The Biogeochemistry of Human Wellbeing

Understanding Ecosystem Functioning, Ecosystem Services, and Biogeochemical processes.

From the NSF/TransLinks Nitrogen Working Group, Segou, Mali, 2008.

Prepared by Shahid Naeem and Cheryl Palm

Sponsored by USAID, Earth Institute, Center for Environmental Research and Conservation (CERC), Dept. Ecology, Evolution, and Environmental Biology (E3B), Wildlife Conservation Society (WCS), and Columbia University.

Background

This document is the outcome of the National Science Foundation funded Nitrogen Working Group which met in Segou, Mali, in 2008, in conjunction with the Millennium Villages Project (http://www.millenniumvillages.org/) and TransLinks (http://translinks.org/Home/tabid/312/ctl/Privacy/language/en-US/Default.aspx), a USAID initiative led by the Wildlife Conservation Society (http://www.wcs.org/), this specific project being led by the Earth Institute of Columbia University (http://www.earth.columbia.edu/sections/view/9) which is one of five partners in the TransLinks consortium.

This report is the foundation and springboard for the following products and activities.

1. A framework for natural resource managers.
2. A series of peer-reviewed journal articles for natural science, environmental economics, conservation biology, and environmental policy.
3. Framework for a workshop to develop a white paper on ecosystem service impacts attributable to development programs that employ nutrient amendments (e.g, fertilizer addition), water modifications (e.g., irrigation), agrobiodiversity, livestock management, and natural resource conservation (e.g., native diversity, including vegetation and wildlife).
4. A policy document describing the biogeochemistry of human wellbeing.
5. A tool for managing biogeochemically based, (e.g., food and fuel production, soil fertility, water quality) ecosystem services to achieve sustainable development and poverty alleviation.

Ecosystem Functioning, Ecosystem Services, and Human Wellbeing

Introduction

Under the auspices of the United Nations, the Millennium Ecosystem Assessment (MEA), with over thirteen hundred social and natural scientists, in cooperation with decision and policy makers, spent five years in assessing the state of our planet. The central framework of this endeavor was straightforward. Simply stated:

Biodiversity → Ecosystem Function → Ecosystem Services → Human Wellbeing.

This framework united biodiversity conservation with ecosystem science and linked these to the services nature provides for humans (Duraiappah and Naeem 2005).

Unfortunately, each of these elements of this MEA framework is complex and difficult to define. As important as this framework is for guiding conservation biology, sustainable development, and poverty alleviation programs that seek to improve human wellbeing in lasting ways, its opacity remains a major deterrent for informing decision making.

Another complication is that both ecosystem functions and services are not independent and often interact with one another. An increase in one is often accompanied by a decrease (or increase) in another. Such interactions are known as *tradeoffs* (negative correlations) and synergies (positive correlations) and add a layer of complexity that further makes the MEA framework rather unwieldy.

In this document, we provide some devices that can help to clarify and provide a means for understanding and implementing the MEA framework in decision making.

Because nitrogen based fertilizer amendments in agro-ecosystems are a common element to food securitization, economic development, and poverty alleviation programs, but can have negative impacts on water quality, disease, and sustainability, we focus on the nitrogen as a means for illustrating the importance and utility of this framework. However, any other ecologically important element, compound, or nutrient, could be used. Indeed, it would be beneficial to develop a more comprehensive analysis that considers carbon, phosphorous, sulfur, potassium, water, and other biogeochemically active materials, and the interactions among them, to provide a handbook for MEA-informed decision making.

Biodiversity → Ecosystem Function

Ecosystem functioning is inextricably linked to biodiversity, though how and why involves a complex array of processes, some biological and some geochemical, or, collectively, *biogeochemical*. Below we explain these aspects of the first linkage of the MEA framework.

Biodiversity, although commonly perceived of as simply the number of species in a region, is actually the sum of all diversity, taxonomic, genetic, ecological, and even spatial and temporal variability. That is, an ecosystem may be more biodiverse than another even if it has fewer species. For example, although an ecosystem may have only a few species, if those species are

- quite different from one another,
- show different seasonality in terms of growth and reproduction,
- consist of genetically heterogeneous populations, and
- species vary considerably in their distribution across the landscape,

then such an ecosystem is more diverse than another more rich in species if its species are

- taxonomically similar
- all grow and reproduce in the same season,
- are made up of genetically homogeneous populations, and
- are uniformly spread over the entire region.

