Accounting for the Value of Ecosystem Assets and Their Services

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Abstract Almost all decisions made by agents (individuals, households, companies, associations, governments, etc.) are preceded by some comparisons of the expected gains from making the decision versus the costs of making the same decision. These comparisons may be completely informal, involving only some rough thoughts on the consequences of the decision or may use an elaborate decision theoretical model (Raiffa H. Decision analysis. Introductory lectures on choices under uncertainty. Random House, New York, 1968). Most decisions made by a household do not need any elaborate theoretical analysis. They are mainly made on the basis of experience. But when a household is going to make a major investment, buying a house, for example, they will try to make a rational choice, given the information they have accessible. Based on this information, they will make a valuation of the consequences, in order to see which side will dominate – buying the house now or wait for another opportunity. In this example, the household will probably consult experts that can translate the consequences of buying the house for the household into something concrete, such as the net income of the household. In this case the household is doing a valuation. Similarly, when a society is going to make a decision on say the construction of a new highway, the society should know how this new highway

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affects the citizens (e.g. higher taxes, shorter transport time, more air pollution and deforestation where the highway is going to be built) before making a decision. In the end, all these factors and many, many more have to be compared in some way or another so that a decision can be made.

Keywords Ecosystem services • Accounting prices • Ecosystem values

1 Introduction

Valuation is a technique for doing just that. In theory, it tries to identify the consequences of the construction of the highway for each affected household and then aggregate this over all households. The former part that is identifying the consequences for households can in principle be done without imposing any moral or ethical values. We are simply interested in whether a household is better or worse off. However, the second part, aggregation, needs values on how we should think of the interpersonal consequences of the construction. Some households may be better off while others will be worse off. The first part is valuation, and economists have developed a rich toolbox for assessing household-specific values.

Thus, valuation was developed as a tool for decision making. However, it is also used to find out whether the welfare in a society has increased over a specified time period. It is very common in newspapers to find references to the gross national product as an index of whether welfare has increase or not. We will introduce a different and more relevant index, namely, wealth per capita. In constructing such an index, it is necessary to value ecosystem services and more important, the capital stocks embodied in an ecosystem. In doing that, essentially the same valuation techniques as used in decision making will be used. In this chapter, we will focus on this latter aspect, although they are very much related to each other (as will be underlined later). This chapter applies the analysis of Dasgupta and Mäler (2000) to valuation of ecosystems services and the ecosystem capital stocks. We are interested in finding the accounting prices of the capital stocks that are defining an ecosystem. These accounting prices are derived from the provisioning services they are supporting, using what is known on the dynamics of the ecosystems. This chapter draws heavily on a number of already published works at the Beijer Institute of Ecological Economics (Arrow et al. 2003; Mäler et al. 2008, 2010).

We have excluded here an analysis on human capital, perhaps the most important asset; we are working on it, and that work is still not published. A working paper on that issue can be requested to the authors.

2 Ecosystems and Ecosystem Services

It will be useful to have a simple background in ecosystem ecology. We have therefore included a quotation from *Encyclopaedia Britannica*. The biosphere is a relatively thin life-supporting stratum of the Earth's surface, extending from a few kilometres into the atmosphere to the deep-sea vents of the ocean. The biosphere is a global ecosystem composed of living organism (biota) and the abiotic (non-living) factors from which they derive energy and nutrients.

Before the coming of life, the Earth was a bleak place, a rocky globe with shallow seas and a thin band of gases – largely carbon dioxide, carbon monoxide, molecular nitrogen, hydrogen sulphide and water vapour. It was a hostile and barren planet. This strictly inorganic state of the Earth is called the geosphere; it consists of the lithosphere (the rock and soil), the hydrosphere (the water) and the atmosphere (the air). Energy from the Sun relentlessly bombarded the surface of the primitive Earth, and in time – millions of years – chemical and physical actions produced the first evidence of life: formless, jellylike blobs that could collect energy from the environment and produce more of their own kind. This generation of life in the thin outer layer of the geosphere established what is called the biosphere, the "zone of life", an energy-diverting skin that uses the matter of the Earth to make living substance.

