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Estimating the environmental costs of soil erosion at multiple scales in Kenya using emergy synthesis

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Abstract

The intrinsic value of soil to national, regional and local agroecological and economic productivity in sub-Saharan Africa is not adequately manifest in financial planning and decision making, challenging long-term sustainability as that resource degrades. While efforts to internalize the external costs of soil erosion in monetary units are available in the literature, we offer an alternative approach based on emergy synthesis, which enumerates the value of soil based on the environmental work required to produce it rather than based on surveys or derived pricing techniques. Emergy synthesis integrates all flows within a system of coupled economic and environmental work in common biophysical units (embodied solar energy or solar emjoules—sej), facilitating direct comparisons between natural and financial capital. Insight into long-term sustainability of human economic production and its basis in natural capital stocks is achieved via a suite of emergy-based indices. Our objective was to provide context for the magnitude of soil erosion losses within the larger resource basis of the Kenyan economy at three scales. Our results suggest that erosion losses at the national scale (4.5E21 sej/yr) are equal in magnitude to national electricity production or agricultural exports (equivalent to $ 390 million annually or 3.8% of GDP). This significant hidden, long-term cost is magnified in the selected district economies. In particular, in Nyando district (a densely populated rural district in western Kenya) we estimate that soil erosion represents over 14% of total emergy flows. The soil intensity of agriculture (SIA = agricultural yield/soil loss, both in emergy units) of Nyando (2.25) illustrates a severely marginalized agricultural sector in comparison with the nation as a whole (SIA = 7.56) or other nations ($\text{SIA}_{\text{USA}} = 81.9$, $\text{SIA}_{\text{Brazil}} = 15.6$). Soil loss measurements across land uses typical in western Kenya allowed emergy evaluation of differential costs and benefits; soil loss represented between 12 and 62% of total emergy use (subsistence agriculture SIA = 8.13, communal rangeland SIA = 1.62). By quantifying the ecological costs of soil erosion in units directly comparable with flows in other sectors of the economic system, we provide a baseline measure of sustainability against which appropriate investment (i.e., scaled to problem magnitude, targeted to hot-spots) in soil conservation may be evaluated.

Keywords: Emergy synthesis; Soil erosion; Kenya; Externality; Natural capital; Systems analysis

1. Introduction

Soil is functionally a non-renewable resource; while topsoil develops over centuries, the world's growing human population is actively depleting the resource over decades. As a non-renewable resource and the basis for 97% of all food production (Pimentel, 1993), strategies to prevent soil depletion are critical for sustainable development. Significant literature exists documenting the magnitude of the

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soil erosion problem. Between 30 and 50% of the world's arable land is substantially impacted by soil loss (Pimentel, 1993), which directly affects rural livelihoods (Lal, 1985; Kerr, 1997) in addition to indirectly affecting aquatic resources (Ochumba, 1990; Eggermont and Verschuren, 2003), lake/river sediment dynamics (Kelley and Nater, 2000; Walling, 2000), global carbon cycling (Duxbury, 1995; Lal, 2003), aquatic and terrestrial biodiversity (Harvey and Pimentel, 1996; Alin et al., 2002) and ecosystem services (Tinker, 1997; Pimentel and Kounang, 1998). Severe soil degradation has been documented throughout sub-Saharan Africa (Thomas and Senga, 1983; Lal, 1985; Pimentel, 1993; Oostwoud and Bryan, 2001; Lufafa et al., 2002), resulting in declining functional capacity (Smaling, 1993; Zobisch et al., 1995; Gachene et al., 1997), ultimately affecting poverty and food security (Sanchez et al., 1997).

Soil loss has ecological and economic impacts at scales ranging from the field, where nutrient depletion, degraded soil structure and lost organic matter affect farm livelihoods (Morgan, 1995), to the watershed and nation, where sediment and nutrient loads alter water quality and storage, and adversely affect ecosystem function (Clark, 1987). Several studies (Smaling, 1993; Sanchez et al., 1997) have documented the significance of erosion in soil functional degradation throughout sub-Saharan Africa at these varied scales, which, given minimal use of soil amendments by rural farmers, has profound implications on sustained regional agricultural production (Lal, 1995). Though some local success in controlling and reversing soil degradation has been documented (Tiffen et al., 1994), the soil resource continues to decline regionally (Sanchez et al., 1997), alarmingly so in areas (Oostwoud and Bryan, 2001).

The link between soil erosion and agricultural yields has been widely cited (Lal, 1995; Mulengera and Payton, 1999), with most attention paid to nutrient limitation. While the severity of the erosion problem is disputed (Crosson, 1986, 1995; Stocking, 1995), it is clear that agricultural yields in Africa have failed to match improvements observed elsewhere (World Bank, 1996), and that a primary constraint to improved yields is soil nutrition. Erosion affects all ecosystem services provided by the soil resource (structure, water holding, carbon storage, etc.) in addition to decreasing nutrient availability (Zobisch et al., 1995). Without quantifying the intrinsic value of these services in the context of the resource basis of the economy, decision makers have no way to evaluate problem severity, nor any quantitative rationale to justify diverting sufficient resources to attenuate it. Indeed, the decision to allocate resources to protect soil or reverse degradation may be based on exaggerated claims of severity (Stocking, 1995). Resource allocations to soil conservation by international agencies and national governments to date have been substantial (Kiome and Stocking, 1995) and it must be recognized that allocating resources to soil conservation requires diversion from other priorities. Our primary objective is to quantify erosion costs in direct comparison with other facets of the internal market economy to better understand the problem and provide a rationale for effective management decisions.

1.1. Evaluating the costs of soil erosion

The literature is replete with efforts to internalize the external (i.e., borne by society, now or in the future, rather than by individuals whose activity engenders the problem—Loehman and Randhir, 1999; Pretty et al., 2000) costs of erosion by placing value on eroded soil (Crosson, 1986; Pimentel et al., 1995; Bojo, 1996; Bandara et al., 2001). Institutional intervention of some kind is then required to adjust market prices to reflect true environmental costs. Most studies focus on links between soil degradation and productivity, but there is increasing attention to off-site impacts as concerns about eutrophication and excess turbidity grow (Clark, 1987; Crul, 1995; Lindenschmidt et al., 1998). Corollary to the concept of valuing eroded soil is that some erosion may be tolerable when tradeoffs necessary to lower loss rates are evaluated (Alfsen et al., 1996); only by comparing erosion costs with intervention benefits can effective policy be deduced.

Soil value can be quantified using many techniques. Most infer value based on market costs of replacing "free" services provided by soils after degradation (e.g. fertilizers, organic amendments); some equate downstream remediation costs (e.g., reservoir dredging) with on-site "external" costs (Starett, 2000). Others infer costs based on the value consumers attach to undegraded lands. Finally, quantification of ecological services is often achieved using surveys to enumerate the "willingness-to-pay" for services provided by soil (Alfsen et al., 1996). For each, the objective is to estimate value in units that allow comparison with market prices.

There have been numerous critiques of economic valuation of ecological services (e.g. Pritchard et al., 2000; Ludwig, 2000), despite their obvious attraction from a practical and regulatory perspective (Hall et al., 2001). One critique is that methods that assess inherent values of natural capital contingent on perceived human values may fail to capture the full extent of ecosystem services. In particular, it seems realistic to argue that failure by humans to appreciate the inherent and long-term value of protecting topsoil is a reason that soil decline continues worldwide and that efforts are ongoing to artificially internalize those costs in market decisions.

Methods that complement efforts to quantify the soil resource value in money units (Bojo, 1996; Kerr, 1997) by avoiding reliance on human preference may provide an informative benchmark against which derived monetary valuation can be compared. Emergy synthesis (Odum, 1996), a technique for valuing environmental work and natural capital offers several advantages over methods assigning money values to services for which no market exists. First, it is based on biophysical processes rather than derived/perceived human value (e.g., hedonic pricing, willingness-to-pay), eliminating preference from the valuation schema. Second, allocation of value is donor based, which frequently simplifies analyses. Value is embodied in natural capital (e.g., topsoil) predicated on the environmental work required to produce it rather than on services that stock provides, which are numerous, coupled, indirect and manifest at varied time and spatial scales, making boundary definitions and scope difficult to standardize.

1.2. System organization and energetics

Ecological and human systems self-organize to transform sources of available energy into work (Odum, 1994); as these transformations occur, a portion of energy previously available loses its ability to do work, increasing entropy at the larger scale. However, energy retained after adaptive transformations has qualities (Odum, 1996) that distinguish it from the original energy (e.g., the ability to reinforce or amplify input flows, feedback control). In adaptive systems, Odum (1996) theorizes that energy is invested in products only where commensurate feed back control (or ecosystem service) is provided to enhance overall system function; as a result, value (in a systems sense) cannot be inferred from energy content alone, but must account for all investments required for production, tracing sources back to common benchmarks to incorporate energy degraded in prior transformations; this framework is called environmental accounting.

A donor value accounting framework, wherein value is derived from biophysical work necessary for production, is useful for evaluating long-term system sustainability. In particular, a loss of a natural capital stock (e.g. topsoil) that has been embedded in a self-organizing system and provides myriad ecological services is valued according to the production requirements for replacement. Human activities that deplete natural capital may have consequences at multiple scales on and off-site, with inherent time lags and non-linear responses; to enumerate all ‘‘receiver’’ costs (e.g. reduced fertility, sedimentation, eutrophication) requires information that may be difficult to acquire and standardize between practitioners (Enters, 1997). As such, donor valuation offers a useful complement to receiver-based methods for measuring sustainability.

1.3. Emergy synthesis

Emergy is defined as the energy required directly and indirectly to create a product or service (Odum, 1996; Odum et al., 2000a). Since each input to a process is itself the product of energy transformations, emergy is often referred to as energy memory, with units referenced to a benchmark energy source (typically solar energy). The emergy unit is the solar emjoule (sej), indicating that emergy is derived from energy flows but is qualitatively different; specifically, emergy accounts for energy degraded (2nd law losses) during sequential transformations from a benchmark (solar energy) to other energy forms. Available energy after each transformation has properties that distinguish it qualitatively from heat. Energy quality (called transformity; units sej/J or sej/g) is the ratio of emergy in a product to the remaining available energy (Odum, 1988).

Transformity values are used to compare process efficiencies (inputs versus outputs) for industrial (Brown and Buranakarn, 2003; Ulgiati and Brown, 1998), agricultural (Ulgiati et al., 1994; Lagerberg, 1999; Brandt-Williams, 2001; Doherty et al., 2002) and forestry (Doherty et al., 2002) systems. They allow direct comparison of biophysical flows in common units; evaluations that ignore energy quality undervalue contributions of small concentrated flows (e.g., human work, top-carnivores) relative to abundant diffuse ones (e.g., sunlight, primary production) (Christensen, 1994). Numerous studies have used emergy synthesis to quantify development tradeoffs that consider both economic and ecological costs and benefits (Brown and McClanahan, 1996; Alejandro Prado-Jatar and Brown, 1997; Portela, 1999; Odum et al., 2000b; Buenfil, 2001). Evaluations have focused on water (Romitelli, 1997; Brandt-Willams, 1999; Howington, 1999), forest products (Doherty et al., 2002), and multi-use forest functions (Tilley and Swank, 2003).

