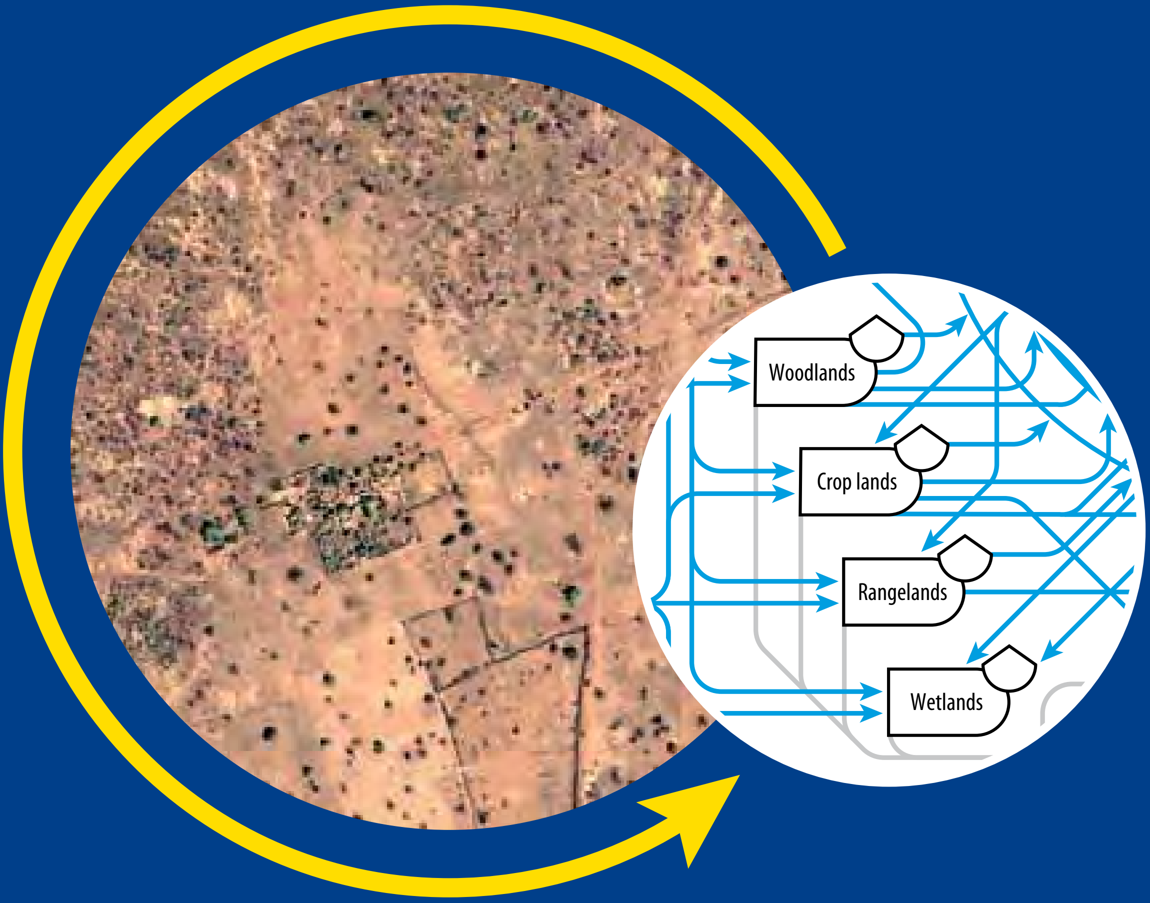
# ECOSYSTEM SERVICES

## and Rural Livelihoods in The Sahel

### *Environmental Accounting and Wealth Surveys*



UNEP

ISBN: 978-92-807-3302-0
UNEP Job Number: DEW/1613/NA

**Disclaimers**

This publication may be reproduced in whole or in part and in any form for educational or nonprofit services without special permission from the copyright holder, provided acknowledgement of the source is made. UNEP would appreciate receiving a copy of any publication that uses this publication as a source. No use of this publication may be made for resale or any other commercial purpose whatsoever without prior permission in writing from the United Nations Environment Programme. Applications for such permission, with a statement of the purpose and extent of the reproduction, should be addressed to the Director, DCPI, UNEP, P.O. Box 30552, Nairobi, 00100, Kenya.

The designations employed and the presentation of material in this publication do not imply the expression of any opinion whatsoever on the part of UNEP concerning the legal status of any country, territory or city or its authorities, or concerning the delimitation of its frontiers or boundaries.

**This report should be cited as:**

UNEP (2012). Ecosystem Services and Rural Livelihoods in the Sahel: Environmental Accounting and Wealth Surveys. United Nations Environment Programme, Nairobi.

**Authors**

Mathew J Cohen[1], Danielle King[1], Sharlynn Sweeney[1], Gemma Shepherd[2], Mark T Brown[1]

The following report is also related to this work:
UNEP (2012). Environmental Accounting of National Economic Systems: An Analysis of West African Dryland Countries within a Global Context. United Nations Environment Programme, Nairobi.

**Acknowledgements**

This document is a product of UNEP's project "An Ecosystem Approach to Restoring West African Drylands and Improving Rural Livelihoods through Agroforestry-based Land Management Interventions".

We gratefully acknowledge the Governments of Burkina Faso, Mali, Mauritania, Niger and Senegal for their participation in this project, and particularly the Government of Mali for hosting the project. We thank the Government of Norway for providing the principal funding for this project.

**Project manager:**

Gemma Shepherd/UNEP.
Email: gemma.shepherd@unep.org

**Design and layout:**

Bounford.com

Printed and bound in Malta by Progress Press Ltd, Malta Progress Press Ltd, P.O. Box 328, 341 St. Paul Street, Cmr 01 Valletta, Malta

---

[1] Centre for Environmental Policy, University of Florida, Gainesville FL USA

[2] United Nations Environment Programme (UNEP), Nairobi, Kenya

# ECOSYSTEM SERVICES

## and Rural Livelihoods in The Sahel

*Environmental Accounting and Wealth Surveys*

UNEP

Center for Environmental Policy
University of Florida

# Contents

# Figure list

# Table list

# 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 Sustainability 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 |

# Preface

Rural populations in the West Africa Sahel are among the poorest in the world in terms of incomes and rely heavily on land resources and ecosystem services for their basic survival. Their primary reliance is on ecosystem goods (e.g. food, wood, fibre) that come directly from the local environment, including land and freshwater ecosystems. However the provision of ecosystem services relies on a range of regulating and supporting services such as nutrient cycling, water regulation, maintenance of soil organic matter, and resistance to soil erosion. Because of their heavy reliance on environmental resources, Sahelian livelihoods and local and national economies are particularly vulnerable to degradation of ecosystems due to decline in availability of ecosystem goods and also due to reduced adaptive capacity resulting from degradation of supporting and regulating services.

Pressure on land resources and ecosystems has intensified greatly over the past several decades due to land use changes created by a burgeoning population, economic development and global markets, exacerbated locally by land governance issues. Demands for food and livestock feed are surging due to factors such as population growth, urbanization and changing diets that include more animal products.

As a result many terrestrial ecosystems are being severely degraded, aggravated by a lack of long-term policies that address land use decisions. Current measures fail to recognize non-economic ecosystem functions that ultimately limit productivity and long-term ecosystem sustainability. Reversing degradation and protecting ecosystem services will require new ways of integrating values of ecosystem services in policy and economic decision making.

This study examines two questions that are fundamental to moving towards new models of a green economy: how much are ecosystem services worth? and what is the empirical link between services and livelihoods? The first part of the report applies environmental accounting to a study of the sustainability of the main land uses in the Sahel, quantifying the services that accrue from them. The most sustainable land uses that result in long-term public benefit are identified, and some of the constraints to their wider adoption are explored.

The second part of the report examines the statistical relationships between land degradation and rural wealth, based on a survey of over 2,700 households within 77 villages across a gradient of environmental conditions. This is one of the first empirical studies under Sahelian conditions to elucidate the direct and compensatory links between ecosystems and the livelihoods of the people who live in them.

We hope that the findings of this research will help in guiding policy decision making on sustainable land use systems for dryland Africa and on strategies for diversification of dryland rural livelihoods.

MTBrown

**Mark T Brown**
Director
Centre for Environmental Policy, University of Florida

Gemma Shepherd

**Gemma Shepherd**
Environmental Affairs Officer and Project Manager
United Nations Environment Programme

CHAPTER 1

# Introduction and overview

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 a wide array of competing policy priorities?

This report attempts to address both questions in the context of the Sahel region of Africa, and drylands more broadly. It is widely acknowledged that the pressures of growth in population and affluence are felt acutely in arid and semi-arid areas, in part because the ecosystems there are fragile and in part because growth in population and, to a lesser extent, affluence has been so rapid. This is exemplified in the West African Sahel (including, for this work, parts of Mali, Niger, Burkina Faso, Senegal and Mauritania) where significant climate variability, land pressure, limited opportunity for resource replacement (i.e., fossil energy surrogates for ecosystem services), and generally weak governance make the rural population highly dependent on local ecosystem services, and therefore presumably particularly vulnerable to declines in those services.

Ecosystem services are notoriously difficult to value. Efforts to quantify particular services (e.g., the value of bees for coffee pollination – Ricketts et al, 2005) 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). In short, the services of pollination, water purification, carbon fixation, microclimate regulation and biodiversity maintenance are provided simultaneously by a tropical forest patch. Ascribing value to that forest based only on one service implicitly discounts other services, and thereby discounts, probably by a substantial margin, the actual value of that ecosystem. However, adding all the services together may over-estimate the value, potentially short-circuiting any policies designed for ecosystem protection. In short, evaluating the role of ecosystem services on the demand side (i.e., the human users), though critical, is complex and deeply contingent on who those users are 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, don't 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 its members 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., 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 from 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 accounting 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 derived from large-area surveillance tools (UNEP, 2012a) 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. This report is divided into two sections reflecting the dual nature of our objectives. The first summarizes the results of the environmental accounting analysis for 11 land use systems 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.

## OVERVIEW OF METHODS

### Environmental accounting

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 1.1). Flows in environmental accounting are reported as the quantity of solar energy required to make them; we call this quantity solar ***emergy*** (Odum, 1988; 1996).

Environmental accounting using emergy involves four basic steps:

1. For any system of interest (in this work we focus on 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 (Figure 1.2) 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-term benefits. As such, environmental accounting can be viewed as an ecosystems approach that is complementary to economic valuation.

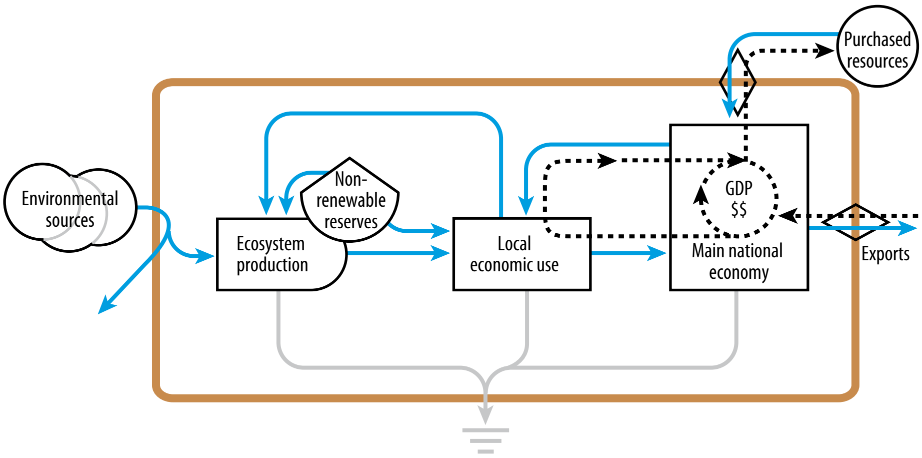
This report presents results of detailed environmental accounting of 17 land-use subsystems typical of dryland agriculture in the Sahel region of West Africa. Environmental accounting is used for four primary tasks in this work: 1) to compare the resource requirements of agricultural production across 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 practiced 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

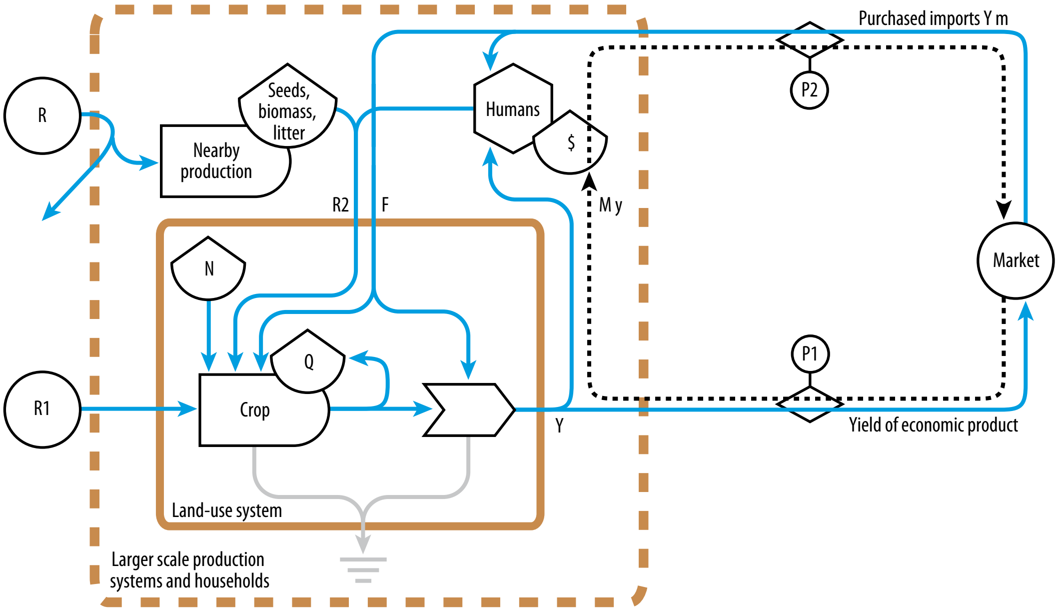
### FIGURE 1.1

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.



### FIGURE 1.2

Generic systems diagram of an agricultural land use showing the internal allocation of environmental and labuor resources, and the integration with the regional market system. Symbols are defined in Table 2.3.



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; in short, 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 land degradation in particular in this example) 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 is this regard is the search for statistical associations between rural livelihoods (measured as the asset wealth of the households, for reasons that will be discussed at length later) 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 the 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); and 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 modelling framework that is intrinsically nested, and report the statistical significance and direction of the relationships between wealth (which was given considerable pre-analysis consideration 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 the economy in mitigating the direct effects of declining environmental services on wealth.

## SUMMARY OF MAJOR FINDINGS

### Environmental accounting

1. Parkland production systems produce yields of both grains and tree products at lower unit emergy values than comparable dedicated lands. In other words, agroforestry in the region appears to have the capacity to improve the balance of trade between rural land users and regional consumers. Moreover, because UEVs are lower, the comparative sustainability of coupled tree-crop land uses is far higher than the non-tree alternative.
2. Large uncertainties in the analysis outputs arise from the comprehensive data requirements of the environmental accounting method, and the comparative costs of data collection. Two areas for which improved data are required are the rates of soil loss, and the labour input requirements for each land use. We conclude, based on a sensitivity analysis of outputs to changes in soil erosion inputs, that even the most dramatic estimates of the differences between parkland agriculture and agriculture without tree co-crops would always favour the tree-based systems.
3. Comparisons of UEVs between Sahelian production methods and 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. As such, 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.
4. For maize production, the lowest UEV (i.e., highest efficiency) was observed for a biomass transfer fallow system. UEVs for conventional dryland agriculture (i.e., those without trees or other subsidies) were higher by a factor of 2–3. For the production of millet, agroforesty methods were more efficient, followed by techniques that require off-field subsidies (e.g., manure). Traditional rain-fed techniques are less efficient, underscoring the environmental utility of modest efforts to mitigate production limitations of nutrient content and water holding capacity.
5. 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.

### Rural poverty and environmental condition

1. Household assets were evaluated for 77 villages spanning a range of environmental condition; in total, asset lists were compiled for 2,757 households. Households were overwhelmingly headed by a male, and many included multiple married men. All subsequent analyses consider and control for household size as a factor in wealth assessment.
2. Using a factor analysis approach to household assets, we infer two primary axes of household wealth: the first, which we refer to as material wealth, is strongly correlated ($r = +0.75$, $p < 0.001$) with wealth inferred from independent wealth rankings of household assets obtained from a previous study. The second, which we refer to as animal wealth, is principally controlled by the number of livestock and the state of those livestock (i.e., whether fattened for market), and

is evidently independent of material wealth. There are strong ethnicity differences in how a household accumulated wealth, with tribes that are or were historically nomadic pastoralists far more likely to store wealth in livestock than in material assets like bicycles, farming implements and household accoutrements.

3. Predictions of household wealth from a suite of geographic and environmental variables yielded statistically significant models: animal wealth was predicted more effectively ($r^2 = 0.36$, $p < 0.001$) than material wealth ($r^2 = 0.16$, $p < 0.001$).
4. We evaluated three levels of ecosystem services as predictors of rural household wealth. Rainfall provides insight into the magnitude of resource availability; this ranged from 380–740 mm across the 77 villages studied. Rain-use efficiency provides insight into the long-term (c. 20 year) average efficiency of primary production given rainfall inputs; this can reasonably be assumed to be related to land use and land degradation. Finally, we used an assessment of the trend in the rain-use efficiency over time as a direct measure of land degradation; positive trends indicate areas where rain-normalized land productivity is increasing over time, and negative trends indicate areas where productive efficiency is declining. For the material wealth values, total rainfall was strongly significantly ($p < 0.001$) related to wealth, but the sign of the association was negative, suggesting that villages with higher rainfall amounts are less wealthy. We interpret this to be a population-density dependent effect. The effects of rain-use efficiency ($p < 0.001$) were also significant, with higher values associated with greater wealth. While the marginal effect of rain-use efficiency trends were not significant, we did observe significant ($p < 0.001$) interaction effects between the magnitude of rain-use efficiency and the time-series trend therein, which suggest that areas with increasing trends also exhibit higher wealth, particularly at high levels of average rain-use efficiency.
5. Results for animal wealth were markedly different. For all three measures of ecosystem services (rainfall, rain-use efficiency, and rain-use efficiency trends), the effects were negative, suggesting that investment in animal wealth may represent an important coping strategy when agricultural efforts are constrained by poor environmental conditions. We note that strong effects of ethnic group were observed in both models, but these are controlled for in our results.
6. Other geographic and local-scale factors (proximity to markets and rivers, regional woody cover) were somewhat important. Distance to nearest major market was not significant ($p = 0.343$) for material wealth, but was for animal wealth (though with a positive association, $p < 0.001$), while distance to open water was significant (and positive) for both wealth categories. Our observations suggest that part of the reason for the inverted association (we expected to see that proximity to riverine resources would increase wealth) was due to the convergence of destitute households on rural towns; distance to rivers was significantly negatively associated with the variance in household wealth within a village, providing some empirical support for that observation.

We conclude that there are significant associations between environmental condition and rural wealth, and that the direction of the associations are generally as expected. This is a striking result; there are few studies that we are aware of that can, so clearly, link the accumulation of wealth to the condition of the environment. However, equally striking is the degree to which dramatic variability in ecosystem services over an area acutely dependent on those services can be compensated for (i.e., the signal masked). In other words, despite a strong influence of the environment on rural farmers, its effects are still muted by the intrinsic capacity of people to engage in compensatory activities that permit the use of other services, perhaps not directly related to land. The fact that ethnic group proved to be a critically important variable to control for in our assessment underscores this inference, since we presume that a large component of compensatory livelihood strategies in degraded environmental conditions are informed by cultural practices.

## CHAPTER 2

# Environmental accounting of rural land uses in the Sahel

## OVERVIEW AND OBJECTIVES

We have compiled data from the literature that permits a comparative analysis of Sahelian land-use systems using environmental accounting. An overview of the methodology and results from this effort are described below. The main objective of this work was to evaluate the environmental costs and benefits of different prevalent land-use systems on a common biophysical basis that allows explicit integration of environmental services. The rationale for this analysis emerged from questions such as whether land uses with interventions aimed at reducing environmental degradation, for example, improved fallows and biomass transfer, are beneficial in comparison with similar land uses without those interventions. An economic analysis can be used to evaluate certain aspects of that question, but the external nature of the environmental stock (i.e., soil) that is being protected precludes decision-making on that basis alone. Our main questions were: 1) What are the effects of agroforestry on the environmental accounts of Sahelian land uses? 2) How significant is soil erosion as a cost for Sahelian land uses, and how does uncertainty in this flow affect the inference of comparative sustainability? 3) How does Sahelian production of key products (millet, maize, cattle, cotton, rice) compare with the same products grown in other places where similar analyses have been performed?

The data required to develop an environmental accounting analysis of a particular land-use system are far more detailed than is typically acquired as part of a standard field trial or comparative land-use analysis. This necessitates the fusion of multiple data sets, often from different sites with different growing conditions. Moreover, the data that we use to develop these analyses presume that the particular period of record or location is representative of the larger Sahelian region. As such, small differences between land-use systems analyses should be interpreted with caution; we focus our attention on large differences between land uses that can reasonably be attributed to real variability in production and yield. To that end, one of our overarching objectives is to provide a rationale for future agro-ecosystems analyses to collect a broader suite of performance measurements. Of particular interest are rates of soil erosion, a notoriously difficult flux to estimate, and labour requirements, both of which were rarely reported for the data sets obtained, and which represent tremendously important system fluxes, the refinement of which could greatly improve systems analyses generally.

Our other primary objective was to evaluate the role of trees in agricultural systems performance. As with labour and soil erosion, there are few instances where the comparative yields are reported side-by-side, which necessitates assumptions about yields and allocation of resources to the two products (e.g., millet and karite nuts). We evaluated the implications for farmer exchanges in local and regional markets, but with the caveat that the assumptions made to achieve our comparisons are difficult to test explicitly with currently available data. We propose, therefore, that future work on the biophysical Parkland system explicitly compare yields side-by-side with non-tree controls (and with the additional assessments of erosion losses and labour requirements). We have tried to be explicit where our inferences are subject to high levels of input data uncertainty.

## METHODS

Procedures for environmental accounting of land uses closely follow that of national accounts, documented in previous reports (UNEP, 2012b). In short, environmental accounting takes a systems view of the question of value, focusing on the environmental resources embodied in all goods and services, regardless of whether they derive from ecosystems or human systems. The central premise and accounting technique is to sum the input resources necessary for the production of a particular product (e.g., millet). The resources required for production come in myriad forms, ranging from exogenous environmental inputs (sunlight, rainfall), to endogenous environmental stocks (soil) and services (pollinators), and local and purchased human inputs (fertilizer, labour, seeds, manure). It is abundantly clear that these flows are qualitatively different, so their direct summation, even after conversion to energy units, would be erroneous. In recognizing differences in energy quality among the many inputs to a system, environmental accounting requires a numeraire that allows their comparison on a common basis. As has been described in detail elsewhere (e.g., Odum, 1996; Brown and Ulgiati, 1997; UNEP, 2012b), the key insight of environmental accounting that permits the comparison of, for example, soil erosion and labour costs, is that they can be reported and enumerated in common units based on the quantity of solar energy necessary, over their entire life cycle, to create them. Solar energy, as the primary exogenous energy form for the Earth system, is embodied in all things, and the quantity of embodied solar energy allows the resource intensity of vastly different inputs to be compared, and ultimately added together.

At the land-use scale, flows of environmental and economic goods and services are reported on a per area basis to facilitate comparisons across systems. For the Sahelian agricultural systems of interest, the system is defined as the field where production processes are occurring. Hence, seeds, manure, chemical fertilizers, and human labour are seen as imports, and harvested material as an export. After the system boundaries are defined, major flows into and out of the system are identified, quantified and transformed into emergy units, using previously computed unit emergy values (UEVs). These quantities permit the conversion of energy or mass flows (e.g., the energy of human labour or the mass of manure) to the common units of the solar energy required to produce them. Typical methods are described at length in Odum (1996), and all calculations and data sources are documented in the emergy tables produced in the analysis (Appendix A contains the emergy tables for all 17 land-use systems).

### Land uses and Interventions

Prominent subsistence, fodder and export crops in the Sudano-Sahelian zone include millet, sorghum, maize, cotton, cowpea, groundnut, rice, 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 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 2.1 lists the land-use systems with emergy analyses completed, with primary data sources identified. Figure 2.1 shows the spatial extent of the sites from which data were obtained for this report.

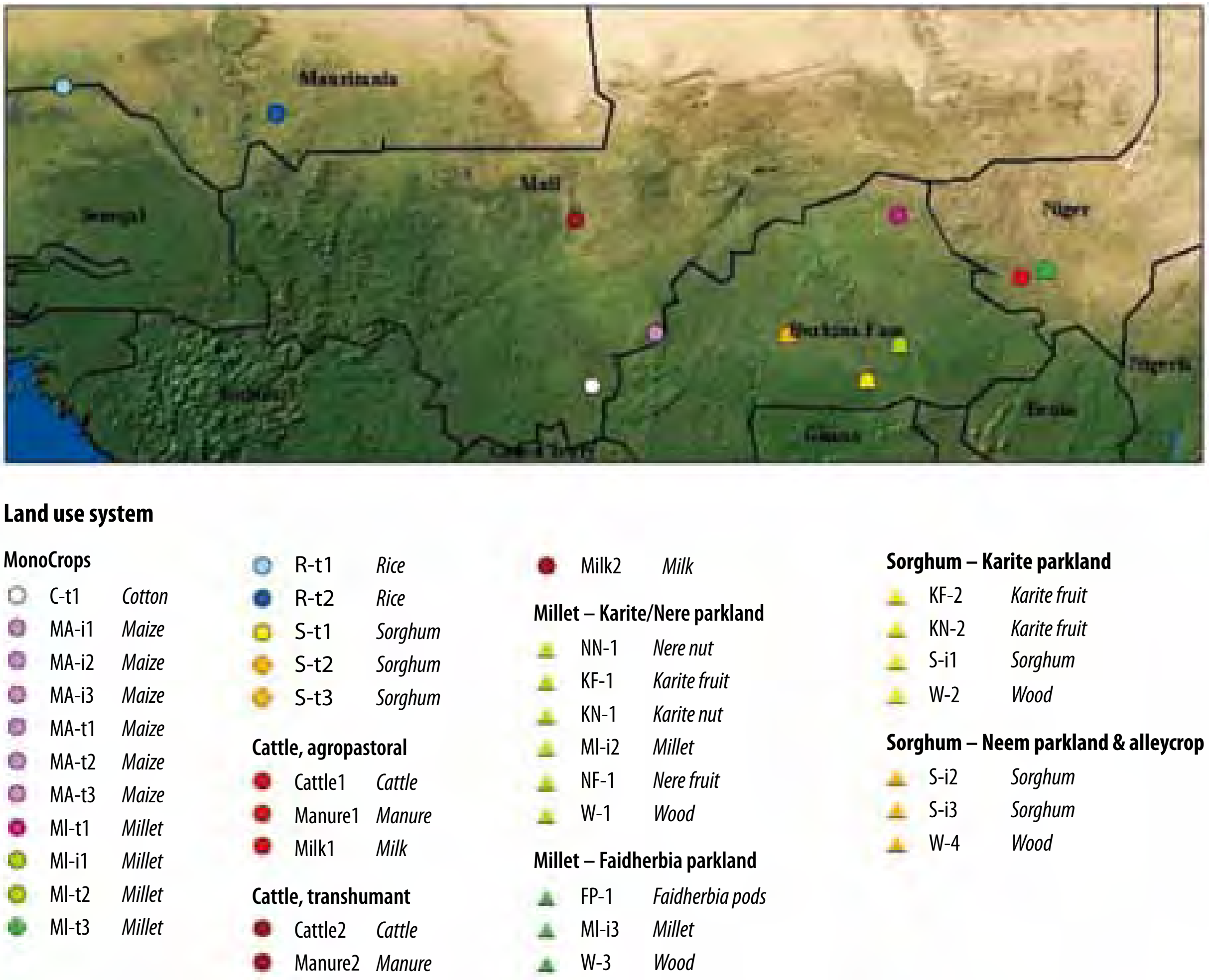
### Data sources

Because of the comprehensive aim of this comparative analysis (crossing five countries, many land-use systems, and a variety of interventions) the emergy accounts rely entirely on data from the literature. A set of primary papers with study locations in the West African Sahel were selected based on the presence within each paper of data regarding inputs and outputs of the land-use systems and interventions described previously. In some cases, most of the required data are found within one paper. More often, several sources need to be consulted in order to perform a complete analysis. Therefore, the emergy accounts developed represent a "theoretical average system" due to various data sources, even though the main data source is used to specify a location. These assumptions are unavoidable with the current data available.

Multiple papers were identified with quantitative values for seed, fertilizer, manure, crop residue, and yields. Unfortunately, there is a distinct lack of published studies which also include labour requirements and erosion estimates, and a lack of erosion estimates across Sahelian land-uses in general, probably due to the difficulties of measuring erosion and because of high spatial variability. We compiled a list of erosion estimates from papers unrelated to those from which the other line item flows were calculated (Buekert and Lamers, 1999; Bodnar et al, 2006; Chappell et al, 1998a; Chappell et al, 1998b; Karambiri et al, 2003; Spaan et al, 2005; Visser et al, 2005 and Warren et al, 2003). A final summary table of regional measurements (Table 2.2) is helpful for synthesis

## FIGURE 2.1

Locations of sites across the Sahel for which environmental accounting analyses were performed. Analysis codes correspond to summary tables below and detailed analysis tables (Appendix A).



purposes, even though the soil erosion estimates used in the analysis are not from the particular system under evaluation. In order to standardize the process of assigning an erosion value to specific land uses, we used this literature review to match specific site conditions based on variables for which we have values, such as slope, rainfall and land cover. We explore the sensitivity of our results to these assumptions about soil loss in a later section.

In addition, labour values are rarely reported and assumptions are made based on broad estimates from unrelated papers. We conclude that the paucity of labour data is one of the primary impediments to

**TABLE 2.1**

Crops and sites in the land use emergy analysis.

| Code | Item | Location | Rain, mm | Method/Intervention | Primary data source |
|---|---|---|---|---|---|
| Cot | Cotton | Mali | 1,000 | traditional farm, no regular fallow | Defoer et al, 1998 |
| MI-t1 | Millet | Burkina | 450 | subsistence farm, manure, no fallow | Krogh, 1997 |
| MI-t2 | Millet | Burkina | 743 | on farm experiment, no fallow or fertilizer | Bayala et al, 2002 |
| MI-i1 | Millet | Burkina | 743 | same as above + Shea mulch and fertilizer | Bayala et al, 2003 |
| MI-i2 | Millet | Burkina | 743 | in parkland with half-pruned trees, no fert. | Bayala et al, 2002 |
| Mi-t3 | Millet | Niger | 428 | no fertilizer, no fallow | Kho et al, 2001 |
| Mi-i3 | Millet | Niger | 428 | in Faidherbia parkland, no other inputs | Kho et al, 2001 |
| R-t1 | Rice | Senegal | 320 | tractor plowed, with pumped water | Wopereis et al, 1999 |
| R-t2 | Rice | Mauritania | 406 | gravity irrigated | van Asten et al, 2005 |
| S-t1 | Sorghum | Burkina | 685 | traditional, no fertilizer | Boffa et al, 2000 |
| S-i1 | Sorghum | Burkina | 685 | in parkland with karite trees, no fert. | Boffa et al, 2000 |
| S-t2 | Sorghum | Burkina | 798 | plots near parkland study | Tilander et al, 1995 |
| S-t3 | Sorghum | Burkina | 798 | plots near alley study | Tilander et al, 1995 |
| S-i2 | Sorghum | Burkina | 798 | parkland, 15 trees/ha, coppiced each yr | Tilander et al, 1995 |
| S-i3 | Sorghum | Burkina | 798 | alleycrop, coppiced each year to 30cm | Tilander et al, 1995 |
| MA-t1 | Maize | Mali | 851 | traditional fallow, on farm experiment | Kaya and Nair, 2001 |
| MA-i1 | Maize | Mali | 851 | improved fallow (leguminous), on farm | Kaya and Nair, 2001 |
| MA-t2 | Maize | Mali | 885 | traditional fallow | Kaya and Nair, 2001 |
| MA-t3 | Maize | Mali | 885 | traditional fallow + manure | Kaya and Nair, 2001 |
| MA-i2 | Maize | Mali | 885 | traditional fallow + chem. fertilizer | Kaya and Nair, 2001 |
| MA-i3 | Maize | Mali | 885 | traditional fallow + biomass transfer | Kaya and Nair, 2001 |
| KF-1 | Karite fruit | Burkina | 743 | parklands with millet crops, no fert | Bayala et al, 2002 |
| KF-2 | Karite fruit | Burkina | 685 | parklands with sorghum crops, no fert | Boffa et al, 2000 |
| KN-1 | Karite nut | Burkina | 743 | parklands with millet crops, no fert | Bayala et al, 2002 |
| KN-2 | Karite nut | Burkina | 685 | parklands with sorghum crops, no fert | Boffa et al, 2000 |
| NF-1 | Nere fruit | Burkina | 743 | parklands with millet crops, no fert | Bayala et al, 2002 |
| NS-1 | Nere seed | Burkina | 685 | parklands with sorghum crops, no fert | Boffa et al, 2000 |
| FP-1 | Faid. Pod | Niger | 428 | Faidherbia parkland w/ millet, no inputs | Kho et al, 2001 |
| W-1 | Wood | Burkina | 743 | parklands with millet crops, no fert | Bayala et al, 2002 |
| W-2 | Wood | Burkina | 685 | parklands with sorghum crops, no fert | Boffa et al, 2000 |
| W-3 | Wood | Niger | 428 | Faid. parkland w/millet, pruned for fodder | Kho et al, 2001 |
| W-4 | Wood | Burkina | 798 | Neem alleycrop prunings | Tilander et al, 1995 |
| Cattle1 | Cattle | Niger | 555 | cattle, agropastoralists | Achard and Benoin, 2003 |
| Cattle2 | Cattle | Mali | 400 | cattle, transhumant pastoralists | Wilson, 1986 |
| Milk1 | Cow milk | Niger | 555 | cattle, agropastoralists | Achard and Benoin, 2003 |
| Milk2 | Cow milk | Mali | 400 | cattle, transhumant pastoralists | Wilson, 1986 |
| Manure1 | Manure | Niger | 555 | cattle, agropastoralists | Achard and Benoin, 2003 |
| Manure2 | Manure | Mali | 400 | cattle, transhumant pastoralists | Wilson, 1986 |

## TABLE 2.2

Summary of soil erosion rates reported in the literature for Sahelian agricultural systems. Environmental accounting analyses are critically dependent on these flows of lost natural capital, and therefore require careful selection of appropriate values for systems that were analyzed but for which erosion rates were not available. Values from this table, accounting for crop type and rainfall, were used to arrive at plausible values for each land use system analyzed. In addition, uncertainties in these values were explored.

| Location | Value | Units | Description | Rain {mm) | Reference |
|---|---|---|---|---|---|
| Burkina Faso | 0.5 | t/ha/yr | Millet in valley with scattered trees, simulated area of 3,000m^2 | 360 | Visser et al., 2005 |
| Burkina Faso | 3.1 | t/ha/yr | Millet in valley with scattered trees, 20m^2 plot, direct measured | 360 | Visser et al., 2005 |
| Burkina Faso | 2.4 | t/ha/yr | Degraded site, no trees, simulated for 2001 | 360 | Visser et al., 2005 |
| Burkina Faso, northern | 4–8.4 | t/ha/yr | Rangeland, 1% slope, Katchari village north of Ouagadougou | 512 | Karambiri et al., 2003 |
| Burkina Faso | 5 | t/ha/yr | Average in low rainfall areas |  | Stoorvogei & Smaling, 1990 in Krogh, 1997 |
| avg. for 0–2% slope | 0 | t/ha/yr | Based on Kenya literature |  | Boscha et al., 1998 |
| avg. for 2–5% slope | 2.5 | t/ha/yr | Based on Kenya literature |  | Boscha et al., 1998 |
| avg. for 5–7% slope | 5 | t/ha/yr | Based on Kenya literature |  | Boscha et al., 1998 |
| W Africa | 7 | t/ha/yr | Average from compiled data |  | Roose, 1981 in Krogh, 1997 |
| avg. for 7–10% slope | 7.5 | t/ha/yr | Based on Kenya literature |  | Boscha et al., 1998 |
| cotton in Kenya | 20 | t/ha/yr | Cotton in Kenya |  | Stoorvogel and Smaling, 1990 |
| maize in Kenya | 20–40 | t/ha/yr | Maize in Kenya |  | Stoorvogel and Smaling, 1990 |
| millet fields, Niger | 26–46 | t/ha/yr | 30y avg. at 20 sites, low slope, sandy tassi soils (net, Cs technique) | 500 | Chappell et al., 1998 |
| millet, Niger | 90 | t/ha/yr | 3 yr avg., unmulched, sandy, 1% slope | 636 | Buerkert, 1999 |
| millet, SW Niger | 40 | t/ha/yr | Gross erosion, average of 15 field-scale sites |  | Warren, 2003 |
| SW Niger | 35 | t/ha/yr | Net loss over 30 years, sandy soils, well-vegetated (wind+water) |  | Chappell, 1996 |
| SW Niger | 16 | t/ha/yr | Net soil flux (accounts for dust dep.), SW Niger region | 500 | Chappell et al., 1998 |
| SW Niger, millet | 23 | t/ha/yr | Net soil flux, millet crops in valley w/3–5 yr fallows | 500 | Chappell et al., 1998 |
| SW Niger | 25 | t/ha/yr | Gross erosion, SW Niger (area with plateau & valley) |  | Lal, 1993 in Chappell, 1998 |
| SW Niger | 12 | t/ha/yr | Estimated net soil flux as 55% of gross erosion |  | Lal, 1993 in Chappell, 1998 |
| Southern Mali | 26 | t/ha/yr | Cultivated fields, 2% slope | 800–900 | Roose, 1985 in Bodnar et al., 2006 |
| Southern Mali | 10–31 | t/ha/yr | Cultivated fields, varying slope | 1,000 | Bishop&Allen, 1989 in Bodnar et al., 2006 |
| Southern Mali, Koutiala | 10 | t/ha/yr | Stonerows, grass strips, live fences, CR, 0–2% slope, 2 x 2km, cotton | 800 | Bodnar et al., 2006 |
| Southern Mali, Koutiala | 42 | t/ha/yr | Cultivated fields, no erosion control, 0–2% slope, 2 x 2km, cotton | 800 | Bodnar et al., 2006 |
| Dust DEPOSITION | 2 | t/ha/yr | Measured average over 8 years for SW Niger |  | Dress et al., 1993 |
| Dust DEPOSITION | 3.5 | t/ha/yr | Average over last 30 years |  | Chappell et al., 1998 |
| Burkina Faso | 0.5 | coef. | Erosion reduction, alley crop/millet, 2% slope, degraded | 790 | Spaan et al., 2005 |
| Burkina Faso | 0.7 | coef. | Erosion reduction, alley crop/ millet, 2% slope, tillage/weeding | 790 | Spaan et al., 2005 |

more refined environmental accounting assessments in the Sahel.

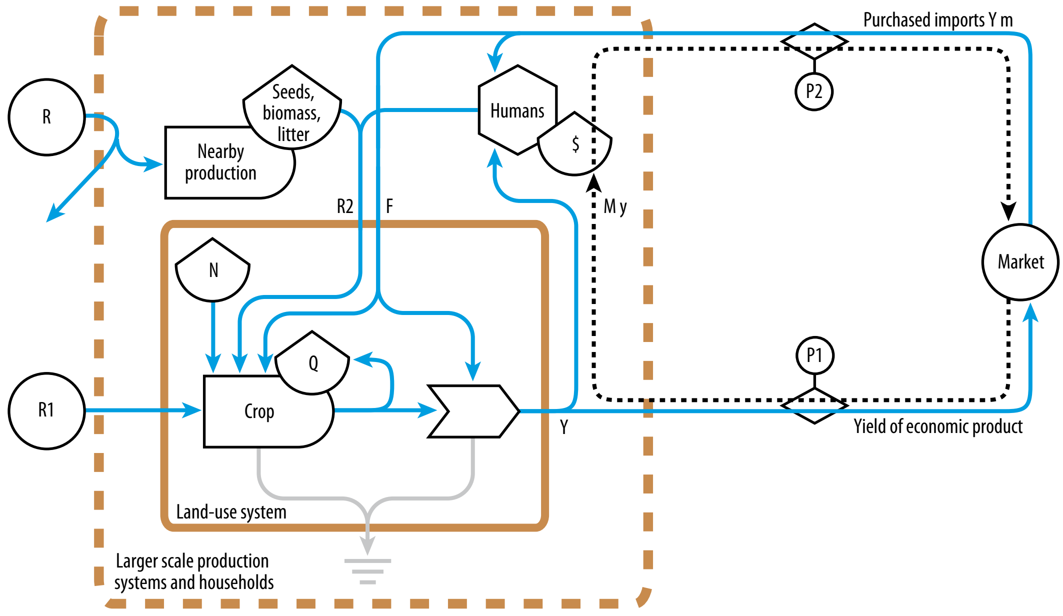
### Summary flows

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 1.1 displays a highly aggregated systems diagram, created and standardized for analyzing Sahelian agricultural production systems. Table 2.2 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). In Figure 2.2, the boundary labelled "Land-use system" represents the system for which the emergy account is created, with inputs coming from four main sources: R1, R2, N, and F. Free, dispersed renewable input is defined as R1, and is the largest renewable environmental flow in the emergy account, typically evapotranspiration. Because several other common system inputs are supported mainly by renewable flows, a second renewable category is defined as R2. This includes flows from nearby areas that are not purchased with money, and may include human and livestock labour, manure, seeds and biomass transfers such as mulch and crop residue. Storages within the system which are subjected to a depletion rate that exceeds replacement rate are defined as non-renewable, and represented as N. In the land-use analysis, N consists of net soil organic matter loss. Purchased inputs from the regional, national or international market are defined as F, and are also classified as non-renewable for the purpose of aggregate emergy flows and indices. Other flows labelled on the diagram are Y, yield of the harvested product; $M_y$, money earned in exchange for the yield; $Y_m$, amount of purchased emergy enabled by the monetary exchange for the yield; and R, the renewable base of R2 flows, not calculated directly in this analysis.

Historically, emergy evaluations and the resulting summary flows and indices have exclusively focused on energy and material flows crossing system boundaries, or used at rates exceeding replacement rates. Because soil condition and land degradation is a major concern in Sahelian land-use systems, it is important also to focus on storages of natural capital within the system, in a similar manner as Lu et al (2006) have done for agro-forest restoration in China. For example, if a given agroforestry intervention results in an increase in soil organic matter, it is important to have system indices that take this benefit into account. The storage Q in Figure 2.2

**FIGURE 2.2**

Summary diagram used to generalize analyses of Sahelian land use systems.
Flows are described in the text and Table 2.3.



represents internal natural capital, and may include measures such as nutrient levels, organic matter, and soil infiltration capacity. Currently, we are examining the literature to establish which natural capital storages can be investigated given the available data.