The biosphere is a system characterised by the continuous cycling of matter and an accompanying flow of solar energy in which certain large molecules and cells are self-reproducing. Water is a major predisposing factor, for all life depends on it. The elements carbon, hydrogen, nitrogen, oxygen, phosphorus and sulphur, when combined as proteins, lipids, carbohydrates and nucleic acids, provide the building blocks, the fuel and the direction for the creation of life. Energy flow is required to maintain the structure of organisms by the formation and splitting of phosphate bonds. Organisms are cellular in nature and always contain some sort of enclosing membrane structure, and all have nucleic acids that store and transmit genetic information.

All life on Earth depends ultimately upon green plants, as well as upon water. Plants utilise sunlight in a process called photosynthesis to produce the food upon which the animals feed and to provide, as a by-product, oxygen, which most animals require for respiration. At first, the oceans and the lands were teeming with large numbers of a few kinds of simple single-celled organisms, but slowly, plants and animals of increasing complexity evolved. Interrelationships developed so that certain plants grew in association with certain other plants, and animals associated with the plants and with one another to form communities of organisms, including those of forests, grasslands, deserts, dunes, bogs, rivers and lakes. Living communities and their non-living environment are inseparable and constantly interact with each other. For convenience, any segment of the landscape that included the biotic and abiotic components is called an ecosystem. A lake is an ecosystem when it is considered in totality as not just water but also nutrients, climate and all of the life contained within it. A given forest, meadow or river is likewise an ecosystem. One ecosystem grades into another along zones termed ecotones, where a mixture of plant and animal species from the two ecosystems occurs. A forest considered as an ecosystem is not simply a stand of trees but is a complex of soil, air and water; of climate and minerals; of bacteria, viruses, fungi, grasses, herbs and trees; and of insects, reptiles, amphibians, birds and mammals.

Stated another way, the abiotic or non-living portion of each ecosystem in the biosphere includes the flow of energy, nutrients, water and gases and the concentration of organic and inorganic substances in the environment. The biotic or living portion includes three general categories of organisms based on their methods of acquiring energy: the primary producer, largely green plants; the consumers, which include all the animals; and the decomposers, which include the microorganisms that break down the remains of plants and animals into simpler components for recycling in the biosphere. Aquatic ecosystems are those involving marine environments and freshwater environments on the land. Terrestrial ecosystems are those based on major vegetational types, such as forest, grassland, desert and tundra. Particular kinds of animals are associated with each such plant province (Biosphere 2009).

A similar definition of ecosystems is given by the Millennium Ecosystem Assessment[1] (MEA 2003) as a dynamic complex of plant, animal and microorganism communities and the non-living environment interacting as a functional unit. Humans are an integral part of ecosystems.

Ecosystems vary enormously in size, a temporary pond in a tree hollow and an ocean basin can both be ecosystems. Ecosystem services are the benefits people obtain from ecosystems. These include provisioning services such as food and water; regulating services such as regulation of floods, drought, land degradation and disease; supporting services such as soil formation and nutrient cycling; and cultural services such as recreational, spiritual, religious and other non-material benefits. The definitions of ecosystem given above do not give a precise guide on how to delimit an ecosystem. In principle, organisms in one area can (and will) interact with organisms elsewhere on the planet, given enough time, and we would end up with one global ecosystem. That is obviously very impractical, so we should adopt a more practical rule for bordering one ecosystem from a different one, and the only way of doing that is to use common sense. When does it seem acceptable to exclude some connections and when is it necessary to include others?

These questions may seem academic for an ecologist, but an economist needs to delimit a system very precisely in order to develop the tools for valuing the services and managing the system in a rational way. The same problem is familiar to regional economists who more or less arbitrarily define the spatial extent of the regions to be studied. In the end, only experience, theoretical insights and common sense can resolve this problem.

We will in the next section treat ecosystems as capital assets. How do we measure the "size" of these assets? We will discuss this question shortly (in Sect. 5).

