.6	1.02E+23
Amphibians	222	9.40	3	28.2	1.27E+23
Fish (fresh and salt)	2,640	9.40	3	28.2	1.07E+22

Emergy in biodiversity of NFS

Taxa	# species on USFS lands (3.17 % of NA)	Emergy/Taxa (E+24 seJ/taxa)	UEV (seJ/species)	Biodiversity Emergy (seJ)	Biodiversity (E+9 em$)
Flowering plants	601	22.7	4.96E+21	2.98E+24	1,568.3
Gymnosperms	4	18.16	1.25E+24	4.47E+24	2,352.5
Ferns	13	9.08	9.31E+22	1.19E+24	627.3
Insects	5,199	4.54	1.15E+20	5.96E+23	313.7
Mammals	15	22.7	2.02E+23	2.98E+24	1,568.3
Birds	35	13.62	5.17E+22	1.79E+24	941.0
Reptiles	12	9.08	1.02E+23	1.19E+24	627.3
Amphibians	7	6.81	1.27E+23	8.94E+23	470.5
Fish (fresh and salt)	84	6.81	1.07E+22	8.94E+23	470.5
Number of species	5,968				
Weighted Avg. UEV		2.85E+21			
Total biodiversity emergy			1.70E+25	8,939.40	

Office equipment		
Weight/area	15 kg/m^2 area	Estimate (Means 2006)
Building area	2.56E+06 m^2	USFS (2006b, unpub)

Mass office equipment	Bldg. Area × kg/m^2 × 1,000 g/kg	
	3.84E+10 g	
UEV	1.13E+10 seJ/g	CEP (2006)
Machinery		
Weight	2.18E+08 lbs	USFS (2006b, unpub)
	454	g/lb
Mass machinery	lbs × g/lb	
	9.91E+10 g	
UEV	1.13E+10 seJ/g	CEP (2006)
Buildings		
Area	2.56E+06 m^2	USFS (2006b, unpub)
Mass/area	3.98E+05 g/m^2	
Building mass	1.02E+12 g	
UEV	6.50E+09 seJ/g	Buranakarn (1998)
Paved roads		
Length	6.30E+06 m	USFS (2006b, unpub)
Area	6.7 m^2	
Depth	0.0508 m depth	
Volume	2.14E+06 m^3 of asphalt	
Density	2,243 kg/m^3 asphalt	
Mass asphalt	m^3 × kg/m^3 × 1,000 g/kg	
	4.81E+12 g	
UEV	2.77E+09 seJ/g	Odum (1996)
Roads, dirt		
Length	5.24E+06 miles	USFS (2006b, unpub)
Cost	6,000 $/mile	
Total cost	3.14E+10 $	
UEV	1.9E+12 seJ/$	CEP (2006)
Roads, gravel		
Length	1.01E+08 m length	USFS (2006b, unpub)
Width	5 m width	
Depth	0.1016 m of gravel	
Volume	5.13E+07 m^3 of limerock	
Density	1,394 kg/m^3 gravel	
Mass gravel	m^3 × kg/m^3 × 1,000 g/kg	
	7.15E+13 g	
UEV	1.68E+09 seJ/g	Odum (1996)
Knowledge		
Emergy value of knowledge emergy in experience		
Employees	31,511	USFS (2006)

Emergy per capital	3.36E+17 seJ/capita	Odum (1996)
Average age	35 years	Estimate
Emergy	(Employees) (emergy per capita)(age)	
Emergy (seJ)	3.71E+23	

Emergy in Natural and Economic Capital of US National Forest System

[a] Szaro (1992)

[b] Renewable emergy driving NA (NEAD 2006)

[c] Estimate of average turnover time of species within taxa

[d] Product of turnover time and renewable emergy

[e] Emergy per taxa divided by number of species in each taxa

Appendix 3

Notes to Table 4

Fish harvest		
Emergy of fish harvested		
Emergy (seJ)	1.67E+21	Table 2 line 25
Estimated dollar expenditures for fishing		
Number persons fishing	1.26E+06	Estimate = 3.7 % of total US fishers
Expenditure/fisher	$1,044	USFWS (2002)
Total expenditures	$1.3E+09	
Extracted firewood		
Emergy of extracted firewood		
Emergy (seJ)	3.59E+20	Table 2 line 18
Estimated dollar expenditures for firewood		
Extracted firewood	7.82E+08 kg	
Economic price	$200/2.0E+6 BTU	EIA (2010)
	9.50E−09 $/J	
Heating value wood	1.55E+04 J/g	
Economic value ($)	(7.892E+8 kg) × (1E+3 g/kg) × (1.55E+4 J/g) × (9.5E−9$/J)	
	$1.2E+08	
Wildlife hunting		
Emergy of wildlife harvested		
Emergy (seJ)	4.96E+20	Table 2, line 24
Estimated dollar expenditures for hunting		
Number of hunters	1,820,000	USFS land = 35 % of hunting on public lands
Expenditure/hunter	$1,585	USFWS (2002)
Total expenditures	$2.9E+09	
Harvested timber		