We use emergy synthesis to evaluate soil loss at three scales in Kenya. Dramatically accelerated soil loss is widely observed throughout Kenya, particularly in western districts where high rural population densities, intense climatic inputs and fragile soils converge. Nationally, erosion is estimated between 25 and 180 million tonnes of soil loss annually (Barber, 1983; Smaling, 1993). Our objective is to place this flow in a quantitative framework that includes other aspects of the economic/environment system for direct comparability, reasoning that a clearer understanding of the problem magnitude will elicit the investments necessary for attenuation.

2. Study area—the Kenyan system

Kenya lies in equatorial East Africa, bordered by Tanzania, Uganda, Sudan, Ethiopia and Somalia (Fig. 1). Diverse climates (extreme aridity to montane rainforest), elevations (0–5500 m), cultural groups (Bantu, Nilotic, Arab, Asian, Caucasian and Khoi-San) and livelihood strategies persist in this small nation (580,000 km^2). Kenya has high population growth rates (>3% per year in the 1980’s, now 1–2%, in part due to the effects of HIV) and is home to 31 million people. Political stability, market capitalism, coastal access, a well-educated population, and a lucrative tourism industry have elevated economic conditions in Kenya above those typical of the region, though the national economy shrank on a per capita basis in recent years (World Bank, 2002). GDP in 2001 was $ 10.2 billion, corresponding to $ 330 per capita, placing Kenya among the

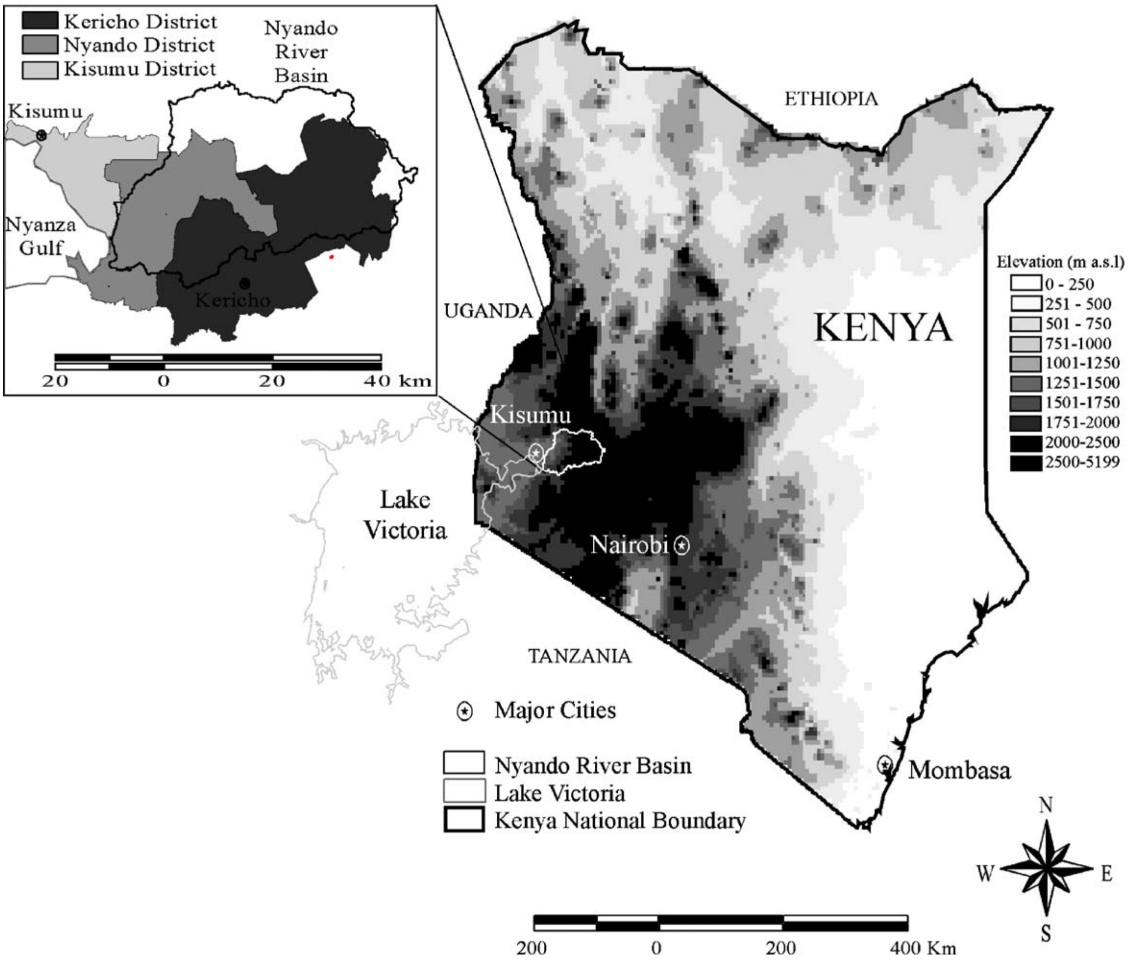


Fig. 1. Map of Kenya, Kisumu, Nyando and Kericho Districts and Nyando River basin. Also shown is national elevation map, Lake Victoria and Kenya's major urban centers.

poorer countries (global ~$ 5000/capita). International debt is significant; Kenya owes over $ 6 billion (World Bank, 2002) resulting in annual service of 25% of export revenue.

Major imports include fuels, fertilizers, metals and machinery (UN 2000). Major exports include agricultural products (~50%, sugar, coffee, tea, pyrethrum, tobacco, cut flowers and sisal), and manufacturing (~20%, petroleum/food processing, engineering services, textiles). Roughly 90% of the population relies on subsistence cropping and animal husbandry. Since only ~7% of the land is arable, rural population densities can exceed 500 km^{-2}. Kenya's major rivers (Mara, Tana, Athi, Nyando, Sondu, Yala-Nzoia) deliver an estimated 313 $\text{t/km}^2\text{/yr}$ of sediment to Lake Victoria and the Indian Ocean (Ministry of Water Development, 1992; FAO, 2001). While land tenure conditions are generally favorable, agricultural extensification has forced cultivation of marginal lands (low rainfall, infertile, steep slopes) and illegal clearing of protected forests (forests cover ~3% of area; loss rate ~1.4%/yr). Kenya's reliance on natural capital includes ecotourism revenue; 700,000 tourists visit Kenya annually, yielding US$ 470 million in 1999.

2.1. Nyando River basin

Conditions of rural poverty are acutely evident in western Kenya where rural population densities are among the highest in Africa, and soil degradation is both prevalent and severe. The political districts (Kisumu, Nyando and Kericho) comprising the Nyando basin (Fig. 1) and regional land use subsystems therein are focal points of this work; this basin has been identified as a regional erosion hot-spot (ICRAF, 2000). The Nyando River drains the western highlands, dropping from 3000 m to Lake Victoria (Nyanza Gulf) at 1184 m. The basin is divided into lowlands (<1500 m) and highlands (>1500 m), separated by a steep escarpment. Lowland climate is sub-humid tropical (~1100 mm rain/yr) with bi-modal rainfall characteristic of equatorial latitudes. Highland climate is humid tropical (~1700 mm rain/yr) exhibiting moderated bi-modal rainfall due to subsidized convection from Lake Victoria; annual insolation and temperature are constant. Lowlands consist primarily of Pleistocene lake plain deposits (Planisols and Vertisols) with deep profiles and moderate to low fertility. Highland soils are deeply weathered (Nitisols, Cambisols) and structurally stable. Dominant lowland agricultural land uses are maize, sugarcane and communal rangeland, while tea, maize, commercial woodlots and paddock grazing (with improved breeds) dominate the highlands. Native ecological communities, now rare, include perennial grasslands in the lowlands, and evergreen broadleaf forest in the highlands. Erosion is particularly severe in the lowlands where, despite shallow relief, networks of gullies and eroded riverbanks threaten transportation, agricultural production, settlements, and downstream water quality. Severe soil crusting is prevalent. Soil degradation prevalence (55% of lands degraded, 25% severely) was estimated by linking ground survey data with satellite imagery in the Awach River basin, a major tributary of the Nyando (Cohen et al., 2005).

3. Methods

Emergy synthesis was applied to economic/environmental systems at three scales in Kenya, starting from the largest scale and focusing on increasingly local systems.

1. A national scale evaluation was developed to quantify the significance of soil degradation to the national economy and provide context for evaluations at smaller scales.
2. Three districts (3rd level of the Kenyan government) in the western region of Kenya that coincide with the Nyando River basin (a hot-spot for erosion, Fig. 1) were evaluated.
3. Land uses that are the primary rural livelihood strategies comprised the local scale. Commercial agriculture (sugar and tea), subsistence agriculture (maize), fuel/timber woodlots, grazing lands, and forests/shrublands (exploited for fuelwood) were examined.

Emergy synthesis of nations, regions and land uses (all on an annual basis) has been standardized to convey generalized information about the energy basis for economic and environmental condition (Ulgiati et al., 1994; Odum, 1996; Doherty et al., 2002); this standard template, with five analytical steps, was followed at each scale (see Doherty et al., 2002 for details):

1. Compilation of cross-boundary flows, internal transformations (environmental and economic) and stock depletion (mining, erosion, forest loss)—this exercise summarizes literature sources (e.g. development reports, economic abstracts, environmental abstracts).
2. Systems diagram development—use the energy systems language (defined in supporting materials) to depict the resource basis. Conventions are given in Odum (1994).
3. Data collection—identify data sources for cross-boundary flows and internal natural capital depletion rates. Summarize economic/environmental production and trade data.
4. Tabular assessment—a standard accounting framework is applied wherein each resource flow is evaluated in physical units, modified by an appropriate transformity to adjust for energy quality (to allow direct comparison between flows of different physical form).
5. Flow aggregation/ index development—summary indices have been developed (Ulgiati et al., 1994) to capture various aspects of environment/economy interactions.

3.1. Emergy tables

Standard analysis templates have been developed to expedite data handling and flow aggregation (Ulgiati et al., 1994; Stachetti unpublished template). Tables consist of named flows (identified as necessary during diagram development), physical units of flow (J, g, $), transformity values that translate physical units into emergy (sej), and total emergy. Since flows are reported on an annual basis, total emergy is expressed in units of sej/yr. A final column in a standard table provides an indirect link with economic measures of value. The macroeconomic value of each flow is reported in equivalent $ (referred to as Em$ to avoid confusion). This value is the emergy flow for each source divided by the emergy money ratio (EMR—see below).

3.2. Transformity values

Transformities specific to Kenya were used where possible, but in most cases previously computed values were used. For Kenya's major agricultural products ($n = 17$), transformities were computed using a standard analysis frame (Brandt-Williams, 2001), linking detailed agroecological inventory and yield data (Jaetzold and Schmidt, 1982) with soil loss estimates (Barber, 1983; Cohen, 2003) and climatological input data (Corbett et al., 1997). These products included raw goods (e.g. maize, sorghum, tea, sugar cane, tobacco), protein sources (fish, cattle) and processed goods (tea and sugar). Transformity values used are given in supporting materials.

Using an appropriate transformity for topsoil was paramount—previous values (1.1E+05 sej/J, Odum, 1996) are based on soil organic matter (SOM) turnover rates for temperate regions where SOM accumulation is more rapid than in the sub-humid seasonal tropics (Nye and Greenland, 1960; Coleman et al., 1989). We estimated emergy requirements for SOM production in two tropical systems (savannah and forest) to determine a more appropriate transformity for the region. Typically, SOM is the ‘‘value-bearer’’ for soil; other functional attributes are subsumed under that component. The rationale for this assumption is that all aspects of soil development (physical, chemical and biological) are coupled, and counting each as a separate cost would ‘‘double-count’’ the emergy required for their parallel production.