### Emergy indices for land-use comparison

After the emergy accounts are developed and line item flows are aggregated into summary emergy flows, emergy indices are calculated for land-use comparisons. Table 2.3 lists descriptions and formulas for the emergy indices. The yield ratios (yield divided by purchased feedbacks from the larger system) can be used to evaluate the relative efficiency of crop production processes. The emergy yield ratio (EYR) of each land-use system output is a measure of its net contribution to the economy beyond its own costs of operation. The emergy benefit ratio (EBR) is a similar measure that also includes changes in storage Q in the system yield, allowing changes in natural capital to increase or decrease overall system yield. The emergy exchange ratio (EER) is the ratio of the emergy in the yield to the emergy of the money received for that yield on the market. If this ratio is less than one, the seller is not receiving any benefit in emergy terms. This index is useful for land-use comparison with respect to market benefit to the farmer. The investment ratio (IR) is the ratio of purchased emergy from the economy to the free indigenous emergy inputs. In agricultural systems, this index measures the intensity of the cropping method used, and in comparison with other systems, shows if the land use is a good user of the emergy that is invested from outside. The environmental loading ratio (ELR) is the total non-renewable flow divided by renewable flows. It represents the potential for environmental stress resulting from the import of concentrated materials and the loss of local non-renewables, such as soil, in the production process. The ESI (emergy sustainability index) is the EYR divided by the ELR, with a higher value representing the ability for a system to achieve higher yield ratios versus lower environmental loading ratios (Brown

**TABLE 2.3**

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 |

and Ulgiati, 1997). A higher ESI can be achieved in two ways: by increasing the ability of the land use to exploit locally renewable sources, or by decreasing the need for non-renewable inputs from outside.

### Unit emergy values for land-use products

The process of calculating total emergy inflow to a production system, such as an agricultural land use which produces a crop, allows the calculation of a UEV specific to the yield of that production system. The UEV is defined as the emergy of the yield (Y), divided by the current units of the yield, in this case, grams or joules. When calculated based on joules of yield, the UEV is also referred to as a *transformity*. The emergy of the yield (Y) of the system is defined as the sum of the inputs, or total emergy use, derived from the emergy accounting table. The UEV, in units of solar emjoules per joule (sej/J), represents the sum of previous solar energy required to produce an energy unit of the current product; therefore, it characterizes the efficiency of production from a systems perspective. When comparing products from land-use systems, if less emergy is required to produce a given amount of product (lower UEV), the process is considered more efficient from a systems perspective.

## RESULTS

The set of land uses is shown in Table 2.4, with the cropping method and any soil fertility interventions noted. The unique land-use codes in the first column consist of a two-letter code identifying the crop, followed by an "N" if no soil amendments are added (may have a fallow period), a "C" if chemical fertilizers are the only amendment and an "I" if local soil fertility interventions are applied. Although fallowing may be considered a soil intervention, it is a widespread, traditional element in many Sahelian cropping systems, so the designation "N" is applied in order to contrast fallow-only interventions with more intensive interventions such as use of manure, crop residues, improved fallows and biomass transfers of tree mulch. A few studies use both organic interventions and chemical fertilizers, making this coding system problematic.

### Summary emergy flows

Summary flows for the land-use systems described in Table 2.4 are located in Table 2.5. All flows are reported on an equal area basis (sej/ha/yr). Areas with lower rainfall typically have lower inputs of free environmental emergy (R1), as is the case with the rice land uses and the millet. Local renewable transfers from nearby systems vary, depending on the interventions used. The irrigation inputs to the rice systems and the high manure use in this particular cotton system result in high R2 values from these land uses. Soil erosion is represented by N, and is currently a best estimate based on a table of erosion rates compiled from the literature. These values may change as more erosion data is collected. Purchased inputs are represented by F. High values of F for rice systems are mainly due to chemical fertilizer inputs and the services associated with those inputs. Relatively high values of F also occur in the cotton system and one of the maize systems, again due to fertilizer inputs. Emergy

**TABLE 2.4**

General information for the current set of crops and sites for which emergy analysis has been performed.

| Code | Item | Location | Rain, mm | Method/Intervention | Long | Lat | Primary data source |
|---|---|---|---|---|---|---|---|
| Ct-I1 | Cotton | Mali | 1,000 | no regular fallow, chemical fertilizers and manure | 11 | 8 | Defoer et al, 1998 |
| Mi-N1 | Millet | Burkina | 743 | on farm experiment, no fallow or fertilizer | 12 03° | 1 43° | Bayala et al, 2002 |
| Mi-I1 | Millet | Burkina | 743 | Shea mulch + rock phosphate | 12 03° | 1 43° | Bayala et al, 2002 |
| Mi-I2 | Millet | Burkina | 450 | subsistence farm, manure, no fallow | 14 20° | 0 20° | Krogh, 1997 |
| Ri-C1 | Rice | Senegal | 200 | tractor plowed, pumped water, chemical fertilizer | 16 35° | 15 02° | Wopereis et al, 1999 |
| Ri-C2 | Rice | Mauritania | 250 | gravity irrigated, chemical fertilizer | 12 46° | 16 08° | van Asten et al, 2005 |
| Ma-N1 | Maize | Mali | 851 | traditional fallow, on farm experiment | 12 15° | 5 25° | Kaya and Nair, 2001 |
| Ma-I1 | Maize | Mali | 851 | improved fallow (legume) and rock P, on farm | 12 15° | 5 25° | Kaya and Nair, 2001 |
| Ma-N2 | Maize | Mali | 885 | traditional fallow, on station | 12 15° | 5 25° | Kaya and Nair, 2001 |
| Ma-I2 | Maize | Mali | 885 | traditional fallow + manure, on station | 12 15° | 5 25° | Kaya and Nair, 2001 |
| Ma-C1 | Maize | Mali | 885 | traditional fallow + chem. fertilizer, on station | 12 15° | 5 25° | Kaya and Nair, 2001 |
| Ma-I3 | Maize | Mali | 885 | traditional fallow + biomass transfer, on station | 12 15° | 5 25° | Kaya and Nair, 2001 |

yields (Y) reflect the total amount of emergy use by the system, and are highest for the rice and cotton systems, due to chemical fertilizers, which contain much more emergy than local renewable resources. The lowest values occur in systems with little input other than the free, dispersed environmental inputs, as seen in the millet systems and the traditional fallow maize systems without chemical fertilizer use.

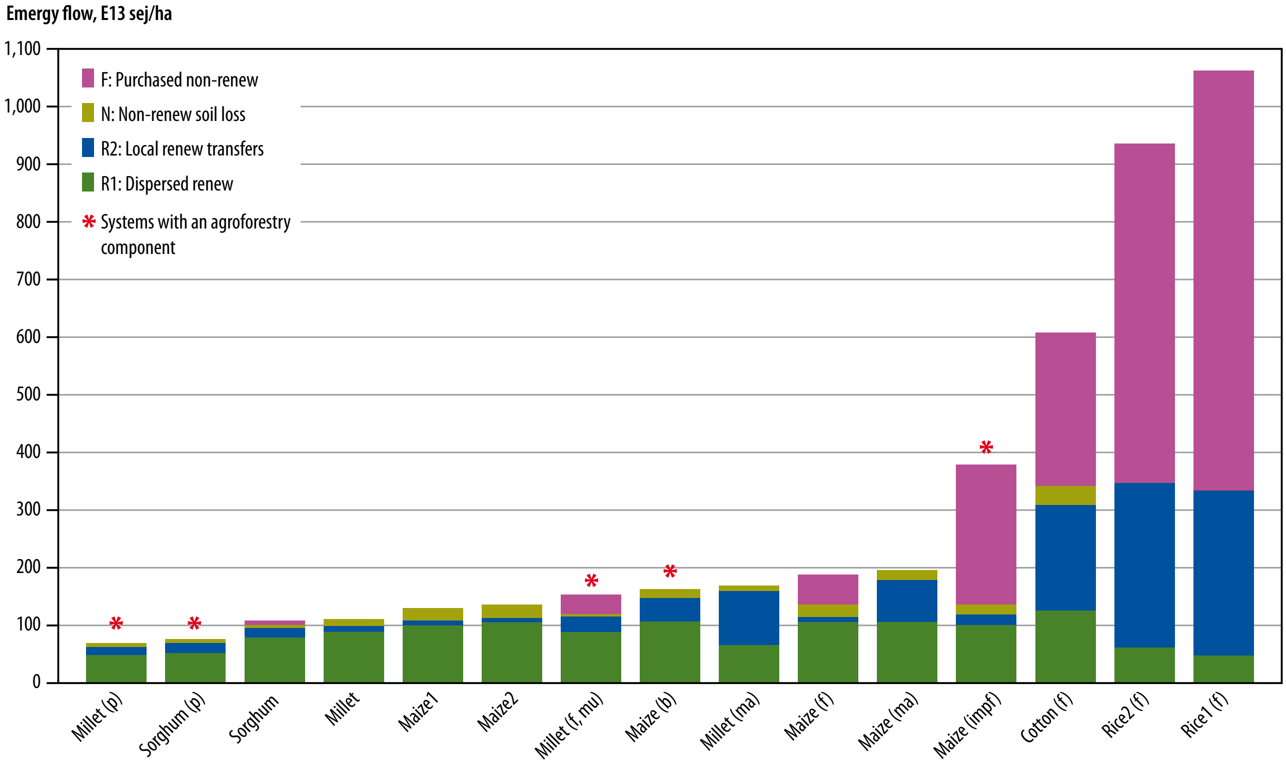
### Emergy indices

Emergy indices denoting various aspects of land-use system processes and condition are shown in Table 2.5. Percent renewable (%R), which is the fraction of total use that is free and locally renewable, is an indication of long-term sustainability, with higher values occurring when system processes are not relying as much on non-renewable flows, such as chemical fertilizers and fossil fuels. Currently, %R only includes free, direct renewable inflow, but may be altered to reflect nearby local renewable resources (R2). The lowest values (less than 30% renewable) occur in the systems employing the greatest amount of chemical fertilizers: cotton, the two rice systems and the improved fallow maize system which uses a relatively large amount of rock phosphate. The highest %R values are found in the systems with little external input: the two traditional fallow maize systems and the millet system with no external inputs.

The emergy yield ratio (EYR) reflects the ability of system processes to exploit local resources. It is the emergy yield (or use) divided by purchased feedback from outside the system; thus, the higher the value, the more the yield is comprised of local emergy. The EYR values for the systems analyzed thus far range from around 2–83. The land-use systems with higher purchased feedback (F) values (rice, cotton, maize with fertilizer, and millet with fertilizer) also all have EYRs less than 5. The rest of the systems do not use chemical fertilizers and all have EYRs greater than 40. It is interesting to note that the two largest EYRs are found in the two systems that only use manure as an amendment. It is important to note that purchased feedback values (the denominator in the EYR) rely on the designation of labour and seeds as purchased or local.

## FIGURE 2.3

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



## TABLE 2.5

Summary of land use subsystems for Sahelian agriculture.

| | | Yield | Summary Flows, E13 sej/ha | | | | | UEV | Emergy Indices | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Code | Item | (kg/ha) | R1 | R2 | N | F | Y | (sej/J) | EER | EYR | %R1 | %R | %Ind | C/D | IR | ELR | ESI |
| Cot | Cotton | 1,602 | 127 | 182 | 323 | 265.1 | 632 | 2.2E+05 | 1.15 | 2 | 0.20 | 0.49 | 0.58 | 2.42 | 0.72 | 1.04 | 2 |
| Ml-t1 | Millet | 194 | 66 | 94 | 12 | 1.7 | 171 | 4.2E+05 | 0.21 | 99 | 0.38 | 0.93 | 0.99 | 1.27 | 0.01 | 0.07 | 1,349 |
| Ml-t2 | Millet | 378 | 89 | 14 | 33 | 1.7 | 136 | 1.7E+05 | 0.53 | 78 | 0.65 | 0.76 | 0.99 | 0.13 | 0.01 | 0.32 | 244 |
| Ml-i1 | Millet | 630 | 89 | 26 | 52 | 29.9 | 167 | 1.3E+05 | 0.71 | 6 | 0.53 | 0.69 | 0.82 | 0.50 | 0.22 | 0.46 | 12 |
| Ml-i2 | Millet | 391 | 89 | 15 | 29 | 1.7 | 132 | 1.1E+05 | 0.56 | 76 | 0.67 | 0.78 | 0.99 | 0.14 | 0.01 | 0.28 | 276 |
| Mi-t3 | Millet | 544 | 59 | 15 | 19 | 4.8 | 94 | 9.1E+04 | 2.08 | 20 | 0.63 | 0.79 | 0.95 | 0.27 | 0.05 | 0.26 | 75 |
| Mi-i3 | Millet | 638 | 59 | 15 | 17 | 4.8 | 91 | 5.3E+04 | 2.49 | 19 | 0.65 | 0.81 | 0.95 | 0.27 | 0.06 | 0.23 | 82 |
| R-t1 | Rice | 5,013 | 49 | 284 | 729 | 729.0 | 1,062 | 1.3E+05 | 1.54 | 1 | 0.05 | 0.31 | 0.31 | 20.67 | 2.19 | 2.19 | 1 |
| R-t2 | Rice | 6,300 | 62 | 284 | 1,760 | 1,759.6 | 2,105 | 2.0E+05 | 6.15 | 1 | 0.03 | 0.16 | 0.16 | 32.95 | 5.09 | 5.09 | 0 |
| S-t1 | Sorghum | 550 | 79 | 15 | 34 | 5.1 | 129 | 1.2E+05 | 0.73 | 25 | 0.61 | 0.73 | 0.96 | 0.19 | 0.04 | 0.36 | 69 |
| S-i1 | Sorghum | 553 | 79 | 15 | 31 | 5.5 | 125 | 9.2E+04 | 0.76 | 23 | 0.64 | 0.76 | 0.96 | 0.20 | 0.05 | 0.32 | 71 |
| S-t2 | Sorghum | 380 | 94 | 16 | 31 | 3.7 | 145 | 2.0E+05 | 0.45 | 40 | 0.65 | 0.76 | 0.97 | 0.15 | 0.03 | 0.29 | 138 |
| S-t3 | Sorghum | 536 | 94 | 16 | 31 | 3.7 | 145 | 1.4E+05 | 0.63 | 40 | 0.65 | 0.76 | 0.97 | 0.15 | 0.03 | 0.29 | 138 |
| S-i2 | Sorghum | 403 | 94 | 15 | 31 | 3.7 | 140 | 1.8E+05 | 0.49 | 38 | 0.67 | 0.78 | 0.97 | 0.15 | 0.03 | 0.28 | 136 |
| S-i3 | Sorghum | 538 | 94 | 19 | 20 | 4.2 | 133 | 9.3E+04 | 0.69 | 32 | 0.70 | 0.85 | 0.96 | 0.21 | 0.03 | 0.18 | 180 |
| MA-t1 | Maize | 238 | 100 | 9 | 21 | 1.3 | 130 | 3.7E+05 | 0.75 | 103 | 0.77 | 0.84 | 0.99 | 0.09 | 0.01 | 0.19 | 538 |
| MA-i1 | Maize | 964 | 100 | 20 | 257 | 241.7 | 377 | 2.6E+05 | 1.05 | 2 | 0.27 | 0.32 | 0.36 | 2.26 | 1.79 | 2.15 | 1 |
| MA-t2 | Maize | 232 | 104 | 9 | 21 | 1.3 | 134 | 3.9E+05 | 0.71 | 106 | 0.77 | 0.84 | 0.99 | 0.09 | 0.01 | 0.18 | 575 |
| MA-t3 | Maize | 531 | 104 | 73 | 19 | 1.3 | 196 | 2.5E+05 | 1.11 | 154 | 0.53 | 0.90 | 0.99 | 0.61 | 0.01 | 0.11 | 1471 |
| MA-i2 | Maize | 709 | 104 | 11 | 74 | 54.1 | 188 | 1.8E+05 | 1.54 | 3 | 0.55 | 0.61 | 0.71 | 0.52 | 0.40 | 0.64 | 5 |
| MA-i3 | Maize | 946 | 104 | 41 | 19 | 3.8 | 165 | 1.2E+05 | 2.35 | 43 | 0.63 | 0.88 | 0.98 | 0.38 | 0.02 | 0.13 | 327 |
| KF-1 | Karite fruit | 25 | 89 | 15 | 29 | 1.7 | 132 | 9.8E+05 | 0.05 | 76 | 0.67 | 0.78 | 0.99 | 0.14 | 0.01 | 0.28 | 276 |
| KF-2 | Karite fruit | 20 | 79 | 15 | 31 | 5.5 | 125 | 4.1E+05 | 0.04 | 23 | 0.64 | 0.76 | 0.96 | 0.20 | 0.05 | 0.32 | 71 |
| KN-1 | Karite nut | 37 | 89 | 15 | 29 | 1.7 | 132 | 3.2E+05 | 0.03 | 76 | 0.67 | 0.78 | 0.99 | 0.14 | 0.01 | 0.28 | 276 |
| KN-2 | Karite nut | 52 | 79 | 15 | 31 | 5.5 | 125 | 2.2E+05 | 0.04 | 23 | 0.64 | 0.76 | 0.96 | 0.20 | 0.05 | 0.32 | 71 |
| NF-1 | Nere fruit | 10 | 89 | 15 | 29 | 1.7 | 132 | 1.2E+06 | 0.07 | 76 | 0.67 | 0.78 | 0.99 | 0.14 | 0.01 | 0.28 | 276 |
| NS-1 | Nere seed | 11 | 89 | 15 | 29 | 1.7 | 132 | 7.4E+05 | 0.02 | 76 | 0.67 | 0.78 | 0.99 | 0.14 | 0.01 | 0.28 | 276 |
| FP-1 | Faid. Pod | 500 | 59 | 15 | 17 | 4.8 | 91 | 3.1E+04 | 2.17 | 19 | 0.65 | 0.81 | 0.95 | 0.27 | 0.06 | 0.23 | 82 |
| W-1 | Wood | 40 | 89 | 15 | 29 | 1.7 | 132 | 1.1E+06 | 0.03 | 76 | 0.67 | 0.78 | 0.99 | 0.14 | 0.01 | 0.28 | 276 |
| W-2 | Wood | 40 | 79 | 15 | 31 | 5.5 | 125 | 7.0E+05 | 0.03 | 23 | 0.64 | 0.76 | 0.96 | 0.20 | 0.05 | 0.32 | 71 |
| W-3 | Wood | 33 | 59 | 15 | 17 | 4.8 | 91 | 4.5E+04 | 0.06 | 19 | 0.65 | 0.81 | 0.95 | 0.27 | 0.06 | 0.23 | 82 |
| W-4 | Wood | 5 | 94 | 19 | 20 | 4.2 | 133 | 7.4E+06 | 0.00 | 32 | 0.70 | 0.85 | 0.96 | 0.21 | 0.03 | 0.18 | 180 |
| Cattle1 | Cattle | 4 | 63 | 0.3 | 13 | 7.6 | 78 | 1.2E+07 | 0.13 | 10 | 0.81 | 0.82 | 0.90 | 0.11 | 0.11 | 0.20 | 51 |
| Cattle2 | Cattle | 3 | 12 | 0.1 | 7 | 1.0 | 39 | 6.5E+06 | 0.21 | 41 | 0.30 | 0.30 | 0.47 | 0.06 | 0.05 | 0.61 | 68 |
| Milk1 | Cow milk | 57 | 63 | 0.3 | 13 | 7.6 | 78 | 3.9E+05 | 0.50 | 10 | 0.81 | 0.82 | 0.90 | 0.11 | 0.11 | 0.20 | 51 |
| Milk2 | Cow milk | 34 | 12 | 0.1 | 7 | 1.0 | 39 | 3.3E+05 | 0.54 | 41 | 0.30 | 0.30 | 0.47 | 0.06 | 0.05 | 0.61 | 68 |
| Manure1 | Manure | 173 | 63 | 0.3 | 13 | 7.6 | 78 | 2.5E+05 | na | 10 | 0.81 | 0.82 | 0.90 | 0.11 | 0.11 | 0.20 | 51 |
| Manure2 | Manure | 83 | 12 | 0.1 | 7 | 1.0 | 39 | 2.6E+05 | na | 41 | 0.30 | 0.30 | 0.47 | 0.06 | 0.05 | 0.61 | 68 |
| Ml-parkKN | Parkland millet | 513 | 89 | 15 | 29 | 1.7 | 132 | na | 0.74 | 76 | 0.67 | 0.78 | 0.99 | 0.14 | 0.01 | 0.28 | 276 |
| SO-parkK | Parkland sorghum | 664 | 79 | 15 | 31 | 5.5 | 125 | na | 0.87 | 23 | 0.64 | 0.76 | 0.96 | 0.20 | 0.05 | 0.32 | 71 |
| Ml-parkF | Parkland millet | 1,170 | 59 | 15 | 17 | 4.8 | 91 | na | 4.73 | 19 | 0.65 | 0.81 | 0.95 | 0.27 | 0.06 | 0.23 | 82 |
| SO-Neem | Alley sorghum | 543 | 94 | 19 | 20 | 4.2 | 133 | na | 0.69 | 32 | 0.70 | 0.85 | 0.96 | 0.21 | 0.03 | 0.18 | 180 |

The environmental loading ratio (ELR) follows a similar pattern to EYR. Systems using a high proportion of non-renewables, such as chemical fertilizers, have higher ELRs. Soil erosion is combined with purchased feedbacks in the numerator, thus systems with relatively higher values for both erosion and purchased inputs have higher ELRs (e.g., maize with rock phosphate). The lowest ELRs are seen in the systems with very few purchased inputs.

The emergy sustainability index (ESI) is the EYR divided by the ELR. Values range from around 1 to 1,500; larger values are considered more sustainable because they maximize yield (EYR) while minimizing load (ELR). Because the component indices of the ESI are strongly affected by purchased inputs (namely chemical fertilizers), the ESI is as well. All systems using chemical fertilizers have ESIs less than 10, while those using other amendments or no amendments have ESIs greater than 180. The millet system using manure only has an extremely high ESI value of 1,519, due to the lowest inputs of non-indigenous resources. Systems with high ESI values are not necessarily efficient or high-yielding, and are generally the opposite in the Sahel region. Rather, having a high ESI means that a system will most likely continue to produce even if subjected to economic shocks, such as global scarcity of fossil fuels or skyrocketing prices of purchased inputs. An overview of land uses by emergy category is shown in Figure 2.3.

### Unit emergy values (UEVs)

Unit emergy values for each system are reported in Table 2.5, and are equal to emergy yield (defined as total emergy use) divided by the energy content of the product. The lowest UEVs are found in the rice systems, due to the relatively high energy yields obtained given the emergy input. Although emergy use is high, the yields are very concentrated in space compared with the other land-use systems (see kg/ha in Table 2.5). The low UEV reflects a relatively efficient use of resources, though many of those resources are non-renewable. The maize system with the biomass transfer of *Gliricidia* cuttings has the next lowest UEV, and the lowest UEV of any of the maize systems studied, suggesting that this intervention may provide the greatest increase in yield for the extra emergy input, compared with the other maize systems. The millet UEVs are in the low, medium and high range, mainly with respect to the crop yields achieved. With a similar level of total emergy input in the various millet systems, lower UEVs occur due to higher crop yields. In addition, the use of shea tree mulch and rock phosphate in Mi-I1 raises the total emergy input, but the increased yield keeps the UEV the lowest of the millet systems. The highest UEVs are seen in the subsistence millet system with manure, and the two maize systems that receive no fertilizers or any other interventions. Even though the total emergy input is among the lowest of all the land-use systems, the yields are low enough to keep the UEVs among the highest of the systems studied so far.

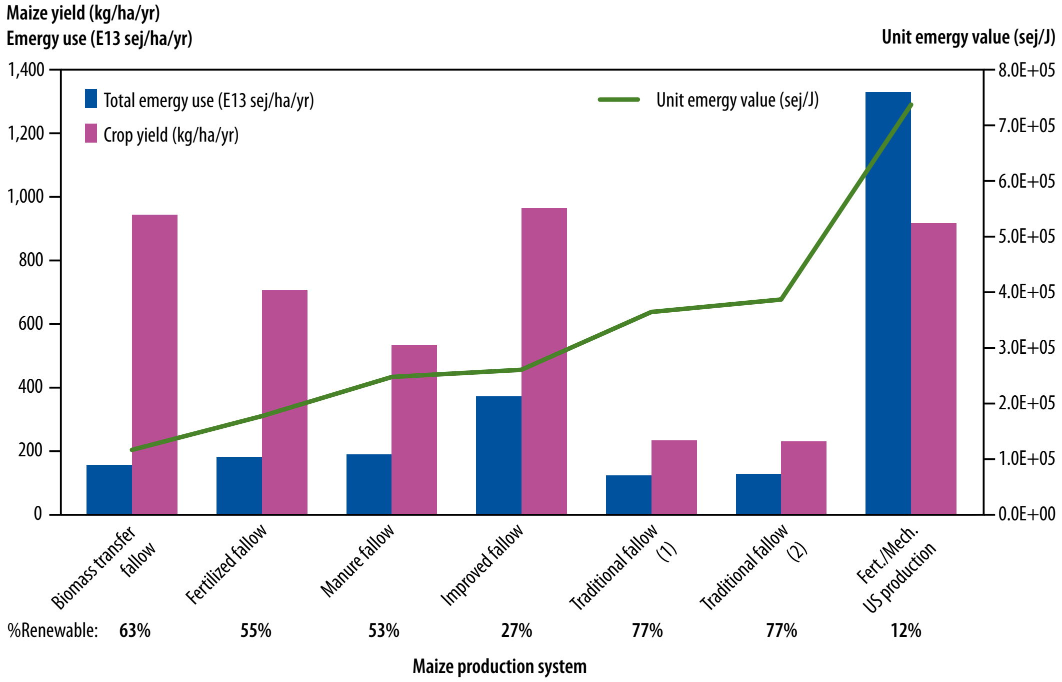
### Comparisons of production systems

A useful technique to evaluate the sustainability of rural agricultural systems is to compare their environmental accounting indices among different local options and with options that have been evaluated elsewhere. Figure 2.4 offers a summary view for the production of maize, comparing six Sahelian systems and a high intensity maize production system in the United States. Shown on the graph are the total crop yields (kg $ha^{-1}$ $yr^{-1}$), emergy use in the system to create that yield, and the resulting unit emergy value. Moreover, the fraction of the resource basis of production from renewable resources is 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. For the Sahelian systems, the lowest UEVs were observed for the non-traditional fallow crops, particularly the biomass transfer fallow system, which produced high yields with low inputs. 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 (e.g., higher land footprint, larger labour requirement per unit yield) that % renewable cannot. In short, the UEV is an excellent measure of system-scale efficiency, and efforts to compare land-use alternatives producing similar goods should include UEV as one of the key metrics.

A similar figure for millet (Figure 2.5) does not include any international comparisons (millet has not been evaluated using modern environmental

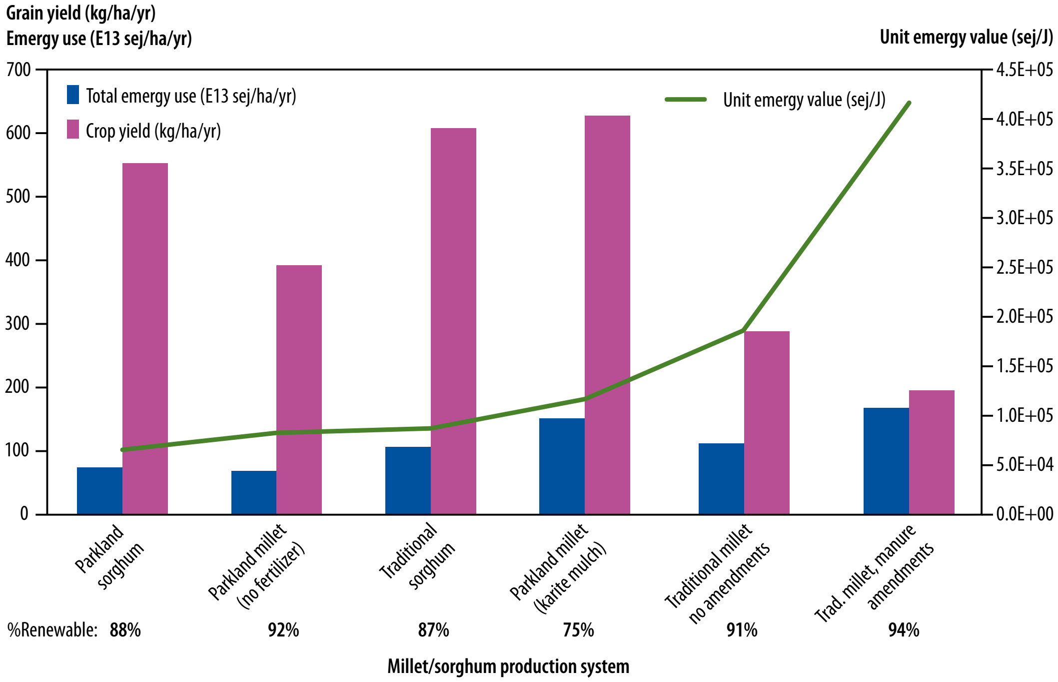
## FIGURE 2.4

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 2.5

Summary of millet 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.



accounting techniques). However, it does show that there are important differences between the various alternative techniques. Of particular note is the observation that Parkland systems (which include the production of tree crops – karite, nere – as a co-product) have the lowest values. Part of the reason for this is that the emergy of labour, soil erosion, rainfall, and other spatially extensive inputs are distributed between the two co-products. This does not discount the result; indeed, it demonstrates that the co-production schemes can be highly beneficial, a topic to which we return below. In short, traditional millet production, wherein there are few amendments, and no co-products, appears to produce millet at higher environmental cost. As before, the use of the % renewable metric can be somewhat misleading; the highest values were observed for the traditional systems (to be expected since they require essentially no exogenous inputs), but low yields make the UEVs for those systems extremely high. Note that, in general, millet is a less emergy intensive crop for this region (UEV ~ 5.0E+04 sej/J for millet vs. 1.0E+05 sej/J for maize).

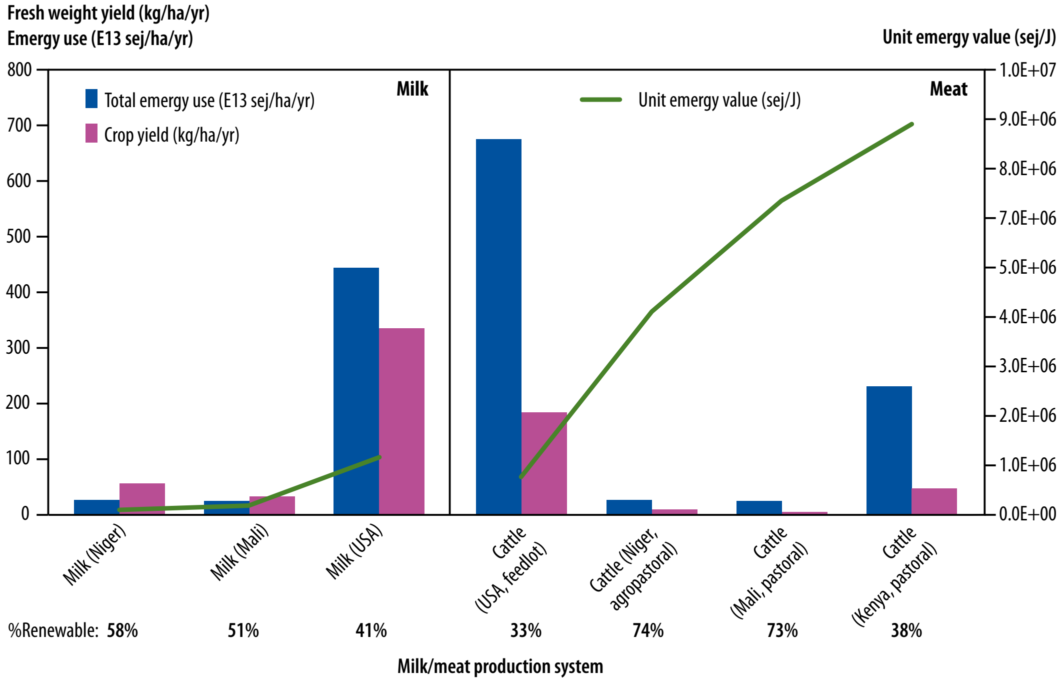
Finally, for the few systems that were analyzed in the Sahel, we report the same comparative information for milk and meat production (Figure 2.6), using both US and Kenyan production systems for comparison. In contrast to the observed patterns for grain production, it appears that US meat production 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 in the Sahel is, with UEVs near 2.0E+05. Notably, the highest UEV for meat production was observed in Kenya.

## 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. While it is not necessarily the case that all transactions should be emergy neutral (EER = 1), comparisons among production

**FIGURE 2.6**

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.



alternatives can often be informative. For the Sahelian agricultural systems that we evaluated, there were three systems for which comparison between agroforest and traditional techniques was possible (one for maize, millet and sorghum). In each case (Figure 2.7) 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.

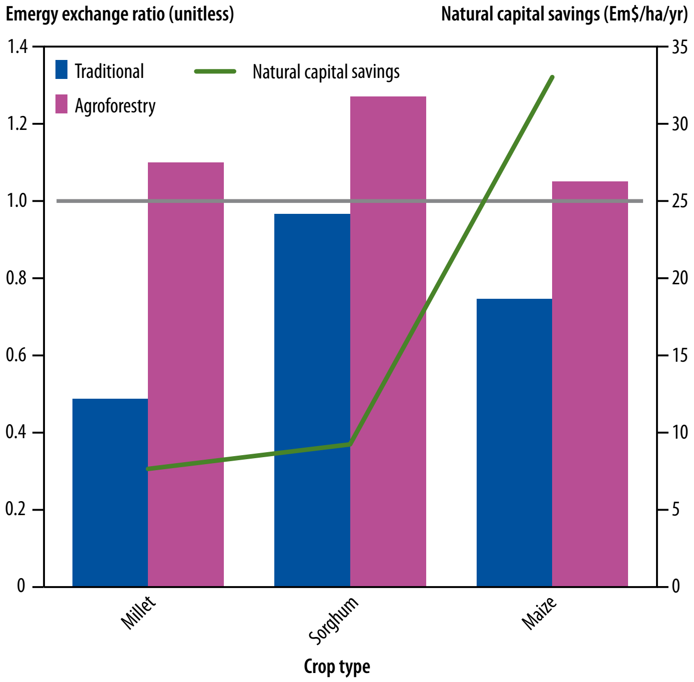
There are two main reasons for this difference. First, the agroforestry operations yield multiple products (karite and neem, specifically) which have high market values, and generally do not compromise grain yields. This means that per unit of emergy input (land and labour), higher emergy yields are 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, as shown by the line in Figure 2.7 that indicates the natural capital savings (in emergy $) of the averted soil loss. This striking result indicates the potential value of perennial inter-cropping, particularly for high-value tree products, and underscores the need for technology extension for tree planting, seedling protection from browsing animals, and better developed markets for the tree crops, both regionally and internationally.

## Erosion scenarios

The natural capital losses associated with soil erosion are hidden from market analyses, but important for global and regional sustainability. As such, there has been a strong emphasis on agricultural production methods that minimize soil erosion. Unfortunately, there are two levels of significant uncertainty when evaluating the soil losses within a systems context. The first is that the actual soil loss rates are highly variable, and obviously the costs of soil erosion are directly proportional to the rates assumed. Indeed, Table 2.2, which summarizes the literature of soil loss rates in the Sahel, illustrates that rates vary over several orders of magnitude, often even within the same agroclimatic zone. To compound this problem, soil loss via water erosion is but one pathway for soil degradation; wind erosion, salinization, compaction, acidification, loss of organic matter, and loss of nutrients (leaching) are all degradation pathways not necessarily captured by estimates of mass loss. A second source of uncertainty derives from the UEV for soil. Typically, UEV estimates have been based

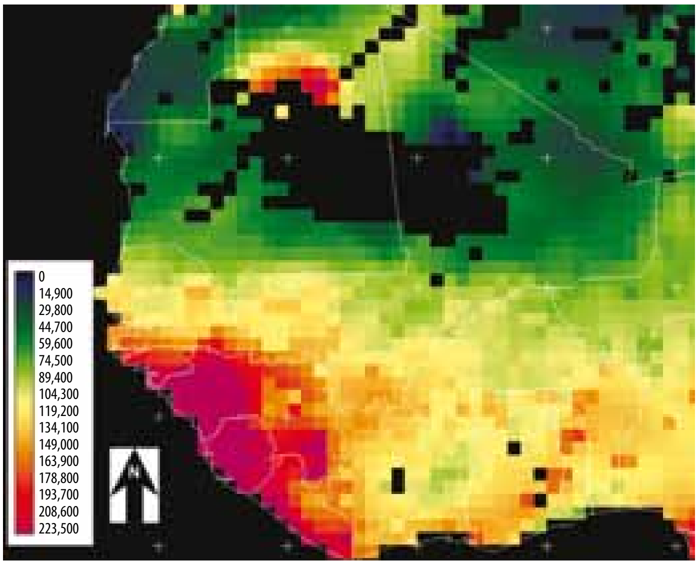
### FIGURE 2.7

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).



### FIGURE 2.8

Unit emergy values for soil loss (after UNEP, 2012b). Using this map, and estimates of soil organic carbon losses with conventional and parkland agricultural systems, we can estimate the regional benefits (c. em$33-131 per hectare per year).



## TABLE 2.6

Erosion scenarios for Millet monocrop and parkland systems. Bold lines indicate the base case.

Monocrop (MI-t2):

| Erosion t/ha | Erosion sej/ha | Total emergy sej/ha | UEV sej/g | EER |
|---|---|---|---|---|
| 6 | 1.3E+14 | 1.2E+15 | 1.5E+05 | 0.60 |
| 8 | 1.8E+14 | 1.2E+15 | 1.6E+05 | 0.58 |
| 10 | 2.2E+14 | 1.3E+15 | 1.6E+05 | 0.56 |
| 12 | 2.7E+14 | 1.3E+15 | 1.7E+05 | 0.54 |
| **14** | **3.1E+14** | **1.4E+15** | **1.7E+05** | **0.53** |
| 16 | 3.6E+14 | 1.4E+15 | 1.8E+05 | 0.51 |
| 18 | 4.0E+14 | 1.5E+15 | 1.8E+05 | 0.49 |
| 20 | 4.5E+14 | 1.5E+15 | 1.9E+05 | 0.48 |
| 22 | 4.9E+14 | 1.5E+15 | 1.9E+05 | 0.46 |

Parkland (MI-parkKN):

| Erosion t/ha | Erosion sej/ha | Total emergy sej/ha | UEV sej/g | EER |
|---|---|---|---|---|
| 4 | 8.3E+13 | 7.2E+14 | 8.7E+04 | 1.11 |
| **6** | **1.2E+14** | **7.6E+14** | **9.3E+04** | **1.08** |
| 8 | 1.7E+14 | 8.0E+14 | 9.8E+04 | 1.05 |
| 10 | 2.1E+14 | 8.4E+14 | 1.0E+05 | 1.02 |
| 12 | 2.5E+14 | 8.8E+14 | 1.1E+05 | 0.99 |
| 14 | 2.9E+14 | 9.3E+14 | 1.1E+05 | 0.97 |
| 16 | 3.3E+14 | 9.7E+14 | 1.2E+05 | 0.94 |
| 18 | 3.7E+14 | 1.0E+15 | 1.2E+05 | 0.92 |
| 20 | 4.2E+14 | 1.1E+15 | 1.3E+05 | 0.9 |

See emergy tables x.x (MI-t2) and x.x (MI-parkKN).

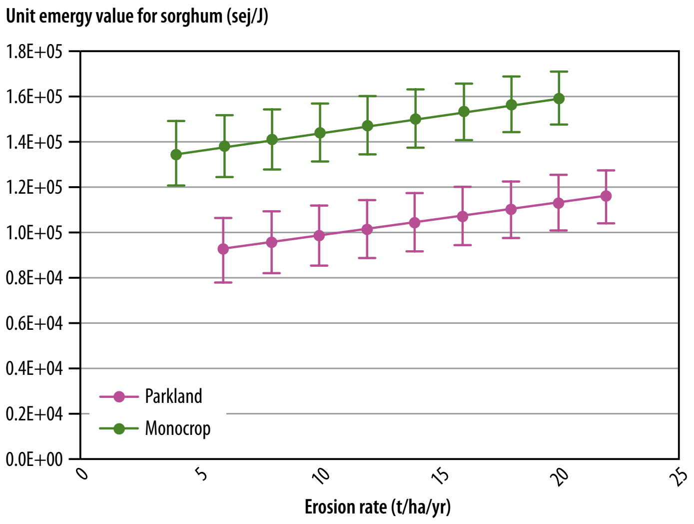
Parkland yields used in EER calculations include tree products.

Erosion rate varies, all other parameters are constant..

on the accumulation of soil organic matter in the temperate zone (Odum, 1996), but UNEP (2012b) report a new technique that permits the estimation of UEVs for all regions of the globe, based on SOM concentrations and input requirements to maintain that quantity in steady state. A summary of that model for the Sahel is depicted in Figure 2.8; it shows that the value of SOM is c. 1.2E5 sej/J for most of the Sahel, which is slightly lower than the global average (2.4E5 sej/J). As per the methods in UNEP (2012b), we estimated the costs of soil erosion based solely on the UEV for soil carbon and the estimated mass loss of that fraction of the soil with erosion. As such, we view the costs inferred here as lower bounds for the actual costs of soil loss.

## FIGURE 2.9

Sensitivity analysis of erosion rate estimates in comparing parkland vs. monocrop methods for the production of sorghum. As shown, even the highest erosion estimate for parkland agriculture yields unit emergy values below those observed for the lowest estimate for monocrop systems.

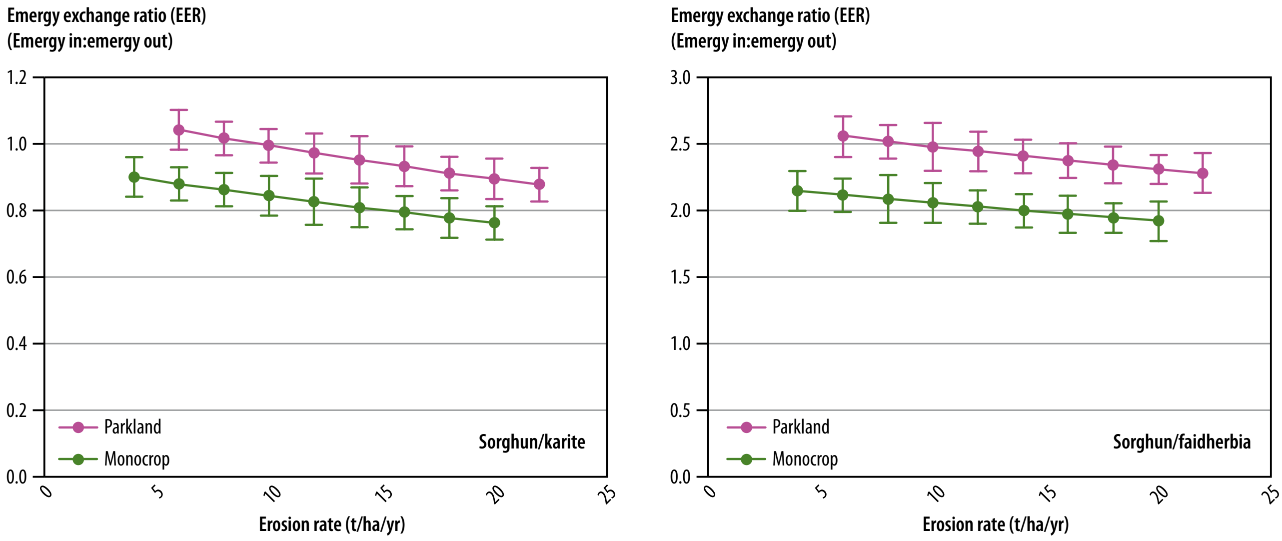


Of particular interest is the value of soil erosion on a land unit basis. We estimate an average of 0.1 to 5 Mg C lost per hectare per year in the Sahel based on Table 2.6, and that Parkland systems avert somewhere between 0.2 and 1 Mg of that SOM loss. The UEV for the region ranges between 0.5 and 1.9E5 sej/J, which, at the national emergy money ratio for Mali (3.4E13 sej/$; UNEP (2012b)), yields an imputed value of SOC retained of between $33 and $130 per hectare per year, an astonishingly high value given the incomes of the region. While there is substantial uncertainty in this estimate, it does underscore the need to consider soil loss when doing whole-system sustainability accounting, and by extension the need to consider the soil loss rates that ensue from land management decisions and regional policies.