Species richness, or the number of species in an ecosystem, though important for conservation and, is not necessarily an informative index of biodiversity.

Biodiversity is sometimes described as *the diversity of life on Earth* as a way to point to the fact that anything that generates diversity, including genetic, spatial, phenological, or functional diversity, is important. It also means that agriculture, aquaculture, villages, urban ecosystems, and all places where biogeochemical processes are active, form important components of biodiversity

Ecosystem functioning refers to the influences of all plants, animals, and microorganisms in an ecosystem have on biogeochemistry (defined below), or elemental cycling and energy acquisition (e.g., primary production) and its loss (e.g., respiration). Ecosystem functions are well known and well studied, though they are often more commonly known by different names such as *production*, *decomposition*, or *nutrient cycling*.

Biogeochemistry. There are many uses of the term *ecosystem functioning*, including the ability to resist invasion by exotic species, the control over the spread of diseases, and even pollination, but its most appropriate use is in relation to *biogeochemical* processes or the biologically driven geochemical cycles. Nitrogen fixation, denitrification, methanogenesis (the production of methane), evapotranspiration (the combination of evaporation and transpiration of water in an ecosystem), primary production, decomposition, ozone production, and many other processes are all biologically driven geochemical processes. That is, Earth has its own geochemistry whether life is present or not, but so long as there are plants, animals, and microorganisms, geochemistry is influenced by life processes and occurs at substantially different rates than it would in the absence of life.

Once biodiversity and ecosystem functioning are defined as above, it is inescapable that that the two are related. That is, if we alter life on Earth or in an ecosystem, we will change how geochemistry is influenced. At the global scale, because atmospheric mixing occurs across the entire biosphere, the production and sequestration of greenhouse gasses is driven by the mass and diversity of plants, animals, and microorganisms that sequester carbon by photosynthesis and/or release it through respiration.

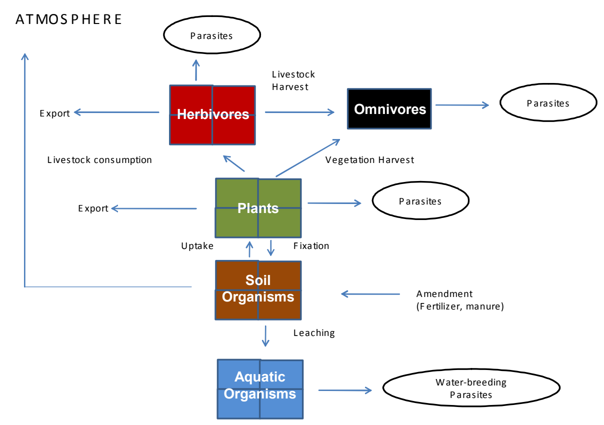

Figure 1. Generic nitrogen ecosystem function diagram. Boxes represent different trophic groups. Arrows reflect flows of nitrogen. Parasites represent small flows of nitrogen, but are important factors that can control the number and mass of organisms in each trophic level.

In Figure 1, we illustrate a generic ecosystem diagram for nitrogen cycling, though it could represent many other elemental or material cycles in an ecosystem. This figure illustrates that changes in biodiversity will clearly alter flows in an ecosystem. For example, changes in the composition and abundance vegetation or the herbivores that feed on them can dramatically alter flows of nitrogen to other components (e.g., soil organisms or aquatic organisms through leaching and runoff). Too often, plant, animal, and microbial ecologists work in isolation. Biogeochemical flows illustrate how integration across taxa in both research and management is a more effective strategy.

Ecosystem functions: Tradeoffs and Synergies

Ecosystem functions are often arbitrarily defined and are complex functions of one another. For example, rates of decomposition and rates of dentrification, or nitrogen accumulated in organic material returning to the atmosphere by microbiological metabolic processes, are often considered separate functions, but they are correlated. Similarly, if soil nitrogen retention declines, then net primary production is likely to decline as well.