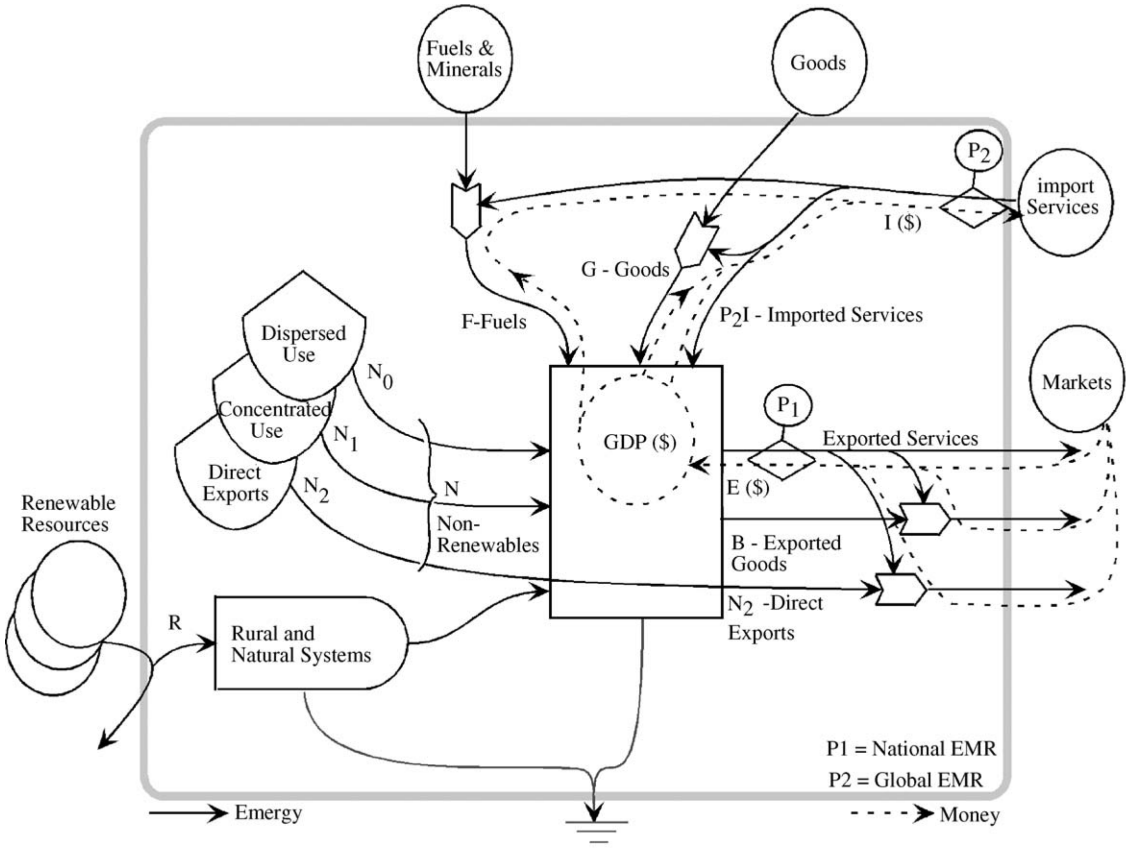
3.3. Emergy evaluation summary indices

Indices derived in Ulgiati et al. (1994), Odum (1996), and Ulgiati and Brown (1998) summarize system resource use intensity, process efficiency, economic–environment interactions and quantify sustainability. These include total emergy use, use per capita and per area, emergy balance of trade, emergy–money ratio, in addition to resource specific indices described below.

To quantify each of the indices (summarized in diagram form in Fig. 2), flows are first aggregated into broad categories. Aggregated flows include renewable energy flows (R), local non-renewable flows (N), imported goods (G), imported fuels and minerals (F), imported services (S_I) and exported goods (B, N_2) and exported services (S_E).

The ratio of gross domestic product (GDP) to total emergy use (U) yields the emergy money ratio (EMR), which describes the purchasing power, in emergy units, of standardized currency (US$; conversions based on mean annual exchange rates) in the local economy (Fig. 2).

The environmental loading ratio (ELR), emergy investment ratio (EIR) and exports:imports (E:I) are used to evaluate performance of a national economy. Each ratio is derived from aggregate flows (Fig. 2): R (renewable), N (local non-renewable), $F + G + S_I$ (imports) and $B + N_2 + S_E$ (exports). ELR reports the ratio of non-renewable ($N + F + G + S_I$) to renewable flows (R); as ELR increases, stress on environmental services is expected due to convergence of sources that intensify existing flow patterns. EIR describes the ratio of purchased inputs ($F + G + S_I$) to



Total Use (U) = $(R + N_0 + N_1 + F + G + P_2I)$
Emergy:Money Ratio (EMR) = U / GNP
Emergy Yield Ratio (EYR) = $U / (N_0 + N_1 + F + G + P_2I)$
Emergy Investment Ratio (EIR) = $(F + G + P_2I) / (N_0 + N_1 + R)$
Environmental Loading Ratio (ELR) = $(N_0 + N_1 + F + G + P_2I) / R$
Emergy Sustainability Index (ESI) = EIR / ELR
% Renewable = $R / (R + N_0 + N_1 + F + G + P_2I)$
% Home Sources = $(R + N_0 + N_1) / U$
Concentrated:Rural = $(N_1 + F + G + P_2I) / (N_0 + R)$

Fig. 2. Standardized economic systems diagram. Shown are aggregated flows and indices that result from these flows. Tabular summaries refer to these flow notations.

total internal flows ($N + R$), and quantifies outside investment to match flows of locally available emergy (i.e., attraction potential). Large EIR values indicate advanced regional or national development; EIR for the USA is 7:1 (Odum, 1996), and 0.46:1 for Thailand (Brown and McClanahan, 1996). $E{:}I$ quantifies the net trade benefit for a nation or region. Values below 1 indicate net imports, generally associated with advanced development (Odum, 1996). The emergy sustainability index (ESI, Brown and Ulgiati, 1999) is the ratio of EIR to ELR; sustainability (ESI) increases with investment (EIR—to remain competitive) and decreases with environmental load (ELR). At the land use subsystem scale, we use the emergy yield ratio (EYR = Y/F) as a measure of return-on-investment in units of environmental work.

3.4. Soil loss indices

Two new metrics were developed specifically to quantify losses of stocks of soil natural capital within the context of a regional energy basis. Typically, soil loss is considered non-renewable energy stock depletion (N in Fig. 3). However, grouping these flows with mined minerals and locally extracted fossil fuels ignores direct ecosystem services that these stocks facilitate. Furthermore, while direct economic benefits of fuel extraction or mineral mining are clear, the benefit of degraded topsoil is not as obvious. It is reasonable to assume that at least a portion of these flows could be prevented given more effective land management policies.

The first new index scales soil loss to the emergy basis for the regional system. The fraction of use soil erosion (FUSE) is computed as % of total use (U) arising from erosion (N_{0a}):

$$\mathrm{FUSE} = \frac{N_{0a}}{U} \tag{1}$$

The second new index provides a cost-benefit ratio for agriculture. The soil intensity of agriculture (SIA) compares agricultural yields (livestock and crops) to the emergy in eroded soil:

$$\mathrm{SIA} = \frac{Y_{ag}}{N_{0a}} \tag{2}$$

where Y_{ag} is the emergy yield from agriculture. Because erosion is embodied as a component of agricultural yields (i.e., soil loss is in both the numerator and denominator), the index minimum is one; values near one indicate strongly deleterious agricultural effects. Large FUSE values indicate substantial external costs to the economy. Both FUSE and SIA are independent of other standard regional analysis indices, and can be computed for all nations for which emergy evaluations have been done for comparative purposes. SIA should vary considerably within and between regions and cropping systems, identifying agricultural and/

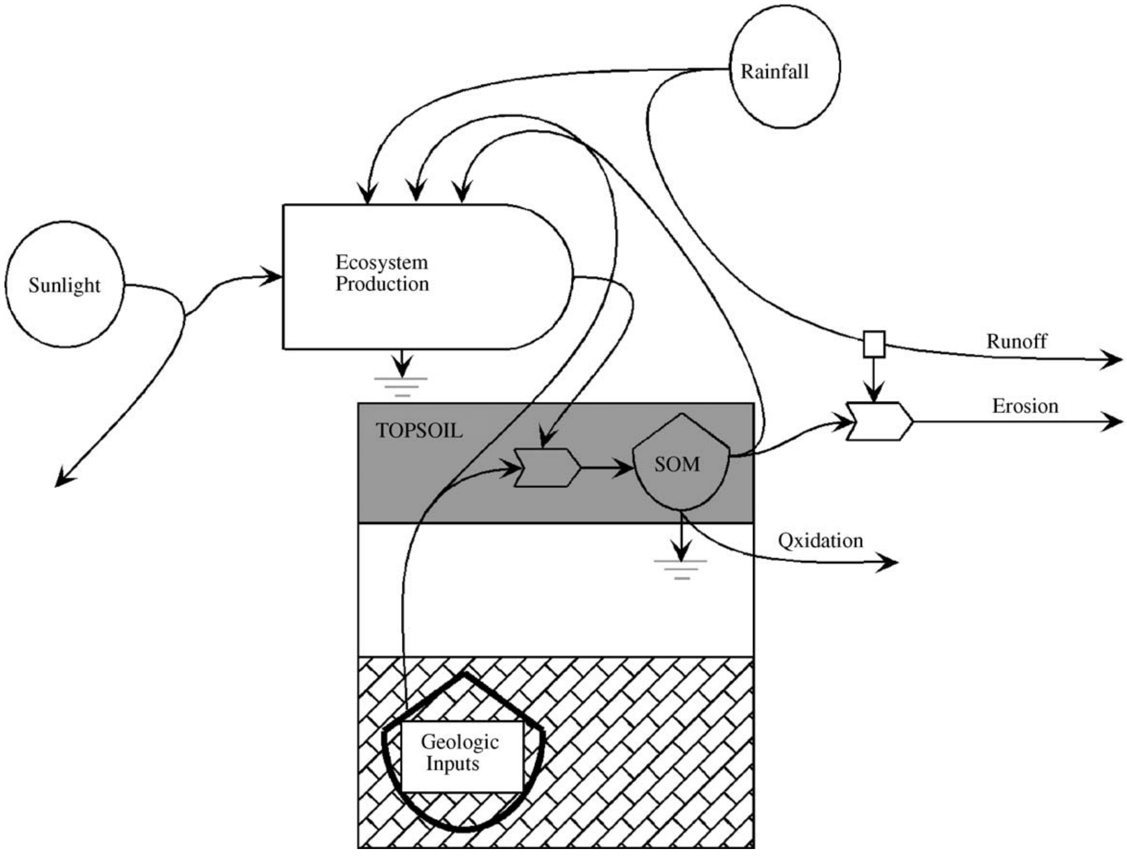


Fig. 3. Simplified schematic of topsoil genesis.

or livestock activities are locally inappropriate. Note that, at the land use scale, SIA is inverse of FUSE; this is not the case at larger scales where total use (U) is not exclusively due to agriculture.