Emergy of harvested timber		
Emergy (seJ)	5.16E+21	Table 2 line 19
Economic value ($)	$2.2E+08	Table 2 line 29
Water supply		
Emergy value of chemical potential of outflowing surface water		
Emergy (seJ)	1.36E+22	Table 2 line 20
Economic value		
Economic value of water supply equal to $50.86/ac.ft (Dunkiel and Sugarman 1998 as reported by Krieger 2001) adjusted to 2005 dollars using an inflation rate of 2.39 %		
Price ($/m^3)	($50.86/ac ft) × ($1.18 2005$/1998$)/(1.23E+3 m^3/ac.ft)	
Price ($/m^3)	0.05	
Volume of water (m^3)	2.54E+11	Table 2, Note 20
Dollar value	$1.2E+10	
Minerals		
Emergy value of minerals		
Emergy (seJ)	6.07E+21	Table 2, line 22
Economic value of minerals	$1.1E+09	USFS (2003)
Fossil fuels		
Emergy value of fossil fuels		
Emergy (seJ)	198.1E+21	Table 2, line 23
Economic value of fossil fuels	$1.7E+09	USFS (2003)
Carbon sink		
Taken as the emergy value of net primary production and assumed to be 40 % GPP		
Emergy NPP (seJ)	(16.6E+12 seJ) × 40 %	
	6.64E+21	
Economic value		
Price ($/tonn)	$6	USEPA (2006)
Quantity (tonn/ha)	0.8	USEPA (2010)
Area (ha)	7.80E+07	
Dollar value	$3.7E+08	
Clean air		
Emergy value of clean air		
Emergy value airborne particulate deposition		
Deposition (g/cm^2)	1.00E−03	USFS (2006b)
Total quantity (g/year) = Area × deposition		
Quantity (g/year)	(7.8E+11 m^2) × (1.0E+04 cm^2/m^2) × (1.0E−3 g/cm^2)	
	7.80E+12	
UEV (seJ/g)	3.04E+09	Brown and Ulgiati (2011)
Emergy (seJ/year)	2.37E+22	
Economic value		
Monetized direct benefits of clean air		

Benefits (2005)	$8.9E+10	USEPA (1999)
USA area	9.8E+08 ha	USDA-FS (2001)
USFS forest area	7.8E+07 ha	
% of USA in USFS	8 %	
Economic value	Total benefits × percent of land in USFS	
	$3.3E+09	
Clean water		
Emergy value of water		
Emergy of ecosystem services required for regulating processes that generate clean water taken as the total renewable emergy driving the FS system		
Emergy	19.9E+21 seJ	Table 2
Economic costs of clean water		
Economic value of ecosystem services that generate clean water based on a WTP. Viscusi et al. (2008) using a state preference valuation reported a value of $31.70/individual or $82.42/household. Krieger (2001) reported a value of $64.16/household (1,985 dollars), which equaled $116/household in 2,005 dollars with annual inflation rate of 3 %. We use the larger value ($116/household). To estimate for USFS system, we assumed 5 % of total USA land area.		
WTP value/household	$116	Krieger (2001)
Number of households	1.11E+08	
% of USA in USFS	8 %	
Dollar value	$1.0E+09	
Gross primary productivity		
Emergy value		
Emergy value of gross primary production (emergy driving GPP) taken as the chemical potential energy of rainfall in dissolution of minerals in rocks and soils, driving transpiration of vegetation		
Emergy in rainfall	1.66E+22 seJ	Table 2 line 2
Economic value		
Annual economic value of GPP was estimated using aggregate value of nutrient cycling from Krieger (2001) ($146.1/ac) in 1994 dollars converted to 2005 using an annual inflation factor of 2.45 % and multiplying by area of National Forests (7.8E+07 ha)		
USFS forest area	7.8E+07 ha	
Annual economic value	($146/ac) × (2.47 Ac/ha) × (1.31 20054/1994$ inflation factor) × (7.8E+07 ha)	Krieger (2001)
Economic value of USFS GPP	$3.7E+10	

Organized recreation		
Emergy of tourists		
Emergy of tourists (seJ)	2.40E+22	Table 2, line 17
Tourists economic expenditures for recreation		
Number of tourists	2.05E+08	Table 2, line 17
Travel costs (per person)	$45	Estimate
Dollar expenditures	$9.2E+09	
Information produced		
Emergy value of information produced from Table 2		
Emergy (seJ)	4.56E+21	Table 2, line 26
Economic value		
Payments for FS Labor	1.67E+08 $/year	USFS (2005)

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