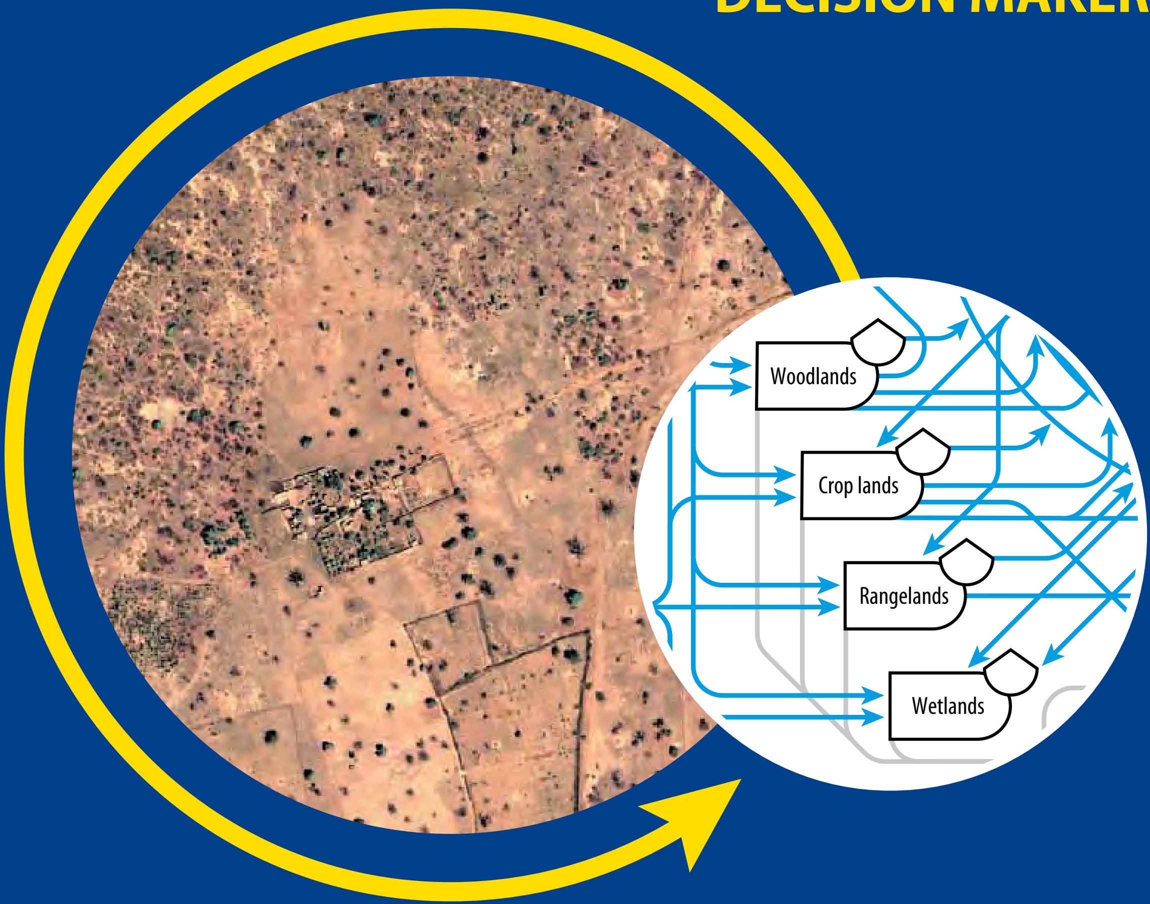
ECOSYSTEM SERVICES

and Rural Livelihoods in The Sahel

Environmental Accounting and Wealth Surveys

SUMMARY FOR DECISION MAKERS



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Contents

Abbreviations and acronyms

AET	annual evapotranspiration
AVHRR	Advanced Very High Resolution Radiometer
fCFA	Central African franc
DAP	diammonium phosphate fertilizer
DM	dry matter
DW	dry weight
EBR	Emergy Benefit Ratio
EEP	ecological economic product
EER	Emergy Exchange Ratio
ELR	Environmental Loading Ratio
ESI	Emergy sSustainability Index
ET	evapotranspiration
EYR	Emergy Yield Ratio
FAO	Food and Agriculture Organisation
FW	fresh weight
GIS	Geographic Information System
GLM	generalized linear models
HH	households
NDVI	Normalized Difference Vegetation Index
NPP	Net Primary Production
OM	organic matter
RNNDVI	Rain-normalized – Normalized Vegetation Index
RUE	rain use efficiency
SOC	soil organic carbon
SOM	soil organic matter
TLU	tropical livestock units
UEV	Unit Emergy Value

Main messages

A central challenge for sustainability is integrating the value of ecosystem services in policy and economic decision-making. Ecosystems produce goods (e.g., wood, fibre, food) and services (e.g., water purification, disease vector control, pollination) that accrue to human users outside the market system, and are therefore treated as free. As a result of not having an explicit market in which to value these services, there is a strong incentive to over-exploit them. Policy intervention is needed to correct this situation and safeguard the natural resource base. However, critical questions facing policy makers are "How much are ecosystem services worth, and what is their contribution to livelihoods?" These questions are especially pertinent for areas such as the West Africa drylands, where the rural population is highly dependent on local ecosystem services, and therefore particularly vulnerable to declines in those services. This report attempts to address these questions in the context of the Sahel region of Africa, and drylands more broadly, using environmental accounting.

Environmental accounting is used in conjunction with data from the literature to evaluate the costs and benefits of different land-use systems in the Sahel when considering environmental services. Based on results from a household survey in Mali, the links between ecosystem services and household wealth are analysed.

ENVIRONMENTAL ACCOUNTING

- Environmental accounting is a tool for holistic evaluation of systems of people and nature based on our physical understanding of energy and material flow through systems. Accounting for basic physical flows and transformations of energy and materials used in economic processes permits direct linkage with macroeconomic value of flows, both where there is a market (that is, where money is a measure of value) and for flows for which no market exists (that is, where we have previously assumed that services are free). The environmental work necessary to generate services is tracked, reasoning that the more work embodied in ecosystem services, the greater the cost of losing that service.
- The central premise of environmental accounting is that sunlight, the basic energy source of the geobiosphere, is a useful common currency for all global processes; solar energy is embodied in all goods, whether environmental or economic. All processes rely on energy and are subject to energy laws. Flows in environmental accounting are reported as the quantity of solar energy required to make them; we call this quantity solar emergy.
- Environmental accounting using emergy involves four basic steps:
  1. Energy systems diagrams are drawn to depict the major flows of natural resources (e.g., solar energy, rainfall, soil), and economic activities (e.g., labour allocation, purchased inputs).
  2. Data on each of the system components and flows in the diagram are acquired (in Joules for energy and grams for material flows).
  3. Energy and material flows are converted into units of solar emergy, the basic accounting unit, using standard conversion factors called unit emergy values. This accommodates the fundamental recognition that different types of energy are not of equivalent quality, and require different amounts of solar energy for their creation.
  4. The different flows of emergy into and among the system components are summed and used to provide different metrics of sustainability and efficiency, accounting for all environmental and economic flows.

ENVIRONMENTAL ACCOUNTING OF SAHELIAN LAND-USE SYSTEMS

- Parkland agroforestry production systems, which integrate trees, crops and livestock, produce yields of both grains and tree products using lower energy and material flows (i.e., at lower unit emergy values) than comparable utilised lands.
- Agroforestry land uses appear to have the capacity to improve the balance of trade between rural land users and regional consumers and have far greater sustainability than land uses without trees.
- Comparisons of Sahelian production methods with those evaluated elsewhere for the same product suggest that Sahelian systems rely far less

heavily on non-renewable resource use (including soil loss), and produce the same products for less emergy investment. Despite low specific yields, the processes are fairly efficient in term of their environmental footprint. The notable exception is the production of beef, which is far less efficient in African pastoral settings (including analyses previously completed in Kenya) than in the United States.