Ecosystem Function → Ecosystem Services

There are many ways to partition the complex web of ecosystem functions that occur in nature, but there are some which are more valued by humans than others. Those ecosystem functions that are valued because they benefit humans are known as **ecosystem services**.

Ecosystem services are classified in many ways, but the MEA provided a classification system that is seeing increasing use. These are *supporting services*, which includes nitrogen cycling, that are the foundation for all other ecosystem services. Other services are classified into *provisioning*, *regulating*, and *cultural*. Examples are provided in Figure 2.

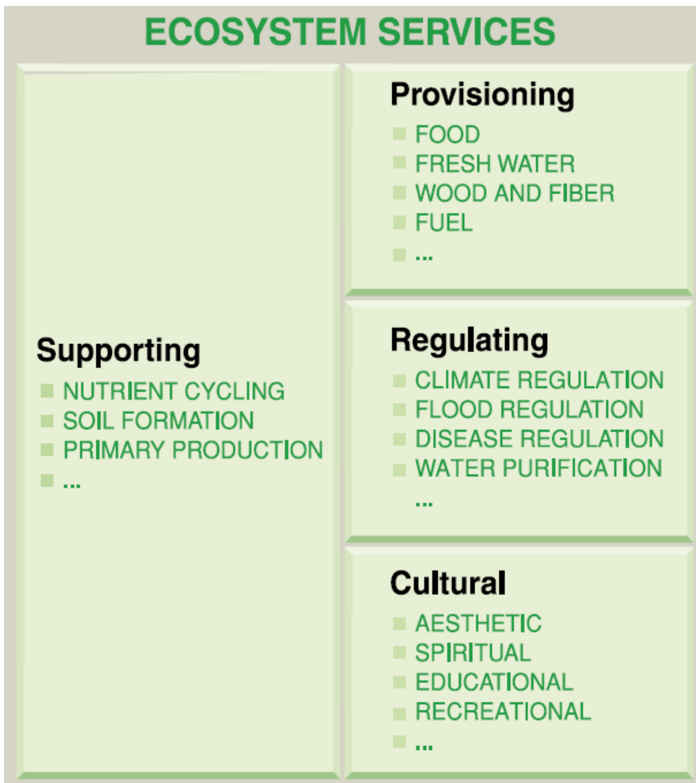

Figure 2. Ecosystem services as classified by the Millennium Ecosystem Functioning (Assessment 2005). This figure is copied without permission from their report.

Biodiversity → Ecosystem Function → Ecosystem Services → Human Wellbeing:

An example for the Millennium Village of Tiby, Mali

Here we illustrate the full MEA framework by example.

Figure 2 provides an example of how biodiversity and ecosystem functioning, specifically N cycling, are clearly linked in an ecosystem. In this case, we model our illustration after the village ecosystem of Tiby, a village in Mali which has volunteered to join the Earth Institute Millennium Villages Project.

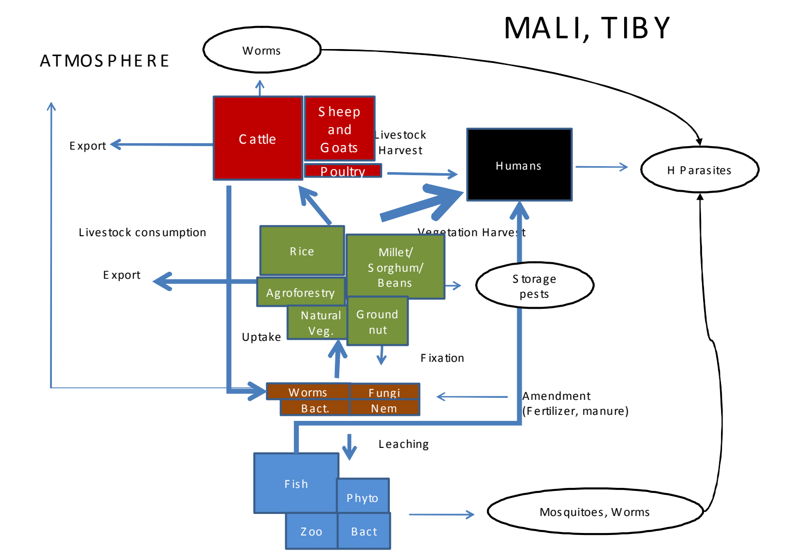

Figure 3. Nitrogen ecosystem function in relation to biological diversity in a Millennium Village of Tiby, Mali.