Because both assumptions (rates and UEVs) confound any inference about the importance of averting soil loss, we explored the sensitivity of our emergy evaluations to variation in soil loss amounts. In particular, since we were interested in comparing the monocrop traditional grain production schemes with the agroforestry alternatives, we explored the

**FIGURE 2.10**

Sensitivity analysis of erosion rate estimates in comparing parkland vs. monocrop methods for the production of sorghum. The EER for the sorghum/faidherbia system was markedly higher than the system in which sorghum and karite were grown together.



degree to which changing assumptions about soil loss impacted the EER. To do this, we varied the soil loss amounts (without changing yields), and explored the changes in the UEV and EER for the resulting products. Table 2.6 summarizes the results for the comparison of traditional and agroforest millet production. What is clear is that regardless of erosion rates, the Parkland millet is lower UEV and the overall system higher EER; that is, even at the highest erosion rate for the Parkland system, and the lowest rate for the monocrop system, the Parkland system appears to be more ecologically efficient at converting local resources into products.

Similar results were obtained for sorghum for both the UEV (Figure 2.9) and EER (Figure 2.10). In short, while large uncertainties exist in each of the analyses, we conclude that they do not compromise the overall conclusion (that agroforest systems are more ecologically efficient).

## DISCUSSION

The utility of the emergy method can frequently be observed in the comparison among alternatives. For example, we compared the production of grains (maize, millet, sorghum) under conventional and agroforest production schemes, focusing our attention on both mass yields, but also soil erosion and labour allocations. Based on our analyses, Parkland production systems produce yields of both grains and tree products at lower unit emergy values than comparable dedicated lands. In other words, agroforestry in the region appears to have the capacity to improve the balance of trade between rural land users and regional consumers. Moreover, because UEVs are lower, the comparative sustainability of coupled tree-crop land uses is far higher than the non-tree alternative.

This result, though useful, should be considered with some caution as there is a large number of embedded assumptions, derived principally from the paucity of regional data. Large uncertainties in the analysis outputs arise from the comprehensive data requirements of the environmental accounting method, and the comparative costs of data collection. Two areas for which improved data are required are the rates of soil loss, and the labour input requirement for each land use. Based on a sensitivity analysis of outputs to changes in soil erosion inputs, we conclude that even the most dramatic estimates of the differences between parkland agriculture and agriculture without tree co-crops would always favour the tree-based systems. The questions of labour allocation to different land uses (and particularly to the comparison of traditional and agroforestry strategies) is essential to help understand which constraints limit spontaneous

**FIGURE 2.11**

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, based on our analyses.

adoption of some technological improvements thought to be of great potential for improving rural livelihoods. What are the total labour requirements of an agroforest system *vis-à-vis* the traditional system? Are households that are labour limited electing to use the traditional techniques despite knowledge of the potential returns from integrating trees into the production scheme? We can only presume, based on the data limitations inherent in our analyses, that locations where spontaneous adoption of alternative productions strategies is limited, particularly those that involve the use of trees as system co-products, may be labour constrained. Compared with other land-use systems that have been evaluated, Sahelian systems appear to be particularly labour intensive. We infer that labour as a critical resource input requires more systematic analysis.

Comparisons of UEVs between Sahelian production methods and those evaluated elsewhere for the same product suggest that Sahelian systems rely less heavily on non-renewable resource use (including soil loss), and produce the same products for less emergy investment. As such, 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.

This is, perhaps, not surprising. Low-input agriculture relies heavily on environmental services, and less on intensifications thereof that occur with irrigation, fertilization and other forms of more industrialized agriculture. Elsewhere, where land resources are more limiting for rural productivity, low specific yields have necessitated intensification. From our synthesis of the literature, this appears to be less the case in the Sahel, perhaps because dryland agriculture is generally water and nitrogen limited, and land as a resource is more abundant.

For maize production, the lowest UEV (i.e., highest efficiency) was observed for a biomass transfer fallow system. UEVs for conventional dryland agriculture (i.e., those without trees or other subsidies) were higher by a factor of 2–3.

For millet production, agroforest methods were more efficient, followed by techniques that require off-field subsidies (e.g., manure). Traditional rain-fed techniques are less efficient, underscoring the environmental utility of modest efforts to mitigate production limitations of nutrient content and water holding capacity. As population and affluence grow in the region, efficient means to intensify land use may become necessary. 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 with fewer resources; differences of 200–300% are substantial and appear to be robust to 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 2.11 illustrates some 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 (see Figure 2.11a), and catastrophic failures that can accompany large fenced exclosures if even a small part of the exclosure is breached (Figure 2.11b), measures like protecting individual trees (Figure 2.11c; 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 be a major resource benefit, likely far exceeding 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 for years into the future. While it would be useful to understand more fully the constraints on tree planting, our conversations and observations suggest this as a possible avenue for further work.

# References

Achard, F. and M. Banoin, 2003. Fallows, forage production and nutrient transfers by livestock in Niger. Nutrient Cycling in Agroecosystems 65: 183–189.

Bagayoko, M., S.C. Mason, S. Traore and K.M. Eskridge, 1996. Pearl millet/cowpea cropping system yields and soil nutrient levels. African Crop Science Journal 4(4): 453–462.

Bationo, A. and B.R. Ntare, 2000. Rotation and nitrogen fertilizer effects on pearl millet, cowpea and groundnut yield and soil chemical properties in a sandy soil in the semi-arid tropics, West Africa. Journal of Agricultural Science 134, 277–284.

Bayala, J., Z. Teklehaimanot and S. J. Ouedraogo, 2002. Millet production under pruned tree crowns in a parkland system in Burkina Faso. Agroforestry Systems 54: 203–214.

Buerkert, A. and J.P.A. Lamers, 1999. Soil erosion and deposition effects on surface characteristics and pearl millet growth in the West African Sahel. Plant and Soil 215: 239–253.

Bodnar, F., W. Spaan and J. Hulshof, 2006. Ex-post evaluation of erosion control measures in southern Mali. Soil and Tillage Research, in press.

Boffa, J.-M., S. J.-B. Taonda, J.B. Dickey and D.M. Knudson, 2000. Field-scale influence of karite (*Vitellaria paradoxa*) on sorghum production in the Sudan zone of Burkina Faso. Agroforestry Systems 49: 153–175.

Bosma, R.H., M. Bos, S. Kante, D. Kebe and W. Quak, 1999. The promising impact of ley introduction and herd expansion on soil organic matter content in southern Mali. Agricultural Systems 62: 1–15.

Brown, M.T. and S. Ulgiati, 1997. Emergy-based indices and ratios to evaluate sustainability: monitoring economies and technology toward environmentally sound innovation. Ecological Engineering 9: 51–69.

Chappell, A., A. Warren, M.A. Oliver and M. Charlton, 1998a. The utility of Cs-137 for measuring soil redistribution rates in southwest Niger. Geoderma 81: 313–337.

Chappell, A., A. Warren, N. Taylor and M. Charlton, 1998. Soil flux (loss and gain) in Southwestern Niger and its agricultural impact. Land Degradation and Development 9: 295–310.

Cohen, M.J., 2003. Systems evaluation of erosion and erosion control in a tropical watershed. Doctoral dissertation, University of Florida, Gainesville, Florida.

Defoer, T., H. De Groote, T. Hilhorst, S. Kante, A. Budelman, 1998. Participatory action research and quantitative analysis for nutrient management in southern Mali: a fruitful marriage? Agriculture, Ecosystems and Environment 71: 215–228.

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

Donovan C., M.C.S. Wopereis, D. Guindo and B. Nebie, 1999. Soil fertility management in irrigated rice systems in the Sahel and Savanna regions of West Africa Part II. Profitability and risk analysis. Field Crops research 61:147–162.

Gandah, M., J. Bouma, J. Brouwer, P. Hiernaux, N. Van Duivenbooden. Strategies to optimize allocation of limited nutrients to sandy soils of the Sahel: a case study from Niger, west Africa. Agriculture, Ecosystems and Environment 94: 311–319.

Karambiri, H., O. Ribolzi, J. P. Delhoume, J. Ducloux, A. Coudrain-Ribstein and A. Casenave, 2003. Importance of soil surface characteristics on water erosion in a small grazed Sahelian catchment. Hydrological Processes 17: 1495–1507.

Kater, L.J.M., and S. Kante and A. Budelman, 1992. Karite (*Vitellaria paradoxa*) and nere (*Parkia biglobosa*) associated with crops in South Mali. Agroforestry Systems 18: 89–105.

Kater, L., I. Dembele and I. Dicko, 2000. The dynamics of irrigated rice farming in Mali. Managing Africa's Soils No. 12. Russell Press, Nottingham.

Kaya, B. and P.K.R. Nair, 2001. Soil fertility and crop yields under improved-fallow systems in southern Mali. Agroforestry Systems 52: 1–11.

Kaya, B., P.E. Hildebrand and P.K.R. Nair, 2000. Modeling changes in farming systems with the adoption of improved fallows in southern Mali. Agricultural Systems 66:51–68.

Kelly, B.A., J.-M. Bouvet and N. Picard, 2004. Size class distribution and spatial pattern of *Vitellaria paradoxa* in relation to farmers' practices in Mali. Agroforestry Systems 60: 3–11.

Krogh, L., 1997. Field and village nutrient balances in millet cultivation in northern Burkina Faso: a village case study. Journal of Arid Environments 35: 147–159.

Langyintuoa, A.S., J. Lowenberg-DeBoer, M. Faye, D. Lambert, G. Ibro, B. Moussa, A. Kergna, S. Kushwaha, S. Musa and G. Ntoukam, 2003. Cowpea supply and demand in West and Central Africa. Field Crops Research 82: 215–231.

Lu, H-F, D.E. Campbell, Z. Li and H. Rena, 2006. Emergy synthesis of an agro-forest restoration system in lower subtropical China. Ecological Engineering 27: 175–192.

Mando, A., B. Ouattara, A.E. Somado, M.C.S. Wopereis, L. Stroosnijder and H. Breman, 2005. Long-term effects of fallow, tillage and manure application on soil organic matter and nitrogen fractions and on sorghum yield under Sudano-Sahelian conditions. Soil Use and Management 21: 25–31.

Manlay, R.J., A. Ickowicz, D. Masse, C. Feller and D. Richard, 2004. Spatial carbon, nitrogen and phosphorus budget in a village of the West African savanna – II. Element flows and functioning of a mixed-farming system. Agricultural Systems 79: 83–107.

Nelson, R.A., R.A. Cramb, K.M. Menz and M.A. Mamicpic, 1998. Cost-benefit analysis of alternative forms of hedgerow intercropping in the Philippine uplands. Agroforestry Systems 39: 241–262.

Odum, H.T., 1996. Environmental Accounting. John Wiley & sons, Inc., New York.

Odum, H.T., M.T. Brown and S. Brandt-Williams, 2000. Handbook of Emergy Evaluation Folio 1: Introduction and Global Budget. Center for Environmental Policy, University of Florida, Gainesville.

Odum, H. T., and E. C. Odum, 1983. "Energy Analysis Overview of Nations." Working Paper, WP-83-82. Laxenburg, Austria: International Institute of Applied System Analysis. 469 pp.

Powell, J.M. and T.O. Williams. Livestock, nutrient cycling and sustainable agriculture in the West African Sahel, Gatekeeper Series No. SA37. International Institute for Environment and Development, London.

De Rouw, A. and J.-L. Rajot, 2004. Soil organic matter, surface crusting and erosion in Sahelian farming systems based on manuring or fallowing. Agriculture, Ecosystems and Environment 104: 263–276.

Sanou, H., N. Picard, P.N. Lovett, M. Dembele, A. Korbo, D. Diarisso and J.-M. Bouvet, 2006. Phenotypic variation of agromorphological traits of the shea tree, *Vitellaria paradoxa* C.F. Gaertn., in Mali. Genetic Resources and Crop Evolution 53: 145–161.

Schlecht, E., P. Hiernaux, F. Achard and M. D. Turner, 2004. Livestock related nutrient budgets within village territories in western Niger. Nutrient Cycling in Agroecosystems 68: 199–211.

Spaan, W.P., A.F.S. Sikking and W.B. Hoogmoed, 2005. Vegetation barrier and tillage effects on runoff and sediment in an alley crop system on a Luvisol in Burkina Faso. Soil & Tillage Research 83:194–203.

Teklehaimanot, Z., 2004. Exploiting the potential of indigenous agroforestry trees: *Parkia biglobosa* and *Vitellaria paradoxa* in sub-Saharan Africa. Agroforestry Systems 61: 207–220.

Tilander, Y., G. Ouedraogo, and F. Yougma, 1995. Impact of tree coppicing on tree-crop competition in parkland and alley farming systems in semiarid Burkina Faso. Agroforestry Systems 30: 363–378.

Tilander, Y. and M. Bonzi, 1997. Water and nutrient conservation through the use of agroforestry mulches, and sorghum yield response. Plant and soil 197: 219–232.

Traore, K., F. Ganry, R. Oliver and J. Gigou, 2004. Litter Production and Soil Fertility in a *Vitellaria paradoxa* Parkland in a Catena in Southern Mali. Arid Land Research and Management 18: 359–368.

UNEP (2012a). 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.

UNEP (2012b). Environmental Accounting of National Economic Systems: An Analysis of West African Dryland Countries within a Global Context. United Nations Environment Programme, Nairobi.

Van Asten, P.J.A., P.M. van Bodegom, L.M. Mulder and M.J. Kropff, 2005. Effect of straw application on rice yields and nutrient availability on an alkaline and a pH-neutral soil in a Sahelian irrigation scheme. Nutrient Cycling in Agroecosystems 72: 255–266.

Visser, S.M., G. Sterk and D. Karssenberg, 2005. Modelling water erosion in the Sahel: application of a physically based soil erosion model in a gentle sloping environment. Earth Surface Processes and Landforms 30: 1547–1566.

Warren, A., H. Osbahr, S. Batterbury and A. Chappell, 2003. Indigenous views of soil erosion at Fandou Beri, southwestern Niger. Geoderma 111: 439–456.

Wopereis, M.C.S., C. Donovan, B. Nebie, D. Guindo and M.K. N'Diaye, 1999. Soil fertility management in irrigated rice systems in the Sahel and Savanna regions of West Africa Part I. Agronomic analysis. Field Crops Research 61: 125–145.

Zougmore R., A. Mando, L. Stroosnijder and E. Ouedraogo, 2004. Economic benefits of combining soil and water conservation measures with nutrient management in semiarid Burkina Faso. Nutrient Cycling in Agroecosystems 70: 261–269.

CHAPTER 3

# Ecosystem services and household asset wealth in rural Mali

## INTRODUCTION

The importance of ecosystem services for supporting human livelihood is often assumed, yet the effect of marginal changes in the provisioning of ecosystem services due to land and water degradation on human well-being is rarely explicitly and systematically demonstrated. Ecosystem services include the goods produced by the environment (i.e., food, fresh water, fuel wood, fibre, biochemicals and genetic resources), the results of environmental processes (i.e., climate regulation, disease regulation, flood regulation and detoxification), cultural benefits (such as spiritual, recreational, aesthetic, educational, communal and symbolic) and supportive services (i.e., soil formation, nutrient cycling and primary production) (Millennium Ecosystem Assessment, 2005; as cited by Mainka, 2008). Services such as atmospheric gas regulation and pollination and the natural capital these services provide are considered to be without substitute and essential to human life and well-being (Costanza et al, 1997).

Ecosystem services can degrade in response to over-use or mismanagement. The relationship between many of these ecosystem services and degradation can be directly measured and clearly understood, such as the effect of riparian deforestation on pollutant processing (Sweeney et al, 2004) and even valued (Costanza et al, 1997). Similarly, the relationship between soil degradation and global food security has been described (Pimentel et al, 1995; Lal, 2009), yet the degree to which soil degradation affects people's ability to sustain their livelihoods when resource substitutes may be available is more ambiguous.

Recent literature indicates development in our understanding of the relationship between poverty in its many forms and various types of environmental degradation. Reardon and Vosti (1995) developed a theoretical framework for the issues that such studies must address in order properly to analyze this relationship, including recognizing both the type of poverty and which natural resources are valued by the community in question.

The empirical studies themselves present conflicting pictures on the nature of the environment-poverty link. Ravnborg (2003) correlates poverty rankings to five natural resource management practices thought to increase environmental degradation (agricultural burning, use of herbicides and pesticides, cutting and selling of firewood, irrigation, and lack of erosion control), concluding that poverty was not a major cause of environmental degradation in the Nicaraguan hillside communities studied. Likewise in Honduras, Ravnborg (2002) concludes that household poverty does not influence soil degradation as measured by soil management strategy and household-observed and -described soil quality. In Peru, Swinton and Quiroz (2003) conclude that while a link between agricultural practices and natural resource sustainability exists, natural capital reduction and poverty were not clearly coupled, with the exception of deforestation. Gray (2004) found in Burkina Faso that poor and wealthy households have different farming practices and concluded that the intensification of wealthier farmers has a higher environmental impact (defined by lower measured soil fertility), which she attributes primarily to poorer farmers not being able to afford animal traction. Bahamondes (2003) found that rising incomes (largely due to an increase in off-farm labour), combined with an increased investment by the government in conservation and development programs in central Chilean communities, have resulted in more investment in farming technologies and a recovery of the vegetative cover, despite increasing livestock herd sizes. Moseley (2005) found no significant relationship between household wealth status and measured soil quality in cotton farms of southern Mali.

Developing the relationship between environmental services and human livelihood is confounded by societies' reliance on fossil energy and the availability of resource substitutes in a global economy which can buffer the effects of the loss of environmental services. In the rural Sahel region of Africa where most people depend on subsistence agriculture, it can be hypothesized that the availability of local ecosystem products (namely food, water and forest products) are directly linked to human survival and well-being.

We assume that reliance on ecosystem services is most pronounced among the rural poor that depend directly on their local environment; rural Mali was chosen as the study region because of well-publicized effects (UNDP, 2007) of climate and soil variability on rural production capacity. Mali is a dryland nation, or a nation composed of arid, semi-arid or dry sub-humid areas where the ratio of precipitation to potential evapotranspiration is less than 0.65 (UNDP, 2007). It is one of the poorest nations in the world, ranking 173rd out of 177 nations according to the Human Development Index (UNDP, 2008). Approximately 70% of Mali's population lives in rural areas (UNDP, 2008). Sixty-five percent of Mali is desert or semi-desert and only 3.8% of the land is arable (Library of Congress Federal Research Division, 2005).

## Well-being

There are many components of poverty, including a lack of the basic materials for a good life, poor health, poor social relations, insecurity and poor freedom of choice and action (MEA, 2005). In rural Mali, many people struggle or fall short of meeting their basic needs of food and shelter. Additionally, in rural subsistence farming areas, such as Mali, households with lower cash savings and earnings may not necessarily be poorer but just less engaged in the formal economy (Gray and Moseley, 2005). Therefore, we focused our attention on asset poverty.

Asset-based poverty measures involve creating a metric or index which weights each asset by its relative importance in the poverty or well-being status of the household. Assets can be weighted in various ways, including by price, to create a metric of total capital value (Takasaki et al, 2000), or by statistically derived weights determined by data reduction techniques such as principal component analysis (Filmer and Pritchett, 2001), factor analysis (Sahn and Stifel, 2000) or multiple correspondence analysis (Booysen et al, 2008).

Shimeles and Thoenen (2005) point out that asset-based measures depict relative poverty and not absolute poverty. However, Von Maltzahn and Durrheim (2008) tested the relationship between income-based and asset-based measures of household wealth and found a high correlation between household income and asset-estimated wealth in four of the five African nations studied (South Africa, Namibia, Swaziland and Zambia) with a lower but significant correlation found between the two measures in the fifth nation (Lesotho).

It should be noted that the relationship between household structure, household production capacity and household well-being is complex and varies even within ethnic regions. Household size, cultural norms, and differential access to markets and resources confound a simple assessment of well-being and must be accounted for in any comparative analysis. Additionally, Booysen et al (2008) found in their study that the asset indices used did not closely track short- or medium-term changes in income or expenditure, and are therefore more appropriate for interpreting long-term variability in welfare.

### Ecosystem services

One way to measure the extent to which an area can provide ecosystem services is to assess the degree of environmental degradation. For example, Cairns and Pratt (1995) discuss how landscapes with lower ecological condition provide ecosystem services of a poorer quality.

Ecosystem services can degrade due to anthropogenic effects on land, water and biodiversity. Models of biodiversity loss are predicted to decrease disease control (Ostfeld and LoGiudice, 2003) and deforestation has been empirically linked to decreases in ecosystem services such as nutrient cycling and the water quality protection (Sweeney et al, 2004).

Measuring ecosystem service delivery as it relates to differential environmental degradation is not always direct. Degradation itself is a broad concept for which there is no one clear metric. For the purpose of exploring the influence of environmental condition on human livelihoods in rural Mali, perhaps the most useful metric of degradation is the loss of the service of primary production, since that process is the foundation of rural livelihoods, providing food, fuel, browse for animals and fibre; as such, the loss of primary production capacity can be substantively linked with multiple aspects of rural livelihood. Moreover, the capacity of the landscape to generate primary productivity can be estimated at relatively high spatial and temporal resolution using remote-sensing tools. In an environmental setting like the Sahel, where there are strong rainfall gradients, in this case with increased rainfall from north to south, which profoundly affect primary production, inference of landscape productivity (e.g., via metrics like the normalized difference vegetation index – NDVI) needs to be conditioned on the amount of rainfall. UNEP (2012) developed regional maps of rain use efficiency (RUE) by estimating 10-day incremental (i.e., not annual biomass production, a key refinement for land used for animal grazing) biomass production (using time series of NDVI) per unit of rainfall. The resulting rain-normalized NDVI (RNNDVI) measures how effectively an area utilizes incident rainfall to yield biomass; as such, it is independent of rainfall amount, which can serve as an additional predictor of rural livelihood.

The multiple pathways of land degradation (e.g., loss of soil carbon, salinization, nutrient depletion) have the relatively consistent end-point of reduced capacity to produce biomass. As such, we use RNNDVI as a proxy for land degradation, and explore temporal trends in that quantity as a measure of the systematic directionality of land degradation. In this way we consider ecosystem services in three ways: the first are boundary flows (e.g., rainfall), which are critical for rain-fed agriculture, and constrain the kinds of livelihood activities that can be pursued in a given area. The second is the mean RNNDVI, which provides insight into the time-averaged capacity of a particular location to create biomass per unit of rainfall. Where rainfall is a large-scale organizing variable constraining what land-use decisions can be made in a particular region, the RNNDVI measures local-scale variability in productive capacity. Finally, trends in RNNDVI over time provide a measure of the directionality of land degradation; lands where the trends is upwards can be considered to be managed more effectively, whereas places where the trend is downwards suggest areas where poor management or low productive capacity necessitate unsustainable exploitation. Incorporation of three scales (spatial and temporal) of ecosystem services provides a unique opportunity to comparatively evaluate what controls the provision of rural livelihoods.

## OBJECTIVE

There is limited information available regarding the consequences of changes in ecosystem services for human well-being relative to social, cultural and economic factors (MEA, 2005). Many questions remain regarding the degree and shape of the relationship between poverty and environmental condition, and, further, the extent to which this link changes with variation in economic development. Nowhere are these questions more important than in sub-Saharan Africa, the only part of the world which has not seen steady improvement in human well-being over the last 30 years (UNDP, 2006; as cited by Mainka, 2008), and has seen a contemporaneous increase in environmental resource pressures from population growth.

The primary objective of this research is to formally test the hypothesis that the quality and availability of environmental services is empirically linked to human well-being. While this hypothesis has been the subject of considerable conjecture (Reardon and Vosti, 1995; de Oliveira et al, 2003; Lufumpa, 2005), it has been difficult to test directly because of issues of scale (i.e., at what scale are well-being and environmental condition most relevantly measured?), questions of definition and detection (i.e., what constitutes a degraded environment, and how is it measured?), and the variety of attributes that complicate any associations (e.g., the effect of market integration, historical contingencies). Coupling a comprehensive observational study of rural household well-being and a remote-sensing approach to the regional assessment of land degradation, and controlling for a suite of well-known geographic, ethnic and social confounders, we test the specific hypotheses that 1) variability in ecosystem services (measured using rainfall, RNNDVI, and RNNDVI trends) impacts rural wealth, and 2) the relationship between ecosystem condition and human well-being is strongest among the poorest households.

## METHODS

### Site description

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 (Coulibaly, 2003) just south of the Sahara Desert. The rainy season (and the only growing season) starts in mid-June with a peak in July and early August, and with the last rains falling in late August or early September. Annual rainfall ranges from approximately 400–800 mm with a mean temperature of 29° C (monthly means range from 21–36° C; Takimoto et al, 2007).

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. There are many ethnicities represented in the Segou region, the dominant of which is the Bambara. Some ethnic groups are known for specific livelihood strategies, such as the traditionally pastoral nomadic Peuls, the fishing Bozo tribe and the Griots who are known as historians and storytellers.

### The Malian household

Villages are controlled by a village chief who is elected by the village elders upon the death of the previous chief. The village land is owned by the commune (a unit of management within the region), but designated to the village chief for appropriation. While there is no legal land tenure within villages, there are few examples of chiefs reclaiming land that has already been distributed to a family. Therefore, land tenure is relatively secure with families having control over their fields for many generations. If a household requires more land than it has, the chief will assign a new plot to be cleared and that land now effectively belongs to the household. Also, often households will borrow unused parts of the fields of other households, sometimes for many years. However, rights to the land remain with the original landholder.

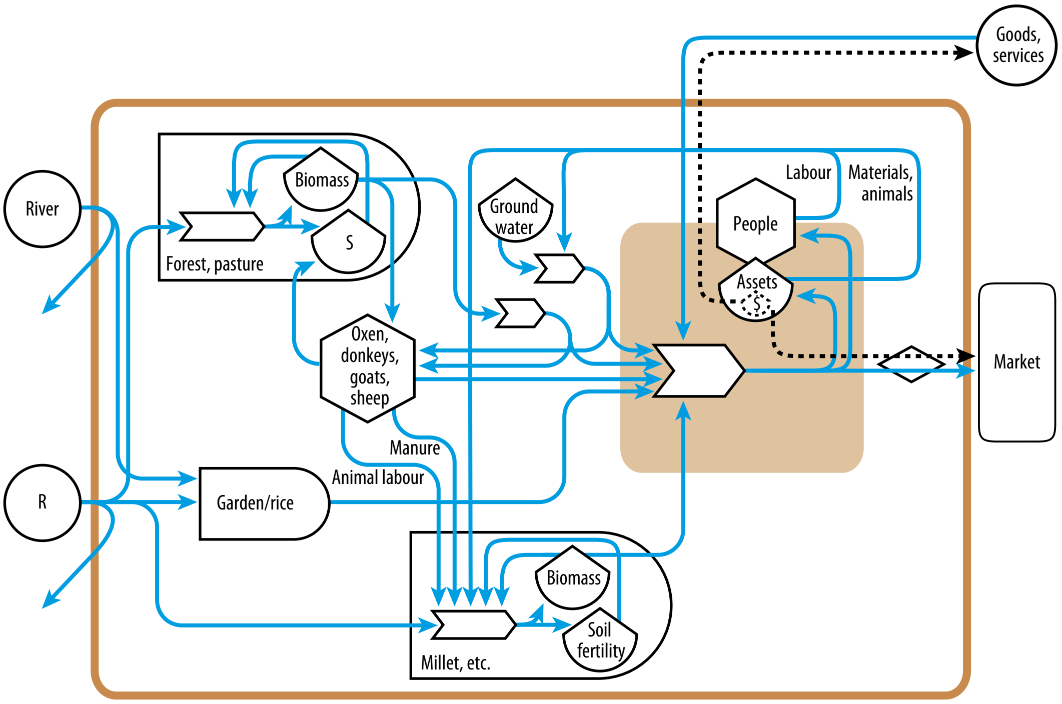
The Malian household is defined by the group of people who eat from the same stock of grains. It is made up of a male head of household, his wives and children, as well as nuclear households consisting of his married sons or brothers. When the head of household dies, leadership passes to his oldest married brother or son. If there are no brothers or sons of an appropriate age, his first wife may become head of household, but usually the wives will move back to their parental households with their children, as without an adult male they do not have enough labour to support fields.

Malian households have a primary field for millet or sorghum which is their main consumption field, and also may have secondary fields. In both their primary field and their secondary fields, millet or sorghum is often intercropped with groundnuts, maize and cowpeas. Labour and inputs are allocated to the primary field first as this is the principal harvest. In some households, harvest from the secondary fields is combined with that from the primary field and all meals and purchases are shared. In other households, married men each have a secondary field from which their family makes supplementary meals and sells off portions of the harvest to purchase needs for that nuclear family. Figure 3.1 below is a diagram of resource and energy flows in a typical Malian household.

As the diagram shows, the household economy is fueled 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; though they are generally corralled within the household compound during the evening if they are not left with a pastoralist for the season.

**FIGURE 3.1**

Systems diagram of a Malian household.



Manure deposited in 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.

## Data collection

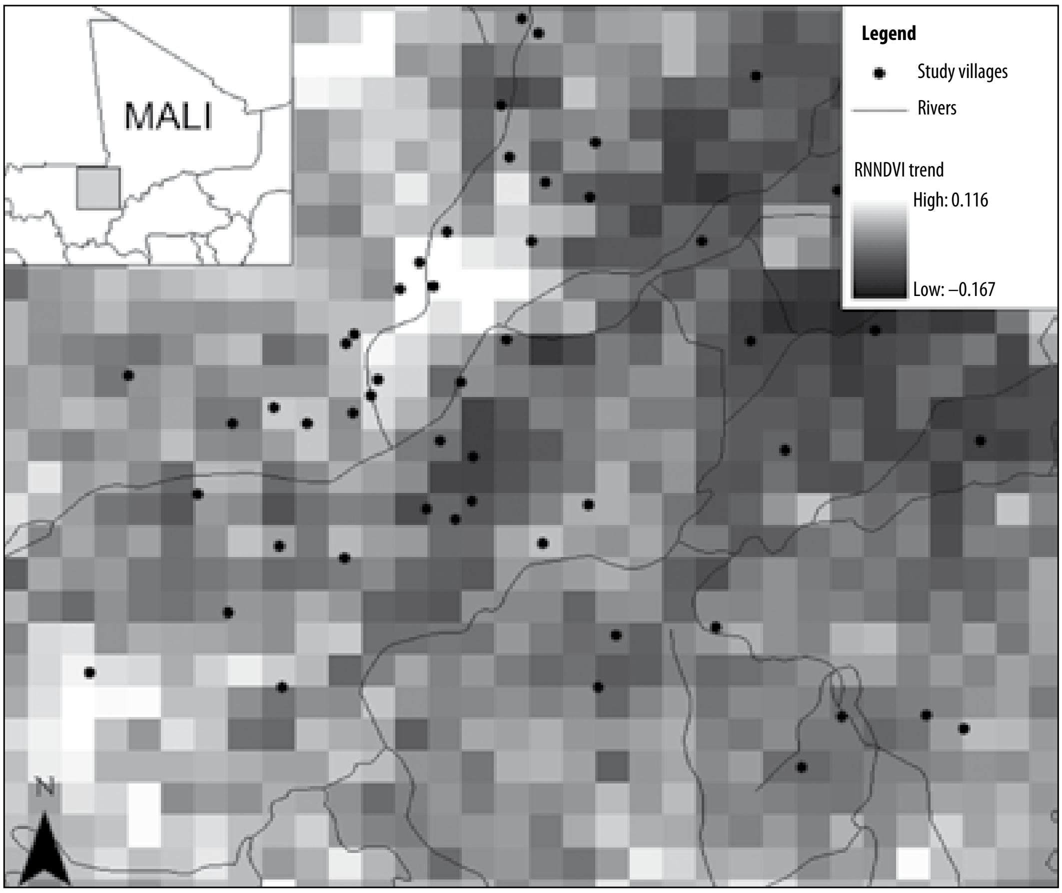
### *Metrics of land degradation*

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 – 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 between 1982 and 2006 was calculated from both ground station data and satellite imagery to create a grid map with a resolution of 8 x 8 km.

RNNDVI was calculated for the Sahel region per pixel (8 x 8 km resolution) using Advanced Very High Resolution Radiometer (AVHRR) derived NDVI from 1982–2006. The RNNDVI calculation uses an incremental Net Primary Production (NPP)-index (which is the difference in NDVI between current and previous 10-day period) adjusted for the effect of bare soil and summed over the year as a proxy for NPP in order to incorporate the effects of heavy rotational grazing on vegetation across large swaths of the Sahel. The average annual RNNDVI is the mean of the annual incremental sums between 1982 and 2006. The RNNDVI Trend is calculated as the normalized z-score slope of the annual RNNDVI measures from 1982–2006. In this scheme, a negative 24-year RNNDVI Trend indicates decreasing environmental water use efficiency, and a positive

**FIGURE 3.2**

Selected study villages displayed on a map of RNNDVI Trends.



trend suggests increasing environmental capacity to use water. Therefore, RNNDVI Trend is a proxy for environmental degradation.

### *Site selection*

Data for this study were collected in 2006 and 2007. Seventy-seven villages were selected using a stratified random selection technique based on the degree of environmental degradation as defined by RNNDVI Trend (Figure 3.2), 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. Details of the selected villages can be found in Appendix A.

### *Well-being*

In each selected village, all households were asked to participate in a well-being assessment. Well-being indices are traditionally based on total expenditure on consumption or total income over some time period (Ravallion, 1996). However, in areas such as rural Mali, most of a household's consumption comes from subsistence production and labour paid in non- market goods. As such, monetary flow may be limited or even non-existent in these households, requiring that relative well-being be estimated based directly on use and accumulation of household assets such as land, livestock holdings and goods as opposed to financial measures.

The well-being assessment used for this study was created based on a socio-economic study in the Segou region which took place between 1973 and 2005, in which 13 villages were asked to identify and rank assets which are indicators of wealth and identify limits of ownership which differentiate poor, moderate and wealthy households (World Agroforestry Center, 2006). We synthesized the rankings from these 13 villages into 34 asset indicators of well-being. Data were collected from households by counting the quantity of each asset

## TABLE 3.1

Asset indicators used to calculate household total capital value. The CFA franc (fCFA – the currency of Mali) has a fixed exchange rate to the euro. One Euro equals 656 fCFA.

| Rank | Indicator | 2007 Price | Rank | Indicator | 2007 Price |
|---|---|---|---|---|---|
| 1 | wife | 229* | 18 | house with metal roof | 1,680 |
| 2 | field | 0† | 19 | personal water well | 272‡ |
| 3 | axe/hoe etc. | 2.2 | 20 | radio | 15.2 |
| 4 | chicken/poultry | 3.3 | 21 | tv | 137 |
| 5 | goats (not for selling) | 19.1 | 22 | orchard | 183‡ |
| 6 | sheep (not for selling) | 55.9 | 23 | store | 183‡ |
| 7 | oxen | 318 | 24 | mill/shelling machine | 1,800 |
| 8 | plow | 44.5 | 25 | Fenced area for animals | 183‡ |
| 9 | donkey | 73.7 | 26 | Fattened goats | 46.2 |
| 10 | cart | 114.3 | 27 | Fattened sheep | 70.0 |
| 11 | grain house | 15.2‡ | 28 | town house | 12,070 |
| 12 | bicycle | 48.3 | 29 | employee | 183‡ |
| 13 | second wife | 229* | 30 | bank account | 0 |
| 14 | cow | 216 | 31 | tractor | 6097 |
| 15 | seeder | 47 | 32 | truck | 15,244 |
| 16 | small motorbike | 49.5 | 33 | pilgrimage to Mecca | -§ |
| 17 | large motorbike | 419 | | | |

* Minimum dowry gifts

† Rural land is borrowed from the village chief, not privately owned

‡ Based on price of labour required (material assets are not purchased)

§ No households had taken a pilgrimage

indicator that a household possessed. A total of 2,756 households within the 77 villages (Figure 3.2) were surveyed.

Table 3.1 presents this asset list and their prices, which were used to calculate a well-being index hereafter called household total capital value. Some of the 34 assets indicators, or well-being creation factors, identified do not have a market value; therefore these assets were not included in the tabulation. The total capital value of a household is the sum product of the asset prices and the actual number of that asset owned (i.e., not simply presence/absence of the asset). Asset prices were determined by taking the average of the price from three different markets in the Segou region. This method is unique as previous studies primarily use a binary or categorical response of asset ownership to derive a well-being index.

## TABLE 3.2

Descriptive statistics for predictor variables. Distance to open water and distance to market are in decimal degrees. Average annual rainfall is in millimeters per year.

| Variable | Min | Max | Mean | Standard Deviation | Variance |
|---|---|---|---|---|---|
| Number of People in Household | 1 | 121 | 17 | 13 | 170 |
| Married Men Per Person in the Household | 0.023 | 1 | 0.152 | 0.079 | 0.006 |
| Number of Households in the Village | 6 | 200 | 76 | 50 | 2,529 |
| Distance to Open Water | 0 | 0.531 | 0.119 | 0.096 | 0.009 |
| Distance to a Market | 0 | 0.300 | 0.090 | 0.073 | 0.005 |
| Average RNNDVI | 0.067 | 0.178 | 0.103 | 0.023 | 0.001 |
| RNNDVI Trend | -0.084 | 0.060 | -0.019 | 0.026 | 0.001 |
| Average Annual Rainfall | 383 | 739 | 579 | 92 | 8,481 |

### Analysis

We used a hierarchical Generalized Linear Model (GLM; Gelman and Hill, 2007) to predict household well-being based on measures of environmental degradation and direct inputs of environmental services, and controlling for geographical and cultural factors that might confound the relationship. At the village scale, these variables include the metrics of environmental services discussed above as well as their first order interactions, distance to open water (to represent access to alternative natural resources and transportation), distance to a market and size of the village (both to represent economic opportunities). First order interaction terms between the metrics of environmental services were also included to determine the relative importance of a metric along a gradient of one of the others. In addition, household ethnicity (as reported by the household regardless of linguistic similarities), household size and married men per person (a proxy for household demographics representing how extended the household unit is) are included as household characteristics potentially impacting livelihood strategies and opportunities, and therefore well-being. Descriptive statistics for the predictor variables can be found in Table 3.2. All values (other than ethnicity, which is a categorical variable) were divided by the variable mean to standardize the variance of the variables. The GLM was also run using only the upper quartile and only the lower quartile of total capital values in each village to test the hypothesis that the relationship between environmental condition and well-being is stronger among the poorest households.

## RESULTS

### Metrics of land degradation

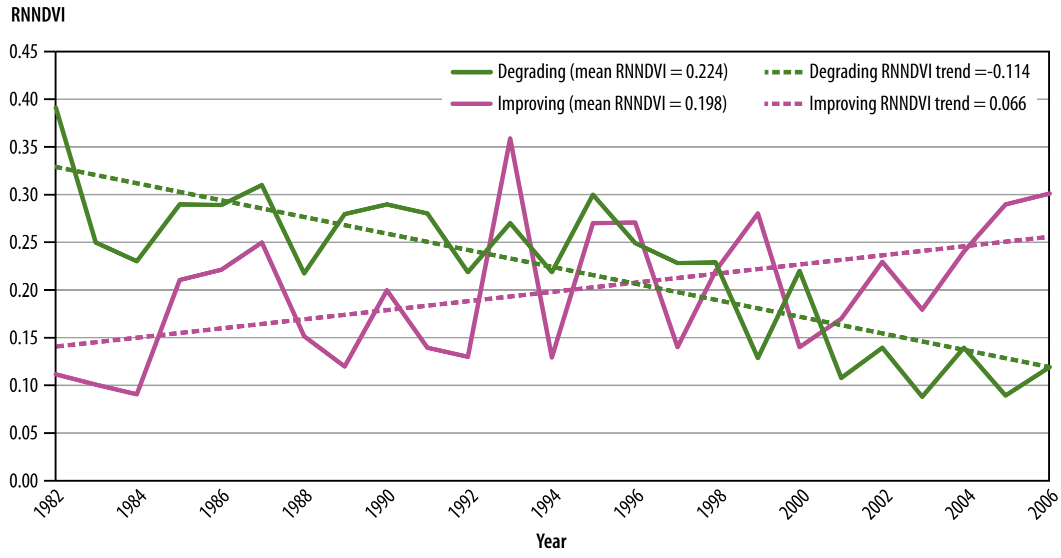
Figure 3.3 shows the annual RNNDVI (which ranges approximately from 0–2.5) for two pixels in the region, one degrading (negative RNNDVI Trend) and one improving (positive RNNDVI Trend) and how theses annual values are translated into the RNNDVI Trend (which ranges approximately from -0.17–0.12). Figure 3.4 shows the distribution of values of average RNNDVI (a) and RNNDVI Trend (b) for the selected villages relative to the distribution of these values for all villages in the Segou region.

### Total capital value

The individual asset prices are strongly associated with the villager asset rankings from the previous wealth study (World Agroforestry Center, 2006) $R^2 = .391$; Figure 3.5), indicating that the villagers' perceived value of assets coincided with the assets' economic value and verifying price as an appropriate weight of an asset's contribution to household well-being. Discrepancies between asset prices and asset rankings may reflect social and market changes which have occurred since the villager rankings were first developed in 1973. For example, a radio was ranked 21 by villagers but has a low monetary

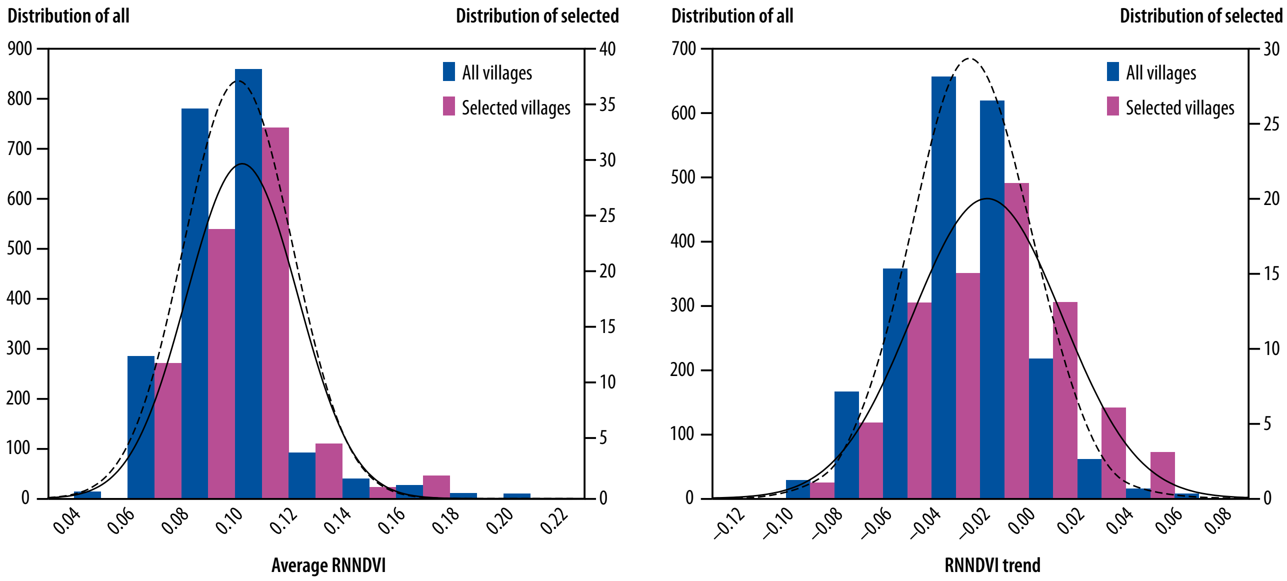
**FIGURE 3.3**

Annual RNNDVI values and 24-year RNNDVI Trend for two land parcels, one with an improving (positive RNNDVI Trend) and one degrading (negative RNNDVI Trend).