3 Ecosystem Services and Human Well-Being

The MEA classifies ecosystem services into more or less obvious groupings, namely, provisioning, regulating, cultural and supporting services (MEA 2003). Humans derive many benefits from these services, and hence, their quantity and quality affect

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[1] The Millennium Ecosystem Assessment was initiated by the United Nations as a complement to the Intergovernmental Panel on Climate Change and with the objective to assess the state of ecosystems.

human well-being in many ways. They directly or indirectly influence the multiple constituents of human well-being, including basic material for a good life, freedom of choice and action, health, good social relations and security (MEA 2003). The constituents of well-being, as experienced and perceived by people, are situation dependant, reflecting local geography, culture and ecological circumstances.

Provisioning services are those services that are directly used by man and openly changing human welfare. Examples are many: fish from the seas, timber from the forest, agricultural output from cultivated land, etc.

Cultural services are services that are not material but still affect man directly. The view of large mammals – whales, elephants, lions, moose, wolfs – is something many persons are willing to pay substantial amounts to see, which is a clear indication that the existence of these animals are welfare enhancing. Similarly, gigantic sequoias, rare orchids, a cloud forest in Costa Rica or a boreal forest in Northern Scandinavia may by their existence provide well-being to many citizens. Thus, these kinds of assets often generate *intrinsic* values. An intrinsic value is roughly defined as the value of change in a resource, even if this change in the resource does not change the behaviour of individuals. We will come back later to a discussion of intrinsic values.

Regulating services do not directly provide welfare to humans. Their importance derives from the fact that they are essentially important intermediary goods and services. Thus, their value derives from the values of the provisional services they are input to.

Similarly, supporting services are another kind of intermediary services that derive their value from the value of the provisioning services they support. Therefore, we will below call the regulating and supporting services simply intermediary services. From a valuation point of view, there is therefore not much difference between regulating and supporting services, and we will treat them as one in what follows. As provisioning services are generating direct inputs to human production agencies (households, private and public organisations, etc.) we will rename them for final demand (or final consumption) in order to keep the text in line with established economic definitions. Thus, we have two different kinds of ecosystem services, final consumption services and intermediary services.

However, it is important to remember that an intermediary service, besides providing a necessary input to production of provisioning services, may also provide a provisioning service directly. An example is given by a forest that regulates the local hydrology (the regulating service) but also provides fuel wood or recreational opportunities. That is, an intermediary service may also be generating final consumption, and we will give many examples of this later. It may be desirable also to repeat that the values of intermediary services is derived from their role in providing final consumption, and we will see many examples of this later.

It is most often assumed without reason that ecosystem services are positive for man. This is not necessarily true. Marine ecosystems support jellyfish which can be very painful for persons that are in contact with them, and they can even be fatal. Mosquitoes carrying malaria parasites are very unwelcome guest in human bodies! Thus, there are negative ecosystem services, and **they should be included in the final valuation**.

For our discussion on valuation techniques later, it may be worthwhile already now to recall that both final consumption and intermediary services may either be characterised as public goods or as private goods. This distinction has nothing to do with whether the producer is a private or public agency. It has to do with whether the output from a service shares the characteristic of a private or public good. A service is a private good when an increase of the use of the service by one household will diminish the potential use by other households.

A public good is just the opposite – a service is a public good if an increase of the use of this service by one household will not diminish the potential use by other households. We will see several examples on the analytical use of this distinction soon. However, two examples may illustrate the distinction.

A forest provides many provisional services, but for now, let us consider the supply of fuel wood. If one household increase its collection of fuel wood, there will be less available for other households to collect (if fuel wood is scarce). Thus, there is a competition between households for fuel wood. This is true irrespective of the institutional arrangements – more fuel wood to one household will necessarily reduce the available fuel wood that can be used by other households. Thus, the fuel wood is a private good.

The forest also controls the hydrology of the surrounding area. A clear cutting of parts of the forest will change the pattern of water flows, and that change will be the same for all inhabitants of the forest area. The change in hydrology is a public (dis) service. The only way for a household to avoid experiencing this change in hydrology is by moving away from the catchment area. But for all those who remain in this area will face the same change in the water flows. The reasons why these concepts are important are two: Valuation depends on whether an ecosystem service is a private or a public good; management of the ecosystems will very much be influenced by the distinction between private and public goods

We will later see that these two reasons are intimately connected.