The figure tracks nitrogen through the various biological components, which include plants, mostly made up of agricultural varieties, and animals, mostly humans, cattle, sheep, goats, and poultry. There are many other animals, such as insects, birds, and a limited amount of wildlife, but these are left out to keep the image simple.

The size of each box represents the quantity of nitrogen in each component or group of organisms, including humans, but sizes have been adjusted more to fit on the page than to reflect actual quantities. Within each trophic group (e.g., plants, herbivores, humans, soil organisms, pests, and aquatic organisms) the predominant flows are indicated by arrows. For example, more nitrogen flows from vegetation to humans than it does to livestock.

Change in any of these components clearly alters nitrogen cycling. For example, reducing or dramatically increasing livestock would strongly influence the amount of nitrogen that would flow to humans. As another example, nitrogen influx into aquatic systems, such as fish ponds, can come from human wastes as well as leaching and runoff from agriculture, both of which can increase mosquito populations. Note that small flows of nitrogen to mosquitoes has enormous health implications because of malaria which suggests that increasing nitrogen fertilizer will both positively impact food supplies but possibly increase malaria prevalence.

Tradeoffs and Synergies Among Ecosystem Services

Ecosystem service tradeoffs and synergies complicate employing the MEA framework in decision making. Ecosystem services are invariably linked to one another such that an increase in one leads to a decrease in others, which constitutes tradeoffs. There are also positive associations in which an increase in one might increase others. Such positive correlations among ecosystem services are known as *synergies*.

Understanding the significance of tradeoffs and synergies requires considering relationships in multiple dimensions which always poses challenges for illustrations. One approach is commonly referred to as the *Spider Diagram* because of its spider-like radial arms. Figure 4 provides an illustration of a spider diagram used to consider the relationship between several ecosystem services in the Millennium Village of Tiby, Mali, which is used throughout this document. In this illustration, eight ecosystem services are plotted with values scaled so that they have equal arm lengths. Thus, while water quality might be measured as nitrate content in parts per million or pathogenic bacterial densities, and food, fodder, and fuel be measured in units such as grams of carbon, scaling them from zero to one can produce a convenient way to consider the pre-intervention state. In the left portion of Figure 4, nitrogen fertilizer has been added to improve the provisioning of food, fodder, and fuel, thus the arm increases dramatically in length. But other ecosystem services are linked and, hypothetically in this example, decline dramatically. Disease regulation, an ecosystem service, can decline (meaning an increase in crop and zoonoitc diseases or an increase in malnutrition because the increase in food was high starch and low protein, vitamin, and essential nutrient content. Green house gas regulation, another ecosystem service, also declines because nitrogen amendments can increase nitrogen-based greenhouse gasses as well as increase methane production from livestock if the increased fodder leads to an increase in livestock production.

The spider diagram is quantifiable and serves as a convenient tool to convey the interactions among ecosystem services without resorting to complex multivariate statistical or graphical devices and more clearly inform environmental decision making