- Intensive management of organic resources (agroforestry, biomass transfers, manure application) was two to three times more efficient than traditional rain-fed techniques, underscoring the environmental utility of modest efforts to mitigate production limitations of soil nutrient content and soil water-holding capacity.
- Given the utility of trees within the context of all agricultural operations that we analyzed, large efforts to protect seedlings from grazing pressure of free-roaming animals are warranted. Development of low-cost seedling protection strategies may provide important amplifying benefits for rural development.
- Large uncertainties in outputs of environmental accounting arise from the paucity of data on many environmental and economic flows. Two priority areas for improved data are the rates of soil loss and the labour input requirements for each land use.

ECOSYSTEM SERVICES AND RURAL LIVELIHOODS

Household assets were evaluated for 77 villages spanning a range of environmental condition in Segou Region of Mali. Asset lists were compiled for 2,757 households. Households were overwhelmingly male-headed and many included multiple married men. All analyses controlled for household size as a factor in wealth assessment.

- Two independent dimensions of household wealth were identified: material wealth and animal wealth. There were strong ethnicity differences in how a household accumulated wealth, with historically nomadic pastoralists far more likely to store wealth in livestock than in material assets like bicycles, farming implements and household accoutrements.
- Material wealth values were statistically associated with areas showing a trend of increasing vegetation growth per unit rainfall over the past 25 years, revealed from satellite remote-sensing data, indicating land improvement.
- Animal wealth was inversely related to measures of ecosystem services (rainfall, vegetation production, and time trends in vegetation production per unit rainfall), indicating that investment in animal wealth may represent an important coping strategy when agricultural efforts are constrained by poor environmental conditions. Strong effects of ethnic group were observed, but controlled for in the results.
- The results show a clear link between the accumulation of wealth and the condition of the environment, but environmental factors had a weak effect compared with factors such as ethnicity and household size. The environmental effects on wealth appear to have been moderated by the intrinsic capacity of people to engage in compensatory activities that permit the use of other services not directly related to land.
- Several geographical factors had counter-intuitive effects on wealth. For example, wealth was not inversely related to distance from rivers and water bodies, and material wealth was not related to distance from markets. These distortions may be due to factors such as the convergence of destitute households on rural towns.

The complexity of the relationships between ecological and socio-economic factors in determining rural wealth points to the need for comprehensive approaches, such as environmental accounting, for guiding development policy.

Valuing ecosystem services

A central challenge for sustainability is integrating the value of ecosystem services in policy and economic decision-making. Ecosystems produce goods (e.g., wood, fibre, food) and services (e.g., water purification, disease vector control, pollination) that accrue to human users outside the market system, and are therefore treated as free. As a result of not having an explicit market in which to value these services, there is a strong incentive to over-exploit them, particularly when long-term sustainability of the resource is a low priority, as is the case where the costs of over-exploitation are borne by society at large, and where land tenure is not secure, or where rural poverty strongly depresses the opportunity for long-range planning. In short, individuals responding to market forces create costs external to that market which require some form of policy intervention to correct. Given the fact that these services are also finite and in many cases non-renewable (due to the different time scales of their creation and current depletion), there are significant social costs embedded in their loss. Crucially, these costs accrue to society at large, now or in the future, and controlling them is a grand challenge. Pressing questions in this regard are: how much are ecosystem services worth; and what is the empirical link between services and livelihoods that can legitimize the claims regarding their value for policymakers who are faced with a wide array of competing policy priorities?

Ecosystem services are notoriously difficult to value. Efforts to quantify particular services (e.g., the value of bees for coffee pollination) are profoundly useful for qualitatively communicating the high cost of replacement value, but are difficult to generalize, for two reasons. The first is that each ecosystem service operates locally, and the manner in which local users leverage those services varies. This results in differential sensitivity to the loss of any particular service, and the generality of an empirical value in one place may not be validated in another. A second problem is that ecosystem services are myriad, and while their additivity is intuitive, there are no well-accepted ways to "bundle" services that avoid double-counting services (i.e., those that overlap substantially, like C sequestration and primary production) but acknowledge the independence of others (e.g., habitat values vs. water storage values of wetlands). For example, a tropical forest patch may simultaneously provide the services of pollination, water purification, carbon fixation, microclimate regulation, and biodiversity maintenance. Ascribing value to that forest based only on one service implicitly discounts other services, and thereby discounts the actual value of that ecosystem (probably by a substantial margin). However, adding all the services together may over-estimate the value, potentially short-circuiting any policies designed for ecosystem protection.

On the other hand, evaluating the role of ecosystem services on the demand side (i.e., the human users), though critical, is complex and deeply contingent on the type of users and how they use the resource. To complicate the inference of the demand-side value of ecosystem services even further, it is necessary to consider the ways in which human users of the myriad services can mitigate the effects of losing one service by compensation. That is, declines in one service may require that the users adopt new strategies for their livelihoods that, in the medium term at least, do not dramatically affect their capacity to maintain their standard of living. For example, land degradation in the Sahel can inhibit the capacity of a household to produce sufficient food, and force them to engage in alternative activities in order to compensate. Those alternative uses of labour could substantially mute the effects of land degradation, at least for households that have the capacity to engage in alternative livelihoods.

The implications of these complexities and contingencies are two-fold: first, it means that assessments of links between rural livelihoods and the loss of a particular ecosystem service (e.g., through land degradation) need to be evaluated across a large population that allows the particular effects on a single household to be averaged. Second, it means that attention to the supply side of ecosystem services (i.e., enumerating services independently of how they are used, but rather on what is required to make them) may provide a useful benchmark for valuation. This report provides a summary of work in the Sahel that addresses both needs.

Using environmental account techniques, which permit a quantitative analysis of ecosystem services from a supply- or donor-perspective, we evaluate the main land uses in the parkland region of the Sahel. Our objective in that regard was to illustrate the magnitude of the services that accrue from the land in this region, where land degradation is an epidemic problem, with the ultimate intent of providing a quantitative basis for making policies at the national and regional scales that protect land resources.

On the demand side, we used a rural wealth survey approach, wherein we evaluated the asset wealth of over 2,700 households across 77 villages, to draw statistical links between land degradation and rural livelihoods. This population-level approach, in which wealth (defined precisely based on local surveys) is evaluated against measures of land degradation that are derived from large-area surveillance tools[1] allows the predicted links between ecosystem condition and wealth to be tested explicitly. We know of no other study that has conditioned the survey of rural wealth on a gradient of environmental condition, and as such, we consider this work to be among the first to permit a detailed view of the direct and compensatory links between ecosystems and the livelihoods of the people that live in them. The report is divided into two sections, reflecting the dual nature of our objectives. The first summarizes the results of the environmental accounting analysis for 17 land-use subsystems in the Sahel. The second summarizes results from the wealth survey, and statistical analyses of the links between measures of ecosystem services (rainfall, rain-use efficiency and land degradation) and household wealth.

1 UNEP (2012). Land Health Surveillance: An Evidence-Based Approach to Land Ecosystem Management. Illustrated with a Case Study in the West Africa Sahel. United Nations Environment Programme, Nairobi.

Overview of methods

ENVIRONMENTAL ACCOUNTING OF LAND USES

Environmental valuation is a method that seeks to integrate the value of nature's work into decision-making by quantifying values of ecological services, based on the biophysical flows (energy, materials, information) necessary to create them. Specifically, we track the environmental work necessary to generate the services, reasoning that the more work embodied in ecosystem services, the greater the cost of losing that service. As such, environmental accounting is a tool for holistic evaluation of systems of people and nature; since environmental work is in both environmental and human systems, a common framework for analysis is made possible. The foundation of the method is our physical understanding of energy and material flow through systems. Accounting for basic physical flows and transformations of energy and materials used in economic processes permits direct linkage with macroeconomic value of flows, both where there is a market (that is, where money is a measure of value) and for flows for which no market exists (that is, where we have previously assumed that services are free).

The central premise of environmental accounting is that sunlight, the basic energy source of the geobiosphere, is a useful common currency for all global processes; solar energy is embodied in all goods, whether environmental or economic. All processes rely on energy and are subject to energy laws (Figure 1). Flows in environmental accounting are reported as the quantity of solar energy that is required to make them; we call this quantity solar *emergy*.

