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A Model-Based Quantitative Assessment of Ecosystem Services in the Scenarios of Environmental Management

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Abstract: It is well recognized that ecological systems generate a spectrum of diverse benefits that are vital to humankind. Sustainable environmental management requires an adequate consideration of ecosystem goods and services. The problem, however, is that many of the ecological and social amenities are not currently incorporated into the decision-making process. A fundamental issue is getting at the quantitative characteristics of the ecosystem services. Publications on this matter note that simulation models of the phenomena in question have to be used for this purpose. In fact, a whole family of simulation models is required. Such models should represent the main components of an ecosystem, their interrelationships and linkages to the system's environment at the appropriate time and space scales. They should also model physical, chemical and biological processes pertaining to the ecosystem being studied. Any planned activity will substantially affect the ecosystem components and their ability to generate goods and services. It is therefore necessary to understand and measure the changes – sometimes irreversible ones – which may occur in the ecosystems and their services under various management interventions and compare the expected benefits with possible losses. This knowledge should be incorporated into the process of decision-making. The paper deals with the quantitative assessment of ecosystem services as a key issue in sustainable environmental management. A model-based framework for the quantifying of the ecosystem services is presented. Forest ecosystems are considered in the case study.

Keywords*:* Ecosystem service; environmental management; anthropogenic dynamics; simulation modelling; quantitative assessment.

1. INTRODUCTION

Ecosystems generate a multitude of useful and even crutial for the human well-being benefits, collectivelly called ecosystem services. The UN-led Millennium Ecosystem Assessment Report (MEA [2004]) has categorized ecosystem services into four broad groups: *provisioning*, such as the production of food and water; *regulating*, such as the control of climate and disease; *supporting*, such as nutrient cycles and crop pollination; and *cultural*, such as spiritual and recreational benefits.

The very idea of sustainable environmental management can be discussed in a practical sense only if all the goods and services generated by the ecosystems are properly quantified, valuated, and incorporated into the decision-making process at its early stages.

The main methodological problem is that the measuring of the ecosystem benefits is a non-trivial task. In most of the cases, the corresponding values can only be obtained by building simulation models of the phenomena in question. As Costanza and Folke [1997] put it, one way to get at these values would be to employ systems-simulation models that incorporate the major linkages in the system at the appropriate time and space scales. The importance of modelling in environmental management is hard to overestimate since, for a number of reasons, experiments on real world objects are extremely limited.

Human society and a chosen type of the socio-economic development produce tremendous pressure upon the global biosphere and its various components. Thus, according to the recent estimates by the World Wildlife Fund (WWF [2006]), the demand on the planet's ecosystems ("the ecological footprint index") has more than tripled since 1961 and now exceeds the world's ability to regenerate by about 25 per cent. The other measure from the Report, the living planet index, shows a rapid and continuing loss of biodiversity.

The environmental impacts of anthropogenic actions are becoming more apparent – air and water quality are increasingly compromised, oceans are being overfished, pests and diseases are extending beyond their historical boundaries, and deforestation is exacerbating flooding downstream. According to Vitousek *et al*. [1997], approximately 40-50% of Earth's ice-free land surface has been heavily transformed or degraded by anthropogenic activities, 66% of marine fisheries are either overexploited or at their limit, atmospheric CO_2 has increased more than 30% since the advent of industrialization, and nearly 25% of Earth's bird species have gone extinct in the last two thousand years.

Given the annual American *per capita* wood consumption of 1.3 ha of forest (Pimental *et al*. [1994]) and the world's probable population of 11 billion in 2065 (UN median estimate, UNDIEA [1992]), 14.3 billion ha of forest would be required, which is 3.5 times the total world forested area, and more than all land on the planet (Rees [1992]).

Obviously, human activities and anthropogenic impacts affect the ability of the ecosystems to generate services as well as the absolute quantities of the services being delivered.

2. METHODOLOGY

In order to quantitatively assess the ecosystem services in the scenarios of environmental management, a framework is required incorporating at the very minimum the following elements: (1) an adequate theoretical understanding of an ecosystem and its various services; (2) an adequate model of an ecosystem describing internal physical, chemical, and biological processes and their interrelationships, structure and components of the ecosystem, laws of its functioning and generation of the services under natural conditions; (3) understanding of the principles governing responses/reactions of the ecosystems to exogenously caused stresses including the ability to produce services; and (4) a model predicting the ecosystem behaviour under the anthropogenic impacts and the quantities of the services (Figure 1).