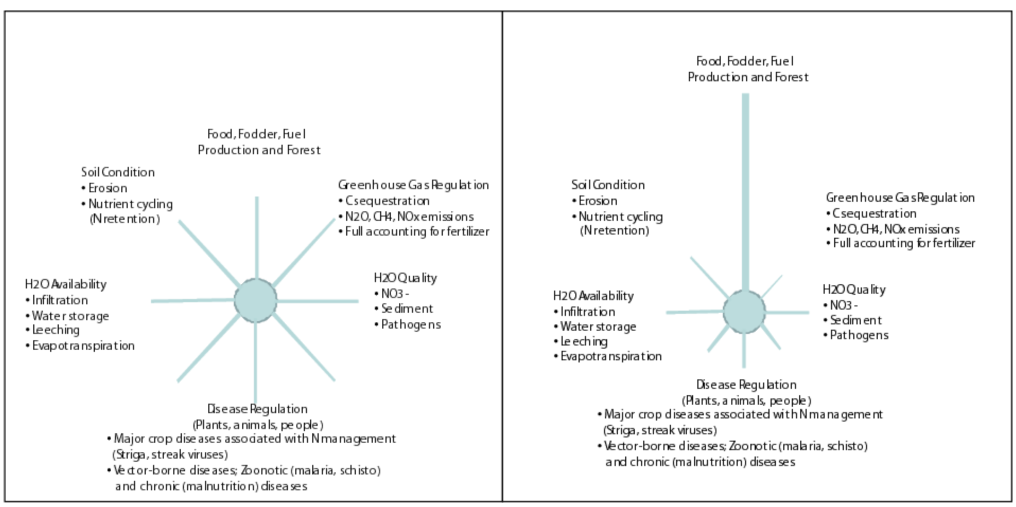

Figure 4. Tradeoffs and synergies among ecosystem services and the *spider diagram.* See text for explanation.

Tradeoffs and Synergies in Functions and Services

The most complicated part of any system, and ecosystems in particular, are the interactions or non-independence of its many parts. That is, as described above, a change in one, such as an increase in primary production, often leads to a change in another, such as a reduction in soil fertility and nitrogen in the soil is relocated into the above ground vegetation.

Much of the history of the development of humanity is, in fact, marked by an emphasis on the growth of a few ecosystem services at the expense of others, as illustrated, by example, in Figure 4. Many environmental problems, such as soil nutrient depletion, soil erosion, algal blooms, outbreaks of crop pests, loss of pollinators, loss of natural resistance to disease, and much more, is attributed to tradeoffs and synergies. Use of pesticides to increase crop yields has resulted in loss of pollinators in coffee plantations (Roubik 2002), fertilizer addition to improve yields has increased the spread of invasive species (Hobbs and Atkins 1988), and increased livestock holdings have led to a number environmental problems, including contributing desertification in some areas (Asner et al. 2004). While humanity has grown successfully from a few individuals to 6.7 billion over the last six million years, much of this growth has been achieved because of land modifications to increase yields in provisioning services, such as food, fuel, fodder, timber, and potable water.

The idea of tradeoffs and synergies is straightforward, even simple, but easily forgotten when pursuing increases in one class of services, usually provisioning services. This idea lies at the heart of the Brundtland Commission report on sustainable development (Development 1987) that began the worldwide shift to sustainable development. The central idea of the Brundtland Commission report was that traditional development increased humanmade capital at the expense of natural capital which is an economic interpretation of the tradeoffs in ecosystem services traditional development often entails.

One might consider sustainable development is managing the tradeoffs and synergies among ecosystem services to improve human wellbeing.

To track tradeoffs and synergies in ecosystem services requires two steps, the first involving documenting the tradeoffs and synergies among ecosystem functions and the second involving documenting the same for ecosystem services. Our focus has been on biogeochemical functions, thus the first step for such functions involves deriving the stocks and flows of the element or nutrient of interest in the system. Of course, there are many, all of which interact, but frequently management decisions involve one or a few proposed changes to an ecosystem, such as nitrogen amendment, irrigation, or changes in livestock abundance.

Tradeoffs and Synergies in Ecosystem Functions

Table 1 illustrates a simplified possible tabulation of the hypothetical stocks and flows of nitrogen for the Tiby Millennium Village used throughout this document (see Fig. 3), but with the addition of other villages in the region. Unfortunately, data are not available, but are currently being assimilated for future analyses, so only a description of what could be measured is described.

Table 1. Ecosystem function stocks and flows. Stocks are described in terms of common measures while flows are described in parentheses. Note that runoff and N amendments are flows while Crop1 and livestock are both stocks and flows. Note that we have selected a single crop (called Crop 1) and have combined all livestock into one variable.