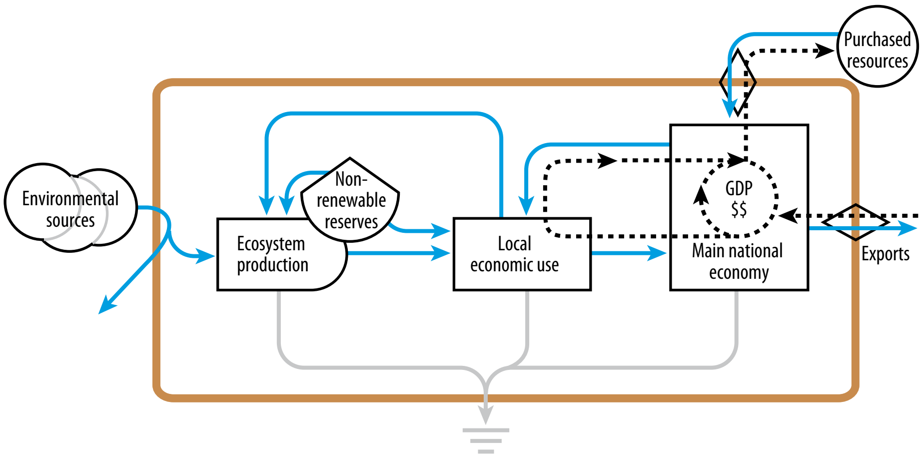
Environmental accounting using emergy involves four basic steps:

1. For any system of interest (in this work we focus on land-use systems in the Sahel) energy systems diagrams are drawn to depict the major flows of natural resources (e.g., solar energy, rainfall, soil), and economic activities (e.g., labour allocation, purchased inputs). The diagrams depict flows that connect system components, both within the system and across the system boundary. For this work we use a generic diagram of a land use system to generalize the process of producing goods that people use from agro-environmental systems.
2. Acquire data on each of the system components and flows in the diagram in standard units (Joules, grams).
3. Convert energy and material flows into emergy using conversion factors called unit emergy values (UEV) to quantify the solar emergy, the basic accounting unit. This accommodates the fundamental recognition that different types of energy are not of equivalent quality, and indeed require different amounts of solar energy for their creation.
4. Synthesize the disparate flows of emergy into and among the system components. This synthesis, where all flows are in common units, permits unique insight into the resource basis of the system and patterns of human-environment interactions. For example, the fraction of total emergy from renewable sources is a useful metric that can be used to evaluate and compare land use systems that produce the same product. Moreover, the relations between emergy and money permit a quantitative comparison of the net exchange for farm goods (i.e., how much emergy is exported from a farm as sold agricultural goods vs. the emergy that is associated with a monetary flow received in exchange).

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

FIGURE 1

Environmental services (both exogenous sources and the processing of those resources into useful products for local economic use) and the financial system are coupled in ways that intrinsically undervalue the work of nature. Policy interventions are necessary to ensure that the costs associated with the loss of natural capital (non-renewable reserves such as soil and biodiversity) are embodied in the incentives that regulate the economy. Because money is not paid for ecosystem services, other accounting systems are useful.



term benefits. As such, environmental accounting can be viewed as an ecosystems approach that is complementary to economic valuation.

This report presents results of detailed environmental accounting of 17 land-use subsystems typical of dryland agriculture in the Sahel region of West Africa. Environmental accounting is used for four primary tasks in this work: 1) to compare the resource requirements of agricultural production across a variety of traditional and agroforestry techniques, 2) to compare the resource requirements of low-input Sahelian agricultural systems with systems that produce similar products in other regions (principally the high-input agriculture practised in North America), 3) to determine the benefits and costs of growing primary grain crops with interspersed trees on the net exchange ratios for farm products, and 4) to determine the relative importance of uncertainties in erosion estimates on the comparisons among land use systems for producing the same primary crop (e.g., millet).

RURAL LIVELIHOODS AND ECOSYSTEM SERVICES

Rural livelihoods in the Sahel are fundamentally dependent on local ecological services. While there are numerous studies to evaluate the costs of the decline in ecosystem services, an important observation is that, as these services have demonstrably declined over the last 150 years, human well-being has actually increased. The most parsimonious explanation for this apparent paradox is that the use of non-renewable energy (e.g., fossil fuels) obscures the direct effects of ecosystem services on human well-being, particularly in the most developed nations. That is, there are compensatory strategies that have developed that permit humanity to obviate the accruing costs of soil loss, biodiversity loss, water contamination and other injuries to the ecological life-support system. Moreover, in each case, the compensatory strategy involves the use of available energy from other non-environmental sources. In short, fossil energy insulates contemporary humanity, at least in part and at least for a time, from the effects of natural capital and ecosystem service losses.

This insulation from the effects of declining environmental quality varies, from the city dwellers in the developed world that are most disconnected from local environmental services (or, in many cases, lack thereof), to rural farmers most distant from the monetary economies of the world, where local ecosystem services are the entirety of their livelihoods. We assert that rural farmers in the Sahel are close to the latter end of the spectrum, and, as such, represent a community most vulnerable to changes (and particularly declines) in ecosystem services. The dramatic and ravaging effects of droughts in the region exemplify this dependence. As such, the role of ecosystem services in the generation and maintenance of wealth should be most clear in this setting: degraded or degrading environmental conditions should be expressed more clearly in the wealth attributes of the local population in the Sahel than in almost any other setting. While it's clear that human societies everywhere engage in compensatory strategies to mitigate the effects of environmental variability and decline, and the Sahelian agricultural system is not expected to be an exception, the expression of vulnerability to environmental degradation (and, in this example, land degradation in particular) is best expressed by the wealth attributes of those most acutely dependent on ecosystem services for their immediate livelihoods. As such, we hypothesize that measures of environmental condition will be correlated with patterns of wealth storage in the Sahel.

Our research in this regard is the search for statistical associations between rural livelihoods (measured as the asset wealth of the households) and environmental services. Services are measured in three ways. The first is the simple input of rainfall, an ecosystem service of enormous value in these dryland agricultural systems. Rainfall is somewhat confounded by the fact that population density roughly correlates (i.e., more rainfall, more people), but the intuitive importance of rainfall as a core input for rural livelihood systems is difficult to overstate. We hypothesize that higher rainfall will lead to greater household wealth, with the caveat that this hypothesis does not account for regional density-dependent effects on wealth creation.

A second ecosystem service is the capacity of a particular piece of land (measured in pixels, given our remote-sensing inference basis) to produce biomass for a given rainfall input. This quantity, which we call the rain-normalized primary production or rain-use efficiency, varies dramatically in both space and time in response to environmental forcing and land cover. For a particular area, however, the long-term mean rain-use efficiency provides a measure of the yield (in a generic biomass sense), and therefore of some property of the soil and biota present. Higher values, therefore, are hypothesized to be associated with higher wealth in the households proximate to that area.

Finally, measures of land degradation (i.e., changes in the productive capacity of the land over time) are crucial for estimating the decline in ecosystem services. We use the trend over the last 40 years in the rain-use efficiency (i.e., the slope of a fitted line over time for the rain-normalized primary production) as a measure of land degradation. We predicted that household wealth would co-vary positively with the trend, such that households where land degradation is being reversed (i.e., positive trends) will exhibit higher accumulated wealth, while those households in areas where land degradation is worsening will exhibit lower accumulated wealth.

All three ecosystem services are derived from climate data (rainfall) and remote-sensing techniques (rain-use efficiency and rain-use efficiency trends). We selected 77 villages in which to evaluate household wealth, based on observed gradients in these three predictors. At the same time, we controlled for the presumed effects on wealth of: ethnicity, proximity to critical resources (rivers, markets), household size and composition. We also explore interaction effects between the environmental services, reasoning, for example, that the effects of changes in rain-use efficiency (i.e., the trend) may be high in low rainfall settings, but less problematic where rainfall is more abundant. We evaluate the predictions using a generalized linear modeling framework that is intrinsically nested, and report the statistical significance and direction of the relationships between wealth (to which considerable pre-analysis consideration was given, to ensure that the measure was robust and representative) and environmental condition.

The results of this work are important: they provide insight into the links between rural livelihoods and environmental condition in an explicit way that can be used to present the human well-being effects of environmental protection in the short term (we note that this in no way discounts the fundamental assertion of sustainability; that loss of ecological function and capacity will present future challenges, even where modern society has been able to mitigate the effects). Moreover, it affords an opportunity to explore the role of culture (particularly the store of knowledge of compensatory/alternative livelihood strategies) and economy in mitigating the direct effects of declining environmental services on wealth.