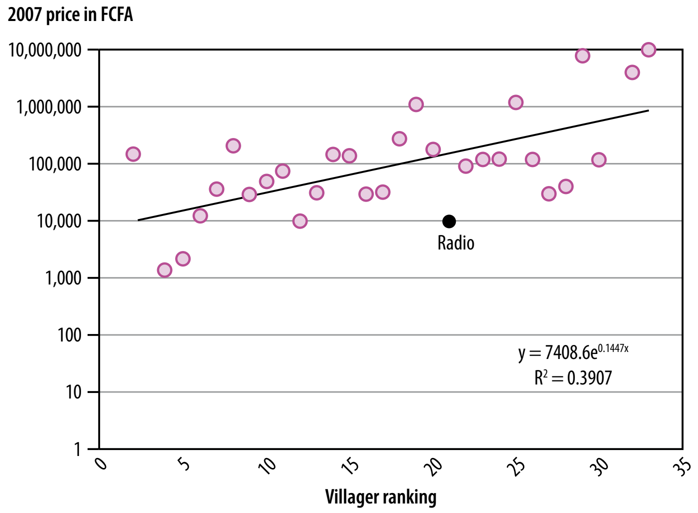
## FIGURE 3.4

The distribution of values of average RNNDVI (a) and RNNDVI Trend (b) for the selected villages relative to the distribution of these values for all villages in the Segou region.



## FIGURE 3.5

Correlation between asset prices and villager rankings.



value. In 2006 and 2007, when data for this study was collected, inexpensive radios were readily available in both regional and village markets, unlike in 1973, when they were a rare status symbol.

### Summary of village wealth

In order to draw an inference about the role of environmental services in rural wealth creation, we require that villages (the scale at which environmental services are evaluated in this work) vary in wealth. Figure 3.6 summarizes the mean wealth for the 77 villages evaluated, indicating that there is a six-fold difference between the wealthiest and poorest villages. Moreover, there is a striking concordance between the mean village wealth and the variance therein. We evaluated the correspondence between these (Figure 3.7) and observed a strong association, suggesting that the coefficient in variation (mean:SD) for wealth can broadly be considered a constant (with a value just below 1).

### Generalized linear models

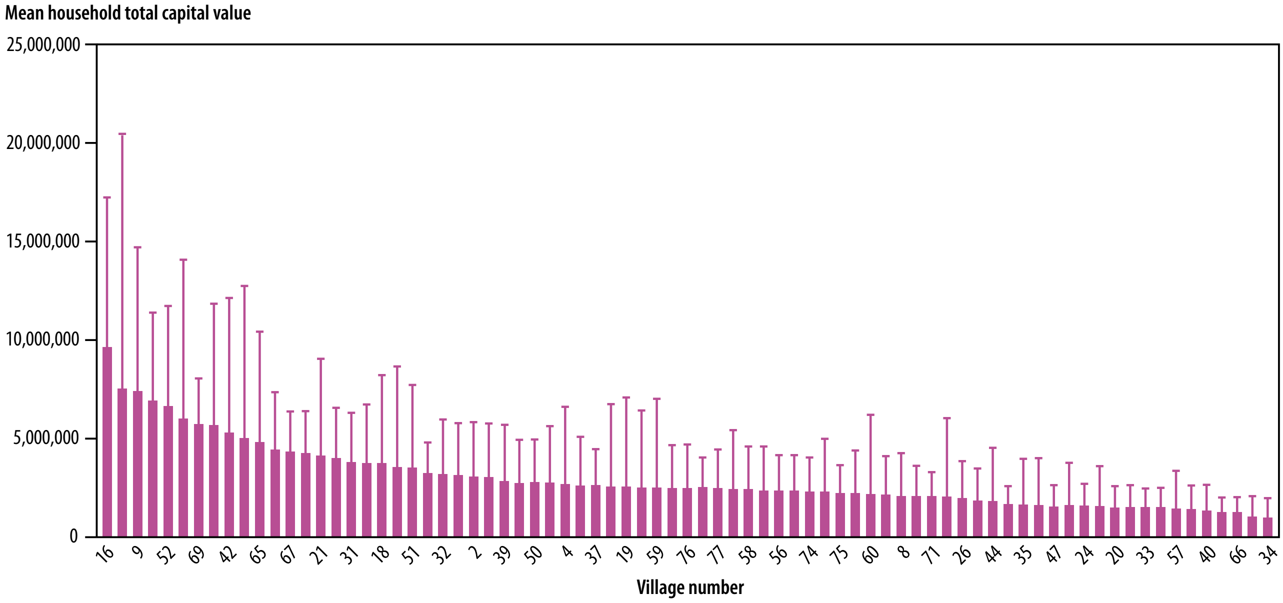
From the households surveyed, those which were female-headed (six households) were taken out of the analysis because such households are very uncommon in the region. The GLM of all households surveyed included 2,750 households. The GLM of the upper quartile and lower quartile of each village included 696 households each.

### All households

Table 3.3 presents estimates of the total capital value model as a function of village- and household-level predictors, including beta values, a measure which relates the predictor value variance to the response variance and indicates the relative

## FIGURE 3.6

Ranked mean village wealth (see Appendix 2 for village names). Note the strong concordance between mean village wealth and wealth variance.

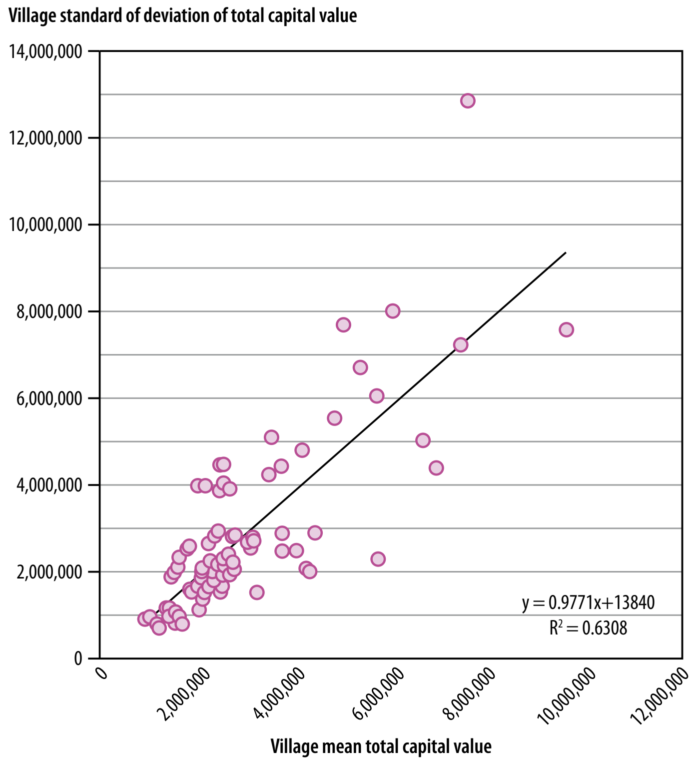


magnitude of the effect of each predictor on total capital value. The relationship between the predicted and observed total capital value can be found in Figure 3.8, and the total model effects of each individual predictor can be found in Figure 3.9. While coefficients of the direct effects of RNNDVI Trend and average RNNDVI are not significant, their interaction is significant and positive. Figure 3.9 shows that both increased RNNDVI Trend and increased average RNNDVI have an overall positive relationship with household total capital value, though the magnitude of the effect is comparatively small. The most influential ecosystem service variable for predicting total capital value is rainfall, which is positively associated (i.e., more rain, more 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 of households in a village are 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 are positively associated with total capital value.

The beta values in Table 3.3 (and subsequent results) indicate the standardized effect of each variable, which eases inference by scaling the effect to a unit change in the predictor. However,

## FIGURE 3.7

Village total capital value mean is positively correlated to the standard deviation ($R^2$ 0.631; Figure 3.6). In villages with households of a higher average total capital value, there is a large spread in total capital values, whereas in villages with households of a lower total capital value, all of the households have low total capital value.



## TABLE 3.3

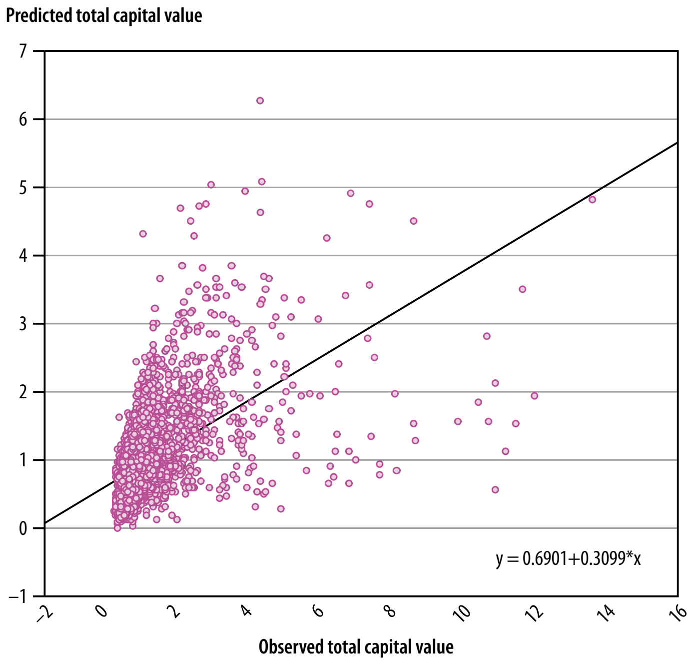
Total capital value model results. Model Adjusted $R^2$ = 0.301, p = 0.000. In addition, of the 25 ethnicities represented in the study, household identification in the Diokarame (parameter estimate = 2.407, p = 0.000, ß = 0.104, n = 4), Peul (parameter estimate = 0.255, p = 0.050, ß = 0.065, n = 300) and Soninke (parameter estimate = 0.601, p = 0.025, ß = 0.044, n = 33) ethnicities had a significant positive association with total capital value and identification in the Sarakole (parameter estimate = -0.304, p = 0.043, ß = -0.052, n = 110) ethnicity had a significant negative association with total capital value.

| | Param. | Std.Err | t | p | Beta (ß) |
|---|---|---|---|---|---|
| Intercept | -2.08 | 1.14 | -1.81 | 0.07 | |
| Number of people in the household | 0.84 | 0.03 | 29.80 | 0.00 | 0.53 |
| Married men per person | 0.12 | 0.04 | 2.76 | 0.01 | 0.05 |
| Number of households in the village | 0.13 | 0.04 | 3.11 | 0.00 | 0.07 |
| Distance from open water | 0.12 | 0.03 | 3.68 | 0.00 | 0.08 |
| Distance from a market | -0.04 | 0.03 | -1.21 | 0.23 | -0.02 |
| RNNDVI trend | -0.15 | 0.19 | -0.80 | 0.42 | -0.16 |
| Rainfall | 2.38 | 1.19 | 2.00 | 0.05 | 0.30 |
| Average RNNDVI | 1.38 | 0.91 | 1.52 | 0.13 | 0.25 |
| RNNDVI trend*Rainfall | -0.03 | 0.17 | -0.15 | 0.88 | -0.03 |
| RNNDVI trend*Average RNNDVI | 0.20 | 0.08 | 2.44 | 0.01 | 0.21 |
| Rainfall*Average RNNDVI | -1.82 | 1.01 | -1.80 | 0.07 | -0.41 |

the ranges vary dramatically (e.g., the range of number of people in the household is much larger than the range of RNNDVI trend). As such, we evaluate the relatively importance based on the t-value. By far the most important variable is household size, an unsurprising result given the way in which the wealth metric is estimated. The most important environmental variable is the interaction of the RNNDVI and the trend therein; the parameter estimate suggests that, 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. While the interaction term between rainfall and mean RNNDVI is not significant (P = 0.07), the negative parameter value suggests that the effect of rain-use efficiency on wealth decreases at higher rainfall.

## FIGURE 3.8

Predicted versus observed total capital value.

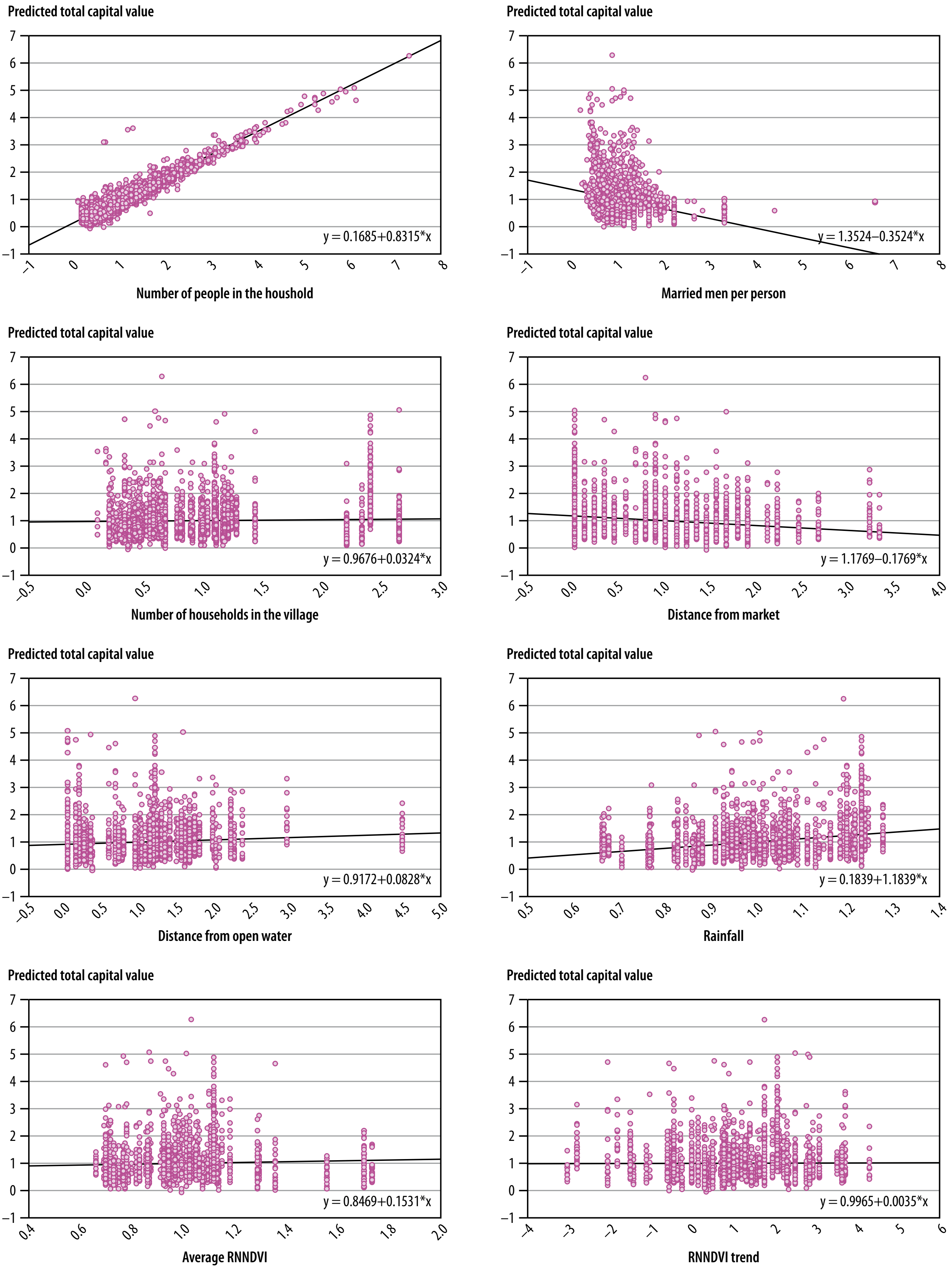


### Upper quartile wealth prediction

Table 3.4 presents the estimates of the total capital value model for the upper quartile of values in each village as a function of the various village-level and household-level predictors. The number of people in the household and the number of households in the village were the only two significant predictors, both of which are positively associated with total capital value. Figure 3.10 shows the relationship between predicted and observed total capital value for the upper quartile of households. Overall effects of the predictors on total capital value can be seen in the scatter plots in Figure 3.11.

## FIGURE 3.9

Scatter plots of total capital value total model effects for each household in each village. The axes have been mean centered.



## TABLE 3.4

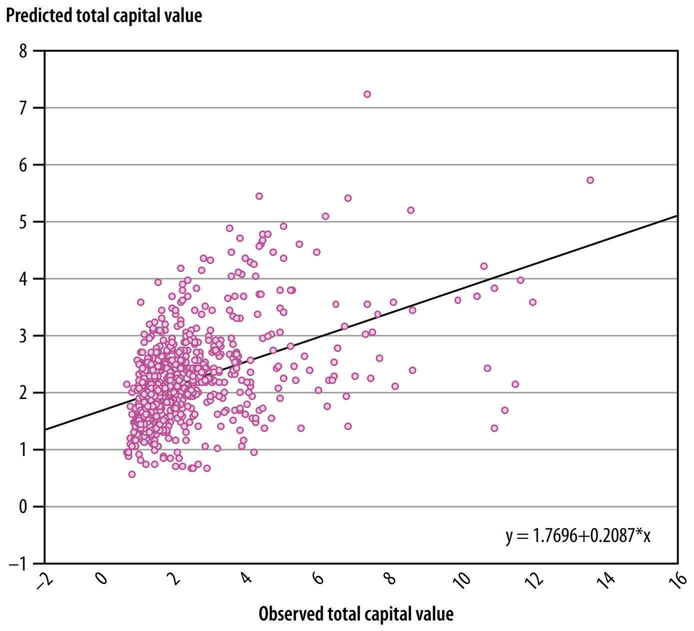
Total capital value model results for the upper quartile of households in each village. Model has an Adjusted $R^2 = 0.175$, $p = 0.000$. In addition, of the 25 ethnicities represented in the study, household identification in the Diokarame (parameter estimate = 5.036, p = 0.002, ß = 0.147, n = 4), Dogon (parameter estimate = 1.370, p = 0.021, ß = 0.089, n = 33) and Soninke (parameter estimate = 2.235, p = 0.031, ß = 0.092, n = 33) ethnicities had a significant positive association with total capital value and the identification in the Sarakole (parameter estimate = -0.995, p = 0.013, ß = -0.115, n = 110) ethnicity had a significant negative association with total capital value.

| | Param. | Std.Err | t | p | Beta (ß) |
|---|---|---|---|---|---|
| Intercept | -4.32 | 3.69 | -1.17 | 0.24 | |
| Number of people in the household | 0.44 | 0.07 | 6.00 | 0.00 | 0.24 |
| Married men per person | 0.00 | 0.19 | -0.01 | 1.00 | 0.00 |
| Number of households in the village | 0.30 | 0.13 | 2.28 | 0.02 | 0.11 |
| Distance from open water | 0.17 | 0.10 | 1.64 | 0.10 | 0.07 |
| Distance from a market | -0.11 | 0.10 | -1.13 | 0.26 | -0.05 |
| RNNDVI trend | -1.07 | 0.62 | -1.74 | 0.08 | -0.78 |
| Rainfall | 6.85 | 3.83 | 1.79 | 0.07 | 0.59 |
| Average RNNDVI | 3.44 | 2.94 | 1.17 | 0.24 | 0.42 |
| RNNDVI trend*Rainfall | 0.78 | 0.57 | 1.37 | 0.17 | 0.57 |
| RNNDVI trend*Average RNNDVI | 0.41 | 0.27 | 1.53 | 0.13 | 0.29 |
| Rainfall*Average RNNDVI | -4.57 | 3.25 | -1.41 | 0.16 | -0.69 |

We previously showed a strong correspondence between wealth and wealth variance at the village scale (Figure 3.7), suggesting that variance is not constant across villages. It is also reasonable to ask whether any of the environmental predictors can help understand the variance in wealth. Table 3.5 summarizes the model of village-level wealth variance, and indicates that of all the variables used, only rainfall was significant. Moreover, this model suggests a positive effect of rainfall on wealth variance. We interpret this mean that as rainfall increases, the capacity of households to engage in non-farming activities (i.e., specialization) increases, which in turn creates conditions where some households can become particularly wealthy.

## FIGURE 3.10

Predicted versus observed total capital value for the upper quartile of households in each village.

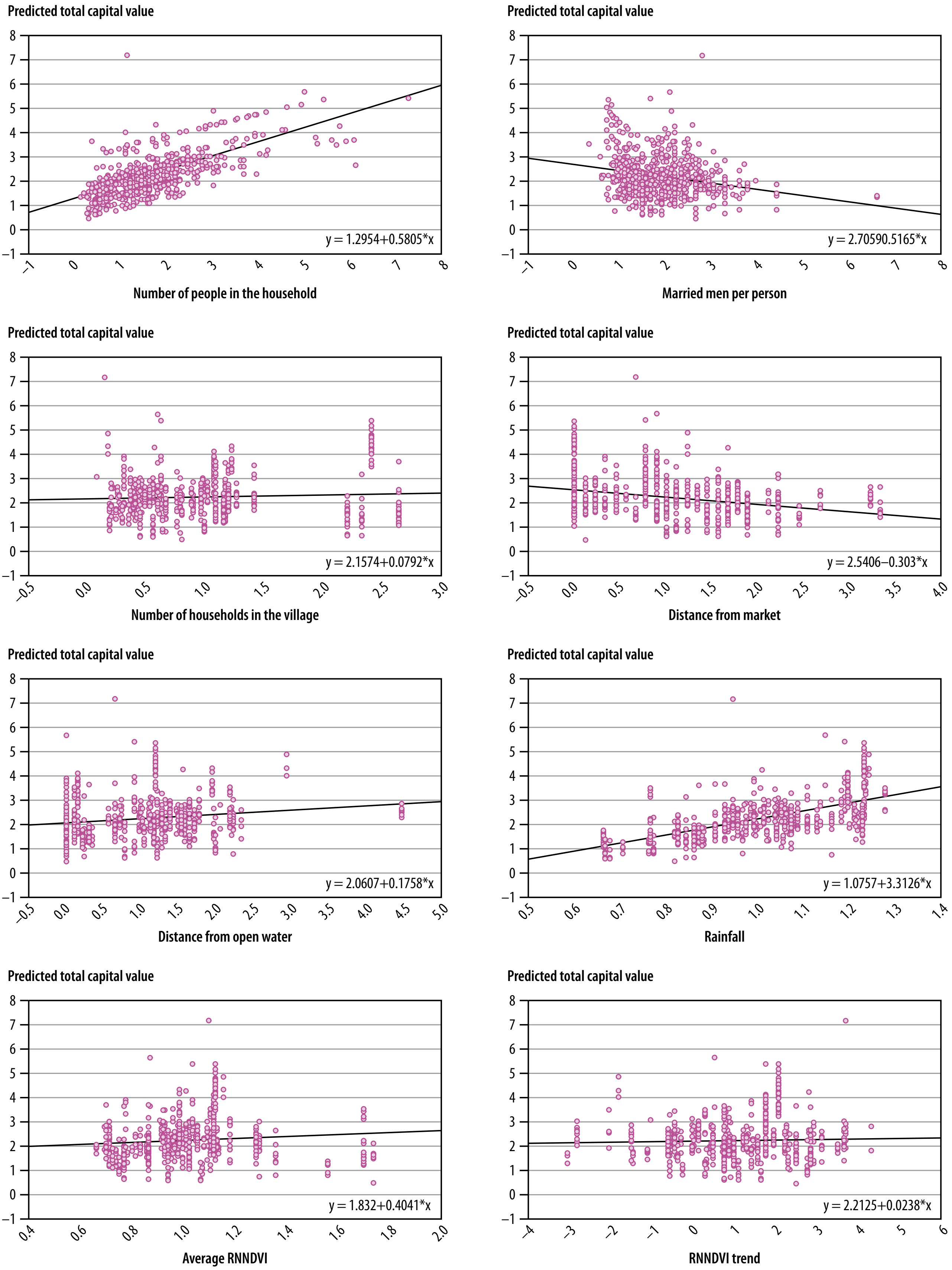


### Lower quartile wealth prediction

Table 3.6 presents estimates of the total capital value model for the lower quartile of households in each village as a function of the various village-level and household-level predictors. Figure 3.12 shows the relationship between predicted and observed total capital value for the lower quartile of households. Overall effects of the predictors on total capital value can be seen in the scatter plots in Figure 3.13. Average annual rainfall and RNNDVI Trend are both negatively associated with total capital value. However Figure 3.13 shows that RNNDVI Trend has an overall positive relationship with total capital value and the interaction term between the two variables is positively associated with total capital

**FIGURE 3.11**

Scatter plots of total capital value total model effects for the upper quartile of households in each village. The axes have been mean centered for each plot.



## TABLE 3.5

Summary of GLM predicting variance in wealth based on social and environmental predictors. Predictors that were not significant ($p > 0.05$) were pooled. The overall model had an adjusted $R^2$ of 0.058 ($p = 0.02$), and only rainfall was significant.

| | Param. | Std. Err | t | p | Beta |
|---|---|---|---|---|---|
| Intercept | -3.62 | 2.21 | -1.64 | 0.11 | |
| Number of households in the village | Pooled | | | | |
| Distance from open water | Pooled | | | | |
| Distance from a market | Pooled | | | | |
| RNNDVI trend | Pooled | | | | |
| Rainfall | 5.16 | 2.16 | 2.39 | 0.02 | 0.27 |
| Average RNNDVI | Pooled | | | | |
| RNNDVI trend*Rainfall | Pooled | | | | |
| RNNDVI trend*Average RNNDVI | Pooled | | | | |
| Rainfall*Average RNNDVI | Pooled | | | | |

## TABLE 3.6

Total capital value model results for the lower quartile of households in each village. Model has an Adjusted $R^2 = 0.385$, $p = 0.000$. Of the 25 ethnicities in the study, household identification in the Bobo (parameter estimate = 0.089, p = 0.007, ß = 0.134, n = 336), Diokarame (parameter estimate = 0.748, p = 0.000, ß = 0.185, n = 4) and Peul (parameter estimate = 0.171, p = 0.000, ß = 0.226, n = 300) ethnicities had a significant positive association with total capital value and the identification in the Bambara (parameter estimate = -0.066, p = 0.019, ß = -0.153, n = 1246) and Somono (parameter estimate = -0.087, p = 0.040, ß = -0.077, n = 83) ethnicities had a significant negative association with total capital value.

| | Param. | Std.Err | t | p | Beta (ß) |
|---|---|---|---|---|---|
| Intercept | 1.21 | 0.37 | 3.28 | 0.00 | |
| Number of people in the household | 0.25 | 0.03 | 8.40 | 0.00 | 0.33 |
| Married men per person | 0.00 | 0.01 | -0.36 | 0.72 | -0.01 |
| Number of households in the village | -0.02 | 0.01 | -1.84 | 0.07 | -0.07 |
| Distance from open water | 0.03 | 0.01 | 2.55 | 0.01 | 0.10 |
| Distance from a market | -0.04 | 0.01 | -3.97 | 0.00 | -0.15 |
| RNNDVI trend | -0.26 | 0.06 | -4.41 | 0.00 | -1.61 |
| Rainfall | -0.98 | 0.39 | -2.54 | 0.01 | -0.72 |
| Average RNNDVI | -0.45 | 0.30 | -1.53 | 0.13 | -0.47 |
| RNNDVI trend*Rainfall | 0.24 | 0.05 | 4.28 | 0.00 | 1.45 |
| RNNDVI trend*Average RNNDVI | 0.03 | 0.03 | 0.98 | 0.33 | 0.16 |
| Rainfall*Average RNNDVI | 0.46 | 0.33 | 1.40 | 0.16 | 0.59 |

value, meaning that at positive RNNDVI Trends, total capital value increases with increasing rainfall and at negative RNNDVI Trends, total capital value decreases with increasing rainfall. According to the beta values, RNNDVI Trend, rainfall and their interaction term are the three most influential predictors of total capital value. At the landscape scale, total capital value is positively associated with being far from open water and negatively associated with being far from markets. The number of people in the household is positively associated with total capital value.

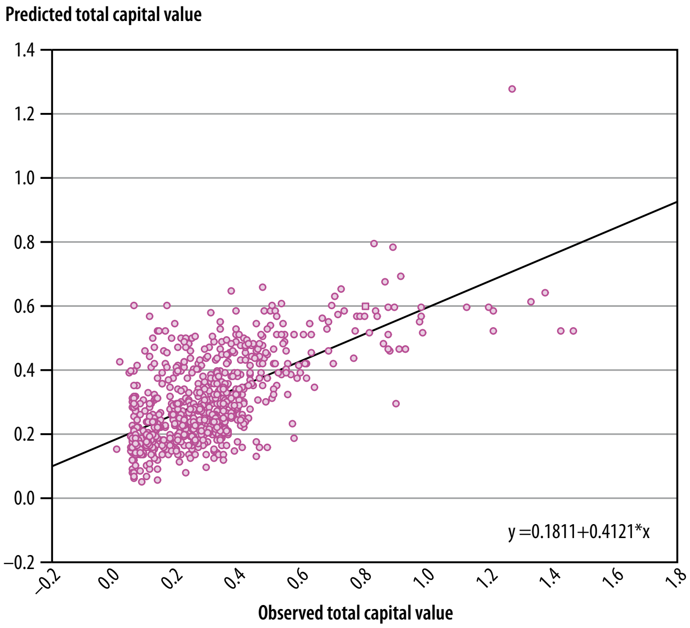
## DISCUSSION

The objective of this study was to predict the relative influence of ecosystem services and environmental degradation on human well-being. To make that assessment requires that techniques to measure both wealth and environmental condition be reasonable proxies for a deeply complex relationship. With regard to environmental variables, the measures of condition are, in our view, the best contemporary estimates of land degradation and ecosystem services from the climate system that can be reasonably obtained. Rainfall is a comparatively simple measurement, and the Sahel has reasonable precipitation datasets that permit fairly accurate and highly resolved measures of rainfall. While that measurement intrinsically relies on interpolation in order to yield an estimate at all locations, the spatial autocorrelation of rainfall patterns in the region is high because of the mechanism of rain formation (the passage of the inter-tropical convergence zone). As such, we view the rainfall predictor as robust. The measures of rain-use efficiency (RNNDVI) and the temporal trends therein are highly technical estimates at a fairly coarse scale (8 x 8 km), and therefore subject to some uncertainty. However, other researchers have used similar techniques to draw important conclusion about desertification and the reversal thereof in the Sahel. Moreover, these two metrics capture the essential elements of ecosystem services: the conversion of incident rainfall into biomass (done on an incremental basis to accommodate land cover types that are grazed), and the trend thereof. While it is difficult to validate the land degradation metric explicitly, the fact that there is systematic variance across the landscape in both RNNDVI and the RNNDVI trend suggests that something about the land surface is changing in a predictable way; we assert that the most parsimonious explanation for that variance is changes in soil condition and the vegetative response to that.

We also need to use measures of wealth that are considered robust and repeatable. While household total capital value is not a complete measure of welfare, it is a useful proxy for the relative well-being of households. It cannot, for example, tell us about aspects of well-being such as personal happiness, however it is likely that households with a higher total capital value are better able to meet their basic needs such as food and shelter and would therefore be in a better position to purchase healthcare or send their children to school. In a region with limited data, our metric is a time-efficient method for estimating household welfare, which allowed us to examine trends on a landscape scale. In an attempt to improve our model and incorporate other social variables which could predict household well-being, we also included variables such as the presence of a school, health centre or functioning water pump (Appendix 2); however, none of these variables were ever significant predictors of total capital value and were left out of the final models. In the end, any analysis of wealth is likely to be incomplete in the same way that any analysis of ecosystem services is incomplete. Given the magnitude of our project (2,700+ households) and the variables that we've selected, it seems reasonable to presume that the presence of significant associations is real. While the absence of the associations is somewhat ambiguous, it is also true that our power to detect a signal is unusually high for a study like this, making us somewhat confident in also interpreting the absence of significant associations.

**FIGURE 3.12**

Predicted versus observed total capital value for the lower quartile of households in each village.

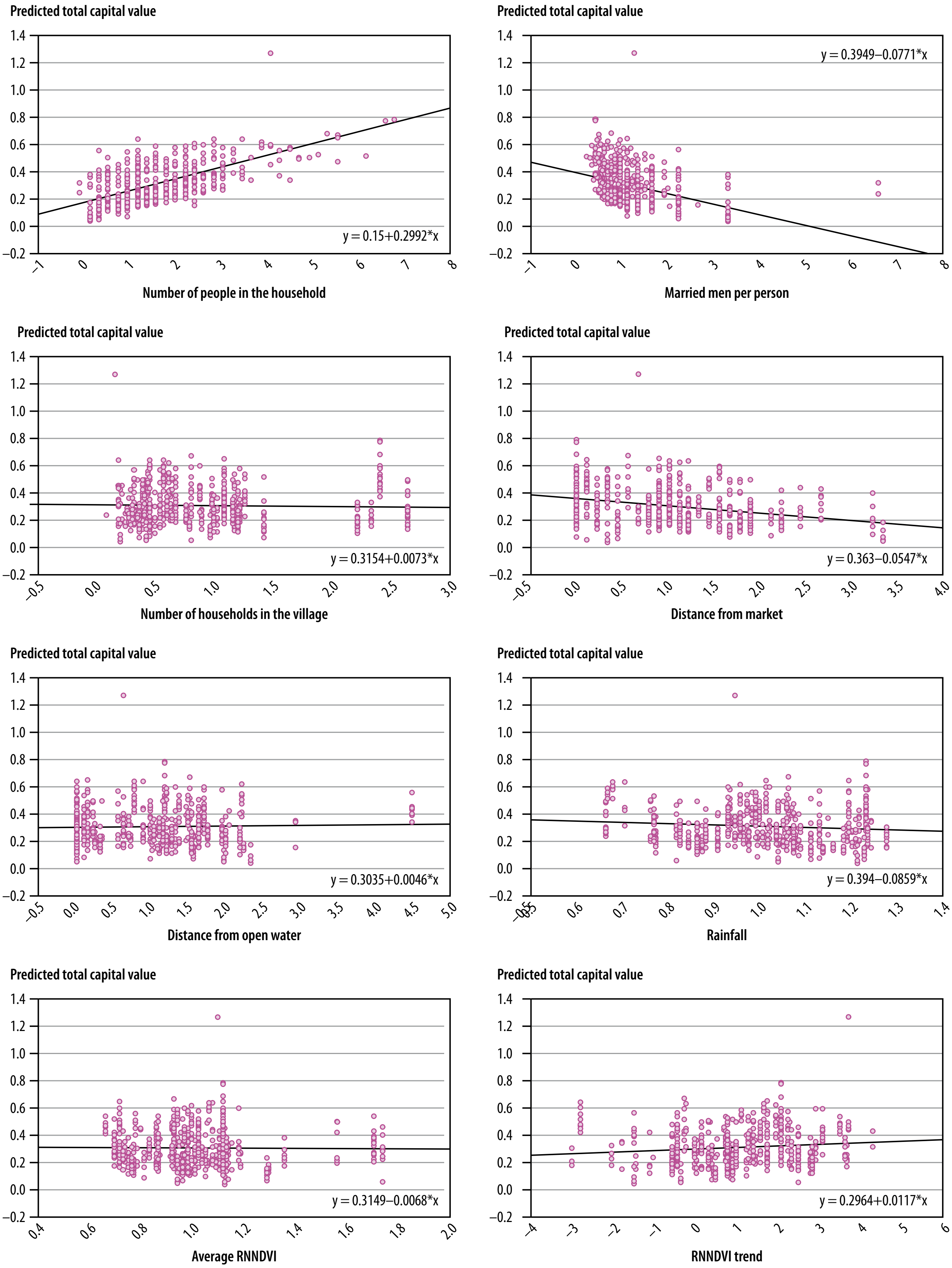


## Household well-being

The strong correlation between total capital value mean and standard deviation (Figure 3.6) by village suggests that the mechanisms that create wealth variance at the village scale grow as that village becomes more affluent. Poor villages may exhibit low standard deviation because opportunities for village members to dramatically expand their wealth, compared with other households in the village, are limited, possibly because of some extrinsic constraint (geographic or environmental). As villages increase in mean wealth, the variance also

## FIGURE 3.13

Scatter plots of total capital value total model effects for the lower quartile of households in each village. The axes have been mean centered for each plot.



increases, suggesting that the distribution of wealth becomes more varied. This would be consistent with the opportunities for some households more fully to engage in the cash economy, and thereby dramatically increase their wealth over what is possible from subsistence livelihood practices alone. The fact that the coefficient of variation (mean:SD) is basically a constant (because a line fits the data so well), suggests that these wealth differentiation mechanisms are always present, but the magnitude of their effect is amplified when there is more wealth. It would be particularly interesting to expand the wealth axis to include villages that are closer to major metropolitan regions and see if the ratio of mean wealth to wealth variance continues to be a constant, or whether increasing integration within a monetary system creates discontinuities in this relationship. For now, we can only speculate about the underlying mechanisms of wealth variance; since rainfall alone was a predictor of village wealth variance (i.e., social and other environmental factors were non-significant), it seems reasonable that environmental conditions may play an important, but perhaps not determinative role.

### All households model

The model for all households in this study predicts household total capital value from environmental, geographic and socioeconomic variables; overall, the model explains over 30% of the variance in the dataset, though that prediction is dominated by the effect of household size.

While distance to a market was not a significant predictor of total capital value, the number of households in the village is positive and significantly associated with total capital value, indicating that living in a village with more opportunity for inter-household trade and economic interaction has a positive relationship with household well-being. Surprisingly, households farther from open water (and therefore with less access to fishing resources and river transport) have higher well-being. Part of this is attributable to the fact that extremely poor households that are forced to relocate often gravitate towards fishing as an alternative livelihood strategy.

Both a higher number of household members and a higher ratio of married men to total household members are positively associated with total capital, suggesting both that having more household members is advantageous to well-being, and also that extended households have an economic advantage over nuclear households. We note, however, that asset wealth should scale positively with household size since many of the elements of wealth (e.g., wives, tools, livestock) are implicitly correlated with size. As such, the fact that our estimates of the effects of the other predictors (environmental and social) are made conditioned on the size and demography of the household is enormously important; without controlling for the effect of household size, that variable would overwhelm the signal, possibly making it impossible to detect.

Among the most important environmental covariates were rainfall and the interaction of Average RNNDVI and RNNDVI Trend, all of which had a positive relationship with total capital value. The positive interaction term suggests that on improving lands (positive RNNDVI Trend), higher levels of environmental condition (average RNNDVI) are associated with higher levels of well-being, while on degrading lands (negative RNNDVI Trend) the opposite is true. From Figure 3.8 we see that a unit increase in rainfall (recall that the values are mean centered) increases total capital value by approximately 118%; the range of rainfall values is approximately 0.7, suggesting that the predicted effect of rainfall on wealth is to enrich households at the high end of the rainfall spectrum by roughly 60% over households at the low end of the spectrum. By the same evaluation, each unit increase in average RNNDVI increases total capital value by approximately 15%, and the difference over the range of average RNNDVI affects total capital value by approximately 17%. Similarly, each unit increase in RNNDVI Trend increases total capital value by approximately 0.4%, with an increase in wealth over approximately 3% over the entire range of values. This suggests that the primary flow necessary for providing primary production (rainfall), the degradation state of the land, as well as its degradation trajectory, while perhaps not as important to human welfare as one might expect, are empirically linked to household well-being in rural Mali. That the relationships are statistically significant supports this contention; that the effect is weak is of considerable importance when evaluating the assertion about the immediacy of the value of natural capital for rural livelihoods.

It was also observed that within-village variance in household total capital value was positively associated with rainfall, meaning that at high rainfall there is a larger variation in household total capital values than at low rainfall. This result suggests that environmental variation may be partly why dispersion in wealth among a community occurs, though the model explains very little of the variation ($r^2 = 0.06$). We infer that at higher rainfall amounts, there are opportunities for alternative livelihood strategies that are not available when rainfall inputs are lower; these opportunities are equally distributed within a community, which is the basis for increased wealth dispersion (variance) with increasing wealth. Regardless of the underlying mechanism that creates variance in wealth, it would be informative to examine the range of mean village wealth over a wider span (perhaps by including villages that are increasingly close to urban areas) to see if the trend of wealth vs. variance persists linearly, or whether there are discontinuities in the relationship that indicate thresholds in the interaction with the monetary economy.

### Upper quartile model

From our second model, using only the upper quartile of total capital values from each village, we wanted to see if the effects of environmental conditions on wealth were particularly strong for the wealthy households. The rationale was that increasing environmental conditions could create livelihood opportunities that would not otherwise be available where all the households in a village are constrained by the production of basic subsistence products. Since those opportunities are not evenly distributed across a population (based on innovation and historical contingency), we reasoned that that effect would be most pronounced among the wealthiest households.

We observed the opposite: among wealthy households, the relationship between environmental services or condition and household well-being disappears. The total model $R^2$ was only 0.175 and the only significant predictors were household size and village size, both of which were positively associated with total capital value. This suggests that well-being among those households with higher capital value is driven primarily by household characteristics and the opportunity for trade and interaction within their village. Another possibility is that these households have higher capital value due to outside influences, such as a family member sending remittances from another city and thereby minimizing their dependence on local landscape variables.

### Lower quartile model

Following similar logic, we examined the effects of the environmental predictors on the poorest 25% of households in each village, reasoning that in areas where environmental conditions are good, even the poorest households should be capable of subsistence, whereas in areas with poorer environmental conditions, the lower bound on livelihood potential would be reduced. Our model using only the lower quartile of total capital values from each village shows that among the households with the lowest well-being, the link between total capital value and environmental services and condition is markedly stronger than with all households. The total model $R^2$ increased to 0.385 and the most influential predictors of well-being (according to beta values found in Table 3.5) became RNNDVI Trend, rainfall and the interaction term between these two variables. While the parameter estimates for the main effect of RNNDVI Trend and rainfall are negative, we see from Figure 3.10 that RNNDVI Trend has an overall positive relationship with total capital value; this occurs because of the strong effect that is exerted via interaction terms. The positive parameter estimate for the interaction term suggests that on improving lands (positive RNNDVI Trend), increased rainfall is associated with increased total capital value but on degrading lands (negative RNNDVI Trend) the effect of increasing rainfall is absent or reversed.

The relationship between rainfall and these households with lower well-being in the lower quadrant model presents a more complex story. Average annual rainfall appears to have a strong negative association with total capital value and, as mentioned above, the directionality of the RNNDVI Trend relationship depends on whether the household is in a high- or low-rainfall area. While we do not have population density data for the region, we propose that the rainfall results may suggest that people have self-organized towards areas of higher rainfall. Therefore high rainfall is not a predictor of well-being but a reflection of where higher population densities have resulted in areas where marginalized households have a smaller relative portion of the available environmental services.

As with the other models, the number of people in the household is positively associated with total capital value. The negative parameter estimate for distance from a market suggests that the households with higher well-being among the lower quartile households are those which are located close to a market, a finding that comports with the possible effects of inter-village interactions on livelihood. Interestingly, as with other models, being farther from open water is positively associated with household well-being.