NITROGEN TRADEOFFS AND SYNERGIES OF ECOSYSTEM FUNCTIONS ECOSYSTEM STOCKS (AND FLOWS)				
	RUNOFF	CROP1	LIVESTOCK	N AMENDMENT
Village 1	Dissolved inorganic N into groundwater and aquatic ecosystems	Standing biomass (harvest/export and livestock consumption)	Standing biomass (harvest/export)	kg N per hectare per year
Village 2	"	"	"	"
Village 3	"	"	"	"

Once a tabulation of stocks and flows is completed, tradeoffs and synergies for ecosystem functions can be tabulated by constructing a table of pair-wise interactions, usually derived from estimated correlations among the stocks and flows. Table 2 provides an example of hypothetical interactions among the stocks and flows tabulated in Table 1. Note that we have assumed that nitrogen amendments increase Crop1, which increases livestock because they have an increased crop residue feed supply, which is why livestock are considered to have a negative impact on nitrogen stored in crops.

Table 2. Tradeoffs and synergies among ecosystem functions. Cell entries are signs of the hypothetical correlations.

NITROGEN TRADEOFFS AND SYNERGIES OF ECOSYSTEM FUNCTIONS VILLAGE 1				
	RUNOFF	CROP1	LIVESTOCK	N AMENDMENT
RUNOFF	1			
CROP1	-	1		
LIVESTOCK	+	-	1	
N AMENDMENT	+	+	+	1

Tradeoffs and Synergies in Ecosystem Services

The second step, tabulation of stocks and flows of ecosystem services, which is the main purpose of the analysis, is much more difficult because there is seldom a one-to-one mapping of ecosystem functions on ecosystem services. For example, the provisioning ecosystem service of food production can be narrowed to a single crop, but the yield of that crop is a function of nitrogen amendments as well as nitrogen losses due to leeching and runoffs as well as consumption by crop pests and competition by invasive species or weeds.

Table 3 illustrates the complexities of mapping ecosystem functions onto ecosystem services. A single ecosystem service may be the end product of multiple ecosystem functions and sometimes the end product of multiple interacting ecosystem functions. As Table 3 illustrates, a single service may be improved by increases in some ecosystem services while degraded by increases in others or show no necessary correlation. Note this tabulation requires the ecosystem function diagram (e.g., Fig. 3).

Table 3. Mapping ecosystem services onto ecosystem functions. Cell entries can be derived qualitatively from the ecosystem stocks and flow diagram (e.g., Fig. 3) or assessed quantitatively through research. Cell entries indicate signs of the hypothetical correlations among ecosystem functions and ecosystem services.

NITROGEN TRADEOFFS AND SYNERGIES OF ECOSYSTEM SERVICES ECOSYSTEM FUNCTION X ECOSYSTEM SERVICE				
	ECOSYSTEM FUNCTION FLOWS			
SERVICES	RUNOFF	CROP1	LIVESTOCK	N AMENDMENT
Service 1 Provisioning Crop1	- Crops retain nitrogen in above ground biomass	1	- Livestock consumes stubble and residues	+
Service 2 Provisioning Livestock	+ Livestock enhance rates of nitrogen mineralization which can increase runoff	+ Livestock have crop residues for feed in addition to forage.	1	+ Larger numbers of livestock can be achieved
Service 3 Regulating Disease Regulation	- Runoff enriches aquatic systems which supports disease vectors which reduces natural regulation	0 No necessary interaction depending on agricultural practice	- Livestock can increase prevalence of vectors and diseases shared by livestock and humans	- Increases vector and pathogen abundance
Service 4 Cultural Recreational	- Increases in water-borne human pathogens which negatively impacts recreational value of freshwater systems for bathing and swimming	- Loss of natural habitat for recreation	- Loss of natural habitat for recreation	- Increases in water-borne human pathogens which negatively impacts recreational value of freshwater systems for bathing and swimming

Having completed the steps above, we can tabulate the tradeoffs and synergies among ecosystem services. Table 4 provides a hypothetical set of pair-wise interactions among ecosystem services.

Note that Table 4 provides the necessary information for constructing ecosystem service spider diagrams as shown in Figure 4.

Note also that there is the possibility of complex associations among ecosystem services that cannot be displayed in simple tables such as used in Table 4. For example, increases in livestock may decrease natural disease regulation and decrease recreational value of an ecosystem. If livestock disease regulation declines, however, then livestock may decline and cultural values of the habitat may benefit by such reductions in livestock.