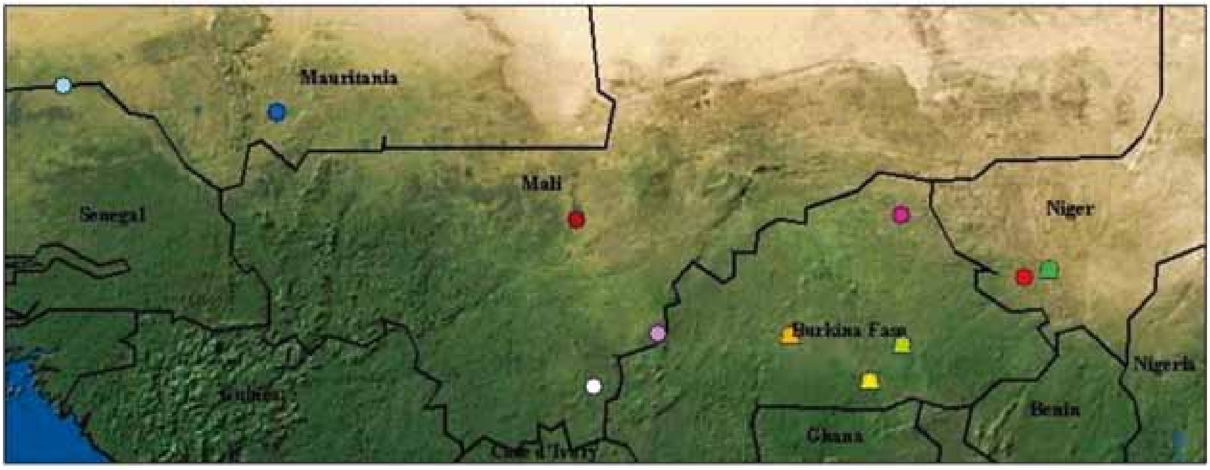
Environmental accounting of rural land uses in the Sahel

LAND USES AND INTERVENTIONS

Prominent subsistence, fodder and export crops in the Sudano-Sahelian zone include millet, sorghum, maize, cotton, cowpea, groundnut, rice, and karite seeds, and nere seeds. In addition, livestock play a crucial role in both agricultural and pastoral systems. Inputs driving these production systems vary due to natural environmental variation, as well as human decisions regarding agricultural methods. The literature was searched extensively for studies

FIGURE 2

Location of sites across the Sahel for which environmental accounting analyses were performed.



Land use system

MonoCrops

- C-t1 *Cotton*
- MA-i1 *Maize*
- MA-i2 *Maize*
- MA-i3 *Maize*
- MA-t1 *Maize*
- MA-t2 *Maize*
- MA-t3 *Maize*
- MI-t1 *Millet*
- MI-i1 *Millet*
- MI-t2 *Millet*
- MI-t3 *Millet*
- R-t1 *Rice*
- R-t2 *Rice*
- S-t1 *Sorghum*
- S-t2 *Sorghum*
- S-t3 *Sorghum*

Cattle, agropastoral

- Cattle1 *Cattle*
- Manure1 *Manure*
- Milk1 *Milk*

Cattle, transhumant

- Cattle2 *Cattle*
- Manure2 *Manure*
- Milk2 *Milk*

Millet – Karite/Nere parkland

- NN-1 *Nere nut*
- KF-1 *Karite fruit*
- KN-1 *Karite nut*
- MI-i2 *Millet*
- NF-1 *Nere fruit*
- W-1 *Wood*

Millet – Faidherbia parkland

- FP-1 *Faidherbia pods*
- MI-i3 *Millet*
- W-3 *Wood*

Sorghum – Karite parkland

- KF-2 *Karite fruit*
- KN-2 *Karite fruit*
- S-i1 *Sorghum*
- W-2 *Wood*

Sorghum – Neem parkland & alleycrop

- S-i2 *Sorghum*
- S-i3 *Sorghum*
- W-4 *Wood*

that covered a range of geographic settings and cropping methods for each major crop. In addition, we searched for data on soil fertility interventions and found studies investigating manure and crop residue effects, and agroforestry interventions such as improved fallows, alley cropping and management of the common parkland tree species *Vitellaria paradoxa* (karite or shea) and *Parkia biglobosa* (nere). Table 1 lists the land-use systems with emergy analyses completed, with primary data sources identified. Figure 2 shows the spatial extent of the sites from which data were obtained for this report.

TABLE 1

Crops and sites in the land use emergy analysis.

Code	Item	Location	Rain, mm	Method/Intervention
Cot	Cotton	Mali	1,000	traditional farm, no regular fallow
MI-t1	Millet	Burkina	450	subsistence farm, manure, no fallow
MI-t2	Millet	Burkina	743	on farm experiment, no fallow or fertilizer
MI-i1	Millet	Burkina	743	same as above + Shea mulch and fertilizer
MI-i2	Millet	Burkina	743	in parkland with half-pruned trees, no fertilizer
Mi-t3	Millet	Niger	428	no fertilizer, no fallow
Mi-i3	Millet	Niger	428	in Faidherbia parkland, no other inputs
R-t1	Rice	Senegal	320	tractor plowed, with pumped water
R-t2	Rice	Mauritania	406	gravity irrigated
S-t1	Sorghum	Burkina	685	traditional, no fertilizer
S-i1	Sorghum	Burkina	685	in parkland with karite trees, no fertilizer
S-t2	Sorghum	Burkina	798	plots near parkland study
S-t3	Sorghum	Burkina	798	plots near alley study
S-i2	Sorghum	Burkina	798	parkland, 15 trees/ha, coppiced each yr
S-i3	Sorghum	Burkina	798	alleycrop, coppiced each year to 30cm
MA-t1	Maize	Mali	851	traditional fallow, on farm experiment
MA-i1	Maize	Mali	851	improved fallow (leguminous), on farm
MA-t2	Maize	Mali	885	traditional fallow
MA-t3	Maize	Mali	885	traditional fallow + manure
MA-i2	Maize	Mali	885	traditional fallow + chemical fertilizer
MA-i3	Maize	Mali	885	traditional fallow + biomass transfer
KF-1	Karite fruit	Burkina	743	parklands with millet crops, no fertilizer
KF-2	Karite fruit	Burkina	685	parklands with sorghum crops, no fertilizer
KN-1	Karite nut	Burkina	743	parklands with millet crops, no fertilizer
KN-2	Karite nut	Burkina	685	parklands with sorghum crops, no fertilizer
NF-1	Nere fruit	Burkina	743	parklands with millet crops, no fertilizer
NS-1	Nere seed	Burkina	685	parklands with sorghum crops, no fertilizer
FP-1	Faid. Pod	Niger	428	Faidherbia parkland w/ millet, no inputs
W-1	Wood	Burkina	743	parklands with millet crops, no fertilizer
W-2	Wood	Burkina	685	parklands with sorghum crops, no fertilizer
W-3	Wood	Niger	428	Faid. parkland w/millet, pruned for fodder
W-4	Wood	Burkina	798	Neem alleycrop prunings
Cattle1	Cattle	Niger	555	cattle, agropastoralists
Cattle2	Cattle	Mali	400	cattle, transhumant pastoralists
Milk1	Cow milk	Niger	555	cattle, agropastoralists
Milk2	Cow milk	Mali	400	cattle, transhumant pastoralists
Manure1	Manure	Niger	555	cattle, agropastoralists
Manure2	Manure	Mali	400	cattle, transhumant pastoralists

FIGURE 3

Summary diagram used to generalize analyses of Sahelian land use systems. Flows are described in Table 2.