3.5. Data sources—national scale

Renewable flow data were compiled from existing and derived data. Insolation and mean tidal range/wave height were all assumed uniform over area and coastline, respectively (US Dept. of Commerce-NOAA, 1994). Existing thematic coverages were used for elevation (Fig. 1), precipitation and land use (Corbett et al., 1997); thematic layers interpolated from point coverages were developed for deep heat (data from Pollack et al., 1993) and wind (Chipeta, 1976).

Production, consumption and trade data were readily available at the national scale. Internal and cross-boundary flows were obtained primarily from a national statistical abstract published by the Kenyan Central Bureau of Statistics (KCBS, 2000), which compiled national accounts from 1999. Numerous ancillary data sources were used, both to quantify flows not available from the statistical abstract and to cross-reference flows to ensure accurate accounting. These sources included United Nations commodity flow data (FAO-UN, 1999), Europa World Yearbook (Europa Publications, 2000), International Trade Statistics Yearbook (UN Dept. of Economic and Social Affairs, 2000), and a World Bank national overview (World Bank, 2002).

Internal agricultural/fisheries/livestock production, geothermal and hydroelectric power production, forest clearing rates and mining data were all compiled from both published (e.g. Rural Planning Department, 1997a,b,c) and Government of Kenya (GoK) publications, including the Ministry of Agriculture and Rural Development (MoARD), Kenya Pipeline Authority (KPA—parastatal agency responsible for fuel refining, transport and sale), Ministry of Fisheries, Kenya Power and Lighting Corporation (KPLC), Ministry of Forestry and Bureau of Mines.

3.6. National soil loss estimation

Two methods were used to estimate annual soil loss quantities: (1) use of soil loss rates on a land use basis (Barber, 1983), adjusted by a sediment delivery ratio (FAO, 2001; Ministry of Water Development, 1992; Brooks et al., 1997); (2) measurements of sediment concentration in rivers (Ministry of Water Development, 1992). Typically, the latter would be considered more reliable for cross-boundary flows, but available data are from the 1970s and cover a very limited number of rivers. Therefore, the first method was used, with the second providing a cross-check.

Average annual soil loss rates by land use (Table 1) were multiplied by areas inferred from national land use maps (Corbett et al., 1997). Soil loss estimates were multiplied by a sediment yield ratio (assumed 5%, Brooks et al., 1997) to avoid including eroded material subsequently deposited downstream (wetlands, concave slopes, etc.). This approach is conservative with regard to real soil degradation costs because material eroded and deposited downstream is assumed to represent zero cost. Since sedimentation in waterways is detrimental to ecosystem processes, it might constitute a substantial additional receiver cost (Crul, 1995).

Forest clearing at the national scale was quantified using a clearing rate of 1.25% per year; Kaufman et al. (1996) estimate clearing rates between 1 and 1.7% per year for the last several decades. Biomass loss through clearing was assumed to be 80 t/ha/yr.

3.7. Data sources—district scale

Renewable flows were derived from national maps. Local non-renewable and trade flows at the district level were acquired from several sources. District development plans (Rural Planning Department, 1997a,b,c) report on climate and agricultural production, demographics and development indicators. Resource consumption and trade between regions for some flows were obtained from parastatal agencies, including electricity consumption (Kenya Power and Lighting Corporation), fuel distribution/refining (Kenya Pipeline Authority) and tea/sugar production (Kenya Tea Development Authority; Kenya Sugar Authority).

Records of manufacturing, mining, services and transportation are not collected, and the limited data were judged suspect. To estimate flows of manufactured commodities (e.g. metals, services, textiles) that are not documented by reliable sources at the district scale, it was assumed that consumption is proportional to utilization of fuels and electricity, using the national analysis as the proportional reference point. Cleveland et al. (1984) found that economic flows are highly correlated with fuel/energy use, supporting this assumption. Each derived flow is computed as:

$$F_{i,j} = F_{i,n} \times \frac{R_j}{R_N} \tag{3}$$

where $F_{i,j}$ is a derived flow for resource i, for district j. The subscript N refers to the flow of the same resource at the national scale. Flows R_N and R_j are the flows of fuel and electricity at the national and district scale, respectively. A strong proportionality relationship between fuel use, electricity use and economic product was observed between the national and district figures.

3.8. District soil loss estimation

Soil loss at the district scale was estimated from field measurements of loss rates for each land use coupled with land use maps. A sediment yield ratio (sediment load:erosion) of 10% was assumed because this region is dominated by small basins, which typically exhibit high yields (Brooks et al., 1997). In particular, significant drainage occurs via small ungauged escarpment streams discharging large

Table 1
Soil erosion rates and spatial extent for major land cover classes in Kenya (after Barber, 1983)

Zone	Area (m^2)	Area (%)	Soil loss (g/m^2)	Annual soil loss (E6 t)
Barren or sparsely vegetated	3.51E+10	6.1	250	8.77E+00
Broadleaf deciduous forest	9.83E+09	1.7	100	9.83E-01
Cropland/grassland mosaic	7.22E+10	12.4	3000	2.17E+02
Cropland/woodland mosaic	2.30E+09	0.4	2500	5.74E+00
Dry cropland and pasture	2.26E+10	3.9	4500	1.02E+02
Evergreen broadleaf forest	1.49E+10	2.6	100	1.49E+00
Grassland	1.06E+11	18.3	500	5.30E+01
Savanna	1.64E+11	28.4	500	8.22E+01
Shrubland	1.39E+11	23.9	750	1.04E+02
Urban	1.55E+08	0.0	5000	7.74E−01
Water bodies	1.40E+10	2.4	0	0.00E+00
Total	5.80E+11			5.75E+02

sediment loads directly to Lake Victoria. Load data for area rivers (FAO, 2001) were not used because only single measurements (often dry season) were available; seasonal rainfall and land use patterns suggest that these underestimate total load.

3.9. Data sources—land use subsystems

We used emergy evaluation to compare common land use subsystems. Western Kenya has limited livelihood diversity, with most inhabitants engaged in subsistence farming and animal husbandry. As a result, major land uses of interest relate to food and fuel production. Land uses analyzed were: subsistence farming (maize), commercial farming (smallholder production of sugarcane and tea), communal and constrained grazing for livestock production, subsistence woodlots, and native forests/shrublands exploited for charcoal production.

Systems diagrams were developed for each land use as a first step, followed by tabular evaluation. Data were compiled on yields and inputs by agro-climatic zone in an effort to distinguish lowland from highland systems. Soil loss rates were measured for each land use in each climatic zone (see below). Data for local cropping system inputs and yields come primarily from a study of farm productivity in western Kenya (Jaetzold and Schmidt, 1982). These data were used to develop transformities for local agricultural products (supplementary materials, Table A2). In addition, climatic inputs (rainfall, wind energy, deep heat) were derived from national maps where specific data were unavailable in Jaetzold and Schmidt (1982).

For livestock, woodlot and forest subsystems, literature data were acquired from Simpson and Evangelou (1984), Raikes (1983), Chavangi and Zimmermann (1987), and ICRAF (2000) describing activities throughout Kenya. Generalized data, however, may fail to capture specific system details. For example, livestock systems vary with altitude, with communal grazing of indigenous (Zebu) cattle and other small ruminants dominating the lowlands and paddock grazing of improved breeds (Fresian hybrids) typical in highland systems. As such, two evaluations were compiled for livestock land uses. While crop productivity varies similarly with elevation/rainfall and soil type, we ignored this effect in our analysis.

3.10. Land use soil loss estimation

Soil loss was estimated from field measurement of surface deflation. Erosion pins were installed at 120 sites throughout the Awach River basin (a tributary of the Nyando), representing regional land uses, soil degradation status and climatic regimes. Each pin (a 12 cm steel nail) was hammered into the ground until the nail head was level with the surface. At each site (30 m × 30 m), three locations were identified; 6 pins were installed in a radial pattern at each location, for a total of 18 pins per site. After three months (long rains—March through June 2001), the sites were revisited. Pins were relocated using a metal detector, and surface deflation (nail exposure) was measured. Bulk density measurements at each site allowed conversion of measured surface deflation to soil mass loss. Annual loss rates were assumed twice measured rates because rainfall during the sample period is roughly half annual rainfall (Corbett et al., 1997); the sample season was typical for total precipitation. No adjustments for sediment yield were necessary because loss rates were observed at the land use analysis scale.

4. Results

4.1. Topsoil transformity

Data on carbon accumulation and turnover in tropical soils, used to develop a transformity value used throughout this study, are given in Table 2. A schematic of topsoil formation processes (Fig. 3) shows the interaction of exogenous sources with internal production to yield a natural capital stock. Annual inputs (rainfall and weathered minerals) were converted to emergy using

Table 2
Annual emergy inputs to ecosystem processes (biomass production, organic matter accumulation)

Note	Savanna ecosystem flows	Physical flows (units/yr)	Units	Transformity (sej/unit)	Emergy (sej/yr)
1	Sunlight	7.66E+08	J	1	7.66E+08
2	Rainfall	7.50E+06	J	31000	2.33E+11
3	Weathering	60	g	1.70E+09	1.02E+11
				Total	3.35E+11
4	Net primary production	1.00E+07	J	3.34E+04	
5	OM production	1.76E+06	J	1.91E+05	

Note	Forest ecosystem flows	Physical flows (units/yr)	Units	Transformity (sej/unit)	Emergy (sej/yr)
1	Sunlight	7.66E+08	J	1	7.66E+08
2	Rainfall	1.10E+07	J	31000	3.41E+11
3	Weathering	80	g	1.70E+09	1.36E+11
				Total	4.77E+11
4	Net primary production	1.42E+07	J	3.36E+04	
5	OM production	2.49E+06	J	1.92E+05	

Notes: (1) insolation is assumed equal between systems at 1.83 kcal/m^2/yr (FAO, 2001); (2) mean rainfall is 2.2 and 1.5 m/yr for forested and savanna systems, respectively; (3) mean weathering rates are assumed to be equal to steady state erosion rates of 60 and 80 g/m^2/yr for savanna and forest systems, respectively; (4) net primary production rates (Young, 1976) are 850 and 600 g/m^2/yr for forest and savanna systems, respectively. Energy content is assumed 4 kcal/g; (5) nominal SOM accumulation rates (Nye and Greenland, 1960; Coleman et al., 1989; Parton et al., 1994) are 170 and 120 g/m^2/yr for forest and savanna systems, respectively. Energy content is assumed 3.5 kcal/g.