### Overall effects of environmental condition on wealth

In all of the models, the impact of ethnicity on the relationship between environmental condition and wealth is surprisingly strong, indicating that cultural differences play an important role in a household's livelihood choices. While this finding is not entirely surprising, it is clearly something that requires additional exploration. Is the reason for this related to historical contingency (i.e., the inheritance of wealth from previous generations), geography (since different tribes occupy different areas), or historical livelihood strategies (e.g., in the case where historically nomadic pastoralists have been forced to be sedentary)? Moreover, the coping strategies that different ethnic groups use to compensate for declining environmental services could be dramatically different; our work illustrates the need to consider ethnicity in a discussion of the effect of environmental services on wealth, and points out that ethnicity-specific coping mechanisms could be a helpful area for additional work.

While all the metrics of environmental services were found to significantly influence well-being in some way, our modelling results suggest that environmental services may not be as important to human well-being as household demographic variables. In short, while the role of environmental services are, at some basic level, priceless, their marginal effect on rural livelihoods appears difficult to detect, and where it is statistically significant, the magnitude of the effect is comparatively small. We do not assert that this discounts the utility of protecting stocks of natural capital, nor do we lend any credence to the idea that this result indicates that ecosystem services can more broadly be discounted. It does, however, raise interesting practical and theoretical issues about the appropriate scale and measurement of humanity's dependence on ecosystems. Among the key caveats for this work is that land degradation occurs over large scales, and the particulars of the process at the local scale may be confounded; our inference of land degradation from the RNNDVI and trends therein may or may not provide a useful proxy for the most important land production attributes (e.g., soil fertility or water holding capacity). Further work exploring these more mechanistic links could quite plausibly increase the strength of the effect of soil condition on wealth creation.

One potential reason for the weak association between environmental condition and household wealth is household resilience. That is, it is conceivable that individual households are able to mitigate for a decline of environmental services, such as rainfall or high levels of land degradation, with resource substitutes or through livelihood diversification. The parameter estimates for significant ethnicities may point to an example of this, as some ethnic groups are historically more apt to participate in specific livelihood activities. Therefore, exploring the various scales at which environmental services have a significant influence on wealth and livelihood decisions is crucial to understanding these relationships. Moreover, the time lags between land degradation and the loss of asset wealth may confound the relationship.

In conclusion, there appears to be good evidence to support the contention that ecosystem services matter in the provision of rural livelihoods, tentatively confirming our main hypothesis. The weakness of that effect, and the relative strength of simple social and demographic attributes (ethnicity and household size), suggests that what effect the environment has 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 obtaining straightforward answers about the role of the environment in human welfare.

# References

Bahamondes, M. (2003). "Poverty-Environment Patterns in a Growing Economy: Farming Communities in Arid Central Chile, 1991-99." *World Development* 31(11): 1947–1957.

Booysen, F., R. Burger, et al (2008). Trends in Poverty and Inequality in Seven African Countries. *PMMA Working Paper* 2007–6.

Cairns, J. J. and J. R. Pratt (1995). *The Relationship Between Ecosystem Health and Delivery of Ecosystem Services*. Evaluating and Monitoring the Health of Large-Scale Ecosystems, Montebello, Quebec, Springer-Verlag Berlin Heidelberg.

Costanza, R., R. d'Arge, et al (1997). "The value of the world's ecosystem services and natural capital." *Nature* 387: 253–260.

Coulibaly, A. (2003). "Country Pasture/Forage Resource Profiles: Mali." *FAO*: Available online: http://www.fao.org/ag/AGP/AGPC/doc/counprof/Mali/Mali.htm#3.%20CLIMATE%20AND%20AGRO%20ECOLOGICAL

De Oliveira, T., A. K. Duraiappah, et al (2003). Challenge Paper: Increasing Capabilities through an Ecosystem Approach for the Drylands. Nairobi, Kenya, UNEP.

Filmer, D. and L. H. Pritchett (2001). "Estimating Wealth Effects without Expenditure Data - or Tears: An Application to Educational Enrollments in States of India." *Demography* 38(1): 115–132.

Gray, L. C. and W. G. Moseley (2005). "A geographical perspective on poverty-environment interactions." *The Geographic Journal* 171(1): 9–23.

Lal, R. (2009). "Soil degradation as a reason for inadequate human nutrition." *Food Security* 1: 45–57.

Library of Congress Federal Research Division (2005). Country Profile: Mali. Available online at http://lcweb2.loc.gov/frd/cs/profiles/Mali.pdf. Accessed September 21, 2008.

Lufumpa, C. L. (2005). "The Poverty-Environment Nexus is Africa." *African Development Review* 17(3): 366–381.

Mainka, S. A., J. A. McNeely, et al (2008). "Depending on Nature: Ecosystem Services for Human Livelihoods." *Environment* 50(2): 42–55.

Millennium Ecosystem Assessment (2005). *Ecosystems and Human Well-being: Synthesis*. Washington, D.C., Island Press.

Moseley, W. G. (2005). "Global cotton and local environmental management: the political ecology of rich and poor small-hold farmers in southern Mali." *The Geographical Journal* 171(1): 36–55.

Ostfeld, R. S. and K. LoGiudice (2003). "Community disassembly, biodiversity loss, and the erosion of an ecosystem service." *Ecology* 84(6): 1421–1427.

Pimentel, D., C. Harvey, et al (1995). "Environmental and Economic Costs of Soil erosion and Conservation Benefits." *Science* 267: 1117–1123.

Ravallion, M. (1996). "Issues in Measuring and Modelling Poverty." *The Economic Journal* 106(438): 1328–1343.

Ravnborg, H. M. (2002). "Poverty and Soil Management - Relationships from Three Honduran Watersheds." *Society and Natural Resources* 15: 523–539.

Ravnborg, H. M. (2003). "Poverty and Environmental Degradation in the Nicaraguan Hillsides." *World Development* 31(11): 1933–1946.

Reardon, T. and S. A. Vosti (1995). "Links between Rural Poverty and the Environment in Developing-Countries - Asset Categories and Investment Poverty." *World Development* 23(9): 1495–1506.

Sahn, D. E. and D. C. Stifel (2000). "Poverty Comparisons Over Time and Across Countries in Africa." *World Development* 28(12): 2123–2155.

Sen, L., X. Xun-cheng, et al (2000). "Characteristics, origin and evolution ages of Aeolian sand in the Sahelian region of Mali" *Chinese Geographical Science* 10(2): 159–167.

Shimeles, A. and R. Thoenen (2005). A methodological note on measuring poverty, United Nations Economic Commission for Africa Working Paper.

Sweeney, B. W., T. L. Bott, et al (2004). "Riparian deforestation, stream narrowing, and loss of stream ecosystem services." *PNAS* 101: 14132–14137.

Swinton, S. M. and R. Quiroz (2003). "Is Poverty to Blame for Soil, Pasture and Forest Degradation in Peru's Altiplano?" *World Development* 31(11): 1903–1919.

Takasaki, Y. , B. L. Barham, et al (2000). "Rapid Rural Appraisal in Humid Tropical Forests: An Asset Possession-Based Approach and Validation Methods for Wealth Assessment Among Forest Peasant Households." *World Development* 28(11): 1961–1977.

Takimoto, A., P. K. Nair, et al (2007). "Socioeconomic potential of carbon sequestration through agroforestry in the West African Sahel." *Mitigation and Adaptation Strategies for Global Change* 13(7): 745–761.

UNDP (2006). *Human Development Report 2006: Beyond Scarcity: Power, Poverty, and the Global Water Crisis.* New York, UNDP.

UNDP (2007). Implementing the Millennium Development Goals in the Drylands of the World. Nairobi, Kenya, UNDP Drylands Development Centre: 56.

UNDP (2008). *Human Development Report 2007/2008: Fighting climate change: Human solidarity in a divided world*. New York, UNDP.

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.

Von Maltzahn, R. and K. Durrheim (2008). "Is poverty multidimensional? A comparison of income and asset based measures in five Southern African countries." *Social Indicator Research* 86: 149-162.

World Agroforestry Center (2006). Rural Wealth Rankings. Unpublished report.

# Appendix A

## Detailed emergy tables for Sahelian land-use systems

**TABLE A.1**

Emergy evaluation of cotton, per ha per year (Cot).

| Note | Description | Data (per ha$^{-1}$ yr$^{-1}$) | Unit | UEV (sej/unit) | Emergy (E13 sej/yr) |
|---|---|---|---|---|---|
| RENEW | | | | | |
| 1 | Sun | 4.4E+13 | J | 1.0E+00 | 4.4 |
| 2 | Rain | 4.9E+10 | J | 3.1E+04 | 153.1 |
| 3 | Evapotranspiration | 4.1E+10 | J | 3.1E+04 | 127.1 |
| LOCAL TRANSFERS | | | | | |
| 4 | Manure from off-farm | 2.8E+09 | J | 5.9E+05 | 165.2 |
| 5 | Labour | 1.3E+09 | J | 1.4E+05 | 17.0 |
| NONRENEW | | | | | |
| 6 | Net topsoil loss | 3.9E+09 | J | 1.5E+05 | 57.5 |
| 7 | Fuel | 0.0E+00 | J | 9.4E+04 | 0.0 |
| 8 | Electricity | 0.0E+00 | J | 2.9E+05 | 0.0 |
| 9 | Potassium | 1.1E+04 | g K | 2.9E+09 | 3.3 |
| 10 | Phosphate | 1.7E+04 | g P | 1.3E+10 | 21.8 |
| 11 | Nitrogen | 3.1E+04 | g N | 1.6E+10 | 49.9 |
| 12 | Services | 5.0E+01 | $ | 3.8E+13 | 190.0 |
| 13 | Total emergy | | | | 631.9 |
| 14 | Total yield, dry weight | 1.6E+06 | g | | |
| 15 | Total yield, energy | 2.8E+10 | J | | |
| 16 | UEV, grams | 3.9E+09 | sej/g | | |
| 17 | UEV, joules | 2.2E+05 | sej/J | | |
| 18 | UEV w/o services | 1.6E+05 | sej/J | | |

Location: Noyaradougou, southern Mali

Main data source: Defoer et al, 1998

Notes, Table A.1

1 Sun

| | | | |
|---|---|---|---|
| Annual net radiation = | 138.7 | W/m^2 | (Maidment, WWB) |
| Area = | 1.00E+04 | m^2 | |
| Annual energy = | (___W/m^2)(31,536,000 sec/yr)(area) | | |
| Annual energy = | 4.37E+13 | J | |
| Emergy per unit input = | 1 | sej/J | (Odum, 1996) |

Notes, Table A.1 *continued*

| | | | | |
|---|---|---|---|---|
| 2 | **Rain** | | | |
| | Avg. annual rainfall = | 1,000 | mm | (DeFoer et al, 1998) |
| | Area = | 10,000 | m^2 | |
| | Annual energy = | (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g) | | |
| | Annual energy = | 4.94E+10 | J | |
| | Emergy per unit input = | 3.10E+04 | sej/J | (Odum, 2000) |
| 3 | **Evapotranspiration** | | | |
| | Avg. annual ET = | 830 | mm | (Ahn and Tateishi, 1992) |
| | Area = | 1.00E+04 | m^2 | |
| | Annual energy = | (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g) | | |
| | Annual energy = | 4.10E+10 | J | |
| | Emergy per unit input = | 3.10E+04 | sej/J | |
| 4 | **Manure** | | | |
| | N contribution from manure = | 1.6 | kg | (DeFoer et al, 1998) |
| | Average N content of manure = | 0.013 | N, % of DM | (FAO, Kenya study) |
| | Mass applied = | 1.23E+02 | kg/ha dry | |
| | Energy content = | 2.3E+04 | J/g | (Cohen, 2006) |
| | Annual energy applied = | (___kg/ha)(1,000 g/kg)(2.3E4 J/g) | | |
| | Annual energy = | 2.78E+09 | J/ha | |
| | Emergy per unit input = | 5.94E+05 | sej/J | (Odum and Odum, 1983) |
| 5 | **Net topsoil loss** | | | |
| | Erosion rate = | 20 | t/ha | (Bishop & Allen, 1989; in Bodnar et al, 2006) |
| | % organic matter in soil = | 0.87 | % | (orgC, DeFoer et al, 1998, x1.73) |
| | Energy cont./g organic= | 5.40 | kcal/g | |
| | Organic matter in topsoil used up = | (total mass of topsoil)(% organic) | | |
| | = | 173,000 | g/ha | |
| | Energy loss = | (loss of organic matter)(5.4 kcal/g)(4186 J/kcal) | | |
| | Annual energy = | 3.91E+09 | J/ha | |
| | Emergy per unit input = | 1.47E+05 | sej/J | (Cohen, 2007) |
| 6 | **Fuel (includes diesel, gasoline, lubricants)** | | | |
| | Fuel use= | 0 | gal | |
| | Annual energy = | (gallons fuel)(1.32E8 J/gal) | | |
| | Annual energy = | 0.00E+00 | J | |
| | Emergy per unit input = | 9.42E+04 | sej/J | (Bastiononi et al, 2005) |
| 7 | **Electricity** | | | |
| | Electricity use = | 0 | kWh | |
| | Annual energy = | (KWh)(3.6E6 J/KWh) | | |
| | Annual energy = | 0.00E+00 | J | |
| | Emergy per unit input = | 2.86E+05 | sej/J | (Odum, 1996) |
| 8 | **Potassium, g K per ha** | | | |
| | K from mineral fertilizer = | 11.4 | kg | |
| | Annual mass applied = | 11,400 | g | |
| | Emergy per unit input = | 2.92E+09 | sej/g | (Odum and Odum, 1983) |
| 9 | **Phosphate, g P per ha** | | | |
| | P from mineral fertilizer = | 16.8 | kg | |
| | Annual mass applied = | 16,800 | g | |
| | Emergy per unit input = | 1.30E+10 | sej/g | (Brandt-Williams, 2002) |

Notes, Table A.1 *continued*

| | | | | |
|---|---|---|---|---|
| 10 | **Nitrogen, g N per ha** | | | |
| | N from mineral fertilizer = | 31.2 | kg | |
| | Annual mass applied = | 31,200 | g | |
| | Emergy per unit input = | 1.60E+10 | sej/g | (Brandt-Williams, 2002) |
| 11 | **Labour** | | | |
| | #people working on farm = | 130 | pers-d/ha | (Ker, 1995, fertilized maize in Zambia) |
| | Annual energy = | (pers-d/ha/yr)*(2,300 kcal/d)*(4,186J/kcal) | | |
| | Annual energy = | 1.25E+09 | J | |
| | Emergy per unit input = | 1.36E+05 | sej/J | (Odum and Odum, 1983) |
| 12 | **Services, $ per ha** | | | |
| | Fertilizer mass applied = | 200 | kg | based on nutrient inputs 8-10 above |
| | Fertilzer cost = | 0.25 | $/kg cotton fert. | (Bationo et al, 1997) |
| | $/yr spent on inputs = | 5.00E+01 | $ | |
| | Mali emergy/$ ratio = | 3.80E+13 | sej/$ | (Sweeney et al, 2007) |
| | Annual emergy = | 1.90E+15 | sej/yr | |
| 13 | **Total emergy (Empower density)** | | | |
| | Total emergy = | 6.3E+15 | | sum of items 3 through 12 |
| 14 | **Yield, dry weight, g** | | | |
| | Estimated avg. yield, seed cotton = | 1.8E+06 | g/ha | (Rapidel et al, 2006) |
| | Yield, dry weight, g = | 1.60E+06 | g/ha | assume 10% moisture |
| 15 | **Yield, energy content, J** | | | |
| | Energy content = | 16 | kJ/g | FAO, 1997, value for crop residue |
| | Yield, energy content, J = | 2.85E+10 | J/yr | |
| | **UEVs** | | | |
| 16 | UEV, grams = | 3.94E+09 | sej/g | item 13/item 14 |
| 17 | UEV, joules = | 2.22E+05 | sej/J | item 13/item 15 |
| 18 | UEV w/o services = | 1.6E+05 | sej/J | (item 13–item 12)/item 15 |

## TABLE A.2

Emergy evaluation of millet, per ha per year (MI-t1).

| Note | Description | Data (per ha$^{-1}$ yr$^{-1}$) | Unit | UEV (sej/unit) | Emergy (E13 sej/yr) |
|---|---|---|---|---|---|
| RENEW | | | | | |
| 1 | Sun | 3.6E+13 | J | 1.0E+00 | 3.6 |
| 2 | Rain | 2.2E+10 | J | 3.1E+04 | 68.9 |
| 3 | Evapotranspiration | 2.1E+10 | J | 3.1E+04 | 65.5 |
| LOCAL TRANSFERS | | | | | |
| 4 | Seeds | 8.8E+07 | J | 5.0E+05 | 4.4 |
| 5 | Manure from off farm | 1.3E+09 | J | 5.9E+05 | 79.5 |
| 6 | Labour | 7.2E+08 | J | 1.4E+05 | 9.8 |
| NONRENEW | | | | | |
| 7 | Net topsoil loss | 1.1E+09 | J | 9.1E+04 | 9.9 |
| 8 | Services | 1.1E+00 | $ | 1.6E+13 | 1.7 |
| 9 | Total emergy | | | | 170.9 |
| 10 | Total millet yield, dry weight | 1.9E+05 | g | | |
| 11 | Total millet yield, energy | 4.1E+09 | J | | |
| 12 | Millet UEV, grams | 8.8E+09 | sej/g | | |
| 13 | Millet UEV, joules | 4.2E+05 | sej/J | | |
| 14 | Millet UEV w/o services | 4.2E+05 | sej/J | | |

Location: Oudalan Province, northern Burkina Faso

Main data source: Lars Krogh, 1997

### Notes, Table A.2

1 Sun

Annual net radiation = 113 W/m^2 (Maidment, WWB)

Area = 1.00E+04 m^2

Annual energy = (___W/m^2)(31,536,000sec/yr)(area)

Annual energy = 3.56E+13 J

Emergy per unit input = 1 sej/J (Odum, 1996)

2 Rain

Avg. annual rainfall = 450 mm (Krogh, 1997)

Area = 10,000 m^2

Annual energy = (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g)

Annual energy = 2.22E+10 J

Emergy per unit input = 3.10E+04 sej/J (Odum, 2000)

3 Evapotranspiration

Avg. annual ET = 428 mm (Ahn and Tateishi, 1992)

Area = 1.00E+04 m^2

Annual energy = (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g)

Annual energy = 2.11E+10 J

Emergy per unit input = 3.10E+04 sej/J

Notes, Table A.2 *continued*

| | | | | |
|---|---|---|---|---|
| 4 | **Seeds** | | | |
| | Avg. seeding rate in Mali = | 6.00 | kg/ha | (ABT, 2000) |
| | Energy content of seed = | 14,651 | J/g | (assume 3.5 kcal/g) |
| | Energy content = | (___g)(14,651 J/g) | | |
| | Annual energy = | 8.8E+07 | J/ha | |
| | Emergy per unit input = | 5.00E+05 | sej/J | (assumed) |
| 5 | **Manure** | | | |
| | P contribution from manure+cropresidue = | 0.40 | kg P/ha/yr | (Krogh, 1997) |
| | Average P content of manure = | 0.500 | P, % of DM | (FAO, Kenya study) |
| | Mass applied = | 0.75* (___kg P applied)/(____fraction P in manure DM) | | |
| | Mass applied = | 59.25 | kg/ha dry | (take out 25% from residues) |
| | Energy content = | 2.3E+04 | J/g | (Cohen diss., assumed) |
| | Annual energy applied = | (___kg/ha)(1,000 g/kg)(2.3E4 J/g) | | |
| | Annual energy = | 1.34E+09 | J/ha | |
| | Emergy per unit input = | 5.94E+05 | sej/J | (Odum and Odum, 1983) |
| 6 | **Net topsoil loss** | | | |
| | Erosion rate = | 12 | t/ha | based erosion data table |
| | % organic in soil = | 0.40 | % | (Krogh, 1997) |
| | Energy cont./g organic= | 5.40 | kcal/g | |
| | Organic matter in topsoil used up = | (total mass of topsoil)(% organic) | | |
| | = | 48000 | g/ha | |
| | Energy loss = | (loss of organic matter)(5.4 kcal/g)(4,186 J/kcal) | | |
| | Annual energy = | 1.09E+09 | J/ha | |
| | Emergy per unit input = | 9.12E+04 | sej/J | (Cohen, 2007) |
| 7 | **Labour** | | | |
| | #people working on farm = | 600 | pers-hr/ha | (Ker, 1995, millet in Gambia) |
| | Annual energy = | (pers-hr/ha/yr)*(day/8 hrs)*(2300 kcal/d)*(4,186J/kcal) | | |
| | Annual energy = | 7.22E+08 | J | |
| | Emergy per unit input = | 1.36E+05 | sej/J | (Odum and Odum, 1983) |
| 8 | **Services, $ per ha** | | | |
| | Seed cost = | 120 | fCFA/kg | (Mali price, ABT, 2000) |
| | $/yr spent on seed inputs = | (___kg seed)(fCFA/kg)(1$/664 fCFA) | | |
| | $/yr spent on seed inputs = | 1.08E+00 | $/yr | |
| | Burkina Faso emergy/$ ratio = | 1.60E+13 | sej/$ | |
| | Annual emergy = | 1.73E+13 | sej/yr | |
| 9 | **Total emergy** | | | |
| | Total emergy = | 1.7E+05 | sej/ha/yr | sum of items 3 through 8 |
| 10 | **Total yield, dry weight** | | | |
| | Estimated avg. yield = | 2.2E+05 | g/ha | (Krogh, 1997) |
| | Dry matter fraction = | 0.90 | | (Adeola et al, 1996) |
| | Dry weight, g = | 1.94E+05 | g/ha | |
| 11 | **Total yield, energy** | | | |
| | Energy content = | 1.89E+04 | J/g | (Adeola et al, 1996) |
| | Total yield, energy = | 4.06E+09 | J | |
| | **UEVs** | | | |
| 12 | UEV, grams = | 8.83E+09 | sej/g | item 9/item 10 |
| 13 | UEV, joules = | 4.21E+05 | sej/J | item 9/item 11 |
| 14 | UEV w/o services = | 4.2E+05 | | (item 9–item 8)/ item 11 |

## TABLE A.3

Emergy evaluation of millet, per ha per year (MI-t2).

| Note | Description | Data (per ha$^{-1}$ yr$^{-1}$) | Unit | UEV (sej/unit) | Emergy (E13 sej/yr) |
|---|---|---|---|---|---|
| RENEW | | | | | |
| 1 | Sun | 4.2E+13 | J | 1.0E+00 | 4.2 |
| 2 | Rain | 3.7E+10 | J | 3.1E+04 | 113.7 |
| 3 | Evapotranspiration | 2.9E+10 | J | 3.1E+04 | 88.6 |
| LOCAL TRANSFERS | | | | | |
| 4 | Seeds | 8.8E+07 | J | 5.0E+05 | 4.4 |
| 5 | Labour | 7.2E+08 | J | 1.4E+05 | 9.8 |
| NONRENEW | | | | | |
| 6 | Net topsoil loss | 2.8E+09 | J | 1.1E+05 | 31.3 |
| 7 | Services | 1.1E+00 | $ | 1.6E+13 | 1.7 |
| 8 | Total emergy | | | | 135.9 |
| 9 | Total millet yield, dry weight | 3.8E+05 | g | | |
| 10 | Total millet yield, energy | 7.9E+09 | J | | |
| 11 | Millet UEV, grams | 3.6E+09 | sej/g | | |
| 12 | Millet UEV, joules | 1.7E+05 | sej/J | | |
| 13 | UEV w/o services | 1.7E+05 | sej/J | | |

Location: Sapone village, 35 km south of Ouagadougou

Main data source: Bayala et al, 2002

Notes, Table A.3

| | | | | |
|---|---|---|---|---|
| 1 | **Sun** | | | |
| | Annual net radiation = | 132.5 | W/m^2 | (Maidment, WWB) |
| | Area = | 1.00E+04 | m^2 | |
| | Annual energy = | (___W/m^2)(31,536,000 sec/yr)(area) | | |
| | Annual energy = | 4.18E+13 | J | |
| | Emergy per unit input = | 1 | sej/J | (Odum, 1996) |
| 2 | **Rain** | | | |
| | Avg. annual rainfall = | 743 | mm | (Bayala et al, 2002) |
| | Area = | 10,000 | m^2 | |
| | Annual energy = | (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g) | | |
| | Annual energy = | 3.67E+10 | J | |
| | Emergy per unit input = | 3.10E+04 | sej/J | (Odum, 2000) |
| 3 | **Evapotranspiration** | | | |
| | Avg. annual ET = | 579 | mm | (Ahn and Tateishi, 1992) |
| | Area = | 1.00E+04 | m^2 | |
| | Annual energy = | (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g) | | |
| | Annual energy = | 2.86E+10 | J | |
| | Emergy per unit input = | 3.10E+04 | sej/J | |

Notes, Table A.3 *continued*

| | | | | |
|---|---|---|---|---|
| 4 | **Seeds** | | | |
| | Avg. seeding rate in Mali = | 6.00 | kg/ha | (ABT, 2000) |
| | Energy content of seed = | 14,651 | J/g | (assume 3.5 kcal/g) |
| | Energy content = | (____g)(14,651 J/g) | | |
| | Annual energy = | 8.8E+07 | J/ha | |
| | Emergy per unit input = | 5.00E+05 | sej/J | (assumed) |
| 6 | **Net topsoil loss** | | | |
| | Erosion rate = | 14 | t/ha | based on erosion data table |
| | % organic in soil = | 0.90 | % | (Bayala et al, 2002) |
| | Energy cont./g organic= | 5.40 | kcal/g | |
| | Organic matter in topsoil used up = | (total mass of topsoil)(% organic) | | |
| | = | 126,000 | g/ha | |
| | Energy loss = | (loss of organic matter)(5.4 kcal/g)(4186 J/kcal) | | |
| | Annual energy = | 2.85E+09 | J/ha | |
| | Emergy per unit input = | 1.10E+05 | sej/J | (Cohen, 2007) |
| 5 | **Labour** | | | |
| | #people working on farm = | 600 | pers-hr/ha | (Ker, 1995, millet in Gambia) |
| | Annual energy = | (pers-hr/ha/yr)*(day/8 hrs)*(2300 kcal/d)*(4,186J/kcal) | | |
| | Annual energy = | 7.22E+08 | J | |
| | Emergy per unit input = | 1.36E+05 | sej/J | (Odum and Odum, 1983) |
| 7 | **Services, $ per ha** | | | |
| | Seed cost = | 120 | fCFA/kg | (Mali price, ABT, 2000) |
| | $/yr spent on seed inputs = | (\_\_\_\_kg seed)(fCFA/kg)(1$/664 fCFA) | | |
| | $/yr spent on seed inputs = | 1.1 | $/yr | |
| | $/yr spent on pruning tool = | 0.10 | $/yr | |
| | Burkina Faso emergy/$ ratio = | 1.60E+13 | sej/$ | |
| | Annual emergy = | 1.89E+13 | sej/yr | |
| 8 | **Total emergy (Empower density)** | | | |
| | Total emergy = | 1.4E+15 | sej/ha/yr | sum of items 3 through 7 |
| 9 | **Total yield, dry weight** | | | |
| | Estimated avg. yield = | 4.2E+05 | g/ha | (Krogh, 1997) |
| | Dry matter fraction = | 0.90 | | (Adeola et al, 1996) |
| | Dry weight, g = | 3.78E+05 | g/ha | |
| 10 | **Total yield, energy** | | | |
| | Energy content = | 1.89E+04 | J/g | (Adeola et al, 1996) |
| | Total yield, energy = | 7.94E+09 | J | |
| | **UEVs** | | | |
| 11 | UEV, grams = | 3.60E+09 | sej/g | item 8/item 9 |
| 12 | UEV, joules = | 1.71E+05 | sej/J | item 8/item 10 |
| 13 | UEV w/o services = | 1.7E+05 | sej/J | (item 8–item 7)/item 10 |

## TABLE A.4

Emergy evaluation of millet in with mulch, per ha per year (MI-I1).

| Note | Description | Data (per ha$^{-1}$ yr$^{-1}$) | Unit | UEV (sej/unit) | Emergy (E13 sej/yr) |
|---|---|---|---|---|---|
| RENEW | | | | | |
| 1 | Sun | 4.18E+13 | J | 1 | 4.2 |
| 2 | Rain | 3.67E+10 | J | 3.10E+04 | 113.7 |
| 3 | Evapotranspiration | 2.86E+10 | J | 3.10E+04 | 88.6 |
| LOCAL TRANSFERS | | | | | |
| 4 | Seeds | 8.79E+07 | J | 5.00E+05 | 4.4 |
| 5 | Vitellaria mulch | 5.70E+09 | J | 2.03E+04 | 11.6 |
| 6 | Labour | 7.22E+08 | J | 1.36E+05 | 9.8 |
| NON-RENEW | | | | | |
| 7 | Net topsoil loss | 2.03E+09 | J | 1.10E+05 | 22.4 |
| 8 | Phosphate | 1.70E+04 | g P | 1.30E+10 | 22.1 |
| 9 | Services | 1.08E+00 | $ | 7.17E+13 | 7.8 |
| 10 | Total emergy | | | | 166.7 |
| 11 | Total millet yield, dry weight | 6.30E+05 | g | | |
| 12 | Total millet yield, energy | 1.32E+10 | J | | |
| 13 | Millet UEV, grams | 2.65E+09 | sej/g | | |
| 14 | Millet UEV, joules | 1.26E+05 | sej/J | | |
| 15 | UEV w/o services | 1.20E+05 | sej/J | | |

### Notes, Table A.4

1 Sun

Annual net radiation = 132.5 W/m^2 (Maidment, WWB)
Area = 1.00E+04 m^2
Annual energy = (___W/m^2)(31,536,000 sec/yr)(area)
Annual energy = 4.18E+13 J
Emergy per unit input = 1 sej/J (Odum, 1996)

2 Rain

Avg. annual rainfall = 743 mm (Bayala et al, 2002)
Area = 10,000 m^2
Annual energy = (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g)
Annual energy = 3.67E+10 J
Emergy per unit input = 3.10E+04 sej/J (Odum, 2000)

3 Evapotranspiration

Avg. annual ET = 579 mm (Ahn and Tateishi, 1992)
Area = 1.00E+04 m^2
Annual energy = (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g)
Annual energy = 2.86E+10 J
Emergy per unit input = 3.10E+04 sej/J

Notes, Table A.4 *continued*

| | | | | |
|---|---|---|---|---|
| 4 | **Seeds** | | | |
| | Avg. seeding rate in Mali = | 6.00 | kg/ha | (ABT, 2000) |
| | Energy content of seed = | 14,651 | J/g | (assume 3.5 kcal/g) |
| | Energy content = | (___g)(14,651 J/g) | | |
| | Annual energy = | 8.8E+07 | J/ha | |
| | Emergy per unit input = | 5.00E+05 | sej/J | (assumed) |
| 5 | **Vitellaria mulch** | | | |
| | Weight Vitellaria mulch applied = | 1,900.0 | kg/ha | (Bayala et al, 2003) |
| | Energy content of mulch = | 3,000 | J/g | assumed, fresh |
| | Annual energy = | (___kg/ha)(1,000 g/kg)(3,000 J/g) | | |
| | Annual energy = | 5.70E+09 | J/ha | |
| | Emergy per unit input = | 2.03E+04 | sej/J | (Doherty, 2002) |
| 6 | **Labour** | | | |
| | #people working on farm = | 600 | pers-hr/ha | (Ker, 1995) |
| | Annual energy = | (pers-hr/ha/yr)*(day/8 hrs)*(2,300 kcal/d)*(4,186J/kcal) | | |
| | Annual energy = | 7.22E+08 | J | |
| | Emergy per unit input = | 1.36E+05 | sej/J | (Odum and Odum, 1983) |
| 7 | **Net topsoil loss** | | | |
| | Erosion rate = | 10 | t/ha | based on erosion data table |
| | % organic in soil = | 0.90 | % | (Bayala et al, 2002) |
| | Energy cont./g organic= | 5.40 | kcal/g | |
| | Organic matter in topsoil used up = | (total mass of topsoil)(% organic) | | |
| | = | 90000 | g/ha | |
| | Energy loss = | (loss of organic matter)(5.4 kcal/g)(4,186 J/kcal) | | |
| | Annual energy = | 2.03E+09 | J/ha | |
| | Emergy per unit input = | 1.10E+05 | sej/J | (Cohen, 2006) |
| 8 | **Phosphate, g P per ha** | | | |
| | P from triple super P (TSP) fertilizer = | 17 | kg P/ha | (Bayala et al, 2003) |
| | Annual mass applied = | 17,000 | g | |
| | Emergy per unit input = | 1.30E+10 | sej/g | (Brandt-Williams, 2002) |
| 9 | **Services, $ per ha** | | | |
| | Seed cost = | 120 | fCFA/kg | (Mali price, ABT, 2000) |
| | $/yr spent on seed inputs = | (___kg seed)(fCFA/kg)(1$/664 fCFA) | | |
| | $/yr spent on seed inputs = | 1.08E+00 | $/yr | |
| | TSP price = | 0.2 | $/kg | (Bationo et al, 1997) |
| | $/yr spent on P inputs = | 3.40E+00 | $/yr | |
| | Total costs = | 4.48E+00 | $/yr | |
| | Burkina Faso emergy/$ ratio = | 1.60E+13 | sej/$ | |
| | Annual emergy = | 7.17E+13 | sej/yr | |
| 10 | **Total emergy (Empower density)** | | | |
| | Total emergy = | 1.67E+15 | sej/ha/yr | sum of items 3 through 9 |
| 11 | **Total yield, dry weight** | | | |
| | Estimated avg. yield = | 7.0E+05 | g/ha | (Bayala et al, 2003) |
| | Dry matter fraction = | 0.90 | | (Adeola et al, 1996) |
| | Dry weight, g = | 6.30E+05 | g/ha | |

Notes, Table A.4 *continued*

| | | | | |
|---|---|---|---|---|
| 12 | **Total yield, energy** | | | |
| | Energy content = | 1.89E+04 | J/g | (Adeola et al, 1996) |
| | Total yield, energy = | 1.32E+10 | J/ha | |
| | UEVs | | | |
| 13 | UEV, grams = | 2.65E+09 | sej/g | item 10/item 11 |
| 14 | UEV, joules = | 1.26E+05 | sej/J | item 10/item 12 |
| 15 | UEV w/o services = | 1.20E+05 | sej/J | (item 10–item 9) / item 12 |

## TABLE A.5

Emergy evaluation of rice, per ha per year (R-t1).

| Note | Description | Data (per $ha^{-1}$ $yr^{-1}$) | Unit | UEV (sej/unit) | Emergy (E13 sej/yr) |
|---|---|---|---|---|---|
| RENEW | | | | | |
| 1 | Sun | 3.2E+13 | J | 1.0E+00 | 3.2 |
| 2 | Rain | 1.6E+10 | J | 3.1E+04 | 49.0 |
| 3 | Evapotranspiration | 1.6E+10 | J | 3.1E+04 | 49.0 |
| LOCAL TRANSFERS | | | | | |
| 4 | Seeds | 1.5E+09 | J | 5.0E+05 | 75.0 |
| 5 | Irrigation water | 5.9E+10 | | 3.1E+04 | 183.8 |
| 6 | Labour | 1.8E+09 | J | 1.4E+05 | 25.1 |
| NONRENEW | | | | | |
| 7 | Net topsoil loss | 0.0E+00 | J | 7.8E+04 | 0.0 |
| 8 | Fuel | 2.2E+10 | J | 9.4E+04 | 211.4 |
| 9 | Phosphate | 2.1E+04 | g P | 1.3E+10 | 27.3 |
| 10 | Nitrogen | 1.2E+05 | g N | 1.6E+10 | 187.2 |
| 11 | Services | 1.6E+02 | $ | 1.9E+13 | 303.1 |
| 12 | Total emergy | | | | 1,061.9 |
| 13 | Total yield, dry weight | 5.0E+06 | g | | |
| 14 | Total yield, energy | 8.4E+10 | J | | |
| 15 | UEV, grams | 2.1E+09 | sej/g | | |
| 16 | UEV, joules | 1.3E+05 | sej/J | | |
| 17 | UEV w/o services | 9.1E+04 | sej/J | | |

Location: Senegal R. valley (Guede), near Podor, 16 35°N, 15 02°W

Main data source: Wopereis et al, 1999

Notes, Table A.5

| | | | | | |
|---|---|---|---|---|---|
| 1 | **Sun** | | | | |
| | | Annual net radiation = | 100.4 | W/m^2 | (Maidment, WWB) |
| | | Area = | 1.00E+04 | m^2 | |
| | | Annual energy = | (___W/m^2)(31,536,000 sec/yr)(area) | | |
| | | Annual energy = | 3.17E+13 | J | |
| | | Emergy per unit input = | 1 | sej/J | (Odum, 1996) |
| 2 | **Rain** | | | | |
| | | Avg. annual rainfall = | 320 | mm | (Wilmott GIS coverage) |
| | | Area = | 10,000 | m^2 | |
| | | Annual energy = | (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g) | | |
| | | Annual energy = | 1.58E+10 | J | |
| | | Emergy per unit input = | 3.10E+04 | sej/J | (Odum, Folio 2000) |
| 3 | **Evapotranspiration** | | | | |
| | | Avg. annual ET = | 320 | mm | (Ahn and Tateishi, 1992) |
| | | Area = | 1.00E+04 | m^2 | |
| | | Annual energy = | (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g) | | |
| | | Annual energy = | 1.58E+10 | J | |
| | | Emergy per unit input = | 3.10E+04 | sej/J | |
| 4 | **Seeds** | | | | |
| | | Avg. rice seeding rate in Mali = | 100.00 | kg/ha | (ABT, 2000) |
| | | Energy content of seed = | 15,000 | J/g | (FAO) |
| | | Energy content = | (___g)(15,000 J/g) | | |
| | | Annual energy = | 1.5E+09 | J/ha | |
| | | Emergy per unit input = | 5.00E+05 | sej/J | (assumed) |
| 5 | **Irrigation water** | | | | |
| | | Average volume of irrigation = | 12,000.0 | m^3/ha | (Palinisami) |
| | | Energy content = | (___m^3)(1E6 g/m3)(4.94 J/g) | | |
| | | Annual energy = | 5.93E+10 | J/ha | |
| | | Emergy per unit input = | 3.10E+04 | sej/J | (Odum, Folio 2000) |
| 6 | **Labour** | | | | |
| | | Lowland rice labour required = | 1,534 | pers-h/ha(Ker, 1995, Gambia values) | |
| | | #people working on farm = | 191.75 | pers-d/ha | (assume 8 hrs/d) |
| | | Annual energy = | (pers-d/ha/yr)*(2,300 kcal/day)*(4,186J/Cal) | | |
| | | Annual energy = | 1.85E+09 | J | |
| | | Emergy per unit input = | 1.36E+05 | sej/J | (Odum and Odum, 1983) |
| 7 | **Net topsoil loss** | | | | |
| | | Erosion rate = | 0 | t/ha | |
| | | % organic in soil = | 0.80 | % | (GIS layer) |
| | | Energy cont./g organic= | 5.40 | kcal/g | |
| | | Organic matter in topsoil used up = | (total mass of topsoil)(% organic) | | |
| | | = | 0 | g/ha | |
| | | Energy loss = | (loss of organic matter)(5.4 kcal/g)(4,186 J/kcal) | | |
| | | Annual energy = | 0.00E+00 | J/ha | |
| | | Emergy per unit input = | 7.80E+04 | sej/J | (Cohen, 2006) |

Notes, Table A.5 *continued*

| | | | | |
|---|---|---|---|---|
| 8 | **Fuel** | | | |
| | Gasoline use= | 170 | gal | (Perry, for Burkina) |
| | Annual energy = | (gallons fuel)(1.32E8 J/gal) | | |
| | Annual energy = | 2.24E+10 | J | |
| | Emergy per unit input = | 9.42E+04 | sej/J | (Bastiononi et al, 2005) |
| 9 | **Phosphate, g P per ha** | | | |
| | P from DAP fertilizer = | 21 | kg/ha | (Wopereis, 1999) |
| | Annual mass applied = | 21,000 | g | |
| | Emergy per unit input = | 1.30E+10 | sej/g | (Brandt-Williams, 2002) |
| 10 | **Nitrogen, g N per ha** | | | |
| | N from urea = | 117 | kg | (Wopereis, 1999) |
| | Annual mass N applied = | 11,7000 | g | |
| | Emergy per unit input = | 1.60E+10 | sej/g | (Brandt-Williams, 2002) |
| 11 | **Services, $ per ha** | | | |
| | Seed cost = | 190 | fCFA/kg | (Mali price, ABT, 2000) |
| | $/yr spent on seed inputs = | (\_\_\_kg seed)(fCFA/kg)(1$/512 fCFA) | | |
| | $/yr spent on seed inputs = | 3.71E+01 | $/yr | |
| | Total fertilizer cost = | 61,000 | cFCA/ha | (Donovan, 1999) |
| | $/yr spent on fertilizer inputs = | 1.19E+02 | $/yr | (512 fFCA/$, 1995) |
| | Total costs = | 1.56E+02 | $/yr | |
| | Senegal emergy/$ ratio = | 1.94E+13 | sej/$ | |
| | Annual emergy = | 3.03E+15 | sej/yr | |
| 12 | **Total emergy (Empower density)** | | | |
| | Total emergy = | 1.1E+16 | | sum of items 3 through 11 |
| 13 | **Total yield, dry weight** | | | |
| | Estimated avg. yield = | 5.6E+06 | g/ha | (Wopereis, 1999) |
| | Dry matter fraction = | 0.90 | | assumed |
| | Dry weight, g = | 5.01E+06 | g/ha | |
| 14 | **Total yield, energy** | | | |
| | Rice energy content = | 1.50E+04 | J/g | (FAO document) |
| | Yield energy content = | 8.36E+10 | J/ha | |
| | **UEVs** | | | |
| 15 | UEV, sej/g = | 2.1E+09 | sej/g | item 12/ item 13 |
| 16 | UEV, sej/J = | 1.3E+05 | sej/J | item 12/ item 14 |
| 17 | UEV w/o services = | 9.1E+04 | sej/J | (item 12–item 11) / item 14 |

## TABLE A.6

Emergy evaluation of rice with rice straw mulch, per ha per year (R-t2).

| Note | Description | Data (per ha$^{-1}$ yr$^{-1}$) | Unit | UEV (sej/unit) | Emergy (E13 sej/yr) |
|---|---|---|---|---|---|
| RENEW | | | | | |
| 1 | Sun | 2.8E+13 | J | 1.0E+00 | 2.8 |
| 2 | Rain | 2.0E+10 | J | 3.1E+04 | 62.2 |
| 3 | Evapotranspiration | 2.0E+10 | J | 3.1E+04 | 62.0 |
| LOCAL TRANSFERS | | | | | |
| 4 | Seeds | 1.5E+09 | J | 5.0E+05 | 75.0 |
| 5 | Irrigation water | 5.9E+10 | J | 3.1E+04 | 183.8 |
| 6 | Labour | 1.8E+09 | J | 1.4E+05 | 25.1 |
| NON-RENEW | | | | | |
| 7 | Net topsoil loss | 0.0E+00 | J | 8.0E+04 | 0.0 |
| 8 | Phosphate | 2.6E+04 | g P | 1.3E+10 | 33.8 |
| 9 | Nitrogen | 1.8E+05 | g N | 1.6E+10 | 280.0 |
| 10 | Services | 1.2E+02 | $ | 1.2E+14 | 1,445.8 |
| 11 | Total emergy | | | | 2,105.5 |
| 12 | Total yield, dry weight | 6.3E+06 | g | | |
| 13 | Total yield, energy | 1.1E+11 | J | | |
| 14 | UEV, grams | 3.3E+09 | sej/g | | |
| 15 | UEV, joules | 2.0E+05 | sej/J | | |
| 16 | UEV w/o services | 6.3E+04 | sej/J | | |