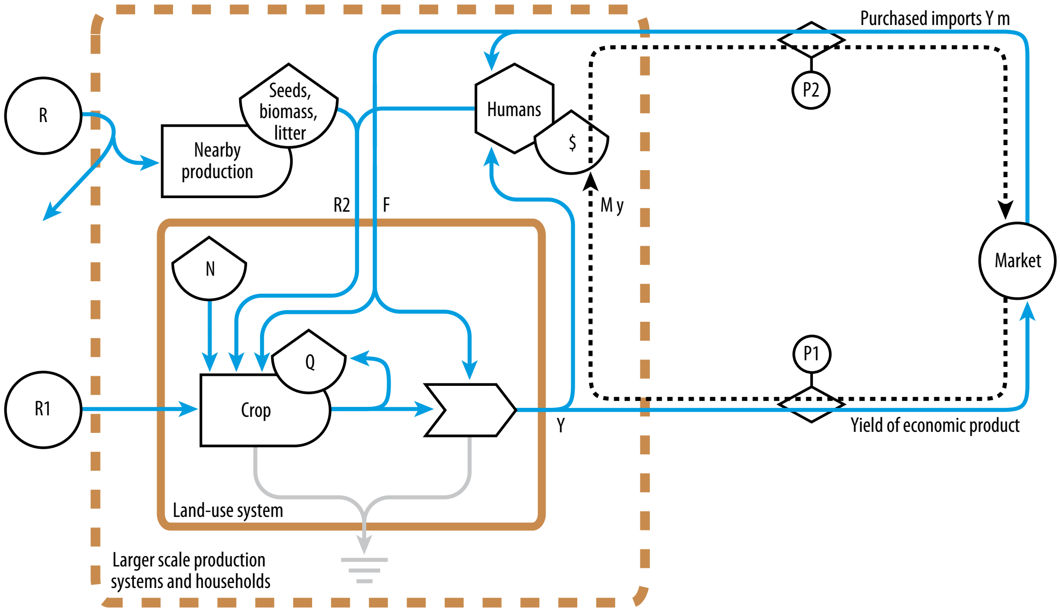


TABLE 2

Formulas for emergy summary flows and indices.

Summary flows	
R1	Dispersed, free renewable emergy (Evapotranspiration for agricultural systems)
R2	Local transfers which are supported mainly by renewable flows (seeds, manure, local labour)
N	Non-renewable flow from within, soil organic matter losses from system
F	Purchased material and service feedbacks (fertilizer, hybrid seeds, fuel, tools, hired labour)
dQ	Total change in ecosystem natural capital storages (soil infiltration capacity, soil organic matter, nutrients)
Economic Parameters	
P1	Market price paid for product ($/kg)
P2	Average emergy per dollar, or emergy to money ratio (EMR) for the country (sej/$)
Yield Flows	
Y	Emergy yield, defined as total emergy use by the production system: R1+R2+N+F
M_y	Money gained from yield: yield in kg * P1
Y_m	Yield realized on market: M_y * P2
EEP	Ecological economic product: dQ+Y
Yield Ratios	
EYR	Emergy yield ratio: Y/F
EBR	Emergy benefit ratio: EEP / (F+N)
Other system indices	
%R	Percent renewable: R1/Y
%Ind	Percent indigenous: (R1+R2+N) / Y
C/D	Concentrated to dispersed: (F+R2) / (R1+N)
EER	Emergy exchange ratio: Y_m /Y
IR	Investment ratio, purchased feedbacks to local flows: F/(R1+R2+N)
ELR	Environmental loading ratio, nonrenewable flows to local renewable: (F+N)/(R1+R2)
ESI	Emergy sustainability index: EYR/ELR

SUMMARY FLOWS

After an account of the main energy and material flows is developed for each land-use, aggregated flows are calculated according to defined formulas. Figure 3 displays a highly aggregated systems diagram, created and standardized for analyzing Sahelian agricultural production systems. Table 2 presents descriptions and formulas for the summary flows and indices. All flows and storages are in units of solar emjoules per hectare per year (sej/ha/yr).

EMERGY VALUATION OF LAND USES

The total emergy flows and proportions of renewable and non-renewable categories for the different land uses (Figure 4) illustrates the large purchased non-renewable inputs and local renewable transfers in the cotton and rice systems compared with traditional millet, sorghum and maize systems.

Figure 5 shows an emergy summary for the production of maize, comparing six Sahelian systems and a high intensity maize production system in the United States. The graph shows the total crop yields (kg ha^{-1} yr^{-1}), emergy use in the system to create that yield, and the resulting unit emergy value. The fraction of the resource basis of production from renewable resources is also reported for each case. Clearly, US agricultural systems rely heavily on exogenous inputs of high quality products (fertilizers, diesel, seeds), and the result is a system that uses only 12% renewable sources, and has the highest UEV of the systems compared. The highest fraction of renewable emergy use was observed for the traditional fallow systems (77% for the two systems evaluated), but with low yields reported from these systems, the UEVs are high. This presents an important evaluation decision: while these systems report extremely high renewable fractions, they are intrinsically less efficient in their resource use. We argue that while % renewable is a valuable metric of sustainability, the UEV is a more integrative measure that considers some of the costs of low yield (i.e., higher land footprint, larger labour requirement per unit yield) that % renewable cannot.

For the few systems that were analyzed in the Sahel, we report the same comparative information for milk and meat production (Figure 6), using both US

FIGURE 4

Summary of emergy flows for the primary crop-based land uses evaluated, showing both to the total emergy use (bar height) and the breakdown of sources (colour coding).

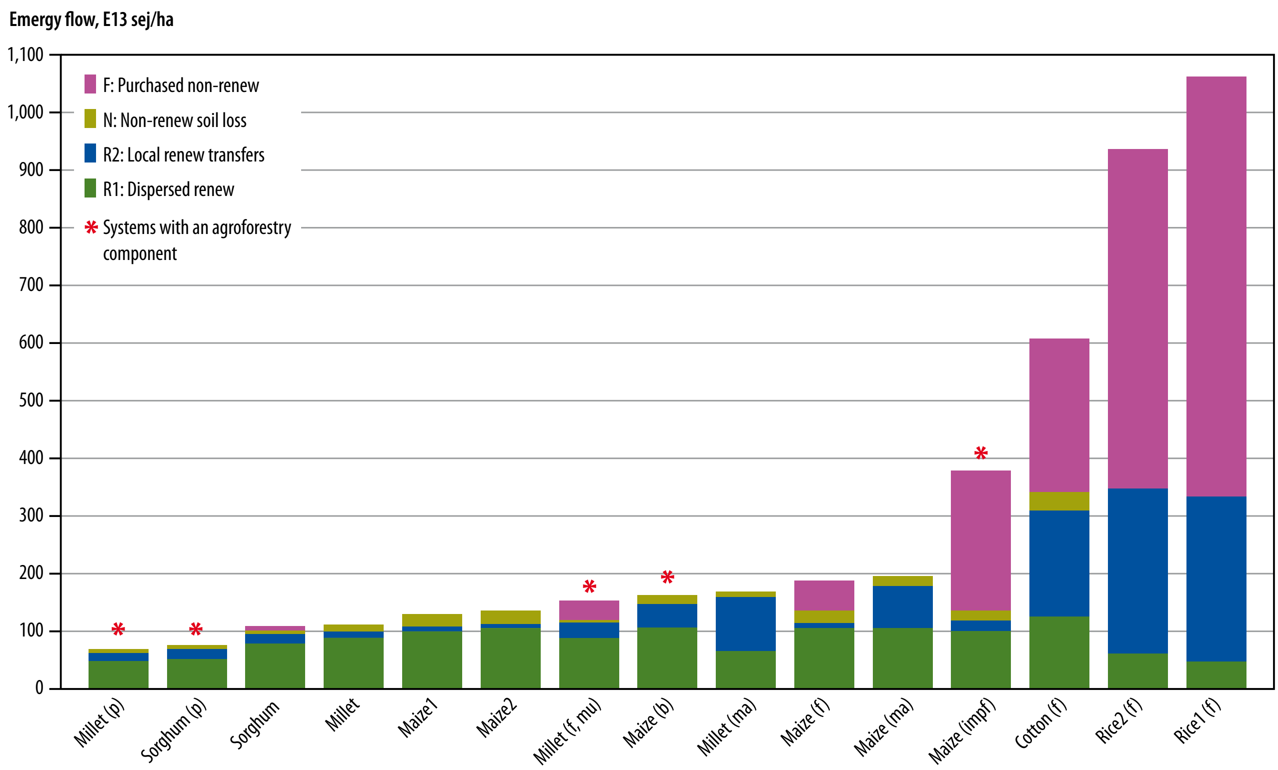


FIGURE 5

Summary of maize production processes for Sahelian agricultural systems. Shown are crop yields, total emergy use, the resulting unit emergy value (UEV) and the fraction of emergy in each process derived from renewable sources. Also shown, for comparison, is a typical maize production system in the United States.