Finally, we note that one can derive the correlations below by direct measurements, but the correlations themselves are not informative when it comes to causation. By stepping through all parts of the exercise, one can devise a series of robust management options to achieve desired goals based on knowledge or at least cognizance of the multiple parts of the system and the interactions among them.

Table 4. Tradeoffs and synergies among ecosystem services. Cell entries indicate the impact of row variables on column variables.

NITROGEN TRADEOFFS AND SYNERGIES OF ECOSYSTEM SERVICES				
	Service 1 Provisioning Crop1	Service 2 Provisioning Livestock	Service 3 Regulating Disease Regulation	Service 4 Cultural Recreational
Service 1 Provisioning Crop1	1			
Service 2 Provisioning Livestock	+	1		
Service 3 Regulating Disease Regulation	0	-	1	
Service 4 Cultural Recreational	-	-	+	1

Conclusions

The Millennium Ecosystem Assessment provided a simple, powerful framework that clearly shows how human wellbeing is inextricably tied to biodiversity and ecosystem functions by way of ecosystem services, but the framework is hard to employ in sustainable development. The MEA framework is difficult because its components (*biodiversity*, *ecosystem function*, *ecosystem service*, and *human wellbeing*) are complex and difficult to define to everyone's satisfaction.

Here, we have expanded the MEA framework in a way that shows its utility in understanding and managing ecosystems for the purposes of achieving sustainable development.

We have focused primarily on biogeochemically defined ecosystem functions and used nitrogen as an example because nitrogen amendments is often a tool used in many development programs.

We have identified five necessary steps for making use of the MEA framework.

1. Construct an ecosystem function stock and flow diagram (e.g., Fig. 2) quantified as best as one can by direct measurement over space and time or by expert opinion (Fig. 3).
2. From this diagram, tabulate the stocks and flows of important ecosystem functions (Table 1)
3. Tabulate the interactions (tradeoffs and synergies) among ecosystem functions
4. Tabulate the relationships among ecosystem services and ecosystem functions noting that they seldom map onto one another one-to-one (e.g., Table 2). That is, each ecosystem service is likely to be made up of different numbers of ecosystem function and correlate with each ecosystem function in different ways.
5. Finally tabulate the tradeoffs and synergies among ecosystem services (e.g., Table 4) and construct a spider diagram of ecosystem services (e.g., Figure 4).

Note that each one of these steps can be done without the other by direct measurement or expert opinion, but then devising management options to optimize the delivery of ecosystem services becomes an exercise that would be mistaking correlation for causation. Each step provides useful insights into the relationship between biodiversity (native and agricultural), ecosystem functions, and ecosystem services.

The important message of this document is that ecosystem functions directly relate to the ecosystem services sustainable development seeks to optimize, but in a complex way. This complexity should not be surprising, nor should it be considered a roadblock to achieving sustainable development. Even if just constructed by expert opinion with a minimum of research and empirical verification, it can serve as a guideline for decision making that may reveal how seemingly simple management decisions, such as using nitrogen amendments to improve yields, requires considering how other ecosystem services, especially supporting, regulating, and cultural, are likely to be affected and what overall consequences to human wellbeing might be.

LITERATURE CITED

Asner, G. P., A. J. Elmore, L. P. Olander, R. E. Martin, and A. T. Harris. 2004. Grazing systems, ecosystem response, and global change. Annual Review of Environment and Resources **29**:261-299.

Assessment, M. 2005. Living beyond our means: Natural assets and human well-being: Statement from the Board. Millennium Assessment.

Development, W. C. o. E. a. 1987. Our common future. Oxford University Press, Oxford.

Duraiappah, A. K., and S. Naeem. 2005. Sunthesis Report on Biodiversity. *in* M. Assessment, editor. Island Press.

Hobbs, R. J., and L. Atkins. 1988. Effects of disturbance and nutrient addition on native and introduced annuals in plant communities in the Western Australian wheatbelt. Australian Journal of Ecology **13**:171-179.

Roubik, D. W. 2002. The value of bees to the coffee harvest. Nature **417**:708.