Ecosystems can be looked upon as a set of capital assets that together with abiotic inputs – water, sunshine, runoff of fertilisers – produces ecosystem services that will, positively or negatively, affect human well-being. This chapter focuses on the study of these assets and in particular on their importance for human well-being. Thus, our immediate interest is not to value ecosystems services but to value the underlying capital stocks.

For doing so, we need to understand the dynamics of ecosystems. We need to know what happens in ecosystems when a particular stock is perturbed. Most of this chapter will be devoted to a discussion of just that: exemplify how to understand ecosystems dynamics.

Focusing on the valuation of capital assets that are making up ecosystems and on ecosystems' dynamics is important because these issues are connected with the analysis of sustainable development. Derived ecosystem values (accounting prices) will also be the tool for judging and comparing alternative policies and management choices.

4 Sustainable Development and Accounting Prices

Before going into a discussion of valuation techniques, it is necessary to discuss the purpose of valuation. Here, we will argue that valuation is primarily a tool for first assessing whether the economic development is sustainable or not and second for generating information for decision makers in a way that supports sustainable development. As mentioned before, this discussion will take place within the framework developed by Dasgupta and Mäler (2000) and Arrow et al. (2003)

4.1 Wealth as an Indicator of Sustainable Development[2]

Let $C_s = (C_{1,s}, C_{2,s}, \ldots, C_{m,s})$ be a list (or vector) of consumer goods and services in period s. The list must contain what we traditionally regard as consumer goods but also environmental amenities, public goods etc. These are included because all of them contribute to human well-being in one way or another.

We add the critical assumption that we have a forecast of the future consumption vectors. Such a forecast obviously must depend on three factors: the present stocks of capital $K_{i,t}$ (where the current period is t and i denotes the ith capital stock), a forecast of future knowledge (including technological) knowledge, a forecast of the future institutions of the economy and a knowledge of the dynamics of stocks involved. Given such a forecast, the forecasted consumption will depend on these four factors. We will focus on the role of the present stocks of capital (but we will touch upon the remaining two a few times later).

Let $K_s = (K_{1,s}, K_{2,s}, \ldots, K_{m,s})$ be a list (or a vector) of capital stocks in the beginning of periods. Given a dynamic system that determine the future capital stocks, we can write

$$K_{t+1} - K_t = \theta\left(C_t, K_t, t\right) \tag{1}$$

We assume, as is standard in economics, that there is a utility function $U(C_1, C_2, \ldots, C_m)$ that describes the production of well-being in any given period. Note that the list of consumption "goods" is not equivalent to what we ordinarily measure as consumption. The list $(C_1, C_2, \ldots, C_m)$ of consumption goods includes all goods and

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[2] Most often, this analysis is presented in models with continuous time. This is in general more convenient – simpler, faster and less cumbersome, but as applications will be based on data organised on discreet intervals, we have chosen to use a time defined in discrete periods. Furthermore, with continuous time, some serious interpretation problems would arise if we introduce randomness into the analysis.

services that affect the feeling of well-being: food, recreation, health, natural amenities and even the improvement of other peoples well-being and also those goods and services that reduce the feeling of well-being (bads) such as pollution, labour and time. Given the assumption in the previous paragraph, the future consumption C_τ will be a function of the present stocks:

$$C_\tau = \alpha\left(\tau, t, K_{1,t}, K_{2,t}, \ldots, K_{m,t}\right) \tag{2}$$

The α function will be called a resource allocation mechanism, and the characteristics of this function are determined by our forecasts of the future knowledge and the future institutions.

We will define social welfare as the present value of the stream of future utilities.

$$W_t = \sum_{s=t}^{\infty} \frac{U\left(C_s\right)}{\left(1+\delta\right)^{s-t}} \tag{3}$$

We will return to the interpretation of the discount rate and the utility function later. Mathematically, the accounting price on assets *i* at time *t* is defined as

$$\tilde{p}_{i,t} = \sum_{s=t}^{\infty} \frac{\partial U\left(C_s\right)/\partial\left(K_{i,t}\right)}{\left(1+\delta\right)^{s-t}} \tag{4}$$