Location: central southern Mauritania, Foum Gleita irrigation scheme: 16 08° N, 12 46° W

Main data source: van Asten et al, 2005

### Notes, Table A.6

1 **Sun**

Annual net radiation = 88 W/m^2 (Maidment, WWB)
Area = 1.00E+04 m^2
Annual energy = (___W/m^2)(31,536,000 sec/yr)(area)
Annual energy = 2.78E+13 J
Emergy per unit input = 1 sej/J (Odum, 1996)

2 **Rain**

Avg. annual rainfall = 406 mm (Wilmott GIS coverage)
Area = 10,000 m^2
Annual energy = (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g)
Annual energy = 2.01E+10 J
Emergy per unit input = 3.10E+04 sej/J (Odum, Folio 2000)

3 **Evapotranspiration**

Avg. annual ET = 405 mm (Ahn and Tateishi, 1992)
Area = 1.00E+04 m^2
Annual energy = (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g)
Annual energy = 2.00E+10 J
Emergy per unit input = 3.10E+04 sej/J

Notes, Table A.6 *continued*

| | | | | |
|---|---|---|---|---|
| 4 | **Seeds** | | | |
| | Avg. rice seeding rate in Mali = | 100.00 | kg/ha | (ABT, 2000) |
| | Energy content of seed = | 15,000 | J/g | (FAO) |
| | Energy content = | (___g)(15,000 J/g) | | |
| | Annual energy = | 1.5E+09 | J/ha | |
| | Emergy per unit input = | 5.00E+05 | sej/J | (assumed) |
| 5 | **Irrigation water** | | | |
| | Average volume of irrigation = | 12,000.0 | m^3/ha | (Palinisami) |
| | Energy content = | (___m^3)(1E6 g/m3)(4.94 J/g) | | |
| | Annual energy = | 5.93E+10 | J/ha | |
| | Emergy per unit input = | 3.10E+04 | sej/J | (Odum, Folio 2000) |
| 6 | **Net topsoil loss** | | | |
| | Erosion rate = | 0 | t/ha | |
| | % organic in soil = | 0.40 | % | (van Asten, 2005) |
| | Energy cont./g organic= | 5.40 | kcal/g | |
| | Organic matter in topsoil used up = | (total mass of topsoil)(% organic) | | |
| | = | 0 | g/ha | |
| | Energy loss = | (loss of organic matter)(5.4 kcal/g)(4,186 J/kcal) | | |
| | Annual energy = | 0.00E+00 | J/ha | |
| | Emergy per unit input = | 8.00E+04 | sej/J | (Cohen, 2006) |
| 7 | **Phosphate, g P per ha** | | | |
| | triple super P (TSP) fertilizer = | 26 | kg/ha | (van Asten, 2005) |
| | Annual mass applied = | 26000 | g | |
| | Emergy per unit input = | 1.30E+10 | sej/g | (Brandt-Williams, 2002) |
| 8 | **Nitrogen, g N per ha** | | | |
| | N from urea = | 175 | kg | (van Asten, 2005) |
| | Annual mass N applied = | 175,000 | g | |
| | Emergy per unit input = | 1.60E+10 | sej/g | (Brandt-Williams, 2002) |
| 9 | **Labour** | | | |
| | Lowland rice labour required = | 1,534 | pers-h/ha | (Ker, 1995, Gambia values) |
| | #people working on farm = | 191.75 | pers-d/ha | (assume 8 hrs/d) |
| | Annual energy = | (pers-d/ha/yr)*(2,300 kcal/day)*(4,186J/Cal) | | |
| | Annual energy = | 1.85E+09 | J | |
| | Emergy per unit input = | 1.36E+05 | sej/J | (Odum and Odum, 1983) |
| 10 | **Services, $ per ha** | | | |
| | Seed cost = | 190 | fCFA/kg | (Mali price, ABT, 2000) |
| | $/yr spent on seed inputs = | (___kg seed)(fCFA/kg)(1$/664 fCFA) | | |
| | $/yr spent on seed inputs = | 2.86E+01 | $/yr | |
| | Total fertilizer cost = | 61,000 | fCFA/ha | (Donovan, 1999, Senegal data) |
| | $/yr spent on fertilizer = | 9.19E+01 | $/yr | |
| | Total costs = | 1.20E+02 | $/yr | |
| | Mauritania emergy/$ ratio = | 1.20E+14 | sej/$ | |
| | Annual emergy = | 1.45E+16 | sej/yr | |
| 11 | **Total emergy (Empower)** | | | |
| | Total emergy = | | | sum of items 3 through 10 |

Notes, Table A.6 *continued*

| | | | | |
|---|---|---|---|---|
| 12 | **Total yield, dry weight** | | | |
| | Estimated avg. yield = | 7.0E+06 | g/ha | (van Asten, 2005) |
| | Dry matter fraction = | 0.90 | | assumed |
| | Dry weight, g = | 6.30E+06 | g/ha | |
| 13 | **Total yield, energy** | | | |
| | Rice energy content = | 1.50E+04 | J/g | (FAO document) |
| | Yield energy content = | 1.05E+11 | J/ha | |
| | **UEVs** | | | |
| 14 | UEV, sej/g = | 3.3E+09 | sej/g | item 11/ item 12 |
| 15 | UEV, sej/J = | 2.0E+05 | sej/J | item 11/ item 13 |
| 16 | UEV w/o services, sej/J = | 6.3E+04 | sej/J | (item 11–item 10) / item 13 |

## TABLE A.7

Emergy evaluation of maize, traditional fallow, per ha per year (MA-t1).

| Note | Description | Data (per ha$^{-1}$ yr$^{-1}$) | Unit | UEV (sej/unit) | Emergy (E13 sej/yr) |
|---|---|---|---|---|---|
| RENEW | | | | | |
| 1 | Sun | 3.82E+13 | J | 1.0E+00 | 3.8 |
| 2 | Rain | 4.20E+10 | J | 3.1E+04 | 130.3 |
| 3 | Evapotranspiration | 3.22E+10 | J | 3.1E+04 | 99.9 |
| LOCAL TRANSFERS | | | | | |
| 4 | Maize seeds | 7.76E+08 | J | 6.4E+04 | 5.0 |
| 5 | Labour | 3.21E+08 | J | 1.4E+05 | 4.4 |
| NON-RENEW | | | | | |
| 6 | Net topsoil loss | 1.57E+09 | J | 1.3E+05 | 19.6 |
| 7 | Services | 3.33E-01 | $ | 3.8E+13 | 1.3 |
| 8 | Total emergy | | | | 130.1 |
| 9 | Total yield, dry weight | 2.38E+05 | g | | |
| 10 | Total yield, energy | 3.55E+09 | J | | |
| 11 | UEV, grams | 5.47E+09 | sej/g | | |
| 12 | UEV, joules | 3.67E+05 | sej/J | | |
| 13 | UEV w/o services | 3.63E+05 | sej/J | | |

Location: Koutilala region farm, Mali

Main data source: Kaya and Nair, 2001

Notes, Table A.7

| | | | | |
|---|---|---|---|---|
| 1 | **Sun** | | | |
| | Annual net radiation = | 121 | W/m^2 | (Maidment, WWB) |
| | Area = | 1.00E+04 | m^2 | |
| | Annual energy = | (___W/m^2)(31,536,000 sec/yr)(area) | | |
| | Annual energy = | 3.82E+13 | J | |
| | Emergy per unit input = | 1 | sej/J | (Odum, 1996) |
| 2 | **Rain** | | | |
| | Avg. annual rainfall = | 851 | mm | (Kaya and Nair, 2001) |
| | Area = | 10,000 | m^2 | |
| | Annual energy = | (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g) | | |
| | Annual energy = | 4.20E+10 | J | |
| | Emergy per unit input = | 3.10E+04 | sej/J | (Odum, 2000) |
| 3 | **Evapotranspiration** | | | |
| | Avg. annual ET = | 653 | mm | (Ahn and Tateishi, 1992) |
| | Area = | 1.00E+04 | m^2 | |
| | Annual energy = | (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g) | | |
| | Annual energy = | 3.22E+10 | J | |
| | Emergy per unit input = | 3.10E+04 | sej/J | |
| 4 | **Maize seeds planted =** | 80cm x 50cm spacing | | (Kaya and Nair, 2001) |
| | Seeds planted at end of fallow = | 6.25E+05 | #/ha | |
| | Seeds planted per year = | 2.08E+05 | #/ha/yr | |
| | Mass of seeds planted = | 0.25 | g/seed | |
| | Annual energy = | (___#seeds)(g/seed)(14.9 kJ/g)(1,000J/kJ) | | |
| | Annual energy = | 7.76E+08 | J | |
| | Emergy per unit input = | 6.40E+04 | sej/J | (Cohen, diss.) |
| 5 | **Labour** | | | |
| | pers-days= | 100 | pers-d/ha | (Franzel et al, 1999) |
| | Annual energy = | (pers-days/ha/yr)*(2,300 kcal/d)*(4,186J/Cal)/3yr | | |
| | Annual energy = | 3.21E+08 | J | |
| | Emergy per unit input = | 1.36E+05 | sej/J | (Odum and Odum, 1983) |
| 6 | **Net topsoil loss** | | | |
| | Erosion rate, cultivated = | 26 | ton/ha/yr (Roose, 1985, in Bodnar et al, 2006) | |
| | Erosion rate, fallow = | 13 | ton/ha/yr | (assume 0.5*cultivated loss rate) |
| | % organic in soil = | 0.40 | % | (GIS layer) |
| | Energy cont./g organic= | 5.40 | kcal/g | |
| | Net loss of OM= | (3yr avg. t/ha)(1e6 g/t)(fraction organic) | | |
| | = | 6.93E+04 | g/ha | |
| | Energy loss = | (loss of organic matter)(5.4 kcal/g)(4,186 J/kcal) | | |
| | Annual energy = | 1.57E+09 | | |
| | Emergy per unit input = | 1.25E+05 | | (GIS model, Cohen, 2006) |
| | total emergy inputs = | | sum of items 3 through 10 | |
| 7 | **Services, $ per ha** | | | |
| | Rock P price = | 0 | $/g | (IDE, 2003) |
| | Total $ spent on inputs = | 3.33E-01 | $/3yrs | Assume $1/yr for tools |
| | Mali emergy/$ ratio = | 3.80E+13 | sej/$ | (Sweeney et al, 2007) |
| | Annual emergy = | 4.22E+12 | sej/yr | |

Notes, Table A.7 *continued*

| | | | | |
|---|---|---|---|---|
| 8 | **Total emergy (Empower density)** | | | sum of items 3 through 7 |
| | Total emergy = | 1.3E+15 | sej/ha/yr | |
| 9 | **Total yield, dry weight** | | | |
| | Estimated avg. yield = | 7.1E+05 | g/ha | (Kaya and Nair, 2001) |
| | Dry weight, g = | 7.14E+05 | g/ha | |
| | Yield per three year cycle = | 2.38E+05 | g/ha | |
| 10 | **Total yield, energy** | | | |
| | Energy content = | 14.9 | kJ/g | (FAO, 1997, maize) |
| | Energy content = | 3.55E+09 | J/ha | |
| | **UEV** | | | |
| 11 | UEV, grams = | 5.47E+09 | sej/g | item 8/item 9 |
| 12 | UEV, joules = | 3.67E+05 | sej/J | item 8/item 10 |
| 13 | UEV, w/o services = | 3.63E+05 | sej/J | (item 8–item 7)/ item 10 |

## TABLE A.8

Emergy evaluation of maize with improved fallow, per ha per year (MA-i1).

| Note | Description | Data (ha$^{-1}$ yr$^{-1}$) | Unit | UEV (sej/unit) | Emergy (E13 sej/yr) |
|---|---|---|---|---|---|
| RENEW | | | | | |
| 1 | Sun | 3.82E+13 | J | 1.0E+00 | 3.8 |
| 2 | Rain | 4.20E+10 | J | 3.1E+04 | 130.3 |
| 3 | Evapotranspiration | 3.22E+10 | J | 3.1E+04 | 99.9 |
| LOCAL TRANSFERS | | | | | |
| 4 | *Gliricidia* tree seedlings | 4.06E+08 | J | 1.3E+05 | 5.1 |
| 5 | Stylo seeds | 7.33E+07 | J | 1.2E+05 | 0.9 |
| 6 | Maize seeds | 7.76E+08 | J | 6.4E+04 | 5.0 |
| 7 | Labour | 6.38E+08 | J | 1.4E+05 | 8.7 |
| NON-RENEW | | | | | |
| 8 | Net topsoil loss | 1.24E+09 | J | 1.3E+05 | 15.4 |
| 9 | Phosphate | 1.00E+05 | g P | 1.1E+10 | 110.0 |
| 10 | Services | 3.46E+01 | $ | 3.8E+13 | 131.6 |
| 11 | Total emergy | | | | 376.7 |
| 12 | Total yield, dry weight | 9.64E+05 | g | | |
| 13 | Total yield, energy | 1.44E+10 | J | | |
| 14 | UEV, grams | 3.91E+09 | sej/g | | |
| 15 | UEV, joules | 2.62E+05 | sej/J | | |
| 16 | UEV w/o services | 1.71E+05 | sej/J | | |

Location: Koutilala region, Mali

Main data source: Kaya and Nair, 2001

## Notes, Table A.8

| | | | | | |
|---|---|---|---|---|---|
| 1 | **Sun** | | | | |
| | | Annual net radiation = | 121 | W/m^2 | (Maidment, WWB) |
| | | Area = | 1.00E+04 | m^2 | |
| | | Annual energy = | (___W/m^2)(31,536,000 sec/yr)(area) | | |
| | | Annual energy = | 3.82E+13 | J | |
| | | Emergy per unit input = | 1 | sej/J | (Odum, 1996) |
| 2 | **Rain** | | | | |
| | | Avg. annual rainfall = | 851 | mm | (Kaya and Nair, 2001) |
| | | Area = | 10,000 | m^2 | |
| | | Annual energy = | | (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g) | |
| | | Annual energy = | 4.20E+10 | J | |
| | | Emergy per unit input = | 3.10E+04 | sej/J | (Odum, 2000) |
| 3 | **Evapotranspiration** | | | | |
| | | Avg. annual ET = | 653 | mm | (Ahn and Tateishi, 1992) |
| | | Area = | 1.00E+04 | m^2 | |
| | | Annual energy = | (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g) | | |
| | | Annual energy = | 3.22E+10 | J | |
| | | Emergy per unit input = | 3.10E+04 | sej/J | |
| 4 | **Tree seedlings** | | | | |
| | | *Gliricidia* seedlings planted = | 1,250 | #/ha/3yrs | (Kaya and Nair, 2001) |
| | | Assumed weight = | 50.0 | g/seedling | |
| | | Energy content = | 19,500 | J/g | (Doherty, 2002) |
| | | Annual energy = | (seedling mass)(#seedlings)(19.5E3 J/g) / 3years | | |
| | | Annual energy = | 4.06E+08 | J | |
| | | Emergy per unit input = | 1.26E+05 | sej/J | (Cohen, 2003) |
| 5 | **Stylo seeds** | | | | |
| | | *Stylosanthes* seeds dispersed = | 15 | kg/ha/3yrs | (Kaya and Nair, 2001) |
| | | Annual energy = | (seed mass)(3.5 kcal/g)(4,186J/kcal) / 3 years | | |
| | | Annual energy = | 7.33E+07 | J | |
| | | Emergy per unit input = | 1.2E+05 | sej/J | (groundnut, Cohen, 2003) |
| 6 | **Maize seeds** | | | | |
| | | Maize seeds planted = | 80cm x 50cm spacing | | (Kaya and Nair, 2001) |
| | | Seeds planted at end of fallow = | 6.25E+05 | #/ha | |
| | | Seeds planted per year = | 2.08E+05 | #/ha/yr | |
| | | Mass of seeds planted = | 0.25 | g/seed | |
| | | Annual energy = | (___#seeds)(g/seed)(14.9 kJ/g)(1,000J/kJ) | | |
| | | Annual energy = | 7.76E+08 | J | |
| | | Emergy per unit input = | 6.40E+04 | sej/J | (Cohen, 2003) |
| 7 | **Labour** | | | | |
| | | Avg. pers-days, maize= | 88 | pers-d/ha/3yr | (Franzel et al, 1999) |
| | | Avg. pers-days, *gliricidia*= | 95 | pers-d/ha/3yr | (Nelson et al, 1998) |
| | | Annual energy = | (pers-days/ha/3yr)*(2,500 kcal/day)*(4,186J/Cal)/3yrs | | |
| | | Annual energy = | 6.38E+08 | J/yr | |
| | | Emergy per unit input = | 1.36E+05 | sej/J | (Odum and Odum, 1983) |

Notes, Table A.8 *continued*

| | | | | | |
|---|---|---|---|---|---|
| 8 | **Net topsoil loss** | | | | |
| | Erosion rate, cultivated = | 15 | ton/ha/yr | (Roose, 1985, in Bodnar et al, 2006) | |
| | Erosion rate, fallow = | 13 | ton/ha/yr | (assume 0.5*cultivated loss rate of 26) | |
| | % organic in soil = | 0.40 | % | | (GIS layer) |
| | Energy cont./g organic= | 5.40 | kcal/g | | |
| | Net loss of OM= | (3yr avg. t/ha)(1e6 g/t)(fraction organic) | | | |
| | = | 5.47E+04 | g/ha | | |
| | Energy loss = | | | (loss of organic matter)(5.4 kcal/g)(4,186 J/kcal) | |
| | Annual energy = | 1.24E+09 | | | |
| | Emergy per unit input = | 1.25E+05 | | | (GIS model, Cohen, 2006) |
| 9 | **Phosphate, g P per ha** | | | | |
| | Rock phosphate applied = | 300 | kg/3yr fallow | | |
| | Rock P applied per year = | 100 | kg | | |
| | Annual mass applied = | 100,000 | g | | |
| | Emergy per unit input = | 1.10E+10 | sej/g | | (Odum, 1996) |
| 10 | **Services, $ per ha** | | | | |
| | Rock P price = | 6.84E-05 | $/g | | (Bationo et al, 1997) |
| | *Gliricidia* seedling price = | 0.043 | $/seedling | 53.418803 | (Kaya et al, 2000) |
| | *Stylosanthes* seeds price = | 0.002 | $/g | 30 | (Kaya et al, 2000) |
| | Total $ spent on inputs = | 1.04E+02 | $/3yrs | | |
| | Mali emergy/$ ratio = | 3.80E+13 | sej/$ | | (Sweeney et al, 2006) |
| | Annual emergy = | 1.32E+15 | sej/yr | | |
| 11 | **Total emergy (Empower density**) | | | | |
| | Total emergy = | 3.77E+15 | sej/ha/yr | | sum of items 3 through 10 |
| 12 | **Total yield, dry weight** | | | | |
| | Estimated avg. yield = | 2.9E+06 | g/ha | | (Kaya and Nair, 2001) |
| | Dry weight, g = | 2.89E+06 | g/ha | | |
| | Yield per three year cycle = | 9.64E+05 | g/ha/yr | | |
| 13 | **Total yield, energy** | | | | |
| | Energy content = | 14.9 | kJ/g | | (FAO, 1997, maize) |
| | Energy content = | 1.44E+10 | J/yr | | |
| | **UEV** | | | | |
| 14 | UEV, grams = | 3.91E+09 | sej/g | | item 11/item 12 |
| 15 | UEV, joules = | 2.62E+05 | sej/J | | item 11/item 13 |
| 16 | UEV. w/o services = | 1.71E+05 | sej/J | | (item 11–item 10) / item 13 |

## TABLE A.9

Emergy evaluation of maize, traditional fallow, per ha per year (MA-t2).

| Note | Description | Data (per ha$^{-1}$ yr$^{-1}$) | Unit | UEV (sej/unit) | Emergy (E13 sej/yr) |
|---|---|---|---|---|---|
| RENEW | | | | | |
| 1 | Sun | 3.82E+13 | J | 1 | 3.8 |
| 2 | Rain | 4.37E+10 | J | 3.10E+04 | 135.5 |
| 3 | Evapotranspiration | 3.35E+10 | J | 3.10E+04 | 103.9 |
| LOCAL TRANSFERS | | | | | |
| 4 | Maize seeds | 7.76E+08 | J | 6.40E+04 | 5.0 |
| 5 | Labour | 3.21E+08 | J | 1.36E+05 | 4.4 |
| NON-RENEW | | | | | |
| 6 | Net topsoil loss | 1.57E+09 | J | 1.25E+05 | 19.6 |
| 7 | Services | 3.33E-01 | $ | 3.80E+13 | 1.3 |
| 8 | Total emergy | | | | 134.1 |
| 9 | Total yield, dry weight | 2.32E+05 | g | | |
| 10 | Total yield, energy | 3.46E+09 | J | | |
| 11 | UEV, grams | 5.77E+09 | sej/g | | |
| 12 | UEV, joules | 3.87E+05 | sej/J | | |
| 13 | UEV w/o services | 3.84E+05 | sej/J | | |

Location: Koutilala region, experimental station, Mali

Main data source: Kaya and Nair, 2001

Notes, Table A.9

| | | | | | |
|---|---|---|---|---|---|
| 1 | Sun | | | | |
| | | Annual net radiation = | 121 | W/m^2 | (Maidment, WWB) |
| | | Area = | 1.00E+04 | m^2 | |
| | | Annual energy = | (___W/m^2)(31,536,000 sec/yr)(area) | | |
| | | Annual energy = | 3.82E+13 | J | |
| | | Emergy per unit input = | 1 | sej/J | (Odum, 1996) |
| 2 | Rain | | | | |
| | | Avg. annual rainfall = | 885 | mm | (Kaya and Nair, 2001) |
| | | Area = | 10,000 | m^2 | |
| | | Annual energy = | (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g) | | |
| | | Annual energy = | 4.37E+10 | J | |
| | | Emergy per unit input = | 3.10E+04 | sej/J | (Odum, 2000) |
| 3 | Evapotranspiration | | | | |
| | | Avg. annual ET = | 679 | mm | (Ahn and Tateishi, 1992) |
| | | Area = | 1.00E+04 | m^2 | |
| | | Annual energy = | (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g) | | |
| | | Annual energy = | 3.35E+10 | J | |
| | | Emergy per unit input = | 3.10E+04 | sej/J | |

Notes, Table A.9 *continued*

| | | | | |
|---|---|---|---|---|
| 4 | **Maize seeds** | | | |
| | Maize seeds planted = | 80cm x 50cm spacing | | (Kaya and Nair, 2001) |
| | Seeds planted at end of fallow = | 6.25E+05 | #/ha | |
| | Seeds planted per year = | 2.08E+05 | #/ha/yr | |
| | Mass of seeds planted = | 0.25 | g/seed | |
| | Annual energy = | (___#seeds)(g/seed)(14.9 kJ/g)(1,000J/kJ) | | |
| | Annual energy = | 7.76E+08 | J | |
| | Emergy per unit input = | 6.40E+04 | sej/J | (Cohen, diss.) |
| 5 | **Labour** | | | |
| | assumed avg. pers-days= | 100 | pers-d/ha | (Franzel et al, 1999) |
| | Annual energy = | (pers-days/ha/yr)*(2,300 kcal/d)*(4,186J/Cal)/3yr | | |
| | Annual energy = | 3.21E+08 | J | |
| | Emergy per unit input = | 1.36E+05 | sej/J | (Odum and Odum, 1983) |
| 6 | **Net topsoil loss** | | | |
| | Erosion rate, cultivated = | 26 | ton/ha/yr (Roose, 1985, in Bodnar et al, 2006) | |
| | Erosion rate, fallow = | 13 | ton/ha/yr (assume 0.5*cultivated loss rate) | |
| | % organic in soil = | 0.40 | % | (GIS layer) |
| | Energy cont./g organic= | 5.40 | kcal/g | |
| | Net loss of OM= | (3yr avg. t/ha)(1e6 g/t)(fraction organic) | | |
| | = | 6.93E+04 | g/ha | |
| | Energy loss = | (loss of organic matter)(5.4 kcal/g)(4,186 J/kcal) | | |
| | Annual energy = | 1.57E+09 | | |
| | Emergy per unit input = | 1.25E+05 | | (GIS model, Cohen, 2006) |
| 7 | **Services, $ per ha** | | | |
| | Rock P price = | 0 | $/g | (IDE, 2003) |
| | Maize seed price = | 0 | $/g | |
| | Total $ spent on inputs = | 3.33E-01 | $/3yrs | $1/yr for tools |
| | Mali emergy/$ ratio = | 3.80E+13 | sej/$ | (Sweeney et al, 2006) |
| | Annual emergy = | 4.22E+12 | sej/yr | |
| 8 | **Total emergy (Empower density)** | | | |
| | Total emergy = | 1.34E+15 | sej/ha/yr | sum of items 3 through 7 |
| 9 | **Total yield, dry weight** | | | |
| | Dry weight grain yield = | 7.0E+05 | g/ha | (Kaya and Nair, 2001) |
| | Yield per three year cycle = | 2.3E+05 | g/ha/yr | |
| 10 | **Total yield, energy** | | | |
| | Energy content = | (___g/ha)(14.9 kJ/g)(1,000J/kJ)/3 years | | |
| | Total energy content = | 3.46E+09 | J/yr | (FAO, 1997, maize) |
| | **UEV** | | | |
| 11 | UEV, grams = | 5.77E+09 | sej/g | item 8/item 9 |
| 12 | UEV, joules = | 3.87E+05 | sej/J | item 8/item 10 |
| 13 | UEV, w/o services = | 3.84E+05 | sej/J | (item 8–item 7)/item 10 |

## TABLE A.10

Emergy evaluation of maize, fallow with manure, per ha per year (MA-t3).

| Note | Description | Data (per $ha^{-1}$ $yr^{-1}$) | Unit | UEV (sej/unit) | Emergy (E13 sej/yr) |
|---|---|---|---|---|---|
| RENEW | | | | | |
| 1 | Sun | 3.82E+13 | J | 1 | 3.8 |
| 2 | Rain | 4.37E+10 | J | 3.10E+04 | 135.5 |
| 3 | Evapotranspiration | 3.35E+10 | J | 3.10E+04 | 103.9 |
| LOCAL TRANSFERS | | | | | |
| 4 | Manure from off-farm | 5.58E+09 | J | 1.14E+05 | 63.3 |
| 5 | Maize seeds | 7.76E+08 | J | 6.40E+04 | 5.0 |
| 6 | Labour | 3.53E+08 | J | 1.36E+05 | 4.8 |
| NON-RENEW | | | | | |
| 7 | Net topsoil loss | 1.39E+09 | J | 1.25E+05 | 17.3 |
| 8 | Services | 3.33E-01 | $ | 3.80E+13 | 1.3 |
| 9 | Total emergy | | | | 195.7 |
| 10 | Total yield, dry weight | 5.31E+05 | g | | |
| 11 | Total yield, energy | 7.91E+09 | J | | |
| 12 | UEV, grams | 3.68E+09 | sej/g | | |
| 13 | UEV, joules | 2.47E+05 | sej/J | | |
| 14 | UEV w/o services | 2.46E+05 | sej/J | | |

Location: Koutilala region, Mali

Main data source: Kaya and Nair, 2001

Notes, Table A.10

| | | | | | |
|---|---|---|---|---|---|
| 1 | Sun | | | | |
| | | Annual net radiation = | 121 | W/m^2 | (Maidment, WWB) |
| | | Area = | 1.00E+04 | m^2 | |
| | | Annual energy = | (___W/m^2)(31,536,000 sec/yr)(area) | | |
| | | Annual energy = | 3.82E+13 | J | |
| | | Emergy per unit input = | 1 | sej/J | (Odum, 1996) |
| 2 | Rain | | | | |
| | | Avg. annual rainfall = | 885 | mm | (Kaya and Nair, 2001) |
| | | Area = | 10,000 | m^2 | |
| | | Annual energy = | (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g) | | |
| | | Annual energy = | 4.37E+10 | J | |
| | | Emergy per unit input = | 3.10E+04 | sej/J | (Odum, 2000) |
| 3 | Evapotranspiration | | | | |
| | | Avg. annual ET = | 679 | mm | (Ahn and Tateishi, 1992) |
| | | Area = | 1.00E+04 | m^2 | |
| | | Annual energy = | (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g) | | |
| | | Annual energy = | 3.35E+10 | J | |
| | | Emergy per unit input = | 3.10E+04 | sej/J | |

Notes, Table A.10 *continued*

| | | | | |
|---|---|---|---|---|
| 4 | **Manure** | | | |
| | Manure applied = | 3,333.33 | kg/ha/yr | (Kaya and Nair, 2001) |
| | Dry weight = | 333.33 | kg/ha | (assume 10% dry matter) |
| | Energy content = | 1.7E+04 | J/g | (Cohen, 2003) |
| | Annual energy applied = | (___kg/ha)(1,000 g/kg)(1.7E4 J/g) | | |
| | Annual energy = | 5.58E+09 | J/ha | |
| | Emergy per unit input = | 1.14E+05 | sej/J | (Odum and Odum, 1983) |
| 5 | **Maize seeds** | | | |
| | Maize seeds planted = | 80cm x 50cm spacing | | (Kaya and Nair, 2001) |
| | Seeds planted at end of fallow = | 6.25E+05 | #/ha | |
| | Seeds planted per year = | 2.08E+05 | #/ha/yr | |
| | Mass of seeds planted = | 0.25 | g/seed | |
| | Annual energy = | (___#seeds)(g/seed)(14.9 kJ/g)(1000J/kJ) | | |
| | Annual energy = | 7.76E+08 | J | |
| | Emergy per unit input = | 6.40E+04 | sej/J | (Cohen, 2003) |
| 6 | **Labour** | | | |
| | assumed avg. pers-days= | 110 | pers-d/ha | (Franzel et al, 1999) |
| | Annual energy = | (pers-days/ha/yr)*(2,300 kcal/d)*(4,186J/Cal)/3yr | | |
| | Annual energy = | 3.53E+08 | J | |
| | Emergy per unit input = | 1.36E+05 | sej/J | (Odum and Odum, 1983) |
| 7 | **Net topsoil loss** | | | |
| | Erosion rate, cultivated = | 20 | ton/ha/yr | (Roose, 1985, in Bodnar et al, 2006) |
| | Erosion rate, fallow = | 13 | ton/ha/yr | (assume 0.5*cultivated loss rate) |
| | % organic in soil = | 0.40 | % | (GIS layer) |
| | Energy cont./g organic= | 5.40 | kcal/g | |
| | Net loss of OM= | (3yr avg. t/ha)(1e6 g/t)(fraction organic) | | |
| | = | 6.13E+04 | g/ha | |
| | Energy loss = | (loss of organic matter)(5.4 kcal/g)(4,186 J/kcal) | | |
| | Annual energy = | 1.39E+09 | | |
| | Emergy per unit input = | 1.25E+05 | | (GIS model, Cohen, 2006) |
| 8 | **Services, $ per ha** | | | |
| | Rock P price = | 0 | $/g | (IDE, 2003) |
| | Maize seed price = | 0 | $/g | |
| | Total $ spent on inputs = | 3.33E-01 | $/3yrs | $1/yr for tools |
| | Mali emergy/$ ratio = | 3.80E+13 | sej/$ | (Sweeney et al, 2006) |
| | Annual emergy = | 4.22E+12 | sej/yr | |
| 9 | **Total emergy (Empower density)** | | | |
| | Total emergy = | 1.96E+15 | sej/ha/yr | sum of items 3 through 8 |
| 10 | **Total yield, dry weight** | | | |
| | Dry weight grain yield = | 1.6E+06 | g/ha | (Kaya and Nair, 2001) |
| | Yield per three year cycle = | 5.3E+05 | g/ha/yr | |
| 11 | **Total yield, energy** | | | |
| | Energy content = | (___g/ha)(14.9 kJ/g)(1000J/kJ)/3 years | | |
| | Energy content = | 7.91E+09 | J/yr | (FAO, 1997, maize) |
| | **UEV** | | | |
| 12 | UEV, grams = | 3.68E+09 | sej/g | item 9/item 10 |
| 13 | UEV, joules = | 2.47E+05 | sej/J | item 9/item 11 |
| 14 | UEV. w/o services = | 2.46E+05 | sej/J | (item 9–item 8) / item 11 |

## TABLE A.11

Emergy evaluation of maize, fallow with biomass transfer, per ha per year (MA-i3).

| Note | Description | Data (per $ha^{-1}$ $yr^{-1}$) | Unit | UEV (sej/unit) | Emergy (E13 sej/yr) |
|---|---|---|---|---|---|
| RENEW | | | | | |
| 1 | Sun | 3.82E+13 | J | 1 | 3.8 |
| 2 | Rain | 4.37E+10 | J | 3.10E+04 | 135.5 |
| 3 | Evapotranspiration | 3.35E+10 | J | 3.10E+04 | 103.9 |
| LOCAL TRANSFERS | | | | | |
| 4 | Maize seeds | 7.76E+08 | J | 6.40E+04 | 5.0 |
| 5 | Improved fallow biomass transfer | 1.56E+10 | J | 2.03E+04 | 31.7 |
| 6 | Labour | 3.53E+08 | J | 1.36E+05 | 4.8 |
| NON-RENEW | | | | | |
| 7 | Net topsoil loss | 1.24E+09 | J | 1.25E+05 | 15.4 |
| 8 | Services | 1.00E+00 | $ | 3.80E+13 | 3.8 |
| 9 | Total emergy | | | | 164.6 |
| 10 | Total yield, dry weight | 9.46E+05 | g | | |
| 11 | Total yield, energy | 1.41E+10 | J | | |
| 12 | UEV, grams | 1.74E+09 | sej/g | | |
| 13 | UEV, joules | 1.17E+05 | sej/J | | |
| 14 | UEV w/o services | 1.14E+05 | sej/J | | |

Location: Koutilala region, Mali

Main data source: Kaya and Nair, 2001

### Notes, Table A.11

1 **Sun**

Annual net radiation = 121 W/m^2 (Maidment, WWB)

Area = 1.00E+04 m^2

Annual energy = (___W/m^2)(31,536,000 sec/yr)(area)

Annual energy = 3.82E+13 J

Emergy per unit input = 1 sej/J (Odum, 1996)

2 **Rain**

Avg. annual rainfall = 885 mm (Kaya and Nair, 2001)

Area = 10,000 m^2

Annual energy = (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g)

Annual energy = 4.37E+10 J

Emergy per unit input = 3.10E+04 sej/J (Odum, 2000)

3 **Evapotranspiration**

Avg. annual ET = 679 mm (Ahn and Tateishi, 1992)

Area = 1.00E+04 m^2

Annual energy = (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g)

Annual energy = 3.35E+10 J

Emergy per unit input = 3.10E+04 sej/J

Notes, Table A.11 *continued*

| | | | | |
|---|---|---|---|---|
| 4 | **Maize seeds** | | | |
| | Maize seeds planted = | 80cm x 50cm spacing | | (Kaya and Nair, 2001) |
| | Seeds planted at end of fallow = | 6.25E+05 | #/ha | |
| | Seeds planted per year = | 2.08E+05 | #/ha/yr | |
| | Mass of seeds planted = | 0.25 | g/seed | |
| | Annual energy = | (___#seeds)(g/seed)(14.9 kJ/g)(1000J/kJ) | | |
| | Annual energy = | 7.76E+08 | J | |
| | Emergy per unit input = | 6.40E+04 | sej/J | (Cohen, 2003) |
| 5 | **Biomass transfer** | | | |
| | N content of Gliricidia applied = | 60.0 | kg/ha/3yr | (Kaya and Nair, 2001) |
| | avg. fraction of N in Gliricidia = | 0.025 | kgN/kg *Gliricidia* DM | (ICRAF, 1995) |
| | Dry weight of Gliricidia applied = | 2,400 | kg/ha/3yr | |
| | Energy content = | 19,500 | J/g | (Doherty, 2002) |
| | Annual energy = | (___kg/ha)(1,000 g/kg)(1.95E4 J/g)/3 yrs | | |
| | Annual energy = | 1.56E+10 | | |
| | Emergy per unit input = | 2.03E+04 | sej/J | (Doherty, 2002) |
| 6 | **Labour** | | | |
| | assumed avg. pers-days= | 110 | pers-d/ha | (Franzel et al, 1999) |
| | Annual energy = | (pers-days/ha/yr)*(2,300 kcal/d)*(4,186J/Cal)/3yr | | |
| | Annual energy = | 3.53E+08 | J | |
| | Emergy per unit input = | 1.36E+05 | sej/J | (Odum and Odum, 1983) |
| 7 | **Net topsoil loss** | | | |
| | Erosion rate, cultivated = | 15 | ton/ha/yr | (Roose, 1985, in Bodnar et al, 2006) |
| | Erosion rate, fallow = | 13 | ton/ha/yr | (assume 0.5*cultivated loss rate of 26) |
| | % organic in soil = | 0.40 | % | (GIS layer) |
| | Energy cont./g organic= | 5.40 | kcal/g | |
| | Net loss of OM= | (3yr avg. t/ha)(1e6 g/t)(fraction organic) | | |
| | = | 5.47E+04 | g/ha | |
| | Energy loss = | (loss of organic matter)(5.4 kcal/g)(4,186 J/kcal) | | |
| | Annual energy = | 1.24E+09 | | |
| | Emergy per unit input = | 1.25E+05 | | (GIS model, Cohen, 2006) |
| 8 | **Services, $ per ha** | | | |
| | Rock P price = | 0 | $/g | |
| | Maize seed price = | 0 | $/g | |
| | biomass transfer price = | N/A | | assume $5 ??? , a little extra for transport effort? |
| | Total $ spent on inputs = | 5.00E+00 | $/3yrs | |
| | Mali emergy/$ ratio = | 3.80E+13 | sej/$ | (Sweeney et al, 2006) |
| | Annual emergy = | 6.33E+13 | sej/yr | |
| 9 | **Total emergy (Empower density)** | | | sum of items 3 through 8 |
| | Total emergy = | 1.65E+15 | sej/ha/yr | |
| 10 | **Total yield, dry weight** | | | |
| | Dry weight grain yield = | 2.8E+06 | g/ha | (Kaya and Nair, 2001) |
| | Yield per three year cycle = | 9.5E+05 | g/ha/yr | |
| 11 | **Total yield, energy** | | | |
| | Energy content = | (___g/ha)(14.9 kJ/g)(1,000J/kJ)/3 years | | |
| | Energy content = | 1.41E+10 | J/yr | (FAO, 1997, maize) |
| | **UEV** | | | |
| 12 | UEV, grams = | 1.74E+09 | sej/g | item 9/item 10 |
| 13 | UEV, joules = | 1.17E+05 | sej/J | item 9/item 11 |
| 14 | UEV. w/o services = | 1.14E+05 | sej/J | (item 9–item 8) / item 11 |

## TABLE A.12

Emergy evaluation of maize, fallow w/ chemical fertilizer, per ha per year (MA-i2).

| Note | Description | Data (per ha$^{-1}$ yr$^{-1}$) | Unit | UEV (sej/unit) | Emergy (E13 sej/yr) |
|---|---|---|---|---|---|
| RENEW | | | | | |
| 1 | Sun | 3.82E+13 | J | 1 | 3.8 |
| 2 | Rain | 4.37E+10 | J | 3.10E+04 | 135.5 |
| 3 | Evapotranspiration | 3.35E+10 | J | 3.10E+04 | 103.9 |
| LOCAL TRANSFERS | | | | | |
| 4 | Maize seeds | 7.76E+08 | J | 6.40E+04 | 5.0 |
| 5 | Labour | 4.14E+08 | J | 1.36E+05 | 5.6 |
| NON-RENEW | | | | | |
| 6 | Net topsoil loss | 1.57E+09 | J | 1.25E+05 | 19.6 |
| 7 | Potash | 2.50E+03 | g | 1.60E+09 | 0.4 |
| 8 | Potassium | 2.50E+03 | g | 7.70E+08 | 0.2 |
| 9 | Nitrogen | 1.75E+04 | g | 7.04E+09 | 12.3 |
| 10 | Services | 1.08E+01 | $ | 3.80E+13 | 41.2 |
| 11 | Total emergy | | | | 188.2 |
| 12 | Total yield, dry weight | 7.09E+05 | g | | |
| 13 | Total yield, energy | 1.06E+10 | J | | |
| 14 | UEV, grams | 2.65E+09 | sej/g | | |
| 15 | UEV, joules | 1.78E+05 | sej/J | | |
| 16 | UEV w/o services | 1.39E+05 | sej/J | | |

Location: Koutilala region, Mali

Main data source: Kaya and Nair, 2001

### Notes, Table A.12

1 Sun

Annual net radiation = 121 W/m^2 (Maidment, WWB)

Area = 1.00E+04 m^2

Annual energy = (___W/m^2)(31,536,000 sec/yr)(area)

Annual energy = 3.82E+13 J

Emergy per unit input = 1 sej/J (Odum, 1996)

2 Rain

Avg. annual rainfall = 885 mm (Kaya and Nair, 2001)

Area = 10,000 m^2

Annual energy = (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g)

Annual energy = 4.37E+10 J

Emergy per unit input = 3.10E+04 sej/J (Odum, 2000)

3 Evapotranspiration

Avg. annual ET = 679 mm (Ahn and Tateishi, 1992)

Area = 1.00E+04 m^2

Annual energy = (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g)

Annual energy = 3.35E+10 J

Emergy per unit input = 3.10E+04 sej/J

Notes, Table A.12 *continued*

| | | | | |
|---|---|---|---|---|
| 4 | **Maize seeds** | | | |
| | Maize seeds planted = | 80cm x 50cm spacing | | (Kaya and Nair, 2001) |
| | Seeds planted at end of fallow = | 6.25E+05 | #/ha | |
| | Seeds planted per year = | 2.08E+05 | #/ha/yr | |
| | Mass of seeds planted = | 0.25 | g/seed | |
| | Annual energy = | (____#seeds)(g/seed)(14.9 kJ/g)(1,000J/kJ) | | |
| | Annual energy = | 7.76E+08 | J | |
| | Emergy per unit input = | 6.40E+04 | sej/J | (Cohen, 2003) |
| 5 | **Labour** | | | |
| | pers-days= | 129 | pers-d/ha | (Franzel et al, 1999) |
| | Annual energy = | (pers-days/ha/yr)*(2,300 kcal/d)*(4,186J/Cal)/3yr | | |
| | Annual energy = | 4.14E+08 | J | |
| | Emergy per unit input = | 1.36E+05 | sej/J | (Odum and Odum, 1983) |
| 6 | **Net topsoil loss** | | | |
| | Erosion rate, cultivated = | 26 | ton/ha/yr (Roose, 1985, in Bodnar et al, 2006) | |
| | Erosion rate, fallow = | 13 | ton/ha/yr (assume 0.5*cultivated loss rate) | |
| | % organic in soil = | 0.40 | % | (GIS layer) |
| | Energy cont./g organic= | 5.40 | kcal/g | |
| | Net loss of OM= | (3yr avg. t/ha)(1e6 g/t)(fraction organic) | | |
| | = | 6.93E+04 | g/ha | |
| | Energy loss = | (loss of organic matter)(5.4 kcal/g)(4,186 J/kcal) | | |
| | Annual energy = | 1.57E+09 | | |
| | Emergy per unit input = | 1.25E+05 | | (GIS model, Cohen, 2006) |
| 7 | **Potash** | | | |
| | K2O from 15-15-15 fertilizer = | 7.5 | kg/3yr | (Kaya and Nair, 2001) |
| | Annual mass applied = | 2,500 | g/ha | |
| | Emergy per unit input = | 1.60E+09 | sej/g | (Odum, 1996) |
| 8 | **Phosphate** | | | |
| | P2O5 from 15-15-15 fertilizer = | 7.5 | kg/3yr | (Kaya and Nair, 2001) |
| | Annual mass applied = | 2,500 | g | |
| | Emergy per unit input = | 7.70E+08 | sej/g | (Odum, 1996) |
| 9 | **Nitrogen** | | | |
| | N from urea = | 45 | kg/3yr | (Kaya and Nair, 2001) |
| | N from 15-15-15 fertilizer = | 7.5 | kg/3yr | (Kaya and Nair, 2001) |
| | Annual mass applied = | 17,500 | g/ha/yr | |
| | Emergy per unit input = | 7.04E+09 | sej/g | (Odum, 1996) |
| 10 | **Services, $ per ha** | | | |
| | Urea price = | 0.2 | $/kg | (Bationo et al, 1997) |
| | Fertilizer price = | 0.25 | $/kg | (Bationo et al, 1997) |
| | Maize seed price = | 0 | $/g | (IDE, 2003) |
| | Total $ spent on inputs = | 3.25E+01 | $/3yrs | |
| | Mali emergy/$ ratio = | 3.80E+13 | sej/$ | (Sweeney et al, 2006) |
| | Annual emergy = | 4.12E+14 | sej/yr | |
| 11 | **Total emergy (Empower density)** | | | |
| | Total emergy = | 1.88E+15 | sej/ha/yr | sum of items 3 through 10 |
| 12 | **Total yield, dry weight** | | | |
| | Dry weight grain yield = | 2.1E+06 | g/ha | (Kaya and Nair, 2001) |
| | Yield per three year cycle = | 7.1E+05 | g/ha/yr | |