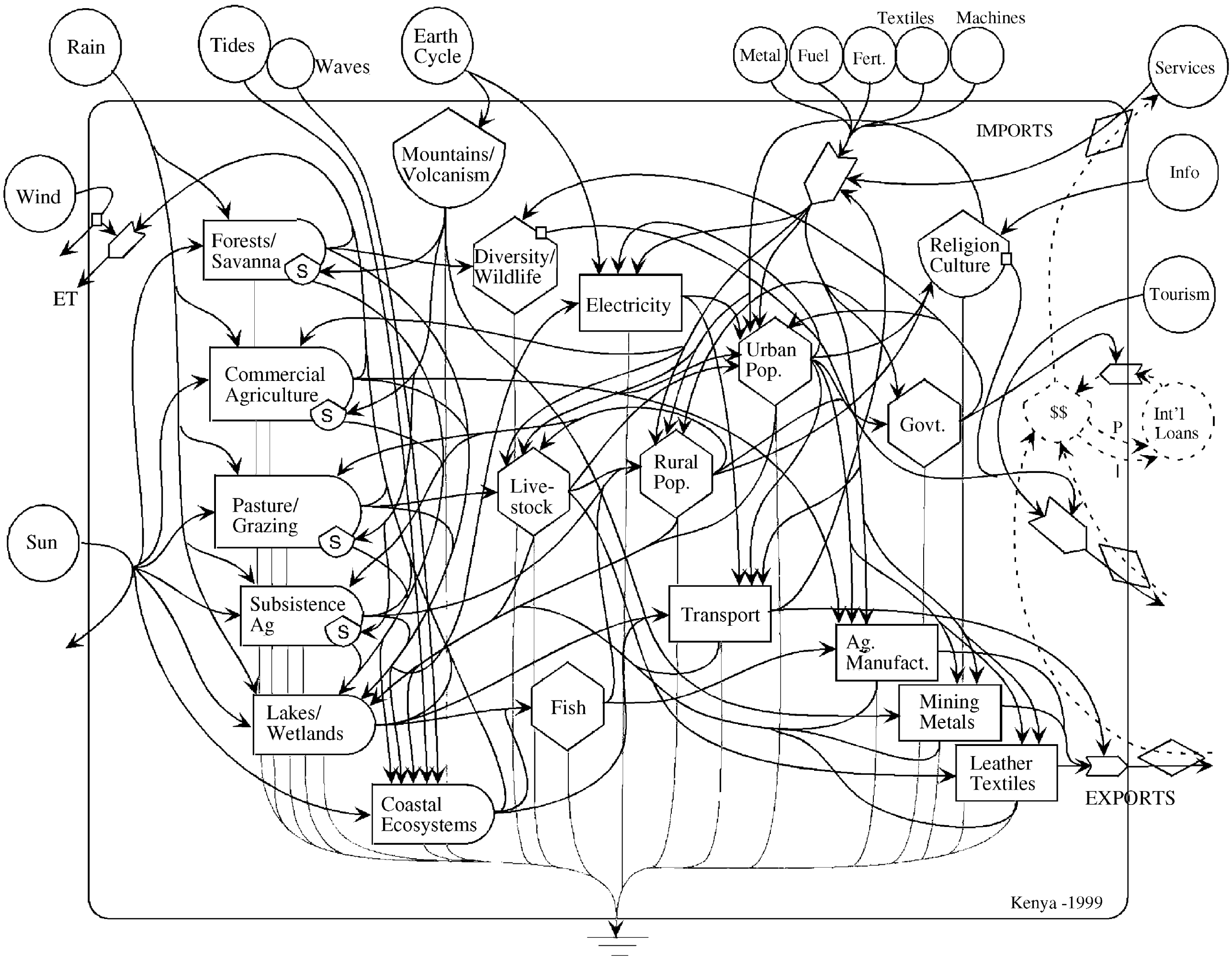


Fig. 4. Detailed systems diagram of the Kenyan national system (ca. 1999).

Table 3
Emergy evaluation of resource basis for Kenya (ca. 1999)[a]

Note	Item	Physical flow	Units	Transformity (sej/unit)[b]	Solar emergy (E20 sej)	EmDollars (E9 1999 US$)
Renewable resources						
1	Sunlight	3.70E+21	J	1	36.96	0.32
2	Evapotranspiration, chemical	1.68E+18	J	31000	519.65	4.46
3	Runoff, geopotential	3.08E+17	J	47000	144.57	1.24
4	Wind, kinetic energy	3.39E+18	J	2450	83.08	0.71
5	Waves	3.34E+17	J	51000	170.49	1.46
6	Tide	5.49E+17	J	73600	404.24	3.45
7	Earth cycle	1.05E+18	J	58000	609.47	5.21
Indigenous production						
8	Hydroelectricity	1.12E+16	J	2.77E+05	31.14	0.27
9	Geothermal electricity	2.25E+15	J	2.69E+05	6.05	0.05
10	Agriculture production[c]	1.62E+17	J	8.84E+04	143.21	1.22
11	Livestock production[c]	1.31E+16	J	1.11E+06	145.42	1.24
12	Fisheries production	7.47E+14	J	9.42E+06	70.38	0.60
13	Fuelwood production	1.72E+17	J	3.09E+04	53.10	0.45
Local non-renewable sources						
14	Const. mater. (sand, ballast)	3.69E+12	g	1.69E+09	62.36	0.53
15	Soda ash	5.81E+11	g	1.69E+09	9.82	0.08
16	Fluorspar, salt, limestone	1.72E+11	g	1.69E+09	2.90	0.02
17	Gold	9.90E+05	g	2.00E+13	0.20	0.00
18	Precious/semi-precious gems	4.30E+07	g	1.00E+13	4.30	0.04
19	Forest clearing	6.18E+16	g	6.72E+04	41.53	0.35
20	Top soil (OM)	2.35E+16	J	1.92E+05	45.18	0.39
Imports						
21	Oil derived products	1.41E+17	J		135.45	1.16
	Crude petroleum	8.20E+16	J	8.90E+04	72.98	
	Refined petroleum	5.80E+16	J	1.06E+05	61.41	
	Petroleum products	1.00E+15	J	1.06E+05	1.06	
22	Metals	4.33E+11	g		29.74	0.25
	Ferrous metals raw	3.94E+11		2.99E+09	11.79	
	Non-ferrous metals	2.50E+10		2.69E+10	6.72	
	Metal structures and tools	1.39E+10		8.06E+10	11.23	
23	Minerals	6.87E+10	g		1.16	0.01
	Cement	3.94E+10		1.73E+09	0.68	
	Clay	1.68E+10		2.86E+09	0.48	
	Glass	1.24E+10		1.08E+07	0.00	
24	Food and agricultural products[c]	1.48E+16	J	1.44E+05	21.36	0.18
25	Livestock, meat, fish[c]	1.27E+14	J	4.20E+06	5.33	0.05
26	Plastics and rubber	1.19E+11	g		9.51	0.08
	Rubber	1.19E+11	g	7.22E+09	8.59	
	Plastics	1.45E+11	g	6.38E+08	0.92	
27	Chemicals	5.31E+11	g		28.23	0.24
	Chemical products, dyes, etc.	1.44E+11		6.38E+08	0.92	
	Fertilizers	3.87E+11		7.06E+09	27.31	
28	Wood, paper, textiles	1.69E+15	J		28.33	0.24
	Wood	3.25E+14		3.09E+04	0.10	
	Paper	9.79E+14		3.61E+05	3.54	
	Textiles	3.87E+14		6.38E+06	24.69	
29	Mechanical and transportation equipment	4.45E+10	g	1.13E+11	50.07	0.43
30	Service in imports	2.75E+09	$	2.08E+12	57.28	0.49
Exports						
31	Food and agricultural products[c]	1.32E+16	J	3.77E+05	49.72	0.42
32	Livestock, meat, fish[c]	4.66E+14	J	3.30E+06	15.40	0.13
33	Wood, paper, textiles	4.87E+15	J		33.22	0.28
	Wood	4.15E+15		1.43E+05	5.91	
	Paper	4.01E+14		3.61E+05	1.45	
	Textiles	2.57E+14		6.38E+06	16.43	
	Leather	6.53E+13		1.44E+07	9.43	
34	Oil derived products	1.20E+16	J	1.06E+05	12.69	0.11
35	Metals	1.81E+11	g		21.20	0.18

Table 3 (*Continued*)

Note	Item	Physical flow	Units	Transformity (sej/unit)[b]	Solar emergy (E20 sej)	EmDollars (E9 1999 US$)
	Ferrous metals	1.67E+11	g	2.99E+09	5.01	
	Non-ferrous metals	2.57E+09	g	2.69E+10	0.69	
	Metal structures and tools	1.14E+10	g	1.35E+11	15.50	
36	Minerals	7.16E+11	g		16.44	0.14
	Cement	6.90E+11	g	1.73E+09	11.94	
	Glass	2.59E+10	g	1.08E+07	0.00	
	Gold and gems	4.40E+07	g	1.02E+13	4.49	
37	Chemicals	7.90E+10	g	6.38E+08	0.50	0.00
38	Mechanical and transportation equipment	1.48E+09	g	1.13E+11	1.67	0.01
39	Plastics and rubber	5.30E+10	g		0.68	0.01
	Plastics	4.78E+10	g	6.38E+08	0.30	
	Rubber	5.26E+09	g	7.22E+09	0.38	
40	Service in exports	1.98E+09	$	1.17E+13	231.14	1.98
41	Tourism	4.74E+08	$	1.17E+13	55.46	0.47

[a] Table footnotes, and raw data/transformity sources are in supplementary information (Table A3).

[b] Transformity values are summarized in supplementary information (Table A1).

[c] Each agricultural and livestock entry aggregates products with differing transformities. The transformity used in each case is a weighted average transformity across all commodities that comprise the physical flow. Transformities for agricultural products for Kenya are summarized in supplementary materials (Table A2).

their respective transformity values, then summed. The emergy driving OM production at the ecosystem scale was divided by the available energy (assuming 3.5 kcal/g) to yield a transformity value; a similar calculation was developed for annual biomass production. The resulting topsoil organic matter transformity is the same for both ecosystems (1.92E5 sej/J) as a result of larger exogenous inputs as well as increased SOM production for forest production.

4.2. National analysis

4.2.1. Systems diagram

A diagram of the Kenyan environmental/economic system (Fig. 4) depicts resource flows entering the system and the organization of major internal components that utilize those resources. Primary renewable flows are sunlight, rainfall, and earth heat; purchased goods, fuels, and services are also shown. Internal production systems include forests and savannas, commercial and subsistence farming, rangelands, wetlands and coral reefs; livestock, fisheries, and native fauna are shown. In addition to direct extraction from these sectors, associated costs of soil erosion are depicted (*S* in each production system represents soil), along with consequent impacts on aquatic resources. Major manufacturing sectors include agricultural processing, metal and mineral processing, and leather and textiles. With tourism, these are the main revenue generators; the diagram shows how revenue is generated and spent importing goods and services from the global market. Purchased sources are aggregated to avoid excessive complexity, but were analyzed in detail (Table 3). Government's role in protecting wildlife, providing services to urban and rural populations and managing loans (principal—*P* and interest—*I*) is shown.

4.2.2. Emergy table

Detailed tabular accounting of Kenya's emergy basis (Table 3, 1999) enumerates renewable resources, indigenous production, local non-renewable resource extraction, imports and exports. Sunlight represents 99.8% of total energy inflow, but only 1.25% of emergy flow (adjusted for energy quality). Conversely, flows of high quality inputs (fuels, services, materials) are energetically insignificant (~0.00001% of total energy), but clearly critical to the Kenyan system, representing over 35% of total use when adjusted for quality. In emergy units, the largest renewable driving the Kenyan economy is rainfall, and to avoid double counting emergy delivered from coupled processes, only this flow (rainfall chemical potential + geopotential) is included in subsequent calculations for *R* (Odum et al., 2000a).

Most indigenous production is from agriculture and livestock, followed by managed forest and fishery yields. Kenya's electricity (geothermal and hydroelectric) is minor in comparison, illustrating limited national electrification. Overall, agriculture and livestock production contribute 1.43E22 and 1.45E22 sej per year. Local non-renewable flows include mining products (mainly ballast materials), forest loss (Item 19) and erosion (Item 20).

All fossil fuel resources are imported; other major imports are embodied services and mechanical/transportation equipment. Major exports are food and agricultural products, wood/ paper/textile products and embodied services (i.e. services that are necessary both directly and indirectly to facilitate exports, quantified using money received multiplied by the Kenyan EMR).