It is worth remembering that forecasted future consumption is a function of the current capital stocks. The intuition behind this definition should be clear: the accounting price of capital stock *i* at time *t*, with utility as the numeraire, is the present value of the future marginal return (measured in utility units) of small perturbation of the stock at time *t*. Very often in the rest of this chapter, we will replace the list with a single variable *C*, but it would be quite easy intellectually to carry with us the whole list, although it might be typographically boring. We will make the rather strong assumption that there is only one individual in society in order to avoid difficulties associated with interpersonal comparisons.

$$W_{t+1} - W_t = \sum_{i=1}^{n} \tilde{p}_{,t}\left(K_{i,t+1} - K_{i,t}\right) + v_t \tag{5}$$

Neglecting the last term, Eq. 5 says that the change in social welfare between two time periods is equal to the sum over all capital stocks of the value of changes in these stocks, when the value is calculated with the accounting prices $\tilde{p}_{it}$. Thus, the economy is on a sustainable path if the changes in welfare from one period to the next are always nonnegative. It is easy from this definition of accounting prices for stocks to derive the corresponding prices for flows (flows of consumption and of capital goods).

4.2 Choice of Numeraire

The analysis above is with utility as the numeraire. The accounting price of one stock is a price in utility: that is, how much utility we would be willing to abstain from in the current period in order to have the stock in the end of the period increased by one unit. In empirical studies, it would not be very convenient to use utility as the numeraire. Instead, we would like using consumption in the current period as the numeraire: that is, using the costs of a basket of consumption goods in the current period as the numeraire. In order to simplify, we assume that the basket contains only one good: good #1. With this as the numeraire, the accounting prices are defined as

$$p_i(s) = \frac{\tilde{p}_i(s)}{\partial U / \partial c_1} \tag{6}$$

However, in order to use these prices with consumption as the numeraire, we need to use the discount rate with consumption as the numeraire r instead of the utility discount rate δ, and this is discussed in the next section.

4.3 Discounting

The way of looking at δ is as a moral parameter indicating how we want to compare well-being of future generations with well-being of the present generations. The utility discount rate is related to the consumption rate of discount rate. This latter concept (r) is basically measuring the marginal rate of future consumption for present consumption. The relation follows from the Ramsay equation:

$$r = \delta + \mathbf{n}g \tag{7}$$

That says the consumption rate r equals the utility rate δ plus the elasticity of marginal utility $\mathbf{n} = -C\left(u'' / u'\right)$ of consumption times the predicted future growth rate g of consumption. **n** can be interpreted as our regard for equity between different generations, regardless of when these generations live[3]; g as how much better a future generation is predicted to find life compared to the present generation; and δ as our preferences for individuals living in the future relative current individuals. The Ramsey equation can be interpreted as a rule that provides us with an "exchange rate" between measuring well-being in utility terms and in consumption terms. We will soon discuss the way of converting streams of utility (or well-being) into streams of consumption and vice versa. One can now show that these accounting

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[3] Can also be interpreted as the relative risk aversion.

prices for stocks and flows are the correct prices for marginal cost-benefit analysis of "small" projects (see Arrow et al. 2003). Thus, these prices are the correct prices with which we should evaluate suggested policy reforms.

Let us now go back to Eq. 5. In this equation, the first term gives the "endogenous" change in social welfare, that is, the change which is due to changes in resources inside the system. The last term v_t reflects changes in social welfare due to causes outside the studied system. For example, changes in a country's terms of trade (for a small country) independent of changes inside the country. The term will also reflect autonomous changes in technology (i.e. technical changes that are independent of capital accumulation in the country). Although both terms of trade and technical changes can be quite important for social well-being, we will neglect these effects in this chapter, that is, we will neglect the "drift term". (For a motivation to this, see Xepapadeas (2005) and Dasgupta and Mäler (2000).) However, the main reason for not including this term in this text is that we want to focus on how to include ecosystem services in this framework.

5 Ecosystems as Capital Assets and Estimation of Accounting Prices

We regard ecosystems as collection of organisms that are interacting with each other and such that these interactions can be described as a dynamic system, and the biomass of the various organisms can be interpreted as capital assets. Thus, the assumption implies that we can interpret an ecosystem as dynamical system with the interactions described by the dynamical equations. However, the number of different organisms in an ecosystem may be extremely large, and in order to make empirical analysis of an ecosystem, we need to aggregate them to a small number of measurable variables. We assume, from now, that the system we are studying have been simplified in this way. We will illustrate with specific models.