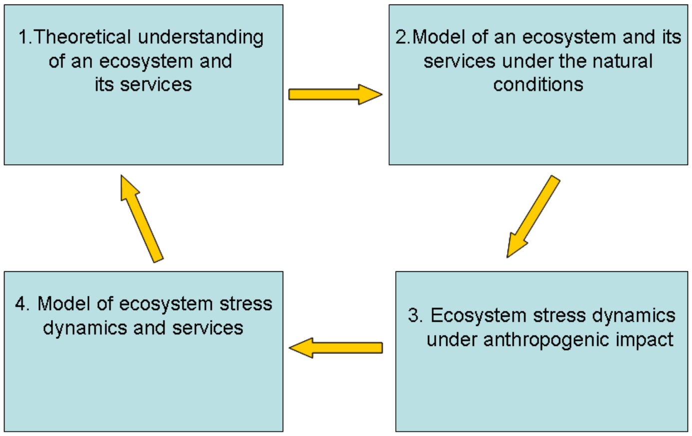

Figure 1. A framework for the quantifying the ecosystem services.

The elements of the framework are interrelated and influence each other. They are discussed in the subsequent sections of the paper.

3. METHODS

3.1 Understanding an ecosystem

The term "ecosystem" was introduced by Tansley [1935] which he defined as the system resulting from the integration of all the living and nonliving factors of the environment. In general systems theory, any system is characterized by: (1) the structure (i.e., parts and their composition); (2) behaviour (i.e., inputs, internal processing and outputs of material, energy or information); (3) interconnectivity (i.e., functional as well as structural relationships between the various parts of a system); and (4) emergentness (i.e., properties and functions arising out of combining the ecosystem components within a single whole structure.

In accordance with the general systemology, a natural ecosystem can be defined as an independent spatiotemporal unit of interrelated living (biotic) components interacting with non-living (abiotic) factors and the processes governing functioning and structure of the ecosystem components (e.g., Muller [1997]; Odum [1983]).

Abiotic factors are broadly classified under the three categories: (1) climatic factors which include the climatic regime and physical factors of the environment like solar radiation, humidity, atmospheric temperature, wind speed and direction, precipitation, current , salinity, *etc*.; (2) edaphic factors which are related to the structure and composition of soil including its physical and chemical properties, like soil and its types, soil profile, minerals, organic matter, soil water, soil organisms; and (3) inorganic substances (like water, carbon, sulphur, nitrogen, phosphorus, potassium, calcium and so on) and organic substances like proteins, lipids, carbohydrates, humic substances *etc*.).

A biotic part of an ecosystem (plants, animals and micro-organisms) is organized in hierarchical structures according to their role in the energetic and metabolic processes called trophic levels. Since 80 to 90% of potential energy is lost as heat at each trophic level, there are usually 4 or 5 trophic levels in an ecosystem.

The basis of any trophic structure is formed by the autotrophs, i.e., plants producing high-energy complex organic compounds from inorganic raw materials by means of photosynthesis. The upper trophic levels are called heterotrophs (or consumers), i.e., generally animals which feed directly on the autotrophic plants or prey upon other organisms at the lower heterotrophic levels. Saprotrophs (or decomposers), i.e., generally micro-organisms (bacteria and fungi) represent a special kind of heterotrophs which break down the complex organic compounds of dead or decaying matter, converting them to a form of nutrients usable to autotrophs.

Biologically, biotic components of an ecosystem are assembled into populations of a particular species whereas two or more populations occupying the same geographical area form a community.

The ecosystem processes (like production, destruction, respiration, transformation, *etc*.) as well as intro- and interspecific interactions (e.g., competition, predation, parasitism, mutualisms, *etc*.) are characterized by the quantitative values of the corresponding parameters.