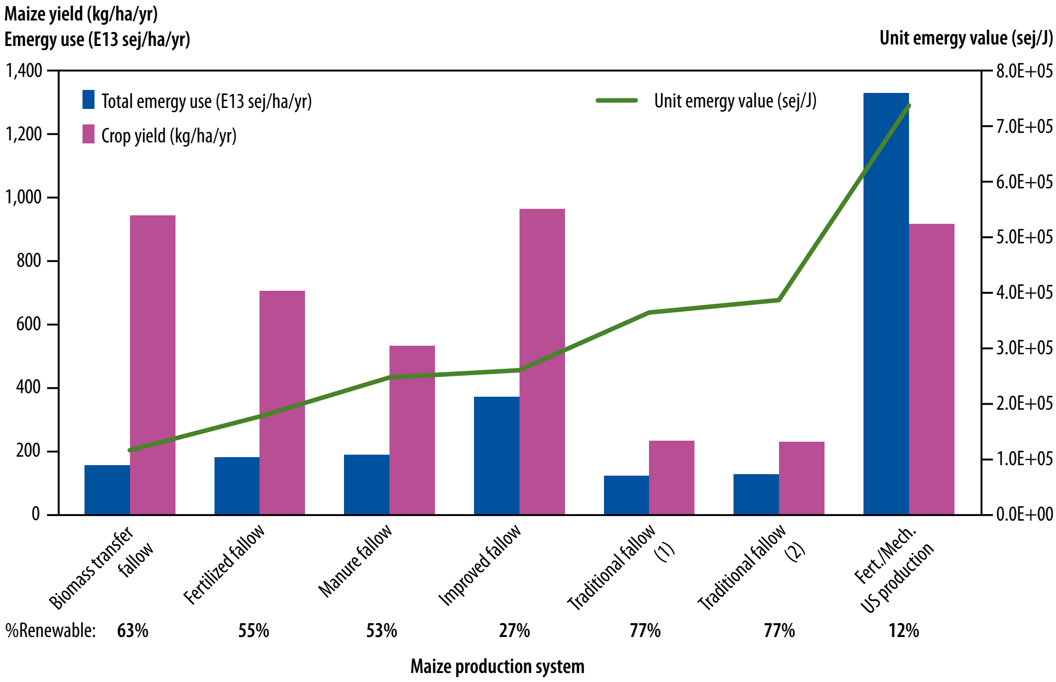
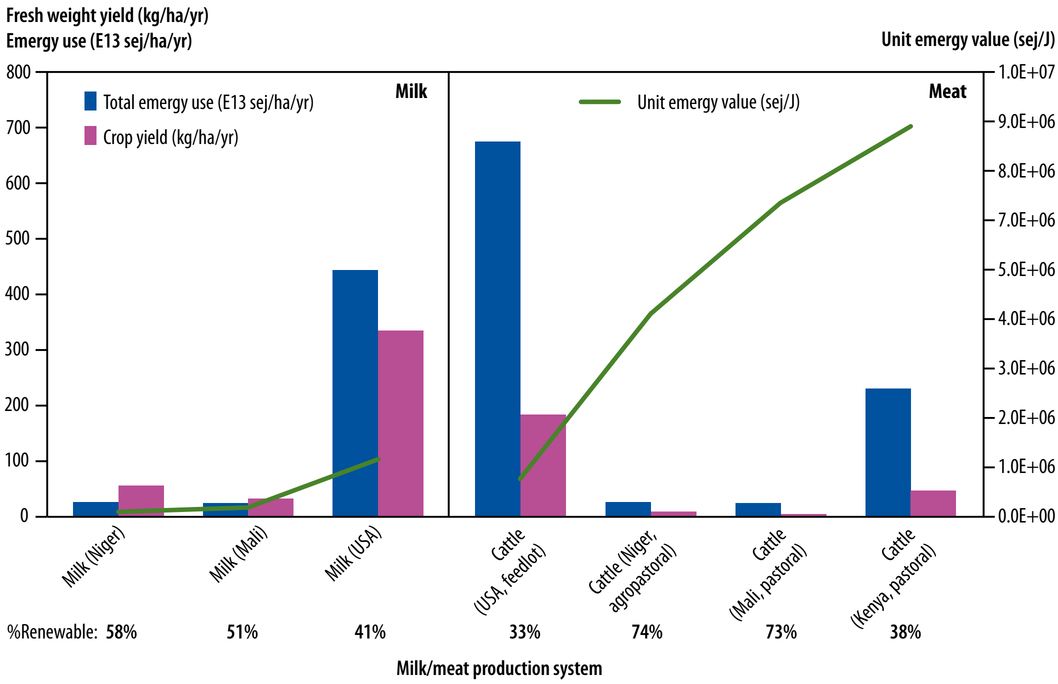


FIGURE 6

Summary of milk and meat production processes for Sahelian agricultural systems. Shown are crop yields, total emergy use, the resulting unit emergy value (UEV) and the fraction of emergy in each process derived from renewable sources. Also shown, for comparison, are typical cattle production systems in Kenya and the United States.



and Kenyan production systems for comparison. In contrast to the observed patterns for grain production, it appears that US meat production is more efficient (i.e., lower UEV) than Sahelian production, while the reverse is true (higher UEV for US production) for milk; it is particularly striking how efficient milk production is in the Sahel.

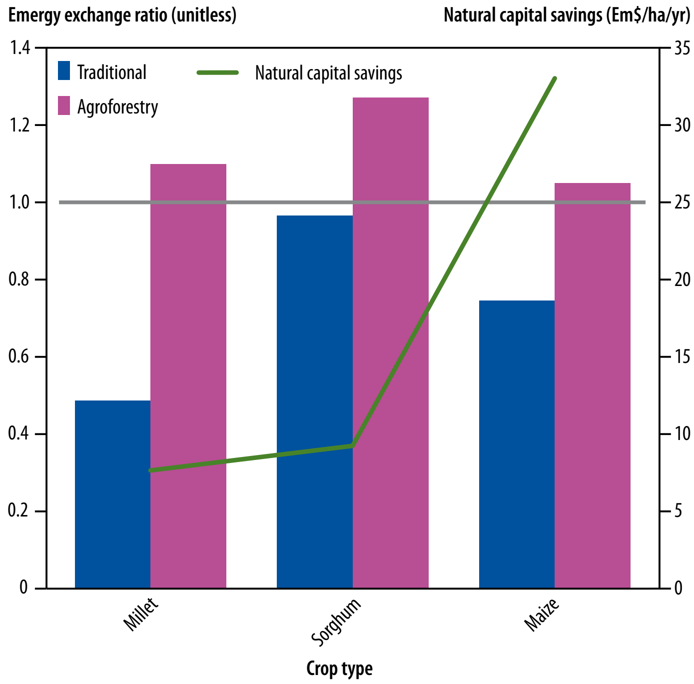
EMERGY EXCHANGE RATIOS (EER)

The ratio of emergy received during market transactions (i.e., the value of money or bartered goods in emergy units) versus the emergy exported is a useful measure of the balance of trade at the household or individual scale. Values greater than 1 indicate net benefit for the farmer selling the product; that is, they get more emergy than they deliver. Similarly, values less than 1 indicate a comparative disadvantage for the farmer selling agricultural products. For the Sahelian agricultural systems that we evaluated, there were three systems for which comparisons between agroforest and traditional techniques were possible (one for maize, millet and sorghum). In each case (Figure 7) the benefit of agroforestry is marked, with EER values for the traditional agricultural methods generally well below 1, and EER values for the agroforestry technique at or above 1.

There are two main reasons for this difference. First, the agroforestry operations yield multiple products (karite and neem, specifically), which have high market values and generally do not compromise grain yields. This means that per unit of emergy input (land and labour), higher emergy yields are possible within the market system. A second reason for this difference is that the agroforestry systems reduce the loss of soil due to wind erosion, and accelerate the accretion of soil carbon. Both yield significant emergy benefits.