4.2.3. Flow aggregation

Flow aggregations (Table 4) include renewable, local non-renewable, imports and exports. Also included are

Table 4
Summary emergy indices for Kenya (ca. 1999) (flow expressions refer to Fig. 2)

Item	Name of index	Expression	Units	Quantity
1	Renewable emergy	R[a]	sej	6.65E+22
2	Indigenous non-renewables	N	sej	1.66E+22
3	Dispersed rural source	N_0	sej	8.70E+21
4	Concentrated use	N_1	sej	8.00E+21
5	Exported without use	N_2	sej	1.40E+21
6	Imported fuels and minerals	F	sej	1.66E+22
7	Imported goods	G	sej	1.42E+22
8	Dollars paid for imports	I	$	2.75E+09
9	Emergy of services in imports	S_I	sej	5.70E+21
10	Dollars received for exports	E	$	1.98E+09
11	Emergy of services in exports	S_E	sej	2.32E+22
12	Total emergy used, U	$N_0 + N_1 + R + F + G + S_I$	sej	1.20E+23
13	Emergy in exports	$B + N_2 + S_E$	sej	4.37E+22
14	Emergy in imports	$F + G + S_I$	sej	3.66E+22
15	Total emergy inflows	$R + F + G + S_I$	sej	1.04E+23
16	Gross district product	GDP	$	1.02E+10
17	Emergy money ratio	$P_1 = U/\mathrm{GDP}$	sej/$	1.17E+13
18	Fraction emergy use, home sources	$(N_0 + N_1 + R)/U$	%	0.69
19	Exports to imports	$(B + N_2 + S_E)/(F + G + S_I)$	–	1.23
20	Fraction used, locally renewable	R/U	%	0.56
21	Fraction of use purchased	$(F + G + S_I)/U$	%	0.31
22	Fraction imported service	S_I/U	%	0.05
23	Fraction of use that is free	$(R + N_0)/U$	%	0.69
24	Ratio of concentrated to rural	$(F + G + S_I + N_1)/(R + N_0)$	–	0.59
25	Population	Pop.	#	3.18E+07
26	Population density	Pop./area (km^2)	#/km^2	54.8
27	Emergy density	U/area (m^2)	sej/m^2	2.07E+11
28	Emergy per capita	U/population	sej/#	3.77E+15
29	Fraction of use as electricity	(Electric use)/U	%	3%
30	Fuel use per person	Fuel/population	sej/#	4.26E+14
31	Emergy investment ratio	$(F + G + S_I)/(R + N)$	–	0.44
32	Environmental loading ratio	$(N + F + S_I + G)/R$	–	0.8
33	Emergy sustainability index	EIR/ELR	–	0.55
34	Fraction soil erosion (FUSE)	$(N_{0a})/U$	%	3.77%
35	Soil intensity of agriculture (SIA)	Ag. prod./(N_{0a})	–	7.56

[a] As is convention in emergy analyses, we use only the largest renewable flow (rainfall, partitioned in chemical and geo-potential) to avoid double counting emergy.

economic data (GDP, trade). These data were aggregated for Kenya based on the conventions in Fig. 2. Imported services (S_I) were quantified using the global EMR (Brown and Ulgiati, 1999) multiplied by money for imports (I). Similarly, services embodied in exports are computed from money received (E) multiplied by the Kenyan EMR (P_1).

4.2.4. Overview indices

Summary indices for Kenya include total use, % renewable, synthesis indices ELR, EIR, ESI, and E:I (Table 4). Kenya is a net exporter (E:I = 1.23) with more emergy exported annually than received, despite a fiscal trade deficit ($ for imports < $ for exports). Kenya purchases a small fraction of its emergy (31%), and electricity represents a lower fraction of use (3%) than the global average (11%). The EIR (0.44) indicates that Kenya receives limited external investment to match local resource consumption, deepening reliance on local sources. The ELR (0.80) is moderately high given a low emergy per capita (3.77E15 sej/person), and the ESI (0.55) is moderately low, though typical of this index for nations dependent on resource extraction.

Of particular interest are FUSE and SIA, which enumerate erosion as a component of the overall resource basis. FUSE indicates that erosion represents nearly 4% of total use. The SIA (7.56) suggests that for each unit of soil loss, 6.56 units of agricultural production are possible.

4.3. District emergy analysis

4.3.1. District descriptions

Striking qualitative differences exist between the developed conditions in Kisumu district and the largely rural conditions in Nyando and Kericho districts (Table 5). Nyando district relies on sugar harvest and processing, and Kericho on tea production, while Kisumu has a more diversified economic infrastructure and significant influx of raw materials that are processed further at local industrial facilities. Cross-boundary trade is diverse for Kisumu, a

Table 5
Overview indices for district evaluations[a]

Item	Name of index	Expression	Units	Kisumu	Kericho	Nyando
1	Renewable emergy flow	R	sej	2.07E+20	6.15E+20	2.74E+20
2	Flow from indigenous non-renewables	N	sej	1.84E+20	5.82E+20	2.27E+20
3	Dispersed rural source	N_0	sej	1.50E+20	4.87E+20	1.92E+20
4	Concentrated use	N_1	sej	3.36E+19	9.50E+19	9.86E+19
5	Exported without use	N_2	sej	7.50E+18	1.77E+20	3.88E+19
6	Imported fuels and minerals	F	sej	7.24E+20	2.56E+20	1.15E+20
7	Imported goods	G	sej	4.68E+20	1.89E+20	1.06E+20
8	Dollars paid for imports	I	$	6.20E+07	2.80E+07	6.10E+06
9	Emergy of services in imports	S_I	sej	7.83E+20	3.49E+20	7.85E+19
10	Dollars received for exports	E	$	6.00E+07	2.20E+07	6.30E+06
11	Emergy of services in exports	S_E	sej	6.12E+20	2.60E+20	1.65E+20
12	Total emergy used, U	$N_0 + N_1 + R + F + G + S_I$	sej	2.37E+21	1.99E+21	8.65E+20
13	Emergy in exports	$B + N_2 + S_E$	sej	1.2E+21	1.01E+21	3.43E+20
14	Emergy in imports	$F + G + S_I$	sej	1.97E+21	7.94E+20	3.00E+20
15	Total emergy inflows	$R + F + G + S_I$	sej	2.37E+21	1.99E+21	8.01E+20
16	Gross district product	GDP	$	2.30E+08	1.70E+08	3.30E+07
17	Emergy money ratio	$P_1 = U/\mathrm{GDP}$	sej/$	1.02E+13	1.18E+13	2.62E+13
18	Fraction emergy use, home sources	$(N_0 + N_1 + R)/U$	%	17%	60%	65%
19	Exports to imports	$(N_2 + Y)/(F + G + S_I)$	–	0.61	1.49	1.27
20	Fraction used, locally renewable	R/U	%	9%	31%	32%
21	Fraction of use purchased	$(F + G + S_I)/U$	%	83%	40%	35%
22	Fraction imported service	S_I/U	%	33%	18%	9%
23	Fraction of use that is free	$(R + N_0)/U$	%	15%	55%	54%
24	Ratio of concentrated to rural	$(F + G + S_I + N_1)/(R + N_0)$	–	5.62	0.81	0.85
25	Population	Pop.	#	5.04E+05	5.97E+05	2.99E+05
26	Population density	Pop./area (km^2)	#/km^2	763.64	237.38	209.09
27	Emergy density	U/area (m^2)	sej/m^2	3.58E+12	7.91E+11	6.03E+11
28	Emergy per capita	U/population	sej/#	4.69E+15	3.32E+15	2.89E+15
29	Fraction of use as electricity	(Electric use)/U	%	5%	5%	2%
30	Fuel use per person	Fuel/population	sej/#	5.42E+14	4.94E+14	1.32E+14
31	Emergy investment ratio	$(F + G + S_I)/(R + N)$	–	5.05	0.66	0.6
32	Environmental loading ratio	$(N + F + S_I + G)/R$	–	10.44	2.24	1.92
33	Emergy sustainability index	EIR/ELR	–	0.48	0.3	0.31
34	Fraction soil erosion (FUSE)	$(N_{0a})/U$	%	2.4%	3.4%	14.2%
35	Soil intensity of agriculture (SIA)	Ag. prod./(N_{0a})	–	4.37	11.11	2.25

[a] Detailed evaluations for each district are given in supplementary materials (Tables A4–A6). Flow aggregations are from Fig. 2.

regional center for services and manufacturing; consequently, Kisumu is a net importer. In contrast, Kericho and Nyando districts are resource exporters; in addition to tea, Kericho provides a substantial milk and agricultural surplus to surrounding districts in addition to acting as the central tea growing and processing region. Nyando primarily exports sugar, but also substantial quantities of building sand (made available due to severe erosion and subsequent deposition). Diagrams at varying aggregation levels are provided in supplementary materials (Fig. A2).

4.3.2. *Evaluation tables and summary indices*

Table 5 summarizes emergy syntheses (details in supplementary materials, Tables A4–A6) using flow aggregations and indices used at the national scale. Kericho district receives the most renewable emergy, primarily as rainfall; however, Kisumu district, which is far smaller (in area) than both Kericho and Nyando districts, receives three times more imported emergy (fuels, goods, services). Second, district economy size varies widely, with a GDP of $ 230 million in Kisumu versus only $ 33 million in Nyando. Finally, the EMR varies substantially between the districts, with higher values in Nyando, indicating their implicit disadvantage when trading with surrounding districts. Like Kenya as a whole, Kericho and Nyando are net emergy exporters; Kisumu (a market center) is a net importer. The discrepancy between exports and imports is most pronounced in Kericho, which supplies increasingly scarce fuel wood to the region. All three districts are more intensively developed than the nation; the emergy density in each is at least 3 times higher than the national average, illustrating the intense use that accompanies high population densities. Further, Kisumu has ELR and EIR values an order of magnitude larger than the national average, and Nyando and Kericho have ELR values more than twice Kenya's. As a result, the emergy sustainability index is lower for these three districts than for the country.