Notes, Table A.12 *continued*

| | | | | |
|---|---|---|---|---|
| 13 | Total yield, energy | | | |
| | Energy content = | (____g/ha)(14.9 kJ/g)(1,000J/kJ)/3 years | | |
| | Energy content = | 1.06E+10 | J/yr | (FAO, 1997, maize) |
| | UEV | | | |
| 14 | UEV, grams = | 2.65E+09 | sej/g | item 11/item 12 |
| 15 | UEV, joules = | 1.78E+05 | sej/J | item 11/item 13 |
| 16 | UEV. w/o services = | 1.39E+05 | sej/J | (item 11–item 10) / item 13 |

## TABLE A.13

Emergy evaluation of millet, in Karite and Nere parkland, per ha per year (MI-parkKN).

| Note | Description | Data (per ha$^{-1}$ yr$^{-1}$) | Unit | UEV (sej/unit) | Emergy (E13 sej/yr) |
|---|---|---|---|---|---|
| RENEW | | | | | |
| 1 | Sun | 4.18E+13 | J | 1 | 4.2 |
| 2 | Rain | 3.67E+10 | J | 3.10E+04 | 113.8 |
| 3 | Evapotranspiration | 2.86E+10 | J | 3.10E+04 | 88.7 |
| LOCAL TRANSFERS | | | | | |
| 4 | Seeds | 8.79E+07 | J | 5.00E+05 | 4.4 |
| 5 | Labour | 7.70E+08 | J | 1.36E+05 | 10.5 |
| NON-RENEW | | | | | |
| 6 | Net topsoil loss | 2.44E+09 | J | 1.10E+05 | 26.9 |
| 7 | Services | 1.08E+00 | $ | 1.60E+13 | 1.7 |
| 8 | Total emergy | | | | 132.2 |
| 8a | Total emergy to millet | | | | 88.5 |
| 8b | Total emergy to shea | | | | 28.9 |
| 8c | Total emergy to nere | | | | 14.8 |

| | | YIELD | | UEV | |
|---|---|---|---|---|---|
| 9 | Millet grain, DW | 3.9E+05 | g | 2.3E+09 | sej/g |
| 10 | Millet grain, energy | 8.2E+09 | J | 1.1E+05 | sej/J |
| 11 | Crop residue, DW | 1.3E+06 | g | 6.7E+08 | sej/g |
| 12 | Crop residue, energy | 2.1E+10 | J | 4.2E+04 | sej/J |
| 13 | Shea fruit pulp, DW | 2.5E+04 | g | 1.2E+10 | sej/g |
| 14 | Shea fruit pulp, energy | 2.9E+08 | J | 9.8E+05 | sej/J |
| 15 | Shea nut, DW | 3.7E+04 | g | 7.9E+09 | sej/g |
| 16 | Shea nut, energy | 8.9E+08 | J | 3.2E+05 | sej/J |
| 17 | Nere fruit pulp, DW | 9.5E+03 | g | 1.6E+10 | sej/g |
| 18 | Nere fruit pulp, energy | 1.2E+08 | J | 1.2E+06 | sej/J |
| 19 | Nere seed, DW | 1.1E+04 | g | 1.3E+10 | sej/g |
| 20 | Nere seed, energy | 2.0E+08 | J | 7.4E+05 | sej/J |
| 21 | Wood production, DW | 4.0E+04 | g | 1.1E+10 | sej/g |
| 22 | Wood production, energy | 4.0E+08 | J | 1.1E+06 | sej/J |
| 23 | Empower density | 1.32E+15 | sej/ha/yr | | |

Location: Sapone village, 35 km south of Ouagadougou: 12 03°N, 1 43°W

Main data source: Bayala et al, 2002

Notes, Table A.13

| | | | | |
|---|---|---|---|---|
| 1 | **Sun** | | | |
| | Annual net radiation = | 132.5 | W/m^2 | (Maidment, WWB) |
| | Area = | 1.00E+04 | m^2 | |
| | Annual energy = | (___W/m^2)(31,536,000 sec/yr)(area) | | |
| | Annual energy = | 4.18E+13 | J | |
| | Emergy per unit input = | 1 | sej/J | (Odum, 1996) |
| 2 | **Rain** | | | |
| | Avg. annual rainfall (1999-2000) = | 743 | mm | (Bayala et al, 2002) |
| | Area = | 10,000 | m^2 | |
| | Annual energy = | (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g) | | |
| | Annual energy = | 3.67E+10 | J | |
| | Emergy per unit input = | 3.10E+04 | sej/J | (Odum, 2000) |
| 3 | **Evapotranspiration** | | | |
| | Avg. annual rainfall (1999-2000) = | 579 | mm | (Ahn and Tateishi, 1992) |
| | Area = | 1.00E+04 | m^2 | |
| | Annual energy = | (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g) | | |
| | Annual energy = | 2.86E+10 | J | |
| | Emergy per unit input = | 3.10E+04 | sej/J | |
| 4 | **Seeds** | | | |
| | Avg. seeding rate in Mali = | 6.00 | kg/ha | (ABT, 2000) |
| | Energy content of seed = | 14,651 | J/g | (assume 3.5 kcal/g) |
| | Energy content = | (___g)(14,651 J/g) | | |
| | Annual energy = | 8.8E+07 | J/ha | |
| | Emergy per unit input = | 5.00E+05 | sej/J | (assumed) |
| 5 | **Labour** | | | |
| | #people working on farm = | 80 | pers-d/ha(Cohen, 2003,subsistence ag) | |
| | Annual energy = | (pers-d/ha/yr)*(2300 kcal/day)*(4,186J/Cal) | | |
| | Annual energy = | 7.70E+08 | J | |
| | Emergy per unit input = | 1.36E+05 | sej/J | (Odum and Odum, 1983) |
| 6 | **Net topsoil loss** | | | |
| | Erosion rate = | 12 | t/ha | assume based on data table |
| | % organic in soil = | 0.90 | % | (Bayala et al, 2002) |
| | Energy cont./g organic= | 5.40 | kcal/g | |
| | Organic matter in topsoil used up = | (total mass of topsoil)(% organic) | | |
| | = | 108,000 | g/ha | |
| | Energy loss = | (loss of organic matter)(5.4 kcal/g)(4,186 J/kcal) | | |
| | Annual energy = | 2.44E+09 | J/ha | |
| | Emergy per unit input = | 1.10E+05 | sej/J | (Cohen, 2006) |
| | Erosion rate for monocrop = | 14 | t/ha | |
| | Organic matter used,monocrop = | 126,000 | g/ha | |
| | Annual energy = | 2.8E+09 | J/ha | |
| 7 | **Services, $ per ha** | | | |
| | Seed cost = | 120 | fCFA/kg | (Mali price, ABT, 2000) |
| | $/yr spent on seed inputs = | (\_\_\_kg seed)(fCFA/kg)(1$/664 fCFA) | | |
| | $/yr spent on seed inputs = | 1.08 | $/yr | |
| | $/yr spent on pruning tool = | 0.10 | $/yr | |
| | Burkina Faso emergy/$ ratio = | 1.60E+13 | sej/$ | |
| | Annual emergy = | 1.89E+13 | sej/yr | |

### Notes, Table A.13 *continued*

| | | | | |
|---|---|---|---|---|
| 8 | **Total emergy** | | | |
| | Total emergy for system = | sum of items 3 to 7 | | |
| | Emergy split amongst species | | | |
| | Average shea transpiration = | 6.13E+04 | L/yr | (Bayala et al, 2002) |
| | Average nere transpiration = | 1.31E+05 | L/yr | (Bayala et al, 2002) |
| | Average mature shea transpiration = | 2.45E+05 | L/ha | (4 fruiting tree/ha, Bayala et al, 2004) |
| | Average mature nere transpiration = | 1.31E+05 | L/ha | (1 fruiting tree/ha, Bayala et al, 2004) |
| | Average total shea transpiration = | 3.68E+05 | L/ha | add 0.5 mature value |
| | Average total nere transpiration = | 1.97E+05 | L/ha | add 0.5 mature value |
| | Total tree transpiration = | 5.65E+05 | L/ha | |
| | | 5.65E+02 | m3/ha | 1 liter = 0.001 m$^3$ |
| | Percent of rain transpired by millet = | 9 | % | (Rockstrom et al, 1998) |
| | Millet transpiration = | 0.06687 | m | |
| | Millet transpiration per hectare = | 6.7E+02 | m3/ha | |
| | Total transpiration per hectare = | 1.23E+03 | m3/ha | |
| | Millet transpiration/total transp. = | 0.542 | | |
| | Shea transpiration/total transp. = | 0.298 | | |
| | Nere transpiration/total transp. = | 0.160 | | |
| | Millet, fraction erosion = | 0.930 | | |
| | Shea, fraction erosion = | 0.050 | | |
| | Nere, fraction erosion = | 0.020 | | |
| 8a | **Emergy to millet** | (0.54*AET)+(0.93*erosion)+(0.9*labor)+seeds+(0.92*serv.) | | |
| 8b | **Emergy to shea** | (0.30*AET)+(.05*erosion)+(0.09*labor)+(0.07*services) | | |
| 8c | **Emergy to nere** | (0.16*AET)+(.02*erosion)+(0.01*labor)+(0.01*services) | | |
| | **Millet yield** | | | |
| | Estimated avg. yield = | 4.3E+05 | g/ha | (Bayala et al, 2002) |
| | Dry matter fraction = | 0.90 | | (Adeola et al, 1996) |
| 9 | Dry weight, g = | 3.91E+05 | g/ha | |
| | Energy content = | 1.89E+04 | J/g | (Adeola et al, 1996) |
| 10 | Energy content = | 8.21E+09 | J/ha | |
| | **Crop residue, dry matter yield** | | | |
| 11 | Estimated avg. yield = | 1.3E+06 | g/ha | (Bayala et al. 2002) |
| | Energy content of yield = | 1.60E+04 | J/g | (avg. crop residue energy, FAO) |
| 12 | Energy content of yield = | 2.11E+10 | J/ha | |
| | **Shea fruit yield** | | | |
| | Average fruit per tree = | 34 | kg/tree | (Bayala et al, 2002) |
| | Average tree density = | 4 | tree/ha | (Bayala et al, 2002) |
| | Shea fresh fruit pulp energy content = | 3935 | J/g FW | (Boffa, 1999) |
| | Shea fruit content (fraction fruit) = | 0.55 | -- | (Maranz et al, 2004) |
| | Shea fruit, FW production = | 74,800 | g/ha | |
| 13 | Shea fruit, DW production = | 24,684 | g/ha | (67% H2O, Maranz, 2004) |
| | Energy content of yield = | (____g FW/ha)(__J/g FW fruit) | | |
| 14 | Energy content of yield = | 2.9E+08 | J/ha | |

Notes, Table A.13 *continued*

| | | | | |
|---|---|---|---|---|
| | Shea nut yield | | | |
| | Shea nut content (fraction nut) = | 0.45 | -- | (Maranz et al, 2004) |
| | Shea nut production, FW = | 61,200 | g/ha | |
| | Shea nut, DM fraction = | 0.6 | | (Boffa, 1999) |
| 15 | Shea nut production, DW = | 36,720 | g/ha | |
| | Shea nut energy content = | 24,237 | J/g | (Boffa, 1999) |
| | Energy content of yield = | (___kg/tree)(__tree/ha)(1E3g/kg)(0.45)(.6)(__J/g nut) | | |
| 16 | Energy content of yield = | 8.9E+08 | J/ha | |
| | Nere fruit yield | | | |
| | Average fruit per tree = | 68 | kg/tree | (Bayala et al, 2002) |
| | Average tree density = | 1 | tree/ha | (Bayala et al, 2002) |
| | Nere pulp content (fraction pulp) = | 0.4 | -- | (Kessler, 1992) |
| 17 | Nere fruit, DW production = | 9,520 | g/ha | (65% H2O, assumed) |
| | Nere dry fruit pulp energy content = | 12,977 | J/g | (Boffa, 1999) |
| | Energy content of yield = | (___g DW/ha)*(___J/ DW g) | | |
| 18 | Energy content of yield = | 1.2E+08 | J/ha | |
| | Nere seed yield | | | |
| | Nere seed content (fraction seed) = | 0.18 | -- | (Kessler, 1992) |
| 19 | Nere seed, DW production = | 11,016 | g/ha | (assume 10% water) |
| | Nere seed energy content = | 18,084 | J/g | (Boffa, 1999) |
| | Energy content of yield = | (___g DW/ha)*(___J/ DW g) | | |
| 20 | Energy content of yield = | 2.0E+08 | J/ha | |
| | Total wood production | | | |
| 21 | Annual harvestable wood production = | 40 | kg/ha | (Bagnoud et al, 1995) |
| | Energy content of wood = | 1.00E+04 | J/g | |
| | Energy content of yield = | (___g/ha)(___J/g) | | |
| 22 | Energy content of yield = | 4.00E+08 | J/ha/yr | |

## TABLE A.14

Emergy evaluation of sorghum, in karite parkland, per ha per year (SO-parkK).

| Note | Description | Data (per ha$^{-1}$ yr$^{-1}$) | Unit | UEV (sej/unit) | Emergy (E13 sej/yr) |
|---|---|---|---|---|---|
| RENEW | | | | | |
| 1 | Sun | 4.2E+13 | J | 1.0E+00 | 4.2 |
| 2 | Rain | 3.4E+10 | J | 3.1E+04 | 104.9 |
| 3 | Evapotranspiration | 2.6E+10 | J | 3.1E+04 | 79.3 |
| LOCAL TRANSFERS | | | | | |
| 4 | Seeds | 9.1E+07 | J | 5.0E+05 | 4.5 |
| 5 | Labour | 7.7E+08 | J | 1.4E+05 | 10.5 |
| NON-RENEW | | | | | |
| 6m | Net topsoil loss, monocrop | 2.7E+09 | J | 1.1E+05 | 29.3 |
| 6p | Net topsoil loss, parkland | 2.3E+09 | J | 1.1E+05 | 25.1 |
| 7 | Services | 1.5E+00 | $ | 3.7E+13 | 5.5 |
| 8m | Total monocrop emergy | | | | 129.1 |
| 8p | Total parkland emergy | | | | 124.9 |
| 8a | Total emergy to sorghum | | | | 95.9 |
| 8b | Total emergy to shea | | | | 29.0 |
| | | YIELD | | UEV | |
| 9m | Sorghum grain, DW, monocrop | 5.5E+05 | g | 2.3E+09 | sej/g |
| 10m | Sorghum grain, energy, monocrop | 1.0E+10 | J | 1.2E+05 | sej/J |
| 9p | Sorghum grain, DW, parkland | 5.5E+05 | g | 1.7E+09 | sej/g |
| 10p | Sorghum grain, energy, parkland | 1.0E+10 | J | 9.2E+04 | sej/J |
| 11 | Crop residue, DW, parkland | 4.3E+06 | g | 2.2E+08 | sej/g |
| 12 | Crop residue, energy, parkland | 6.9E+10 | J | 1.4E+04 | sej/J |
| 13 | Shea fruit pulp, DW | 2.0E+04 | g | 1.5E+10 | sej/g |
| 14 | Shea fruit pulp, energy | 2.4E+08 | J | 1.2E+06 | sej/J |
| 15 | Shea nut, DW | 5.2E+04 | g | 5.6E+09 | sej/g |
| 16 | Shea nut, energy | 1.3E+09 | J | 2.3E+05 | sej/J |
| 17 | Wood production, DW | 4.00E+04 | g | 7.2E+09 | sej/g |
| 18 | Wood production, energy | 4.00E+08 | J | 7.2E+05 | sej/J |
| 19 | Empower Density | 1.2E+15 | sej/ha/yr | | |

Location: Thiougou village, Zoundweogo province, 11 26° N, 0 51° W

Main data source: dataset for lower Karite branches pruned, Boffa et al, 2000

Notes, Table A.14

1 Sun

Annual net radiation = 132.5 W/m^2 (Maidment, WWB)

Area = 1.00E+04 m^2

Annual energy = (___W/m^2)(31,536,000 sec/yr)(area)

Annual energy = 4.18E+13 J

Emergy per unit input = 1 sej/J (Odum, 1996)

Notes, Table A.14 *continued*

| | | | | |
|---|---|---|---|---|
| 2 | **Rain** | | | |
| | Annual rainfall (1993) = | 685 | mm | (Boffa et al, 2000) |
| | Area = | 10,000 | m^2 | |
| | Annual energy = | (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g) | | |
| | Annual energy = | 3.38E+10 | J | |
| | Emergy per unit input = | 3.10E+04 | sej/J | (Odum, 2000) |
| 3 | **Evapotranspiration** | | | |
| | Annual ET (1993)= | 518 | mm | (Ahn and Tateishi, 1992) |
| | Area = | 1.00E+04 | m^2 | |
| | Annual energy = | (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g) | | |
| | Annual energy = | 2.56E+10 | J | |
| | Emergy per unit input = | 3.10E+04 | sej/J | |
| 4 | **Seeds (local, white variety)** | | | |
| | Average sorghum seed weight = | 2.30E-02 | g/seed | (Boffa et al, 2000) |
| | Hills per hectare planted = | 2.70E+04 | hills/ha | (Boffa et al, 2000) |
| | Seeds per hill planted = | 1.00E+01 | seeds/hill | (Zaongo et al, 1997) |
| | Energy content of seed = | 14,651 | J/g | (assume 3.5 kcal/g) |
| | Energy content = | (__g/seed)(___seeds/hill)(___hills/ha)(14651 J/g) | | |
| | Annual energy = | 9.1E+07 | J/ha | |
| | Emergy per unit input = | 5.00E+05 | sej/J | (assumed) |
| 5 | **Labour** | | | |
| | #people working on farm = | 80 | pers-d/ha(Cohen, 2003, subsistence ag) | |
| | Annual energy = | (pers-d/ha/yr)*(2,300 kcal/day)*(4,186J/Cal) | | |
| | Annual energy = | 7.70E+08 | J | |
| | Emergy per unit input = | 1.36E+05 | sej/J | (Odum and Odum, 1983) |
| 6 | **Net topsoil loss** | | | |
| | Erosion rate = | 12 | t/ha | assume based on data table |
| | % organic in soil = | 0.87 | % | (%orgC, Boffa et al, 2000) |
| | Energy cont./g organic= | 5.40 | kcal/g | |
| | Organic matter in topsoil used up = | (total mass of topsoil)(% organic) | | |
| | = | 103,800 | g/ha | |
| | Energy loss = | (loss of organic matter)(5.4 kcal/g)(4,186 J/kcal) | | |
| 6p | Annual energy = | 2.35E+09 | J/ha | |
| | Emergy per unit input = | 1.07E+05 | sej/J | (Cohen, 2006) |
| | Erosion rate for monocrop = | 14 | t/ha | |
| | Organic matter used,monocrop = | 121,100 | g/ha | |
| 6m | Annual energy = | 2.7E+09 | J/ha | |
| 7 | **Services, $ per ha** | | | |
| | Seed cost = | 120 | fCFA/kg | (Mali price, ABT, 2000) |
| | $/yr spent on seed inputs = | (\_\_\_kg seed)(fCFA/kg)(1$/500 fCFA) | | |
| | $/yr spent on seed inputs = | 1.49E+00 | $/yr | |
| | $/yr spent on pruning tool = | 0.10 | $/yr | |
| | Burkina Faso emergy/$ ratio = | 2.30E+13 | sej/$ | |
| | Annual emergy = | 3.66E+13 | sej/yr | |

Notes, Table A.14 *continued*

| | | | | |
|---|---|---|---|---|
| 8 | **Total emergy** | | | |
| | Total emergy, monocrop system = | item 3 + 4 + 5 + 6m + 7 | | |
| | Total emergy, parkland system = | item 3 + 4 + 5 + 6p + 7 | | |
| 8a | **Total emergy to sorghum** | | | |
| | Average sorghum transpiration = | 1.5E+02 | mm | (Zaongo et al, 1997) |
| | Average shea crown radius = | 2.42E+02 | cm | (Boffa et al, 2000) |
| | Shea density = | 1.20E+01 | trees/ha | (Boffa et al, 2000) |
| | Areal coverage of shea = | 2.21E+02 | m^2 | |
| | Fractional coverage of shea = | 0.022 | | |
| | Fractional coverage of sorghum = | 0.978 | | |
| | Sorghum transpiration = | 1.42E+03 | m3/ha | |
| | Fraction AET transpired by sorghum = | 0.27 | | |
| | Sorghum+shea transpiration = | 2.15E+03 | m3/ha | |
| | Fraction of env. emergy to sorghum = | 0.66 | | (sorghum fraction of total Transp.) |
| | Fraction erosion to sorghum = | 0.98 | | (based on %cover) |
| | Emergy to sorghum = | (0.66*AET) +(0.98*erosion) + (0.9*labor) + (0.94*services) | | |
| 8b | **Total emergy to shea** | | | |
| | Average indv. shea transpiration = | 6.13E+04 | L/tree/yr | (Bayala et al, 2002) |
| | Total shea transpiration = | 7.36E+05 | L/ha | (based on 12 trees/ha) |
| | Total shea transpiration = | 7.36E+02 | m3/ha | |
| | Total AET per hectare = | 5.18E+03 | m3/ha | 1 liter = 0.001 $m^3$ |
| | Fraction of AET tranpsired by shea = | 0.14 | | |
| | Fraction of env. emergy to shea = | 0.34 | | (shea fraction of total Transp.) |
| | Fraction erosion to shea = | 0.02 | | (based on %cover) |
| | Emergy to shea = | (0.36*AET) +(0.02*erosion)+(0.1*labour)+(0.06*services) | | |
| | **Sorghum yield monocrop** | | | |
| | Yield away from trees, TD=12 = | 6.11E+05 | g/ha | (Boffa et al, 2000, Table5) |
| | Dry matter fraction = | 0.90 | | (millet, Adeola et al., 1996) |
| 9m | Dry weight, g = | 5.50E+05 | g/ha | |
| | Energy content = | 1.89E+04 | J/g | (millet, Adeola et al, 1996) |
| 10m | Energy content = | 1.04E+10 | J/ha | |
| | **Sorghum yield parkland** | | | |
| | Avg. yield in parkland, TD=12 = | 6.14E+05 | g/ha | (Boffa et al, 2000, Table5) |
| | Dry matter fraction = | 0.90 | | (millet, Adeola et al, 1996) |
| 9p | Dry weight, g = | 5.53E+05 | g/ha | |
| | Energy content = | 1.89E+04 | J/g | (millet, Adeola et al, 1996) |
| 10p | Energy content = | 1.04E+10 | J/ha | |
| | **Crop residue, dry matter yield** | | | |
| 11 | Estimated avg. yield = | 4.3E+06 | g/ha | (Boffa et al, 2000) |
| | Energy content = | 1.60E+04 | J/g | (avg. crop residue energy, FAO) |
| 12 | Energy content = | 6.86E+10 | J/ha | |

Notes, Table A.14 *continued*

| | | | | |
|---|---|---|---|---|
| | **Shea fruit yield** | | | |
| | Average shea fruit production, FW = | 6.0E+04 | g FW/ha | (Kessler, 1992) |
| | Shea fruit (fraction DW) = | 0.33 | -- | (Maranz et al, 2004) |
| 13 | Average shea fruit production, DW = | 19,800 | g DW/ha | |
| | Shea fresh fruit pulp energy content = | 3,935 | J/g FW | (Boffa, 1999) |
| | Energy content = | (___g FW/ha)(__J/g FW fruit) | | |
| 14 | Energy content = | 2.4E+08 | J/ha | |
| | **Shea nut yield** | | | |
| 15 | Average shea kernel production = | 52,000 | g DW/ ha/yr | (Boffa et al, 2000) |
| | Shea kernel energy content = | 24,237 | J/g | (Boffa, 1999) |
| | Energy content = | (___g/ha)(__J/g) | | |
| 16 | Energy content = | 1.3E+09 | J/ha | |
| | **Stemwood production** | | | |
| 17 | Annual wood production = | 40 | kg/ha | (Bagnoud et al, 1995) |
| | Energy content of wood = | 1.00E+04 | J/g | |
| | Energy content of yield = | (___g/ha)(___J/g) | | |
| 18 | Energy content of yield = | 4.00E+08 | J/ha/yr | |

## TABLE A.15

Emergy evaluation of millet, in Faidherbia parkland, per ha per year (Ml-parkF).

| Note | Description | Data ($ha^{-1} yr^{-1}$) | Unit | UEV (sej/unit) | Emergy (E13 sej/yr) |
|---|---|---|---|---|---|
| | RENEW | | | | |
| 1 | Sun | 4.2E+13 | J | 1.0E+00 | 4.2 |
| 2 | Rain | 2.1E+10 | J | 3.1E+04 | 65.5 |
| 3 | Evapotranspiration | 1.9E+10 | J | 3.1E+04 | 59.3 |
| | LOCAL TRANSFERS | | | | |
| 4 | Seeds | 8.8E+07 | J | 5.0E+05 | 4.4 |
| 5 | Labour | 7.7E+08 | J | 1.4E+05 | 10.5 |
| | NON-RENEW | | | | |
| 6m | Net topsoil loss, monocrop | 1.4E+09 | J | 1.0E+05 | 14.6 |
| 6p | Net topsoil loss, parkland | 1.2E+09 | J | 1.0E+05 | 12.5 |
| 7 | Services | 1.4E+00 | $ | 3.3E+13 | 4.8 |
| 8m | Total monocrop emergy | | | | 93.5 |
| 8p | Total parkland emergy | | | | 91.4 |
| 8a | Total emergy to millet | | | | 63.6 |
| 8b | Total emergy to Faidherbia | | | | 27.8 |
| | | YIELD | | UEV | |
| 9m | Millet grain, DW, monocrop | 5.4E+05 | g | 1.7E+09 | sej/g |
| 10m | Millet grain, energy, monocrop | 1.0E+10 | J | 9.1E+04 | sej/J |
| 9p | Millet grain, DW, parkland | 6.4E+05 | g | 1.0E+09 | sej/g |
| 10p | Millet grain, energy, parkland | 1.2E+10 | J | 5.3E+04 | sej/J |
| 11 | Crop residue, DW | 3.3E+06 | g | 1.9E+08 | sej/g |
| 12 | Crop residue, energy | 5.4E+10 | J | 1.2E+04 | sej/J |
| 13 | F. albida pods, pruned trees, DW | 5.0E+05 | g | 5.6E+08 | sej/g |
| 14 | F. albida pods, pruned, energy | 9.0E+09 | J | 3.1E+04 | sej/J |
| 15* | Fodder/prunings production, DW | 7.5E+06 | g | 3.7E+07 | sej/g |
| 16* | Fodder/prunings production, energy | 4.5E+10 | J | 6.2E+03 | sej/J |
| 17 | Wood production, DW | 3.3E+05 | g | 8.6E+08 | sej/g |
| 18 | Wood production, energy | 6.1E+09 | J | 4.5E+04 | sej/J |
| 19 | Empower Density | 9.1E+14 | sej/ha/yr | | |

*Assume system can produce all fodder or all pods, but not both in the same year.

Location: village of N'Dounga, 30km SE of Niamey, Niger

Main data source: Kho et al, 2001

### Notes, Table A.15

1 Sun

Annual net radiation = 132.5 W/m^2 (Maidment, WWB)

Area = 1.00E+04 m^2

Annual energy = (___W/m^2)(31,536,000 sec/yr)(area)

Annual energy = 4.18E+13 J

Emergy per unit input = 1 sej/J (Odum, 1996)

Notes, Table A.15 *continued*

| | | | | |
|---|---|---|---|---|
| 2 | **Rain** | | | |
| | Annual rainfall (1993) = | 428 | mm | (Kho et al, 2001) |
| | Area = | 10,000 | m^2 | |
| | Annual energy = | (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g) | | |
| | Annual energy = | 2.11E+10 | J | |
| | Emergy per unit input = | 3.10E+04 | sej/J | (Odum, 2000) |
| 3 | **Evapotranspiration** | | | |
| | Annual ET (1993)= | 387 | mm | (Ahn and Tateishi, 1992) |
| | Area = | 1.00E+04 | m^2 | |
| | Annual energy = | (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g) | | |
| | Annual energy = | 1.91E+10 | J | |
| | Emergy per unit input = | 3.10E+04 | sej/J | |
| 4 | **Seeds** | | | |
| | Average millet seed weight = | 8.00E-03 | g/seed | online source |
| | Hills per hectare planted = | 1.00E+04 | hills/ha | (Kho et al, 2001) |
| | Seeds per hill planted = | 7.50E+01 | seeds/hill | (Kho et al, 2001) |
| | Energy content of seed = | 14,651 | J/g | (assume 3.5 kcal/g) |
| | Energy content = | (__g/seed)(___seeds/hill)(___hills/ha)(14,651 J/g) | | |
| | Annual energy = | 8.8E+07 | J/ha | |
| | Emergy per unit input = | 5.00E+05 | sej/J | (assumed) |
| 5 | **Labour** | | | |
| | #people working on farm = | 80 | pers-d/ha (Cohen, 2003, subsistence ag) | |
| | Annual energy = | (pers-d/ha/yr)*(2,300 kcal/day)*(4,186J/Cal) | | |
| | Annual energy = | 7.70E+08 | J | |
| | Emergy per unit input = | 1.36E+05 | sej/J | (Odum and Odum, 1983) |
| 6 | **Net topsoil loss** | | | |
| | Erosion rate, parkland = | 12 | t/ha | assume based on data table |
| | % organic C in soil = | 0.45 | % | (org.C%, Kho et al, 2001 *1.73) |
| | Energy cont./g organic= | 5.40 | kcal/g | |
| | Organic matter in topsoil used up = | (total mass of topsoil)(% organic) | | |
| | = | 53,976 | g/ha | |
| | Energy loss = | (loss of organic matter)(5.4 kcal/g)(4186 J/kcal) | | |
| 6p | Annual energy, parkland = | 1.22E+09 | J/ha | |
| | Emergy per unit input = | 1.03E+05 | sej/J | (Cohen, 2006) |
| | Erosion rate, monocrop = | 14 | t/ha | |
| | Organic matter used,monocrop = | 62,972 | g/ha | |
| 6m | Annual energy, monocrop = | 1.4E+09 | J/ha | |
| 7 | **Services, $ per ha** | | | |
| | Seed cost = | 120 | fCFA/kg | (Mali price, ABT, 2000) |
| | $/yr spent on seed inputs = | (____kg seed)(fCFA/kg)(1$/500 fCFA) | | |
| | $/yr spent on seed inputs = | 1.44E+00 | $/yr | |
| | Burkina Faso emergy/$ ratio = | 2.30E+13 | sej/$ | |
| | Annual emergy = | 3.31E+13 | sej/yr | |
| | **Total emergy** | | | |
| 8m | Total emergy for monocrop system = | item 3 + 4 + 5 + 6m + 7 | | |
| 8p | Total emergy for parkland system = | item 3 + 4 + 5 + 6p + 7 | | |

Notes, Table A.15 *continued*

| | | | | |
|---|---|---|---|---|
| | **Emergy split amongst species** | | | |
| | Average millet transpiration = | 3.9E+01 | mm | (Rockstrom et al, 1998) |
| | Millet transpiration per hectare = | 3.9E+05 | m3/ha | (assume 90% cover) |
| | Faidherbia density = | 2.50E+01 | trees/ha | (Moussa, 1997 IN Payne et al, 1998) |
| | Faidherbia total trunk coverage = | 10.000 | m2/ha | (Kho et al, 2001) |
| | Faidherbia trunks, % coverage = | 0.010 | | (calc'd as 0.1%, but assume 1%) |
| | Faidherbia avg. transpiration = | 3.1E+01 | mm/yr | (Roupsard et al, 1999) |
| | Faidherbia stand transpiration volume = | 3.1E+05 | m3/ha | |
| | Total transpiration (crop+tree) = | 7.0E+05 | m3/ha | |
| | Fraction transpiration, millet = | 0.55 | | |
| | Fraction transpiration, F. albida = | 0.45 | | |
| | Fraction erosion, millet = | 0.99 | | (based on %cover) |
| | Fraction erosion, F. albida = | 0.01 | | (based on %cover) |
| 8a | **Emergy to millet** | (0.55 * AET) + (0.99*erosion) + (0.9 * labour) + seeds + services | | |
| 8b | **Emergy to Faidherbia** | (0.45 * AET) +(.01*erosion) + (0.09 * labour) | | |
| | **Millet grain yield** | | | |
| | Total DM yield away from trees = | 3.4E+06 | g/ha | (Kho et al, 2001) |
| | Total DM yield under canopy = | 4.5E+06 | g/ha | (31% higher, Kho et al, 2001) |
| | Grain fraction of total DM biomass = | 0.16 | | (based on ratio from Fatondji et al, 2006) |
| 9m | Grain DM yield in open = | 5.4E+05 | g/ha | |
| | Energy content, monocrop = | 1.0E+10 | J/ha | |
| | Grain DM yield under canopy = | 7.1E+05 | g/ha | |
| | Tree density = | 25.00 | trees/ha | |
| | Avg. tree crown area = | 135.00 | m2 | (Kho et al, 2001) |
| | % of ha under crown = | 0.34 | | |
| 9p | Parkland millet yield, DW g = | 6.4E+05 | g/ha | |
| | Energy content = | 1.89E+04 | J/g | (millet, Adeola et al, 1996) |
| 10p | Energy content, parkland = | 1.21E+10 | J/ha | |
| | **Crop residue, dry matter yield** | | | |
| | Residue fraction of total DM biomass = | 0.84 | | (based on Bayala et al, 2002 ratio) |
| | Residue DM yield in open = | 2.9E+06 | g/ha | |
| | Residue DM yield under canopy = | 3.7E+06 | g/ha | |
| 11 | Parkland millet yield, DW g = | 3.3E+06 | g/ha | |
| | Energy content = | 1.60E+04 | J/g | (avg. crop residue energy, FAO) |
| 12 | Energy content = | 5.36E+10 | J/ha | |
| | **Faidherbia pod yield** | | | |
| 13 | Avg. pod production, pruned tree, DW = | 5.0E+05 | g DW/ha | (Le Houerou, 1980) |
| | Pod energy content = | 18,000 | J/g | (nere nut, Boffa, 1999) |
| | Energy content = | (___g DW/ha)(__J/g DW) | | |
| 14 | Energy content = | 9.0E+09 | J/ha | |
| | **Fodder production (prunings)** | | | |
| 15 | Annual pruning production = | 300,000 | g DM/tree | (FAO, grassland species profiles) |
| | Energy content of prunings = | 6.00E+03 | J/g | (ME, Lamers et al, 1994) |
| | Energy content of yield = | (___g/tree)(trees/ha)(___J/g) | | |
| 16 | Energy content of yield = | 4.50E+10 | J/ha/yr | |
| | **Wood production** | | | |
| | Annual production, harvestable wood = | 3.25E+05 | g DM/ha | (Lamers et al, 1994) |
| | Energy content of wood = | 1.89E+04 | J/g | (Lamers et al, 1994) |
| | Energy content of yield = | (___g/ha)(___J/g) | | |
| | Energy content of yield = | 6.14E+09 | J/ha/yr | |

## TABLE A.16

Emergy evaluation of sorghum, alley-cropping in neem parkland, per ha per year (SO-Neem).

| Note | Description | Data (per ha$^{-1}$ yr$^{-1}$) | Unit | UEV (sej/unit) | Emergy (E13 sej/yr) |
|---|---|---|---|---|---|
| RENEW | | | | | |
| 1 | Sun | 4.18E+13 | J | 1 | 4.2 |
| 2 | Rain | 3.94E+10 | J | 3.10E+04 | 122.2 |
| 3 | Evapotranspiration | 3.03E+10 | J | 3.10E+04 | 93.9 |
| LOCAL TRANSFERS | | | | | |
| 4P | Seeds | 9.10E+07 | J | 5.00E+05 | 4.5 |
| 4A | Seeds | 1.05E+08 | J | 5.00E+05 | 5.3 |
| 5P | Labour | 7.70E+08 | J | 1.36E+05 | 10.5 |
| 5A | Labour | 1.00E+09 | J | 1.36E+05 | 13.6 |
| NON-RENEW | | | | | |
| 6P | Net topsoil loss | 2.50E+09 | J | 1.08E+05 | 27.0 |
| 6A | Net topsoil loss | 1.46E+09 | J | 1.08E+05 | 15.7 |
| 7P | Services | 1.59E+00 | $ | 2.30E+13 | 3.7 |
| 7A | Services | 1.83E+00 | $ | 2.30E+13 | 4.2 |
| | | | | | |
| 8P | Total parkland emergy | | | | 139.6 |
| 8A | Total alleycrop emergy | | | | 132.7 |
| 8Pa | Total emergy to sorghum | | | | 133.3 |
| 8Pb | Total emergy to neem | | | | 6.2 |
| 8Aa | Total emergy to sorghum | | | | 94.2 |
| 8Ab | Total emergy to neem | | | | 38.5 |
| | | YIELD | | UEV | |
| 9 | Sorghum grain, DW (P) | 4.0E+05 | g | 3.3E+09 | sej/g |
| 10 | Sorghum grain, energy (P) | 7.6E+09 | J | 1.8E+05 | sej/J |
| 11 | Sorghum grain, DW (A) | 5.4E+05 | g | 1.8E+09 | sej/g |
| 12 | Sorghum grain, energy (A) | 1.0E+10 | J | 9.3E+04 | sej/J |
| 13 | Neem leaf production, DW (A) | 8.2E+05 | g | 4.7E+08 | sej/g |
| 14 | Neem leaf production, energy (A) | 1.3E+10 | J | 2.9E+04 | sej/J |
| 15 | Wood production, DW (P) | 2.50E+02 | g | 2.5E+11 | sej/g |
| 16 | Wood production, energy (P) | 2.50E+06 | J | 2.5E+07 | sej/J |
| 17 | Wood production, DW (A) | 5.20E+03 | g | 7.4E+10 | sej/g |
| 18 | Wood production, energy (A) | 5.20E+07 | J | 7.4E+06 | sej/J |
| | | | | | |
| 19 | Empower Density | 1.4E+15 | sej/ha/yr | | |

Location: central valley of Burkina Faso 12 14° N, 2 16° W

Main data source: Tilander et al, 1995

### Notes, Table A.16

1 **Sun**

Annual net radiation = 132.5 W/m^2 (Maidment, WWB)

Area = 1.00E+04 m^2

Annual energy = (___W/m^2)(31,536,000 sec/yr)(area)

Annual energy = 4.18E+13 J

Emergy per unit input = 1 sej/J (Odum, 1996)

Notes, Table A.16 *continued*

| | | | | |
|---|---|---|---|---|
| 2 | **Rain** | | | |
| | Annual rainfall (1993) = | 798 | mm | (Tilander et al, 1995) |
| | Area = | 10,000 | m^2 | |
| | Annual energy = | (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g) | | |
| | Annual energy = | 3.94E+10 | J | |
| | Emergy per unit input = | 3.10E+04 | sej/J | (Odum, 2000) |
| 3 | **Evapotranspiration** | | | (Ahn and Tateishi, 1992) |
| | Annual ET (1993)= | 613 | mm | |
| | Area = | 1.00E+04 | m^2 | |
| | Annual energy = | (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g) | | |
| | Annual energy = | 3.03E+10 | J | |
| | Emergy per unit input = | 3.10E+04 | sej/J | |
| 4 | **Seeds (red grain variety)** | | | |
| | Average sorghum seed weight = | 2.30E-02 | g/seed | (Boffa et al, 2000) |
| | Hills per hectare planted, parkland = | 2.70E+04 | hills/ha | (Boffa et al, 2000) |
| | Hills per hectare planted, alley = | 31250 | hills/ha | (Tilander et al, 1995) |
| | Seeds per hill planted = | 1.00E+01 | seeds/hill | (Zaongo et al, 1997) |
| | Energy content of seed = | 14,651 | J/g | (assume 3.5 kcal/g) |
| | Energy content = | (__g/seed)(___seeds/hill)(___hills/ha)(14,651 J/g) | | |
| | Annual energy, parkland and mono = | 9.1E+07 | J/ha | |
| | Emergy per unit input = | 5.00E+05 | sej/J | (assumed) |
| | Annual energy, alley = | 1.1E+08 | J/ha | |
| | Emergy per unit input = | 5.00E+05 | sej/J | |
| 5 | **Labour** | | | |
| | #people working on mono or park = | 80 | pers-d/ha(Cohen, 2003, subsistence ag) | |
| | Annual energy = | (pers-d/ha/yr)*(2300 kcal/day)*(4186J/Cal) | | |
| 5P | Annual energy = | 7.70E+08 | J | |
| | Emergy per unit input = | 1.36E+05 | sej/J | (Odum and Odum, 1983) |
| | Labour for alleycrop, incl, establishment = | 104 | pers-d/ha | |
| | Annual energy = | (pers-d/ha/yr)*(2,300 kcal/day)*(4,186J/Cal) | | |
| 5A | Annual energy = | 1.00E+09 | J | |
| | Emergy per unit input = | 1.36E+05 | sej/J | |
| 6 | **Net topsoil loss** | | | |
| | Prakland Erosion rate = | 12 | t/ha | assume based on data table |
| | % organic C in soil = | 0.92 | % | (%OM, Tilander) |
| | Energy cont./g organic= | 5.40 | kcal/g | |
| | Organic matter in topsoil used up = | (total mass of topsoil)(% organic) | | |
| | = | 110,400 | g/ha | |
| | Energy loss = | (loss of organic matter)(5.4 kcal/g)(4186 J/kcal) | | |
| 6P | Annual energy = | 2.50E+09 | J/ha | |
| | Emergy per unit input = | 1.08E+05 | sej/J | (Cohen, 2006) |
| | Erosion rate for monocrop = | 14 | t/ha | assume based on data table |
| | Organic matter used,monocrop = | 128,800 | g/ha | |
| | Annual energy = | 2.9E+09 | J/ha | |
| | Erosion rate for alleycrop = | 7 | t/ha | (0.5 x mono,Spaan et al, 2005) |
| | Organic matter used,monocrop = | 64,400 | g/ha | |
| 6A | Annual energy = | 1.5E+09 | J/ha | |