FIGURE 7

The emergy exchange ratio (emergy exported:emergy received) for farmer transactions comparing conventional monocropping and agroforest inter-cropping (with additional marketable products). Also shown are the best estimates of the annual benefits of agroforestry systems *vis-à-vis* monocrop systems in conserving soil resources, reported in em$ (i.e., money equivalent of emergy saved).



POLICY IMPLICATIONS

Our analysis suggests quite clearly that future intensification should consider the production of co-products (e.g., karite, neem, mango). Lower UEVs suggest the production of a good yield with fewer resources; differences of 200–300% are substantial and appear to be robust for uncertainty in erosion estimates (though labour estimates are a significant unknown).

Given the utility of trees within the context of all agricultural operations that we analyzed, the dramatic efforts to protect seedlings from the grazing pressure of free roaming animals are well warranted. Development of low-cost seedling protection strategies may provide important amplifying benefits for rural development. Figure 8 illustrates some of common and extreme measures that local residents have taken to mitigate the effects of browsing animals on their planted trees. Based on the very obvious browse effects exerted by those animals on mature trees (Figure 8a), and catastrophic failures that can accompany large fenced exclosures if even a small part of the exclosure is breached (Figure 8b), measures like protecting individual trees (Figure 8c, d, e) appear well warranted. Simple measures to assist local farmers in this regard may be of enormous leveraging potential: the addition of trees to the landscape appears to a major resource benefit, likely far to exceed the modest (but high risk) costs of ensuring the survival of seedlings. These leverage points in the development process are often sought because they amplify the investment far more than other less targeted approaches might, because of the long-term recursive benefits that can be obtained.

FIGURE 8

A) Parkland system with a clear browse level evident on the leaves of the trees. B) fields of planted trees are often protected by large exclosure fences (both live and dead), but any breach in that perimeter can be catastrophic. Exclosures (C, D, E) of varying resource intensity were observed throughout the region, indicating that local farmers frequently want trees to grow, but cannot ensure their survival given the free-range animal populations. Development of low-cost reusable exclosures that minimize the risks of acquiring and planting trees could yield significant amplified benefits for rural livelihoods.

Ecosystem services and household asset wealth in rural Mali

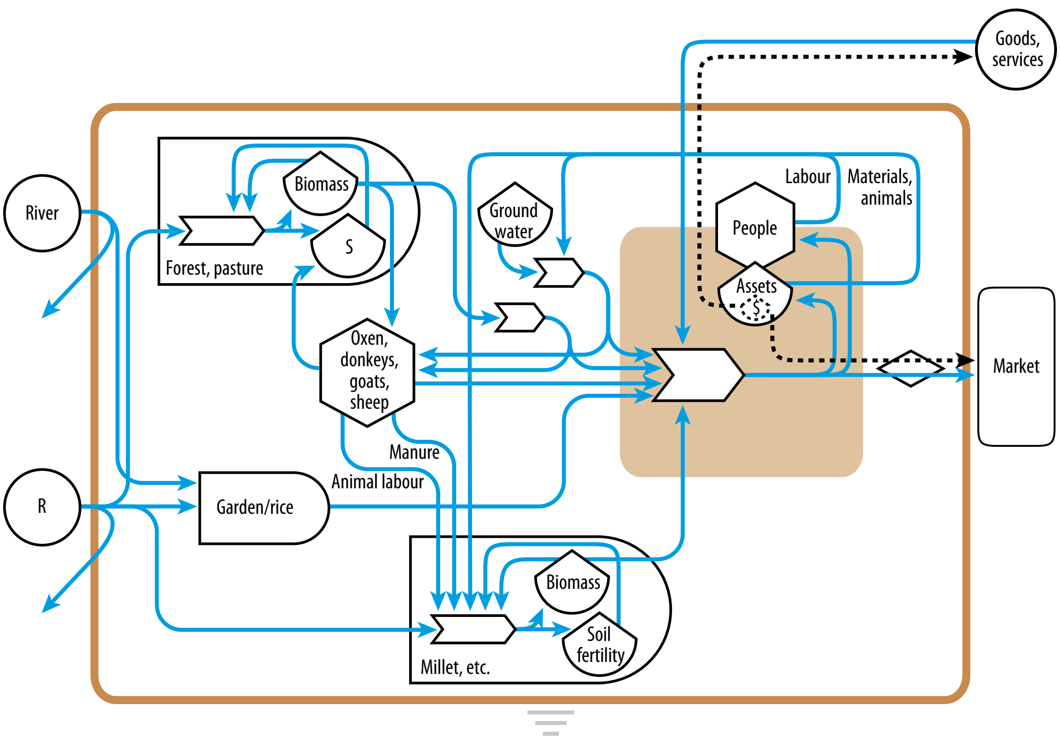
WEALTH SURVEYS

Research for this study was conducted in the Segou region of Mali, which is located in the Sahel zone, a semi-arid to arid area of transition with little relief just south of the Sahara Desert. Annual rainfall ranges from approximately 400–800 mm with a mean temperature of 29° C. Data were collected at the household level, as the household is the primary social unit of production and where livelihood decisions are made. Livelihood activities in Mali include agriculture (primarily millet, sorghum, rice, ground nuts, cowpeas, cotton, maize and vegetables), livestock rearing (cows, goats, and sheep which are primarily free range), small trade, crafts and day labour.

Figure 9 depicts resource and energy flows in a typical Malian household. The household economy is supported by the production of millet or sorghum fields, garden vegetables and/or rice, and forest/pasture resources. The forest/pasture areas are used for the extraction of fuel wood, animal fodder, and other products such as traditional medicine. Animals also graze freely. Manure deposited in

FIGURE 9

Systems diagram of a Malian household.



the household compound is transferred to the fields before the planting season. The household economy production function, which is driven by these three types of land use, as well as livestock and water storages, creates the labour, which is fed back into these land uses. This labour also feeds back into the production function in the form of household labour and resource transformations into marketable products. Production of livestock and sale of products at market leads to asset and wealth accumulation, which are constantly revolving within the household economy to allow for the purchase of goods and services, such as tools for the field, supplementary food items, fertilizer or educational fees. Often, family members who have left the household and acquired off-farm employment send remittances back to the household.