Finally, soil degradation indices illustrate the need to target interventions. FUSE in Kisumu and Kericho is comparable with the national average while soil erosion in Nyando represents 14% of total use. This flow is larger than

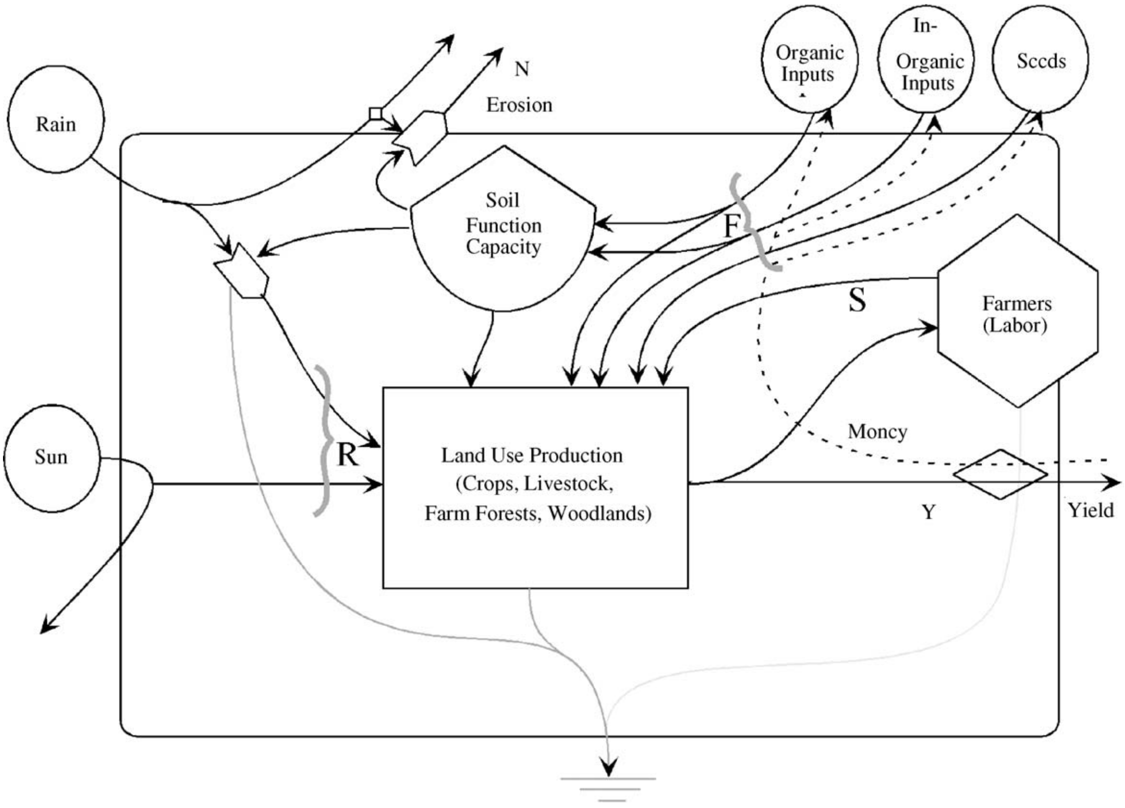


Fig. 5. Generic land use subsystem diagram with aggregated flows (renewable—R, non-renewable—N, purchased—F, and labor/service—S), and yield (Y).

all district crop production and equivalent to 50% of imports. SIA indicates a similar condition; agricultural activity in Nyando has a net benefit of 2.25, substantially below the national average. In contrast, agriculture in Kericho has a higher SIA than the national average. The moderate SIA in Kisumu is due to the proportion of that district that is urbanized, leading to erosion rates not due exclusively to agricultural activity.

4.4. Regional land use subsystem analysis

4.4.1. Subsystem descriptions

A generic diagram (Fig. 5) depicts aggregated flows and exogenous resources derived from synthesis of management practices, inputs and yields for each land use subsystem. Land use yield is depicted as the interaction of renewable resources, purchased inputs and human labor. Soil erosion is an unintended consequence, depleting a stock of soil functional capacity; this flow is highly variable across land use systems. Yields generate variable cash income, which may be used to purchase farm inputs or diverted to other livelihood needs. More specific systems diagrams for each subsystem are provided in supplementary materials (Figs. A3 and A4).

Subsistence agriculture is the primary livelihood activity. Major crops include maize, sorghum, beans, cassava, millet and cooking bananas. For this work, we present an analysis of maize production in both lowland and highland climate regimes. Emergy evaluations for other crops (maize/bean intercropping, sorghum, etc.) are presented as supplementary materials (Table A2). Maize farming in the region makes limited use of agrochemicals (fertilizers, herbicides), resulting in heavy reliance on human labor; improved varieties are only occasionally used. The main renewable input is rainfall (Jaetzold and Schmidt, 1982). Human labor (weeding, planting, tillage, and harvesting) is an estimated 130 person-days per hectare per year.

Commercial agriculture is dominated by outgrower operations (i.e., small farms selling yields to central processing facilities), as opposed to large commercial farms. An important input for both sugar and tea production is the purchase of improved varieties (cuttings or seedlings). Chemical inputs, primarily fertilizers, are more widely used for commercial crops because of increased access to cash resources from their sale. For this study, only lowland sugarcane production was evaluated (though highland systems exist); only highland tea growing operations were analyzed (lowlands are outside the viable agro-climatic zone for tea production).

Livestock production is a critical livelihood strategy throughout rural Kenya. As population growth has forced intensification, highland production has shifted from free range to paddock grazing with primarily improved breeds that are fed on pasture grasses and harvested napier grass (*Pennisetum purpureum*), and require greater disease control efforts. In contrast, communal grazing continues to be the

Table 6
Comparison of soil loss rates (g/m^2/yr), emergy flows (Fig. 5), summary indices and computed transformities for seven land use subsystems for highland and lowland climatic regimes[a]

Climate regime	Flows and indices[b]	Land use subsystems						
		Subsistence agriculture (maize)	Commercial agriculture		Livestock production[c]		Woodlots	Forest/shrubland[d]
			Sugarcane	Tea	Communal	Paddock		
Highlands (average soil loss = 1268 g/m^2/yr)	Soil loss[e]	1300 (844)	–	1484 (2469)	2526 (4154)	1817 (4809)	1000 (970)	600 (1954)
	R	233	–	208	193	207	213	194
	N	66	–	113	269	138	76	46
	F	161	–	318	7	23	18	0
	S	140	–	137	35	45	54	43
	Ag. yields	3.10E+06	–	5.10E+06	2.89E+03	6.36E+03	1.00E+07	6.00E+06
	EIR	1.01	–	1.42	0.12	0.20	0.25	0.18
	ELR	1.57	–	2.73	1.23	1.00	0.69	0.46
	EYR	1.99	–	1.70	9.31	6.01	5.03	6.56
	SIA	9.12	–	6.88	2.02	3.00	4.75	6.20
	Transformity[f]	1.11E+05	–	1.03E+05	1.08E+08	7.04E+07	2.46E+04	3.22E+04
	FUSE	0.11	–	0.15	0.49	0.33	0.21	0.16
Lowlands (average soil loss = 3226 g/m^2/yr)								
	Soil loss	2767 (6105)	1800 (2708)	–	3543 (2051)	2884 (3227)	2263 (3767)	882 (2600)
	R	194	196	–	143	152	171	139
	N	191	137	–	269	219	172	62
	F	127	84	–	7	13	18	0
	S	140	137	–	35	45	54	43
	Ag. yields	2.10E+06	5.30E+07	–	2.89E+03	3.76E+03	8.00E+06	5.70E+05
	EIR	0.70	0.68	–	0.10	0.16	0.21	0.21
	ELR	2.39	1.88	–	2.06	1.83	1.42	0.76
	EYR	2.43	2.48	–	10.84	7.37	5.79	5.66
	SIA	3.41	4.00	–	1.72	1.96	2.41	3.91
	Transformity[f]	9.79E+04	6.31E+03	–	1.74E+08	1.24E+08	3.54E+04	4.17E+04
	FUSE	0.29	0.25	–	0.58	0.51	0.41	0.26

[a] Detailed emergy evaluations are given in supplementary materials (Tables A7–A13; Table A2 summarizes transformity values for an additional 11 agricultural commodities).

[b] Aggregated flows (*R*, *N*, *F*, *S*) are E+13 sej/ha/yr. Ag. yields are g dry weight/ha/yr except meat (wet weight).

[c] Transformity values for livestock production are for meat.

[d] Transformity values are for wood, not charcoal.

[e] Soil loss rates are derived from observations of surface deflation and reported in g/m^2/yr as mean (std. error) from a mixed effects model (Cohen, 2003). Site counts for each land use subsystem are (from left to right): 3, 0, 3, 6, 14, 4, 7 (highlands) and 6, 7, 0, 35, 6, 7, 9 (lowlands).

[f] All transformities are sej/J for dry weight yields except meat (wet weight).

primary strategy in the lowlands despite relatively high stock densities. Cattle are primarily Zebu breed, which tend to be resistant to diseases typical in ruminants in tropical Africa (Simpson and Evangelou, 1984), and preferred where access to veterinary services are limited. Labor requirements for paddock grazing are higher, but are offset by substantially higher milk and meat yields than for lowland animal husbandry.

Supplies of fuelwood and timber are limited, making managed forests critical in both zones. Lowland woodlots are comprised of species adapted to ~1000 mm of annual rainfall (e.g., *Acacia* spp., *Terminalia brownii*, *Grevillea robusta*). Highland systems are dominated by *Eucalyptus* spp. and *Acacia mearnsii*, in addition to other species that coppice readily. A common practice in the highlands is harvesting tree leaves as fodder for paddock-grazed animals. Labor requirements are relatively high during initial planting, but reduce substantially until harvest; coppicing reduces subsequent labor investment. Turnover times for maximal woodlot yield are between 8 and 12 years; one hectare produces roughly 100 m^3 of wood over that period.

Native forest cover (both highland broadleaf forests and lowland shrublands) has been reduced to remnant patches, primarily on steep escarpment slopes with low population densities. Charcoal production is a major yield from these communal lands despite 85% energy loss during conversion (Chavangi and Zimmermann, 1987). Frequently, soils beneath these wooded systems are shallow and stony because of their location on steep escarpments, so limited use is made of the land after clearing. Labor is directed at harvesting and charcoal-firing; profits are not reinvested (e.g. replanting, soil stabilization) (Chavangi and Zimmermann, 1987).

4.4.2. Soil loss rates

Observed erosion rates by land use and climate zone (Table 6) correspond reasonably with national published rates for Kenya (Table 1). Disparities include significantly higher observed rates in forests/shrublands, dramatically different rates between highland and lowland subsistence agriculture and significant variability within land use categories. For lowland and highland animal husbandry, soil loss rates were high (range 1817–3543 $g/m^2/yr$), particularly for communal grazing sites. Woodlots in the highlands were relatively protective, but lowland woodlots exhibited rapid loss rates (1000 versus 2263 $g/m^2/yr$, respectively), primarily as a result of limited ground-cover. The lowest soil loss on managed lands in the lowlands was for small-scale sugarcane production (1800 $g/m^2/yr$); loss rates under highland commercial tea production were similar (1484 $g/m^2/yr$). Additional observations were made in wetlands (limited erosion pin retrieval due to deposition) and severely degraded lands (max loss = 25,000 $g/m^2/yr$; mean = 13,500 $g/m^2/yr$). Overall, rates were three times higher in the lowlands (Vertisols/Planosols, sodic phases, frequent drought) than in the highlands (Nitosols). Using baseline weathering rates as a benchmark (~100 $g/m^2/yr$ for tropical conditions; Pimentel, 1993), these values are clearly unsustainable, even for less exploited systems (e.g., shrublands supporting low density grazing).

4.4.3. Emergy analyses

Emergy syntheses for each subsystem are summarized in Table 6 (details in supplementary materials)—aggregate flows are from Fig. 2. All indices (including soil loss rates) can be directly compared across land uses and climatic zones except transformity, which is specific to each subsystem's product (transformity comparison across climate regimes is informative). Comparing SIA between systems (at this scale, SIA = 1/FUSE), we observe that subsistence agriculture followed by commercial tea production and forest charcoal operations (9.12, 6.88 and 6.20, respectively) provide the highest net benefit in the highland climatic zone. Both forms of animal husbandry have substantially lower SIA values than other land uses. For lowland subsystems, the highest SIA is for sugarcane production, followed by charcoal production, and subsistence agriculture (4.0, 3.91 and 3.41, respectively). As before, livestock land uses are lower, with erosion representing over 60% of use for lowland communal grazing.