Therefore, an adequate description of an ecosystem (E) is a three-compartment tuple which includes a set $\{C\}$ of biotic and abiotic components and factors (i.e., ecosystem composition), a set $\{S\}$ of their particular assemblages and interrelationships (i.e., ecosystem structure) and a set $\{P\}$ of ecosystem parameters designating quantitative values of the ecological processes involving components and interactions between them:

$$\mathrm{E} = \langle \{C\}, \{\mathrm{S}\}, \{P\} \rangle \cdot \tag{1}$$

3.2 A model of an ecosystem

At any given time instant t, the components (or sub-systems) of an ecological system can be represented by a non-negative n-dimensional state vector $\mathbf{x}(t) = (x_1(t), ..., x_n(t)) \in \Omega \subseteq \Re^n$. The coordinates of vector $\mathbf{x}(t)$ quantitatively designate elements of the set $\{S\}$, i.e. both biotic and abiotic constituencies of the ecosystem and their properties, such as richness and density of species or their assemblages, concentrations of organic and inorganic matters and polluting substances, *etc*. The system is influenced by exogenous perturbations denoted as an r-dimensional vector $\mathbf{u}(t) = (u_1(t), ..., u_r(t)) \in \mathrm{U} \subseteq \Re^{\mathrm{r}}$. Parameters of the ecosystem, i.e., elements of the set $\{P\}$, are represented by an m-dimensional vector $\mathbf{p}(t) = (p_1(t), ..., p_m(t)) \in \mathrm{P} \subseteq \Re^m$. In general case, each coordinate of $\mathbf{x}(t)$ will depend on all coordinates, inputs **u** and parameters **p**; each parameter $p_j(t)$ also depends on external disturbances. Then, a model for the evolution of the ecosystem is governed by an equation:

$$M[t,\ \mathbf{x}(t), \mathbf{u}(t), \mathbf{p}(t)] = 0 \tag{2}$$

with the initial conditions $\mathbf{x}(t_0) = \mathbf{x_0}$. Here M is the model dynamics operator. Admissible states of the model $(\mathbf{x},\ \mathbf{u}, \mathbf{p}) \in \Omega \times \mathrm{U} \times \mathrm{P} \subseteq \Re^{n+r+m}$. Depending on the aim of research, a particular ecosystem being modelled and observation data available, the operator M may be in a form of an algebraic expression, differential or integral operator. Often in ecological applications, M characterizes ecosystem dynamics in terms of ordinary differential equations, in which case (2) can be rewritten as:

$$\frac{d\mathbf{x}}{dt} = \mathbf{F}(t,\ \mathbf{x}(t),\ \mathbf{u}(t), \mathbf{p}(t,\ \mathbf{u}(t))). \tag{3}$$

The structure of the modelled real-world ecosystem $\{S\}$ is expressed through the values of the state variables and parameters and a particular structure of model (3), i.e., mathematical form of functions f_i $(i = \overline{1, n})$ and the parameter values.

3.3 Anthropogenic dynamics of an ecosystem

Exogenous perturbations caused by anthropogenic impacts may affect and change different components of the real-world ecosystem as represented by its mathematical models like (2) or (3), including: (1) initial conditions; (2) environmental abiotic factors; (3) biological populations in biotic assemblages and the corresponding values of the model variables; (3) parameter values; and (4) ecosystem structure. The two latter kinds of stresses may alter the strength and qualitative nature of inter- and intraspecific community interactions whereby, for example, initially noninteracting species may begin competing or exhibiting other non-neutral interactions, and *vice versa* (Justus [2006]).

An ecosystem with stress impacting its structure (S-type) can cross a critical point, shift to a new structural quality and get from one basis of homeostasis to another one. In this case, the perturbed dynamics of an ecosystem is a sequence of critical time instants t_1^{crit}, t_2^{crit},..., t_l^{crit}, at which structural transformations occur. An ecosystem passing over a critical point must be studied and modelled as a new system, though a new model can, to a different extent, inherit certain features of the old one (Pusachenko [1989]). In terms of a generalized ecosystem model (2), critical transformations appear as a sequence of models, each one suitable only for a certain "stability" domain where the ecosystem maintains its structure:

$$M_0 \xrightarrow[t_1^{crit}]{S\text{-}stress} M_1 \xrightarrow[t_2^{crit}]{S\text{-}stress} \dots \xrightarrow[t_l^{crit}]{S\text{-}stress} M_l. \qquad (4)$$

Consequently, a new model has to be built and analyzed once the ecosystem crossed a critical point and fell within a new domain of structural stability. Several important questions require answers:

- what change in the ecosystem should be considered as a critical transformation leading to a new structural domain?
- will one species extinction mark a critical transformation?
- is the critical transformation reversible or irreversible?