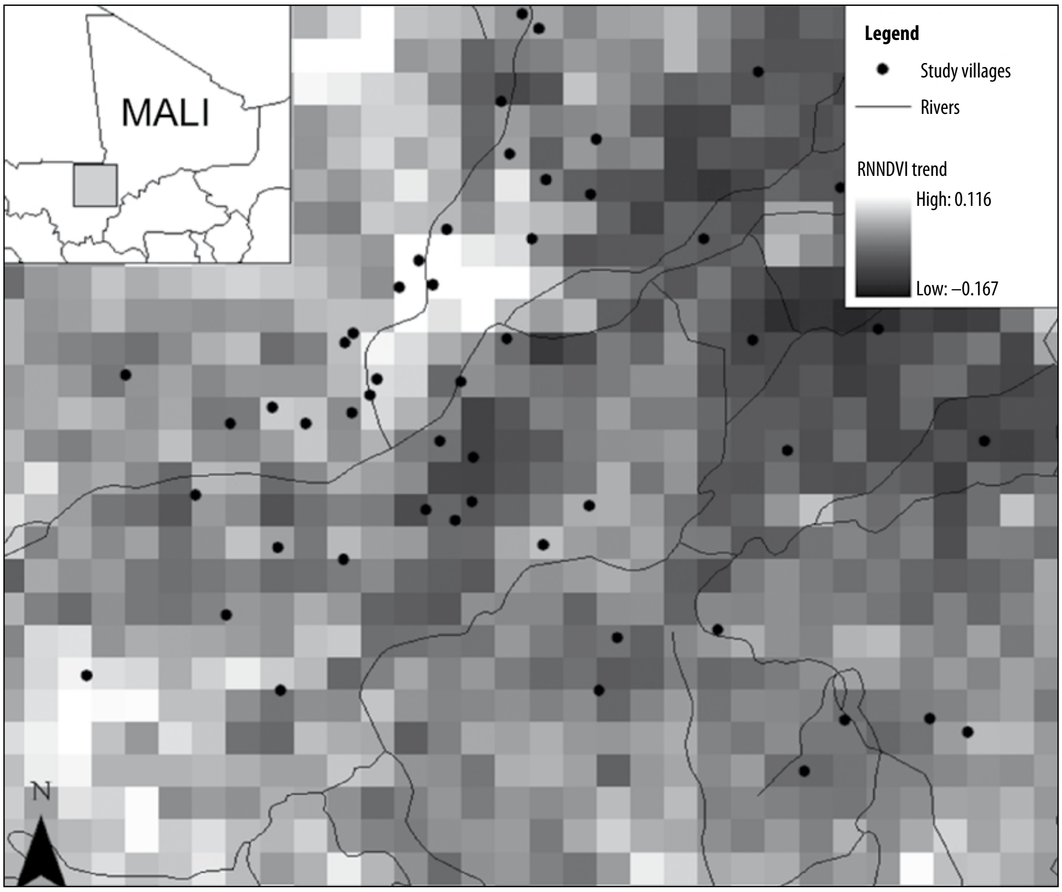
ENVIRONMENTAL SERVICE INDICATORS

Three metrics of environmental condition, compiled from remotely-sensed data, were used to represent the environmental services on which households depend. These three metrics are average rainfall, average annual rain-normalized vegetation index (RNNDVI) and RNNDVI trend. Average rainfall was selected as a metric because the Sahel is a drought-prone area where agriculture may be water limited. The average annual rainfall from 1982–2006 was calculated from both ground station data and satellite imagery to create a grid map with a resolution of 8 x 8 km. The RNNDVI trend, calculated over the same period, indicates environmental water use efficiency: a positive trend suggests increasing environmental capacity to use water. Therefore, RNNDVI trend is a proxy for environmental degradation or improvement.

Data for this study were collected in 2006 and 2007. A total of 2,756 households within the 77 villages were surveyed. The villages were selected using a stratified random selection technique based on the degree of environmental degradation as defined by

FIGURE 10

Selected study villages displayed on a map of RNNDVI trends.



RNNDVI trend (Figure 10), choosing those villages with extremes in access to open water and access to markets (two potential confounders to wealth at the landscape scale), geographically spread throughout the region.

WEALTH LEVELS

The mean wealth level for the 77 villages evaluated displayed a six-fold difference between the wealthiest and poorest villages. Variation in wealth within villages increase with average village wealth level (Figure 11).

RELATIONSHIP BETWEEN WEALTH AND ENVIRONMENTAL SERVICES

We used a hierarchical Generalized Linear Model to predict household well-being, based on measures of environmental degradation and direct inputs of environmental services (Table 3), controlling for geographical and cultural factors that might confound the relationship.

By far the most important variable was household size, which is expected, given the way in which the wealth metric was estimated. The most important environmental variable was the interaction of the mean RNNDVI and its trend: where the trend is positive, increasing mean RNDDVI increases wealth, whereas in regions with declining trends, the effect of increased rain-use efficiency is to lower wealth. Also important is the effect of rainfall, which indicates a significant positive effect of increased rainfall on wealth.

At the landscape scale, distance to market was not a significant predictor of total capital value, however increased distance to open water and the number

TABLE 3

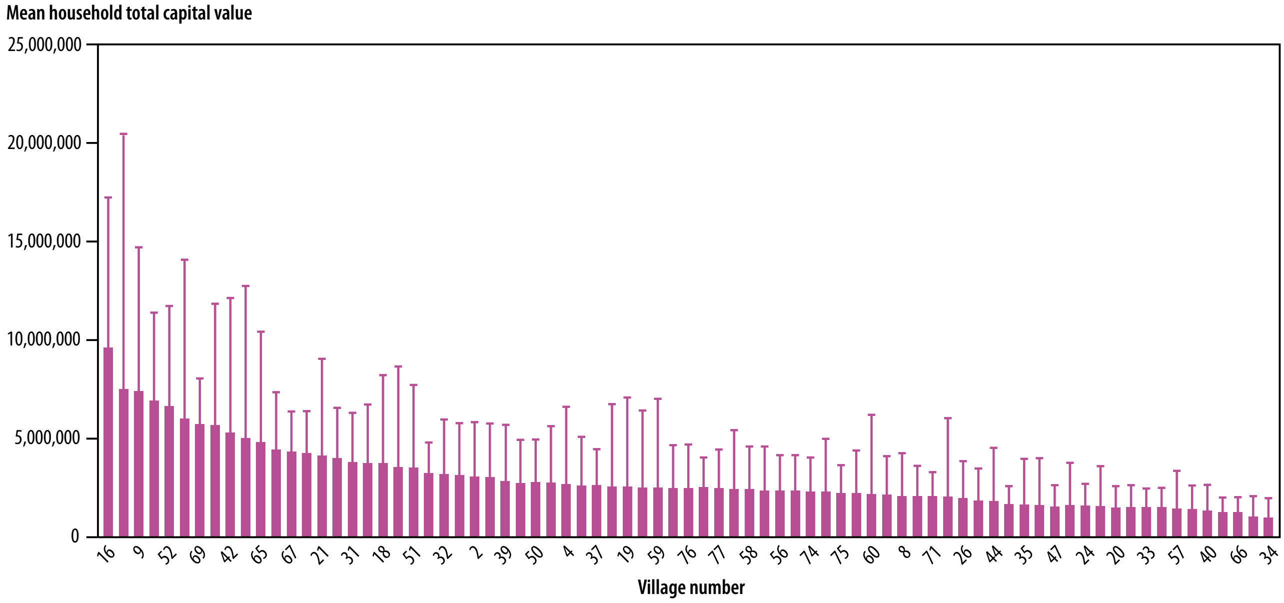
Statistical model results for the effect of variables on household total capital value (wealth level) based on data from 2,750 households.

	t	p
Intercept	-1.81	0.07
Number of people in the household	29.80	0.00
Married men per person	2.76	0.01
Number of households in the village	3.11	0.00
Distance from open water	3.68	0.00
Distance from a market	-1.21	0.23
RNNDVI trend	-0.80	0.42
Rainfall	2.00	0.05
Average RNNDVI	1.52	0.13
RNNDVI trend*Rainfall	-0.15	0.88
RNNDVI trend*Average RNNDVI	2.44	0.01
Rainfall*Average RNNDVI	-1.80	0.07

RNNDVI trend is an index of land degradation based on vegetation cover trends adjusted for rainfall trends. The t-value gives a measure of the relative importance of each variable in influencing household wealth. The p-value gives an indication of the statistical significance of the t-value, with values of less than 0.05 indicating a level of certainty of greater than 95% probability. The model accounted for about 30% of the total variation in household wealth.

FIGURE 11

Ranked mean village wealth with variance shown as error bars.



of households in a village were both positively associated with total capital value. At the household level, both the number of people in the household and the number of married men per person were positively associated with total capital value.

POLICY IMPLICATIONS

There appears to be good evidence to support the contention that ecosystem services matter in the provision of rural livelihoods. The weakness of that effect, and the relative strength of simple social and demographic attributes (ethnicity and household size), suggests the effect the environment on rural household wealth creation can be modulated by compensatory strategies. That this is possible, even at this distal end of the development spectrum, illustrates the complexity of providing simple answers about the role of the environment in human welfare and points to the need for livelihood diversification as an adaptive strategy. This is even more pertinent with increased uncertainties about environmental services in the future due to climate change.

A central challenge for sustainability is integrating the value of ecosystem services in policy and economic decision making. Ecosystems produce goods (e.g. wood, fibre, food) and services (e.g. water purification, disease vector control, pollination) that accrue to human users outside the market system, and are therefore often treated as free and tend to be over-exploited. The rural poor in Sahelian countries are highly dependent on land resources and as a consequence they are particularly vulnerable to degradation of local ecosystem services.

In this report, eenvironmental accounting is used in conjunction with data from the literature to evaluate the costs and benefits of different land-use systems in the Sahel on environmental services and ultimately on the populations that depend on them. The analysis illustrates the magnitude of services that accrue from the land in this region, where land degradation is an epidemic problem, and points to policies that protect land resources. Based on results from a rural wealth survey of over 2,700 households across 77 villages in Mali, the links between ecosystem service degradation and household wealth are analysed.

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