Notes, Table A.16 *continued*

| | | | | |
|---|---|---|---|---|
| 7 | **Services, $ per ha** | | | |
| | Seed cost = | 120 | fCFA/kg | (Mali price, ABT, 2000) |
| | $/yr spent on seed inputs = | (\_\_\_kg seed)(fCFA/kg)(1$/500 fCFA) | | |
| | $/yr spent on seed inputs, P = | 1.49E+00 | $/yr | |
| | $/yr spent on seed inputs, P = | 1.73E+00 | $/yr | |
| | $/yr spent on pruning tool = | 0.10 | $/yr | |
| | Burkina Faso emergy/$ ratio = | 2.30E+13 | sej/$ | |
| 7P | Annual emergy, P = | 3.66E+13 | sej/yr | |
| 7A | Annual emergy, A = | 4.20E+13 | sej/yr | |
| 8 | **Total emergy** | | | |
| | Total emergy for system | | | |
| 8a | **Total emergy to sorghum** | | | |
| | Average sorghum transpiration = | 1.5E+02 | mm | (Zaongo et al, 1997) |
| | Average neem crown radius, park = | 1.50E+00 | m | (Tilander et al, 1995) |
| | Neem density, park = | 1.50E+01 | trees/ha | (assume) |
| | Areal coverage of neem, park = | 1.06E+02 | m^2 | |
| | fractional coverage of neem, park = | 0.011 | | |
| | Neem density, A = | 625.000 | trees/ha | |
| | Areal coverage of neem, A = | 1.10E+03 | m^2 | (assume .75m radius) |
| | Fractional coverage of neem, A = | 0.110 | | (reaches 20% cover before cut again) |
| | Fractional coverage of sorghum, park = | 0.989 | | |
| | Fractional coverage of sorghum, alley = | 0.890 | | |
| | Fraction of AET transpired by sorghum P = | 0.23 | | |
| | Fraction of AET transpired by sorghum A= | 0.21 | | |
| | Sorghum+nere transpiration, park = | 1.51E+02 | mm | |
| | Sorghum+nere transpiration, alley = | 2.01E+02 | mm | |
| | Fraction AET emergy to sorghum (P) = | 0.95 | | (sorghum fraction of total T) |
| | Fraction AET emergy to sorghum (A)= | 0.64 | | |
| | Fraction erosion to sorghum = | %cover | | |
| | Emergy to sorghum, P = | (0.95*AET)+(0.99*erosion)+(0.9*labour)+(0.94*services) | | |
| | Emergy to sorghum, A = | (0.64*AET)+(0.89*erosion)+(0.80*labour)+(0.95*services) | | |
| 8b | **Total emergy to neem** | | | |
| | % rain transpired by park neem = | 1.0 | % | (based on Allen & Grime,1995) |
| | % rain transpired by alley neem = | 9.0 | % | |
| | Neem transpiration, park = | 7.98E+00 | mm | (15 trees/ha) |
| | Neem transpiration, alley = | 7.18E+01 | mm | (625 trees/ha) |
| | Total AET per hectare = | 6.13E+03 | m3/ha | 1 liter = 0.001 $m^3$ |
| | Fraction AET transpired by neem, park = | 0.01 | | |
| | Fraction AET transpired by neem, alley = | 0.12 | | |
| | Fraction of AET emergy to neem, P = | 0.05 | | |
| | Fraction of AET emergy to neem, A = | 0.36 | | |
| | Fraction erosion to neem = | %cover | | |
| | Emergy to neem, P = | (0.05*AET)+(0.01*erosion)+(0.1*labour)+(0.06*services) | | |
| | Emergy to neem, A = | (0.36*AET) +(0.11*erosion)+(0.2*labour)+(0.05*services) | | |

Notes, Table A.16 *continued*

| | | | | |
|---|---|---|---|---|
| | **Sorghum yield, parkland** | | | |
| | Yield away from trees, park = | 3.8E+05 | g/ha | (Tilander et al, 1995) |
| 9 | Avg. yield in parkland = | 4.0E+05 | g/ha | (based on Tilander et al, 1995) |
| | Energy content = | 1.89E+04 | J/g | (millet, Adeola et al, 1996) |
| 10 | Energy content = | 7.62E+09 | J/ha | |
| | **Sorghum yield, alley crop** | | | |
| | Yield away from trees, alley = | 5.4E+05 | g/ha | (Tilander et al, 1995) |
| 11 | Avg. yield in alley = | 5.4E+05 | g/ha | (Tilander et al, 1995) |
| | Energy content = | 1.89E+04 | J/g | (millet, Adeola et al, 1996) |
| 12 | Energy content = | 1.02E+10 | J/ha | |
| | **Neem leaf yield (left as mulch)** | | | |
| 13 | Leaf production = | 819 | kg DM/ha | (Tilander et al, 1995) |
| | Leaf energy content = | 1.60E+04 | J/g | (avg. crop residue energy, FAO) |
| | Energy content = | (___g/ha)(__J/g) | | |
| 14 | Energy content = | 1.3E+10 | J/ha | |
| | **Stemwood production** | | | |
| 15 | Annual wood production (P) = | 0.2496 | kg/ha | (based on Tilander et al, 1995) |
| | Energy content of wood = | 1.00E+04 | J/g | |
| | Energy content of yield = | (___g/ha)(___J/g) | | |
| 16 | Energy content of yield = | 2.50E+06 | J/ha/yr | |
| | **Stemwood production** | | | |
| 17 | Annual wood production (P) = | 5.2 | kg/ha | (Tilander et al, 1995) |
| | Energy content of wood = | 1.00E+04 | J/g | |
| | Energy content of yield = | (___g/ha)(___J/g) | | |
| 18 | Energy content of yield = | 5.20E+07 | J/ha/yr | |

## TABLE A.17

Emergy evaluation of cattle and milk, agropastoralism, per ha per year (Cow1).

| Note | Description | Data (per ha$^{-1}$ yr$^{-1}$) | Unit | UEV (sej/unit) | Emergy (E13 sej/yr) |
|---|---|---|---|---|---|
| RENEW | | | | | |
| 1 | Sun | 4.2E+13 | J | 1.0E+00 | 4.2 |
| 2 | Rain | 2.7E+10 | J | 3.1E+04 | 85.0 |
| 3 | Evapotranspiration | 2.5E+10 | J | 3.1E+04 | 77.3 |
| LOCAL TRANSFERS | | | | | |
| 4 | Labour | 2.3E+07 | J | 1.4E+05 | 0.3 |
| 5 | Forage, plateau rangelands (calc'd UEV) | 4.5E+09 | J | 1.7E+05 | 77.3 |
| 6 | Forage, fallow fields (calc'd UEV) | 2.0E+10 | J | 3.9E+04 | 77.3 |
| 7 | Forage, croplands (crop residue&weeds) | 2.4E+10 | J | 3.2E+04 | 77.3 |
| NON-RENEW | | | | | |
| 8 | Net topsoil loss | 6.8E+08 | J | 1.2E+05 | 8.1 |
| 9 | Services | 2.0E+00 | $ | 3.8E+13 | 7.6 |
| | | | | | |
| 10 | Total emergy to forage (AET) | | | | 77.3 |
| 11 | Total emergy to cattle (82% of livestock) | | | | 77.9 |
| | | YIELD | | UEV | |
| 12 | Milk, dry weight | 5.7E+04 | g | 1.4E+10 | sej/g |
| 13 | Milk, energy | 2.0E+09 | J | 3.9E+05 | sej/J |
| 14 | Cattle biomass increase, mass | 3.1E+03 | g | 2.5E+11 | sej/g |
| 15 | Cattle biomass increase, energy | 6.6E+07 | J | 1.2E+07 | sej/J |
| 16 | Manure production, dry weight | 1.7E+05 | g | 4.5E+09 | sej/g |
| 17 | Manure production, energy | 3.1E+09 | J | 2.5E+05 | sej/J |
| | | | | | |
| 18 | Empower Density | 7.8E+14 | sej/ha/yr | | |
| 19 | Cattle UEV w/o services | 9.0E+06 | sej/J | | |
| 20 | Milk UEV w/o services | 3.5E+05 | sej/J | | |

Location: Ticko, Niger

Main data source: Achard and Banoin, 2003; Wilson, 1986

Notes, Table A.17

| | | | | |
|---|---|---|---|---|
| 1 | **Sun** | | | |
| | Annual net radiation = | 132.5 | W/m^2 | (Maidment, WWB) |
| | Area = | 1.00E+04 | m^2 | |
| | Annual energy = | (___W/m^2)(31,536,000 sec/yr)(area) | | |
| | Annual energy = | 0.00E+00 | J | |
| | Emergy per unit input = | 1 | sej/J | (Odum, 1996) |
| 2 | **Rain** | | | |
| | Avg. annual rainfall = | 555 | mm | (Achard and Banoin, 2003) |
| | Area = | 10,000 | m^2 | |
| | Annual energy = | (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g) | | |
| | Annual energy = | 2.74E+10 | J | |
| | Emergy per unit input = | 3.10E+04 | sej/J | (Odum, 2000) |

Notes, Table A.17 *continued*

| | | | | |
|---|---|---|---|---|
| 3 | **Evapotranspiration** | | | |
| | Avg. annual ET = | 505 | mm | (Ahn and Tateishi, 1992) |
| | Area = | 1.00E+04 | m^2 | |
| | Annual energy = | (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g) | | |
| | Annual energy = | 2.49E+10 | J | |
| | Emergy per unit input = | 3.10E+04 | sej/J | |
| 4 | **Labour** | | | |
| | Person hours for livestock management = | 0.71 | h/d/TLU | (Grandin, 1983) |
| | Cattle stocking rate = | 0.2 | TLU/ha | (Achard and Banoin, 2003) |
| | Annual energy = | (h/d/TLU)(365 d/yr)(0.15 TLU/ha)(104 kcal/hr)*(4186J/Cal) | | |
| | Annual energy = | 2.26E+07 | J | |
| | Emergy per unit input = | 1.36E+05 | sej/J | (Odum and Odum, 1983) |
| | **Forage, rangelands & fallows** | | | |
| 5 | Forage in plateau rangelands = | 432 | kg DM/ha | (Achard and Banoin, 2003) |
| | Energy content of biomass = | 2.47 | Mcal/kg DM | (Universidad de Buenos Aires-Fac. Agronomia) |
| | Energy in biomass = | (__kg DM/ha)(2.47 Mcal/kg DM)(1,000 kcal/Mcal)(4.19E3 J/kcal) | | |
| | | 4.47E+09 | J/ha | |
| 6 | Forage in fallow fields = | 1.90E+03 | kg DM/ha | (Achard and Banoin, 2003) |
| | Energy content of biomass = | 2.47 | Mcal/kg DM | |
| | Energy in biomass = | (__kg DM/ha)(2.47 Mcal/kg DM)(1,000 kcal/Mcal)(4.19E3 J/kcal) | | |
| | | 1.97E+10 | J/ha | |
| 7 | Forage in croplands (crop residues) = | 2,350 | kg DM/ha | (Achard and Banoin, 2003) |
| | Energy content of biomass = | 2.47 | Mcal/kg DM | |
| | Energy in biomass = | (__kg DM/ha)(2.47 Mcal/kg DM)(1,000 kcal/Mcal)(4.19E3 J/kcal) | | |
| | | 2.43E+10 | J/ha | |
| | Emergy per unit input = | Emergy of AET/energy biomass | | |
| 8 | **Net topsoil loss** | | | |
| | Erosion rate = | 6 | t/ha | (Karambiri et al, 2003) |
| | % organic in soil = | 0.50 | % | (DeFoer et al, 1998) |
| | Energy cont./g organic= | 5.40 | kcal/g | |
| | Organic matter in topsoil used up = | (total mass of topsoil)(% organic) | | |
| | = | 30,000 | g/ha | |
| | Energy loss = | (loss of organic matter)(5.4 kcal/g)(4186 J/kcal) | | |
| | Annual energy = | 6.78E+08 | J/ha | |
| | Emergy per unit input = | 1.20E+05 | sej/J | (Cohen et al, 2007) |
| 9 | **Services, $ per ha** | | | |
| | $/yr spent on inputs = | 2.00 | $ | assumed |
| | Mali emergy/$ ratio = | 3.80E+13 | sej/$ | (Sweeney et al, 2007) |
| | Annual emergy = | 7.60E+13 | sej/yr | |
| 11 | **Total emergy to cattle** | | | |
| | Emergy = | (0.8 * AET)+labour+topsoil loss+services | | |
| | Milk production (based on fulani pastoral data) | | | |
| | Milk production, volume = | 2.35 | L/cow/day | (Lambourne & Butterworth, 1983) |
| | Milk production, mass = | (___L/cow/d)(365 d/yr)(1.03 kg/L) | | |
| | = | 883.4825 | kg/cow/yr | |
| | Lactating portion of herd = | 25 | % | (Wilson, 1986) |
| | Average cow per TLU = | 1.3 | cow/TLU | (Wilson, 1986) |

Notes, Table A.17 *continued*

| | | | | |
|---|---|---|---|---|
| | Milk production, mass = | (___TLU/ha)(1.3 cow/TLU)(25% lactating)(___g/cow/yr) | | |
| 12 | = | 5.74E+04 | g/ha/yr | |
| | Energy content in milk = | 34,700 | J/g | (Nicholson, 1984) |
| | Milk production, energy = | (___g/ha/yr)(34,700 J/g) | | |
| 13 | = | 1.99E+09 | J/ha/yr | |
| | **Calf production (based on fulani pastoral data)** | | | |
| | Calf production per kg breeding cow = | 1.6E-01 | kg/kg/y | (wet weight, Wilson, 1986) |
| | Cattle stocking rate = | 2.00E-01 | TLU/ha | (Achard and Banoin, 2003) |
| | Average adult cow mass = | 2.30E+02 | kg | (Wilson, 1986) |
| | Breeding females as percent of herd = | 3.00E+01 | % | (Wilson, 1986, less 10%) |
| | Calf production, mass = | (_TLU/ha)(250 kg/TLU)(.3)(0.4dw/ww)(_kg-calf/kg-cow)(1E3g/kg) | | |
| | = | 9.60E+02 | g DW/ha | |
| | Energy content in calf = | 21.3 | kJ/g, DW | (dehydrated beef, FAO, 1953) |
| | Calf production, energy = | (___g/ha)(21,300 J/g) | | |
| | = | 2.04E+07 | J/ha/yr | |
| | **Existing cattle biomass increase** | | | |
| | Cattle growth, ages 1-4 yrs = | 5.1E+04 | g/calf/yr | (Wilson, 1986) |
| | Cattle stocking rate = | 2.00E-01 | TLU/ha | (Achard and Banoin, 2003) |
| | Average cow per TLU = | 1.3 | cow/TLU | (Wilson, 1986) |
| | Percent of herd that is 1-3 yrs = | 40 | % | (Wilson, 1986) |
| | Cattle growth, ages 1-3, mass = | (___TLU/ha)(1.3 cow/TLU)(.40 young)(___g/calf/yr)(0.4 dw/lw) | | |
| | = | 2.13E+03 | g/ha | |
| | Energy content in cattle = | 21.3 | kJ/g, DW | (dehydrated beef, FAO, 1953) |
| | Cattle biomass increase, energy = | (___g/ha)(21,300 J/g) | | |
| | = | 4.53E+07 | J/ha/yr | |
| 14 | **Total biomass increase, DW** | 3.09E+03 | g/ha | (calf birth + cattle growth) |
| 15 | **Total biomass increase, energy** | 6.57E+07 | J/ha | (calf birth + cattle growth) |
| | **Manure production** | | | |
| | Manure production per TLU = | 866 | kg DM/TLU/yr | (Achard and Banoin, 2003) |
| 16 | Manure production per ha = | 173 | kg DM/ha | |
| 17 | Energy content = | (___kg DM/ha)(18 MJ/kg DM)(1E6 MJ/J) | | |
| | = | 3.12E+09 | J/ha | |

## TABLE A.18

Emergy evaluation of cattle and milk, Fulani transhumant system, per ha per year (Cow2).

| Note | Description | Data (per ha$^{-1}$ yr$^{-1}$) | Unit | UEV (sej/unit) | Emergy (E13 sej/yr) |
|---|---|---|---|---|---|
| RENEW | | | | | |
| 1 | Sun | 4.2E+13 | J | 1 | 4.2 |
| 2 | Rain | 2.0E+10 | J | 3.1E+04 | 61.3 |
| 3 | Evapotranspiration | 1.6E+10 | J | 3.1E+04 | 49.0 |
| LOCAL TRANSFERS | | | | | |
| 4 | Labour | 1.4E+07 | J | 1.4E+05 | 0.2 |
| 5 | Forage, grass, rangelands (calc'd UEV) | 1.6E+10 | J | 3.2E+04 | 49.0 |
| 6 | Forage, shrub foliage, rangelands (calc'd UEV) | 3.7E+09 | J | 1.3E+05 | 49.0 |
| NON-RENEW | | | | | |
| 7 | Net topsoil loss | 6.8E+08 | J | 1.2E+05 | 8.1 |
| 8 | Services | 2.5E-01 | $ | 3.8E+13 | 1.0 |
| | | | | | |
| 9 | Total emergy to forage (AET) | | | | 49.0 |
| 10 | Total emergy to cattle (80% cattle) | | | | 39.2 |
| | | YIELD | | UEV | |
| 11 | Milk production, mass | 3.4E+04 | g | 1.1E+10 | sej/g |
| 12 | Milk production, energy | 1.2E+09 | J | 3.3E+05 | sej/J |
| 13 | Cattle biomass increase, mass | 2.0E+03 | g | 1.4E+11 | sej/g |
| 14 | Cattle biomass increase, energy | 4.4E+07 | J | 6.5E+06 | sej/J |
| 15 | Manure production, dry weight | 8.3E+04 | g | 4.7E+09 | sej/g |
| 16 | Manure production, energy | 1.5E+09 | J | 2.6E+05 | sej/J |
| | | | | | |
| 17 | Empower Density | 3.9E+14 | sej/ha/yr | | |
| 18 | Cattle UEV w/o services | 8.8E+06 | sej/J | | |
| 19 | Milk UEV w/o services | 3.2E+05 | sej/J | | |

Location: Central Mali, Fulani transhumant pastoralists w/emphasis on milk

Main data source: Wilson, 1986

### Notes, Table A.18

| | | | | | |
|---|---|---|---|---|---|
| 1 | Sun | | | | |
| | | Annual net radiation = | 132.5 | W/m^2 | (Maidment, WWB) |
| | | Area = | 1.00E+04 | m^2 | |
| | | Annual energy = | (___W/m^2)(31,536,000 sec/yr)(area) | | |
| | | Annual energy = | 4.18E+13 | J | |
| | | Emergy per unit input = | 1 | sej/J | (Odum, 1996) |
| 2 | Rain | | | | |
| | | Avg. annual rainfall = | 400 | mm | (Wilson, 1986) |
| | | Area = | 10,000 | m^2 | |
| | | Annual energy = | (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g) | | |
| | | Annual energy = | 1.98E+10 | J | |
| | | Emergy per unit input = | 3.10E+04 | sej/J | (Odum, 2000) |

Notes, Table A.18 *continued*

| | | | | |
|---|---|---|---|---|
| 3 | **Evapotranspiration** | | | |
| | Avg. annual ET = | 320 | mm | (Ahn and Tateishi, 1992, and Wilmott) |
| | Area = | 1.00E+04 | m^2 | |
| | Annual energy = | (mm/yr)(0.001 m/mm)(area)(1E6 g/m3)(4.94 J/g) | | |
| | Annual energy = | 1.58E+10 | J | |
| | Emergy per unit input = | 3.10E+04 | sej/J | |
| 4 | **Labour** | | | |
| | Person hours for livestock management = | 0.71 | h/d/TLU | (Grandin, 1983)<br>(Sahel Average, Powell, 1996) |
| | Stocking rate of all livestock = | 0.15 | TLU/ha | |
| | Stocking rate of cattle = | 0.12 | TLU/ha | (80% cattle, Sahel avg, Powell, 1996) |
| | Annual energy = | (h/d/TLU)(365 d/yr)(0.12 TLU/ha)(104 kcal/hr)*(4186J/Cal) | | |
| | Annual energy = | 1.35E+07 | J | |
| | Emergy per unit input = | 1.36E+05 | sej/J | (Odum and Odum, 1983) |
| | **Forage, rangelands** | | | |
| 5 | Grass biomass in rangelands = | 1,500 | kg DM/ha | (Wilson, 1986) |
| | Energy content of grass biomass = | 2.47 | Mcal/kg DM | (Universidad de Buenos Aires-Fac. Agronomia) |
| | Energy in grass biomass = | (__kgDM/ha)(2.47 Mcal/kg DM)(1,000kcal/Mcal)(4.19E3J/kcal) | | |
| | | 1.55E+10 | J/ha | |
| 6 | Shrub foliage biomass in rangelands = | 149 | kg DM/ha | (Mortimore, 1999) |
| | Energy content of shrub biomass = | 5.9 | MJ/kg DM | (Wilson, 1980) |
| | Energy in shrub biomass = | (__kg DM/ha)(5.9 MJ/kg DM)(1E6 J/MJ) | | |
| | = | 3.68E+09 | J/ha | |
| | Emergy per unit input = | Emergy of AET + erosion / energy biomass | | |
| 7 | **Net topsoil loss** | | | |
| | Erosion rate = | 6 | t/ha | (Karambiri et al, 2003) |
| | % organic in soil = | 0.50 | % | (DeFoer et al, 1998) |
| | Energy cont./g organic= | 5.40 | kcal/g | |
| | Organic matter in topsoil used up = | (total mass of topsoil)(% organic) | | |
| | = | 30,000 | g/ha | |
| | Energy loss = | (loss of organic matter)(5.4 kcal/g)(4186 J/kcal) | | |
| | Annual energy = | 6.78E+08 | J/ha | |
| | Emergy per unit input = | 1.20E+05 | sej/J | (Cohen et al, 2007) |
| 8 | **Services, $ per ha** | | | |
| | $/yr spent on inputs = | 0.25 | $ | assume |
| | Mali emergy/$ ratio = | 3.80E+13 | sej/$ | (Sweeney et al, 2007) |
| | Annual emergy = | 9.50E+12 | sej/yr | |
| 10 | Total emergy to cattle | | | |
| | Emergy = | (0.8 * AET)+labour+topsoil loss+services | | |
| | Milk production | | | |
| | Milk production, volume = | 2.35 | L/cow/day | (Lambourne & Butterworth, 1983) |
| | Milk production, mass = | (___L/cow/d)(365 d/yr)(1.03 kg/L) | | |
| | = | 883.4825 | kg/cow/yr | |
| | Lactating portion of herd = | 25 | % | (Wilson, 1986) |
| | Average cow per TLU = | 1.3 | cow/TLU | (Wilson, 1986) |
| 11 | Milk production, mass = | (___TLU/ha)(1.3 cow/TLU)(25% lactating)(___g/cow/yr) | | |
| | = | 3.45E+04 | g/ha/yr | |

Notes, Table A.18 *continued*

| | | | | |
|---|---|---|---|---|
| | Energy content in milk = | 34,700 | J/g | (Nicholson, 1984) |
| 12 | Milk production, energy = | (___g/ha/yr)(34,700 J/g) | | |
| | = | 1.20E+09 | J/ha/yr | |
| | **Calf production (fulani pastoral)** | | | |
| | Calf production per kg breeding cow = | 1.6E-01 | kg/kg/yr | (Wilson, 1986) |
| | Cattle stocking rate = | 1.20E-01 | TLU/ha | (Wilson, 1986) |
| | Average adult cow mass = | 2.30E+02 | kg | (Wilson, 1986) |
| | Breeding females as percent of herd = | 4.00E+01 | % | (Wilson, 1986) |
| | Calf production, mass = | (_TLU/ha)(250kg/TLU)(0.4)(.4dw/lw)(_kg-calf/kg-cow)(1E3g/kg) | | |
| | = | 7.68E+02 | g/ha | |
| | Energy content in calf = | 21.3 | kJ/g, DW | (dehydrated beef, FAO, 1953) |
| | Calf production, energy = | (___g/ha)(21,300 J/g) | | |
| | = | 1.64E+07 | J/ha/yr | |
| | **Cattle biomass increase** | | | |
| | Cattle growth, ages 1-4 yrs = | 5.1E+04 | g/calf/yr | (Wilson, 1986) |
| | Cattle stocking rate = | 1.20E-01 | TLU/ha | (Wilson, 1986) |
| | Average cow per TLU = | 1.3 | cow/TLU | (Wilson, 1986) |
| | Percent of herd that is 1-3 yrs = | 40 | % | (Wilson, 1986) |
| | Cattle growth, ages 1-3, mass = | (___TLU/ha)(1.3 cow/TLU)(.4 calves)(.4 dw/lw)(___g/calf/yr) | | |
| | = | 1.28E+03 | g/ha | |
| | Energy content in cow = | 21.3 | kJ/g, DW | (dehydrated beef, FAO, 1953) |
| | Cattle biomass increase, energy = | (___g/ha)(21,300 J/g) | | |
| | = | 2.72E+07 | J/ha/yr | |
| 13 | **Total biomass increase, DW** | 2.04E+03 | g/ha | (calf birth + cattle growth) |
| 14 | **Total biomass increase, energy** | 4.35E+07 | J/ha | (calf birth + cattle growth) |
| | **Manure production:** | | | |
| | Manure production per cow = | 535 | kg DM/#/yr | (Siebert et al, 1987) |
| | Manure production per TLU = | 696 | kg DM/TLU | |
| 15 | Manure production per ha = | 83 | kg DM/ha | |
| 16 | Energy content = | (___kg DM/ha)(18 MJ/kg DM)(1E6 MJ/J) | | |
| | = | 1.50E+09 | J/ha | |

# Appendix B

## Summary of erosion scenarios for each traditional and parkland grain production system

**TABLE B.1**

Erosion scenarios for millet monocrop and parkland systems.

| Monocrop (MI-t2): | | | | | Parkland (MI-parkKN): | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Erosion t/ha | Erosion sej/ha | Total emergy sej/ha | UEV sej/g | EER | Erosion t/ha | Erosion sej/ha | Total emergy sej/ha | UEV sej/g | EER |
| 6 | 1.3E+14 | 1.2E+15 | 1.5E+05 | 0.60 | 4 | 8.3E+13 | 7.2E+14 | 8.7E+04 | 0.86 |
| 8 | 1.8E+14 | 1.2E+15 | 1.6E+05 | 0.58 | 6 | 1.2E+14 | 7.6E+14 | 9.3E+04 | 0.83 |
| 10 | 2.2E+14 | 1.3E+15 | 1.6E+05 | 0.56 | 8 | 1.7E+14 | 8.0E+14 | 9.8E+04 | 0.80 |
| 12 | 2.7E+14 | 1.3E+15 | 1.7E+05 | 0.54 | 10 | 2.1E+14 | 8.4E+14 | 1.0E+05 | 0.77 |
| 14 | 3.1E+14 | 1.4E+15 | 1.7E+05 | 0.53 | 12 | 2.5E+14 | 8.8E+14 | 1.1E+05 | 0.74 |
| 16 | 3.6E+14 | 1.4E+15 | 1.8E+05 | 0.51 | 14 | 2.9E+14 | 9.3E+14 | 1.1E+05 | 0.72 |
| 18 | 4.0E+14 | 1.5E+15 | 1.8E+05 | 0.49 | 16 | 3.3E+14 | 9.7E+14 | 1.2E+05 | 0.69 |
| 20 | 4.5E+14 | 1.5E+15 | 1.9E+05 | 0.48 | 18 | 3.7E+14 | 1.0E+15 | 1.2E+05 | 0.67 |
| 22 | 4.9E+14 | 1.5E+15 | 1.9E+05 | 0.46 | 20 | 4.2E+14 | 1.1E+15 | 1.3E+05 | 0.65 |

See emergy tables (MI-t2) and (MI-parkKN). Parkland yields used in ER calculations include tree products. Erosion rate varies, all other parameters are constant.

**TABLE B.2**

Erosion scenarios for sorghum monocrop and sorghum-karite parkland systems.

| Monocrop (S-t1): | | | | | Parkland (S-i1 from SO-parkKN table): | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Erosion t/ha | Erosion sej/ha | Total emergy sej/ha | UEV sej/g | EER | Erosion t/ha | Erosion sej/ha | Total emergy sej/ha | UEV sej/g | EER |
| 6 | 1.3E+14 | 1.1E+15 | 1.1E+05 | 0.84 | 4 | 8.2E+13 | 8.0E+14 | 7.6E+04 | 1.01 |
| 8 | 1.7E+14 | 1.2E+15 | 1.1E+05 | 0.81 | 6 | 1.2E+14 | 8.4E+14 | 8.0E+04 | 0.97 |
| 10 | 2.1E+14 | 1.2E+15 | 1.2E+05 | 0.78 | 8 | 1.6E+14 | 8.8E+14 | 8.4E+04 | 0.94 |
| 12 | 2.5E+14 | 1.2E+15 | 1.2E+05 | 0.76 | 10 | 2.1E+14 | 9.2E+14 | 8.8E+04 | 0.90 |
| 14 | 2.9E+14 | 1.3E+15 | 1.2E+05 | 0.73 | 12 | 2.5E+14 | 9.6E+14 | 9.2E+04 | 0.87 |
| 16 | 3.3E+14 | 1.3E+15 | 1.3E+05 | 0.71 | 14 | 2.9E+14 | 1.0E+15 | 9.6E+04 | 0.85 |
| 18 | 3.8E+14 | 1.4E+15 | 1.3E+05 | 0.69 | 16 | 3.3E+14 | 1.0E+15 | 1.0E+05 | 0.82 |
| 20 | 4.2E+14 | 1.4E+15 | 1.4E+05 | 0.67 | 18 | 3.7E+14 | 1.1E+15 | 1.0E+05 | 0.79 |
| 22 | 4.6E+14 | 1.5E+15 | 1.4E+05 | 0.65 | 20 | 4.1E+14 | 1.1E+15 | 1.1E+05 | 0.77 |

See emergy tables (S-t1) and (SO-parkKN). Parkland yields used in ER calculation include tree products. Erosion rate varies, all other parameters are constant.

## TABLE B.3

Erosion scenarios for millet mono+B37crop and millet-*Faidherbia* parkland systems.

| Monocrop (MI-t3): | | | | | Parkland (MI-i3 from MI-parkF table): | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Erosion t/ha | Erosion sej/ha | Total emergy sej/ha | UEV sej/g | EER | Erosion t/ha | Erosion sej/ha | Total emergy sej/ha | UEV sej/g | EER |
| 6 | 6.3E+13 | 8.5E+14 | 8.3E+04 | 1.09 | 4 | 4.1E+13 | 5.5E+14 | 4.6E+04 | 1.29 |
| 8 | 8.3E+13 | 8.7E+14 | 8.5E+04 | 1.08 | 6 | 6.2E+13 | 5.7E+14 | 4.8E+04 | 1.28 |
| 10 | 1.0E+14 | 8.9E+14 | 8.7E+04 | 1.06 | 8 | 8.3E+13 | 5.9E+14 | 4.9E+04 | 1.26 |
| 12 | 1.3E+14 | 9.1E+14 | 8.9E+04 | 1.05 | 10 | 1.0E+14 | 6.2E+14 | 5.1E+04 | 1.25 |
| 14 | 1.5E+14 | 9.4E+14 | 9.1E+04 | 1.04 | 12 | 1.2E+14 | 6.4E+14 | 5.3E+04 | 1.23 |
| 16 | 1.7E+14 | 9.6E+14 | 9.3E+04 | 1.03 | 14 | 1.4E+14 | 6.6E+14 | 5.4E+04 | 1.22 |
| 18 | 1.9E+14 | 9.8E+14 | 9.5E+04 | 1.02 | 16 | 1.7E+14 | 6.8E+14 | 5.6E+04 | 1.21 |
| 20 | 2.1E+14 | 1.0E+15 | 9.7E+04 | 1.01 | 18 | 1.9E+14 | 7.0E+14 | 5.8E+04 | 1.19 |
| 22 | 2.3E+14 | 1.0E+15 | 9.9E+04 | 1.00 | 20 | 2.1E+14 | 7.2E+14 | 6.0E+04 | 1.18 |

See emergy tables (MI-t3) and (MI-parkF ). Parkland yields used in ER calculations include tree products. Erosion rate varies, all other parameters are constant.

## TABLE B.4

Erosion scenarios for sorghum monocrop and sorghum-neem parkland systems.

| Monocrop (S-t2): | | | | | Parkland (S-i2 from data in SO-Neem table): | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Erosion t/ha | Erosion sej/ha | Total emergy sej/ha | UEV sej/g | EER | Erosion t/ha | Erosion sej/ha | Total emergy sej/ha | UEV sej/g | EER |
| 6 | 1.3E+14 | 1.3E+15 | 1.8E+05 | 0.51 | 4 | 8.9E+13 | 1.3E+15 | 1.7E+05 | 0.57 |
| 8 | 1.8E+14 | 1.3E+15 | 1.8E+05 | 0.50 | 6 | 1.3E+14 | 1.3E+15 | 1.7E+05 | 0.55 |
| 10 | 2.2E+14 | 1.4E+15 | 1.9E+05 | 0.48 | 8 | 1.8E+14 | 1.4E+15 | 1.8E+05 | 0.53 |
| 12 | 2.7E+14 | 1.4E+15 | 2.0E+05 | 0.46 | 10 | 2.2E+14 | 1.4E+15 | 1.8E+05 | 0.51 |
| 14 | 3.1E+14 | 1.4E+15 | 2.0E+05 | 0.45 | 12 | 2.7E+14 | 1.4E+15 | 1.9E+05 | 0.49 |
| 16 | 3.6E+14 | 1.5E+15 | 2.1E+05 | 0.44 | 14 | 3.1E+14 | 1.5E+15 | 2.0E+05 | 0.48 |
| 18 | 4.0E+14 | 1.5E+15 | 2.1E+05 | 0.42 | 16 | 3.6E+14 | 1.5E+15 | 2.0E+05 | 0.46 |
| 20 | 4.5E+14 | 1.6E+15 | 2.2E+05 | 0.41 | 18 | 4.0E+14 | 1.6E+15 | 2.1E+05 | 0.45 |
| 22 | 4.9E+14 | 1.6E+15 | 2.3E+05 | 0.40 | 20 | 4.5E+14 | 1.6E+15 | 2.1E+05 | 0.44 |

See emergy tables (SO-Neem). Parkland yields used in ER calculations include tree products. Erosion rate varies, all other parameters are constant.

## TABLE B.5

Erosion scenarios for sorghum monocrop and sorghum-Neem alleycrop systems.

| Monocrop (S-t3): | | | | | Parkland (S-i3 from data in SO-Neem table): | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Erosion t/ha | Erosion sej/ha | Total emergy sej/ha | UEV sej/g | EER | Erosion t/ha | Erosion sej/ha | Total emergy sej/ha | UEV sej/g | EER |
| 6 | 1.3E+14 | 1.3E+15 | 1.3E+05 | 0.72 | 3 | 6.0E+13 | 8.6E+14 | 8.5E+04 | 0.75 |
| 8 | 1.8E+14 | 1.3E+15 | 1.3E+05 | 0.70 | 4 | 8.0E+13 | 8.8E+14 | 8.7E+04 | 0.74 |
| 10 | 2.2E+14 | 1.4E+15 | 1.3E+05 | 0.68 | 5 | 1.0E+14 | 9.0E+14 | 8.9E+04 | 0.72 |
| 12 | 2.7E+14 | 1.4E+15 | 1.4E+05 | 0.65 | 6 | 1.2E+14 | 9.2E+14 | 9.1E+04 | 0.71 |
| 14 | 3.1E+14 | 1.4E+15 | 1.4E+05 | 0.63 | 7 | 1.4E+14 | 9.4E+14 | 9.3E+04 | 0.70 |
| 16 | 3.6E+14 | 1.5E+15 | 1.5E+05 | 0.61 | 9 | 1.8E+14 | 9.8E+14 | 9.7E+04 | 0.68 |
| 18 | 4.0E+14 | 1.5E+15 | 1.5E+05 | 0.60 | 11 | 2.2E+14 | 1.0E+15 | 1.0E+05 | 0.66 |
| 20 | 4.5E+14 | 1.6E+15 | 1.6E+05 | 0.58 | 13 | 2.6E+14 | 1.1E+15 | 1.0E+05 | 0.64 |
| 22 | 4.9E+14 | 1.6E+15 | 1.6E+05 | 0.56 | 15 | 3.0E+14 | 1.1E+15 | 1.1E+05 | 0.62 |

See emergy tables (SO-Neem). Parkland yields used in ER calculations include tree products. Erosion rate varies, all other parameters are constant.

# Appendix C

## Details of study villages

| Village Number | Cercle (Admin. District) | HH | Total HH in village | Weekly market present | Water pump Present | School present | Mosque present | Health Centre |
|---|---|---|---|---|---|---|---|---|
| 1 | San | 37 | 47 | No | Yes | Yes | Yes | No |
| 2 | San | 52 | 74 | No | Yes | Yes | Yes | No |
| 3 | Segou | 17 | 30 | No | Yes | No | No | No |
| 4 | Segou | 26 | 50 | No | Yes | No | Yes | No |
| 5 | Segou | 11 | 43 | No | No | No | Yes | No |
| 6 | Baraoueli | 16 | 23 | No | Yes | No | Yes | No |
| 7 | Segou | 12 | 16 | No | No | No | Yes | No |
| 8 | Segou | 39 | 57 | Yes | Yes | Yes | Yes | Yes |
| 9 | Bla | 31 | 90 | Yes | Yes | Yes | Yes | Yes |
| 10 | Bla | 8 | 45 | No | Yes | No | Yes | No |
| 11 | Baraoueli | 13 | 13 | No | Yes | Yes | Yes | Yes |
| 12 | Segou | 18 | 34 | No | Yes | No | Yes | No |
| 13 | Segou | 9 | 14 | No | No Data | No Data | No Data | No Data |
| 14 | Segou | 38 | 42 | No | No | Yes | Yes | No |
| 15 | Segou | 24 | 42 | No | Yes | Yes | Yes | No |
| 16 | Segou | 4 | 11 | No | No Data | No Data | No Data | No Data |
| 17 | Segou | 20 | 27 | Yes | No Data | No Data | No Data | No Data |
| 18 | San | 23 | 30 | No | No | No | Yes | No |
| 19 | Segou | 21 | 33 | No | Yes | Yes | Yes | No |
| 20 | Tominian | 40 | 77 | No | Yes | Yes | Yes | No |
| 21 | Segou | 17 | 23 | No | No Data | No Data | No Data | No Data |
| 22 | Segou | 13 | 14 | No | No | No | Yes | No |
| 23 | Segou | 18 | 18 | No | No Data | No Data | No Data | No Data |
| 24 | Segou | 29 | 29 | No | No Data | No Data | No Data | No Data |
| 25 | Segou | 25 | 40 | Yes | Yes | Yes | Yes | Yes |
| 26 | Baraoueli | 15 | 15 | No | No Data | No Data | No Data | No Data |
| 27 | Segou | 39 | 67 | No | Yes | Yes | Yes | No |
| 28 | Tominian | 29 | 60 | No | Yes | Yes | Yes | No |
| 29 | San | 39 | 88 | Yes | Yes | Yes | Yes | No |
| 30 | Segou | 20 | 33 | No | No | No | Yes | No |
| 31 | Tominian | 42 | 46 | No | No | Yes | Yes | No |
| 32 | Tominian | 49 | 50 | No | Yes | No | Yes | No |
| 33 | Segou | 15 | 19 | No | Yes | No | Yes | No |
| 34 | Segou | 26 | 34 | No | Yes | Yes | Yes | No |
| 35 | Segou | 19 | 20 | No | Yes | Yes | Yes | No |
| 36 | Baraoueli | 58 | 59 | No | No Data | No Data | No Data | No Data |
| 37 | Segou | 29 | 29 | No | No | No | Yes | No |
| 38 | Segou | 6 | 6 | No | No Data | No Data | No Data | No Data |
| 39 | Segou | 19 | 21 | No | Yes | No | Yes | No |
| 40 | Segou | 28 | 31 | No | No Data | No Data | No Data | No Data |

| Village Number | Cercle (Admin. District) | HH | Total HH in village | Weekly market present | Water pump Present | School present | Mosque present | Health Centre |
|---|---|---|---|---|---|---|---|---|
| 41 | Segou | 39 | 81 | Yes | No | Yes | Yes | No |
| 42 | Segou | 30 | 37 | No | Yes | No | Yes | No |
| 43 | Bla | 37 | 47 | No | Yes | Yes | No | No |
| 44 | Segou | 32 | 32 | Yes | No Data | No Data | No Data | No Data |
| 45 | Bla | 42 | 92 | No | Yes | Yes | No | No |
| 46 | Control | 20 | 40 | No | Yes | Yes | Yes | No |
| 47 | Segou | 13 | 33 | No | No | No | Yes | No |
| 48 | Baraoueli | 73 | 73 | No | No | Yes | Yes | No |
| 49 | Baraoueli | 74 | 107 | No | Yes | No | Yes | No |
| 50 | Bla | 26 | 27 | No | No | No | No | No |
| 51 | Bla | 72 | 81 | No | Yes | No | Yes | No |
| 52 | Bla | 96 | 182 | Yes | Yes | No | Yes | Yes |
| 53 | Macina | 72 | 200 | Yes | Yes | Yes | Yes | Yes |
| 54 | Macina | 46 | 75 | No | No | Yes | No | No |
| 55 | Macina | 85 | 167 | No | No | Yes | Yes | No |
| 56 | Macina | 9 | 15 | No | No | No | Yes | No |
| 57 | Niono | 17 | 26 | No | No | Yes | Yes | Yes |
| 58 | Niono | 25 | 48 | No | Yes | No | Yes | No |
| 59 | Macina | 46 | 176 | No | No | Yes | No | No |
| 60 | Control | 88 | 88 | No | No | Yes | No | No |
| 61 | Segou | 27 | 32 | No | No | No | Yes | No |
| 62 | Niono | 35 | 60 | No | Yes | Yes | Yes | No |
| 63 | Niono | 82 | 82 | Yes | Yes | Yes | Yes | Yes |
| 64 | Tominian | 71 | 95 | Yes | Yes | Yes | Yes | No |
| 65 | Segou | 17 | 23 | No | No | Yes | Yes | Yes |
| 66 | Niono | 79 | 200 | No | Yes | Yes | Yes | No |
| 67 | Niono | 35 | 42 | No | No | No | No | No |
| 68 | Niono | 14 | 14 | No | No | No | Yes | No |
| 69 | Niono | 33 | 33 | No | No | No | No | No |
| 70 | Niono | 87 | 87 | No | Yes | Yes | Yes | No |
| 71 | Niono | 45 | 45 | No | Yes | No | Yes | No |
| 72 | Niono | 22 | 22 | No | No | No | Yes | No |
| 73 | Niono | 33 | 33 | No | No | Yes | Yes | No |
| 74 | Macina | 76 | 82 | No | Yes | Yes | Yes | No |
| 75 | Segou | 30 | 30 | No | Yes | No | Yes | No |
| 76 | Tominian | 41 | 66 | No | Yes | No | Yes | No |
| 77 | Segou | 80 | 90 | No | Yes | Yes | Yes | Yes |

# Index

Page numbers in *italics* indicate figures or tables

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.

**www.unep.org**

United Nations Environment Programme
P.O. Box 30552 - 00100 Nairobi, Kenya
Tel.: +254 20 762 1234
Fax: +254 20 762 3927
e-mail: uneppub@unep.org
www.unep.org

UNEP