An ecosystem can be viewed in terms of its dominant species. A switch from one group of dominant species to another one is an example of structural transformation. Myster [2001] suggested that the ecosystem structural pattern must be tied to the functions that are critical for the continued operation of the ecosystem. Primary plant-based functions of productivity/ respiration/decomposition (Watt [1947]) as well as nutrient cycling and energy transfer/loss are the most important ecosystem functions. These characteristics can be used as indicators of critical transitions leading the ecosystem to a new structural domain.

Therefore, ecosystem services have to be quantitatively assessed only from a model suitable for a given domain of structural stability.

4. CASE STUDY: FOREST ECOSYSTEMS

4.1 Forest services

A unique role of forests among other ecosystems is determined by the fact that few ecosystems can generate as many services as forests. They provide overall ecosystem health and sustainability, protect water and air quality, support biodiversity and wildlife habitats, supply recreation and aesthetic enjoyment, *etc*.

Table 1. Three categories of forest-generated benefits

Economic amenities	**Ecological amenities**	**Social amenities**
Wood products (timber and fuel wood) Non-timber products: • wild food (honey, mushrooms, wild fruits and latex, berries, fibers, nuts, hunting meat from wild animals, birds, and fish) • raw material (cork, resin, mastic gum) • medicinal plants • plant genetic resources	Landscape stabilization Soil protection from erosion Soil moisturizing Soil enrichment by nutrients (fertilization) Pest control Water quantity regulation (hydrological function) Water purification (hydrochemical function) Flood control Climate regulation Carbon sequestration Oxygen generation Global warming mitigation Fisheries protection Wildlife habitat	Human habitat function Recreation opportunities Tourist opportunities Aesthetic function Sanitary functions: • Disease buffering • Therapeutic • Dust sequestration • Noise reduction Educational function

According to the concept of a *forest ecological-economic-social* (FEES) system (Khaiter [1993]), the set of possible forest-related benefits can be classified into three main categories: (1) *ecological* amenities that combine protective and conservational influences on the environment; (2) *economic* amenities related to the generation of food, fodder, and industrial raw materials that are used or that can be potentially used by an economy; and (3) *social* amenities that include the creation of comfortable conditions for humans from sanitary, cultural, aesthetical, recreational, and environmental points-of-view. A sample list of forest benefits in each of these three categories is shown in Table 1.

Environmentally sustainable management and utilization of forests in the interests of today's and future generations is only possible if there is a means by which the decision makers can adequately quantified all the goods and services being produced by forest ecosystems.

Let vector $\mathbf{b}^{\mathbf{E}}$ denote quantitative values of economic amenities, vector $\mathbf{b}^{\mathbf{L}}$ – quantitative values of ecological amenities, and vector $\mathbf{b}^{\mathbf{S}}$ – quantitative values of social amenities. Each of the vectors $\mathbf{b}^{j}$ (j = E, L, S) can be considered as the output of the forest ecosystem model like M in (7).

4.2 Mutually possible services

It is assumed that all the goods and services generated by the ecosystems are equally important to the society and should be included in the valuation and decision-making process. However, a competitive or even mutually exclusive nature of the benefits has to be taken into the consideration. For example, the usage of the social amenities of a forest park as a source of cultural, spiritual or recreational joys will negatively affect and reduce its ecological services and make it practically impossible to utilize most of the economic goods. Therefore, in practical terms, a full set of all the ecosystem goods and services is not an attainable value but rather an ideal one. If **B** denotes the full set of all the ecosystem goods and services ($\mathbf{B} = \mathbf{b}^{\mathbf{E}} \cup \mathbf{b}^{\mathbf{L}} \cup \mathbf{b}^{\mathbf{S}}$), at every moment of time, t, and for each planned scenario of exploitation, $u_k(t) \in \mathbf{u}(t)$, there will be the subset of mutually compatible benefits, $\mathbf{B}^u(t) \subset \mathbf{B}$.

The only way to determine $\mathbf{B}^u(t)$ is to rely on the expert knowledge on the behaviour of a particular ecosystem being then converted into the formal heuristic or production rules.

4.3 Forest hydrology

The regulation of water flows (i.e., the hydrological role) is one of the most prominent ecological services supplied by a forest. In order to quantify it, it is necessary to compare the components of the water balance in an experimental watershed with and without forest cover. It is obvious that the availability of such "paired" watersheds is extremely limited since the watershed without timber stand could be obtained only after the trees in the forested watershed are cut down. Using two physically different watersheds would limit the comparability of the results due to the uniqueness of each watershed in terms of local topology, geology, and vegetation. Subsequently, the results registered in an experimental watershed are not always applicable to other watersheds, even if they are within the same geographical area and of approximately the same size.