The EIR, ELR and EYR offer additional information about the ability of each land use to integrate in the larger economic system. For example, EIR for highland tea production indicates strong attraction potential for external resources while wood production systems appear to give high yield (EYR > 6) but attract little outside investment. ELR values are higher in the lowlands as a result of elevated erosion rates in that zone. High EYR for communal livestock production in the lowlands illustrates the need for indices like SIA and FUSE, because most of the yield in that system is lost soil. As a result, the transformity of meat is an order of magnitude larger than transformities for other production systems that have been evaluated (Brandt-Williams, 2001).

5. Discussion

Our primary objective – to place the estimated ecosystem value of soil in a national economic context – can be demonstrated by computing the equivalent economic product due to a soil stock. Dividing the emergy content of one hectare of topsoil organic carbon by the national EMR (1.17E13 sej/$), this equates to US$ 11,000 per hectare. The transformity of SOM in this work is nearly twice as high as previous calculations (1.07E+05 sej/J for temperate forest soils; Odum, 1996). The observed difference is a result of different organic matter accretion dynamics in the tropics where sub-humid conditions, warm temperatures, and termites result in rapid oxidation rates that are manifest in the small quantity of recalcitrant soil organic carbon entering the SOM pool each year. Since

Table 7
Comparison of Kenyan summary indices with other national economies (nations are sorted by the national fraction soil erosion (FUSE))

	Year	*U*	*U*:*P*	*U*:*A*	GDP	EMR	ELR	FUSE (%)	SIA
Kuwait[a]	1996	5.74E+22	3.39E+16	3.22E+12	3.10E+10	1.85E+12	6.24	0.01	–[a]
Canada[a]	2001	2.68E+24	8.78E+16	2.91E+11	5.99E+11	4.47E+12	3.07	0.02	49.5
Japan[a]	2001	3.59E+24	2.83E+16	9.51E+12	4.50E+12	7.98E+11	2.88	0.02	37.8
Switzerland[a]	2000	2.54E+23	3.52E+16	6.15E+12	2.70E+11	9.40E+11	2.85	0.12	64.4
Botswana[a]	1996	3.99E+22	2.85E+15	6.86E+10	4.00E+09	9.97E+12	0.28	0.13	27.9
France[a]	2001	1.32E+24	2.21E+16	2.39E+12	1.40E+12	9.43E+11	26.06	0.27	42.1
USA[b]	1999	1.18E+25	4.18E+16	1.25E+12	9.94E+12	1.19E+12	8.1	0.44	81.9
Australia[a]	2001	1.63E+24	8.41E+16	2.13E+11	3.40E+11	4.80E+12	0.3	0.61	25.6
Ireland[a]	1996	4.67E+22	3.33E+15	6.64E+11	5.90E+10	2.68E+12	3.32	0.76	70.9
Brazil[c]	1994	3.10E+24	2.20E+16	3.63E+11	7.20E+11	4.32E+12	0.75	1.77	15.6
China[a]	2001	6.64E+24	5.17E+15	7.12E+11	9.80E+11	6.78E+12	1.23	2.15	22.5
India[a]	2001	2.62E+24	9.31E+15	7.96E+11	4.42E+11	5.93E+12	33.05	2.91	11.1
Tanzania[a]	1998	4.78E+22	2.01E+15	4.62E+10	3.07E+09	1.56E+13	0.14	3.32	11.4
Kenya[d]	2001	1.20E+23	3.77E+15	2.07E+11	1.02E+10	1.17E+13	0.80	3.77	7.6
Malawi[a]	1996	7.67E+21	9.35E+14	6.45E+10	1.50E+09	5.12E+12	0.4	4.12	3.1
South Africa[a]	2001	9.26E+23	2.14E+16	7.72E+11	4.12E+11	2.25E+12	1.3	4.35	9.6
Guatemala[a]	1996	1.28E+22	7.63E+15	8.10E+11	3.67E+10	2.40E+12	0.49	4.75	11.3

Sources: (a) M.T. Brown (unpublished data), (b) G. Stachetti (unpublished data), (c) Odum (1996), (d) this study. All values in this table are reported for the Odum (2000) common emergy benchmark.

[a] Kuwaiti agriculture is extremely limited; the computed SIA value is inappropriate. *U*: total emergy use, *P*: population, *A*: area, GDP: gross national product, EMR: emergy money ratio, ELR: environmental loading ratio, ESI: emergy sustainability index, FUSE: fraction soil erosion, SIA: soil intensity of agriculture.

transformity measures environmental work embodied in a product, doubling the transformity indicates a doubling of ecosystem value. Additional refinements (developing a transformity value for particular soil types) are clearly needed.

Transformity values for other commodities were, surprisingly, not substantially different between temperate and tropical productions systems. For example, the transformity for maize in Kenya was computed as 1.11E5 sej/J; by comparison, corn in Florida has a transformity of 1.26E5 sej/J (Brandt-Williams, 2001). However, we view the use of locally computed transformity values for analysis as a major priority for refinements to the emergy methodology.

Among the significant findings at the national scale are levels of summary indices (trade balance, sustainability) and the magnitude of soil erosion. Table 7 summarizes some indices in comparison with other nations. Kenya clearly has low emergy per capita (falling in 4th quartile) and high EMR. A moderate trade imbalance ($E{:}I = 1.23$), typical of developing nations (Odum, 1996; Brown, 2003), occurs because the Kenyan EMR (1.17E13 sej/\$) is an order of magnitude higher than the world EMR (2.08E12 sej/\$) suggesting that each unit of standardized currency (\$) has greater purchasing power in Kenya than in global markets. ELR for Kenya is relatively high, particularly given the small economic product (GDP) generated by that environmental load.

Of particular interest is the magnitude of soil erosion (4.52E21 sej/yr) in comparison with other national flows (Table 3); soil loss is comparable to total national electricity production or agricultural exports, and only slightly smaller than the national tourist industry. When put in equivalent dollar units, soil loss represents a cost to Kenya of \$ 390 million; forest losses add an additional \$ 350 million for a total annual natural capital depletion equivalent to over 7% of GDP.

Comparison of FUSE and SIA with other nations (Table 7) reveals that, while FUSE is higher in Malawi, Guatemala, and South Africa, only Malawi has the combined condition of high FUSE and low SIA as was observed in Kenya. This demonstrates the compounding effects of low input agriculture and high-risk soils/land uses on national soil conservation needs in sub-Saharan Africa. The advantage of using these indices as a benchmark for national or regional analysis (particularly through time) is that they relate both erosion and production, embodying the tradeoffs between increased land use intensity and the external costs thereof.

At the district scale, local targeting of intervention resources is needed. While total flows (sej/yr) are not comparable between nation and district (or between districts of different size), scaled flows (per capita and per area) and all ratio indices (ELR, EIR, FUSE, SIA, etc.), are comparable. The national EMR (1.17E13) is larger than the EMR for Kisumu and Kericho, and nearly half that of Nyando suggesting that the former two benefit from within-country trade, while the latter is at an implicit disadvantage. As with trade between nations with differing EMR, this arises because each unit of currency flowing into Nyando buys more real wealth than can be purchased from outside. The % electricity, FUSE, SIA and emergy per capita all reinforce the qualitative observation of acute poverty and environmental degradation in Nyando.

Our observations of approximate soil erosion rates across the landscape demonstrate dramatic variability observed within what are treated as homogeneous units (e.g., lowland annual cropping systems, highland woodlots; Table 6). Their approximate consistency with other published values suggest that they the method is reliable, and our resulting ability discriminate between erosion rates across land-use subsystems and climate zone make them useful for this work. The main assumption that differs between scales – that of the sediment yield ratio – necessitates further refinements to the way that erosion losses are evaluated.

At the land use subsystem scale, pronounced differences in the system-scale costs and benefits between different land uses are observed. As an example, compare indices and transformity values across climatic zones. Despite higher renewable inputs in the highlands, transformity values are generally lower than in the lowlands, suggesting comparative ecological advantage of highland agriculture. The largest differences are for subsistence agriculture and woodlot production. When comparing like products, systems that produce a product with the lowest level of input (i.e., maximize system scale efficiency by minimizing transformity) should be reinforced through policy. Those land uses exhibiting lower efficiencies should be converted to other uses that maximize local comparative advantage (e.g., conversion of communal livestock systems to sugarcane for lowland areas) to enhance overall system performance.

The SIA index can be used to orient policy on selecting appropriate land use subsystems. While erosion rates in the lowlands are comparable between subsistence maize cropping and paddock grazing, the SIA is substantially different (3.41 versus 1.96, respectively). Similarly, while the loss rates under sugarcane production are more than double those under shrublands, the SIA would suggest that this is a reasonable trade-off with respect to overall benefit. Finally, while woodlots may tend to reduce erosion rates in the highlands vis a vis agricultural systems, the net benefit of that protection does not outweigh the benefits of increased productivity.

Constraints to reorienting the regional system given prevailing poverty among the rural subsistence farmers are clear; in particular, the socio-cultural importance of animal husbandry and reliance on subsistence production are impediments to regional optimization, and efforts to improve land management at the large scale will need to simultaneously address food/fuel security issues. Difficult as it is to imagine or affect large-scale transformation of landscapes and livelihoods in the region, findings such as these need to be incorporated in regional planning.

We view linkages between scales as a crucial outcome of our work. While the scope and intensity of the problem at the national scale warrants capital investments from government, where and how to maximize investment effectiveness requires nested analyses. The ability of government to provide incentives or discourage land use practices as necessary requires resources be made available and an understanding of how to use them emerges. Assessing the national condition with respect to natural capital depletion provides essential context for interpreting analyses at smaller scales, and analyses at smaller scales offer preliminary insight on how resources mobilized at the large scale are best employed. Further, comparative analysis between land uses, districts and other nations places findings in perspective, and could aid non-governmental organizations in prioritizing their intervention, research and educational activities.

6. Conclusions

1. Soil erosion represents a significant hidden cost of development at multiple scales in Kenya's environmental/economic system. At the national scale, 3.8% of total emergy use is due to soil loss (an additional 3.5% is due to forest clearing), equivalent to $ 390 million in macroeconomic value or to the value of agricultural exports or electricity production.
2. Analysis of three districts in western Kenya showed that erosion is particularly serious in Nyando district, which, in contrast to Kisumu (manufacturing) and Kericho (commercial tea production) districts, has limited economic infrastructure. Soil erosion represents almost 15% of total use in Nyando; lowland agriculture practiced there has a net benefit of 2.25:1, which indicates deeply marginalized rural farmers.
3. Land subsystems reveal dramatic differences in their emergy basis, both between land use and climatic zone. Animal husbandry operations, and particularly communal grazing, have low SIA values; for lowland communal grazing, 60% of total emergy use is erosion.
4. Plant-based subsistence and commercial agricultural activities are more sustainable with respect to soil loss and net agricultural benefit than other land uses (e.g., communal livestock production). Woodlot operations are effective land uses in the highlands, but demonstrate limited potential in the lowlands, where soil loss rates under planted forests were high.
5. Overall, there is a need to translate the quantitative findings of this work into three policy outcomes. First, improved resource allocation towards attenuating soil loss are clearly necessary based on the apparent problem magnitude. Second, resources need to be targeted for maximum effect, whereby districts and regions that are particularly at-risk should receive the bulk of any external assistance. Finally, incentives to encourage appropriate land use planning with respect to maximizing net benefit of rural agriculture need to be devised.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at 10.1016/j.agee.2005.10.021.

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