To overcome these methodological difficulties, an approach has been suggested (Khaiter [1993]) that is based on a simulation modelling "Forest hydrology" (SMFH) of the processes of moisture transformation in a forested watershed. The SMFH simulates the processes of forest hydrology, and calculates crown interception, evaporation from snow and water, snowmelt, water release from snow, freezing and thawing of soil-grounds, infiltration, formation of all kinds of runoff, and transpiration. The model produces as outputs the values of the water balance components, and provides a quantitative assessment of the hydrological service of the forest.

The SMFH represents the distribution of precipitation using the following water balance equation:

$$PR = EVC + EVF + EVS + Q_{SUR} + Q_{SUB} + TR + \Delta SM + Q_{GR}\,, \tag{5}$$

where PR is atmospheric precipitation; EVC, EVF, and EVS are evaporation from canopy, floor and soil, respectively; Q_{SUR}, Q_{SUB} are surface and sub-surface runoffs, respectively; TR is transpiration; ΔSM is the variation of soil moisture content; and Q_{GR} is inflow to the groundwater table.

The modelling of moisture transformation takes place at three levels (or *hydrological niches*): (1) tree crown, (2) forest floor, and (3) soil layer of a given thickness. The balance condition should obviously be satisfied for each of the hydrological niches:

$$\frac{dW^j}{dt} = \sum_i INC_i^j - \sum_k OUT_k^j \tag{6}$$

where j denotes a hydrologic niche (j = 1, 2, 3); W^j is the moisture content in the jth hydrological niche; INC_i^j, OUT_k^j are the ith income and kth outcome water balance item, respectively, for the jth hydrological niche.

In order to quantitatively assess the hydrological service of forest, it must be formally defined. It could be expressed through the positive influence of forest vegetation on both the richness of streamflows and the soil moisture content. Given that traditionally in hydrology, all items from the water balance are considered as positive (or useful) ones, except for losses to evapotranspiration and surface runoff, a formalization of the notion of the *hydrological service of a forest* and its estimation $\Delta QUSE$ was proposed (Khaiter [1991, 1993]) in the form of the following expression:

$$\Delta QUSE = \sum_{t=1}^{T} \left\{ \left[\Delta SM^f(t) + Q_{SUB}^f(t) + Q_{GR}^f(t) \right] - \left[\Delta SM^o(t) + Q_{SUB}^o(t) + Q_{GR}^o(t) \right] \right\}, \tag{7}$$

where the superscripts f and o denote forested and open (forestless) watersheds, respectively; t is the time variable; T is duration of a specified time interval.

The computer experiments with the SMFH have been carried out for a watershed representing boreal forest with a 40-50 year-old spruce tree stand, sandy and sandy loam soils, and a plant density of 0.9. The computed estimate of the hydrological service in this simulation was 2720 cubic meters per hectare per year. Two extreme situations (i.e., forested vs. open watershed) have been modelled and compared in the simulations. In terms of the forest-management practices, such a transformation corresponds to complete clear-cutting. Obviously, anthropogenic activities may lead to any intermediate scenarios.

Management activities will first affect soil density, SD, and percent of forested area, $F\%$ (e.g., Khaiter [1991]), i.e., $SD = SD(\mathbf{u}(t))$ and $F\% = F\% (\mathbf{u}(t))$. These two factors have been used in the building of the response surface, approximating the data generated by simulation experiments. As a result, the following response function was obtained:

$$\Delta QUSE = -542.9 \cdot SD + 31.8396 \cdot F\% - 14.378 \cdot SD \cdot F\% + 922.9. \tag{8}$$

Eq. (8) can be recommended as an estimator of the hydrological service of forest. Similar simulation models are obviously needed to quantify all other forest ecosystem services and goods for sustainable environmental management of a forest watershed.

4. CONCLUSIONS

A model-based framework for the quantifying of the ecosystem services is presented. The main elements of the framework discussed in the paper include: an adequate understanding and modelling of the ecosystems, their dynamics and ability to produce various benefits under both natural and anthropogenically disturbed conditions. A set of the mutually compatible benefits is important for the practical needs of sustainable environmental management and has to be properly identified in the decision-making process.

Forest ecosystems are considered as a case study. An application of the framework is demonstrated in quantitative assessment of the hydrological service of forest and its variation under the scenarios of human activities on a forested watershed.

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