5.1 Odum's Control Model

Odum (Odum and Odum 2000) tried to develop a complete model of an ecosystem by writing down differential equations for all important assets in the system in which exogenous factors (human intervention, solar radiation, precipitation, etc.) appear as inputs to the equations. By solving this system, we would consequently be able to predict the future evolution of these assets, and by doing that, we could evaluate the value of the changes in the stocks and thereby judge whether the economy is on a sustainable path or not. However, it is notoriously difficult to solve such a system unless the equations are linear with constant coefficients.[4] This approach

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[4] There are numerical solution procedures that would give us a chance of evaluating the system.

was used by a group at Resources for the Future (RFF) in the early 1970s to model the Delaware Estuary (Russel et al. 1976). In this application, the dynamics were rather simple. The main variable was the flow of the river that carried sediments (nutrients) and pollutants downstream, and linearisation of the equations were considered acceptable. Besides this, we are not acquainted with any other studies based on this approach. Our next model type can be considered as a generalisation of the Odum's approach but will also be limiting its applicability to only one or two assets.

5.2 The Schaeffer Model of a Fishery

Although the Schaeffer model is not an ecosystem model as it only includes one species, we include this surplus model[5] in our discussion on valuation as it will set the tone for more general models.

Let x_t be the stock of fish in the beginning of period t. The dynamics of this stock is given by

$$x_{t+1} - x_t = g x_{i,t}\left(1 - \frac{x_t}{\overline{x}}\right) - h_t \tag{8}$$

where h_t is the harvest in period t, g is the intrinsic growth rate and $\overline{x}$ is the carrying capacity of the system.[6] If the current stock is very small compared to the carrying capacity, the biomass will approximately grow at the constant rate g. However, that is not sustained forever as food for the species is limited, and thus, the growth rate must go down. If the harvest is zero, the limiting stock will be the carrying capacity. With positive harvest, the limiting stock will be smaller. The harvest is, of course, a provisional service, and there are no regulating services in the system according to the model.

We can now try to derive the accounting price for the fish stock at beginning of the period which may in general be different from the price of the catch. However, we must first make a forecast of the future of the fishery. Such a forecast will be influenced by the institutions controlling the use of the fishery. Let us start by assuming

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[5] Surplus model definition can be found in books on fishery economics; see, for example, (Clark 2010). Roughly speaking, the biomass of the fishery grows at a rate depending on the available food and the consumption of the fishes. If the growth is greater than the natural consumption, there will be a surplus that man can exploit.

[6] This seems to be very simple model mathematically, but it is surprisingly complex and can for high growth values generate chaotic behaviour. See May (1976) for an interesting analysis. See Aniyar (2002) for the case when access is defined in terms of a dynamic process and for a complete analysis, including the case of fixed costs.

the system to be optimally managed. The optimum is defined as the harvest strategy that maximises the present value of future harvests:

$$\sum_{s=t}^{\infty} \frac{ph_t - C(e_t)}{(1+r)^{s-t}} \tag{9}$$

where e_t is the fishing effort in period t (say measured by number of boats in the fishery), $C(e_t)$ is the cost of the effort and p is the price net of fishing costs, for the harvest.

A necessary condition for an optimal management is the existence of an accounting price, q_s, on the fish stock.

$$q_s = p - \frac{C'(e_s)}{x_s} \tag{10}$$

In a steady state, the accounting price is thus equal to output price minus the marginal cost effort per unit of fish stock. Note that the service of the fish stock is a provisional service (final service in our terminology) and that service is a private good with a market price, and if our assumption of the dynamics is correct, the estimation of the accounting price is very simple.

Let us now assume that the fishery is an open-access fishery, that is, anyone can enter and leave the fishery without cost.[7] That implies that as soon as expected profit is positive, fishermen will enter the fishery, and when it is negative, they will leave. In equilibrium, net revenues must be zero.[8] The rent from the fishery has been completely dissipated. But that implies that the accounting price must be zero. Or at the margin, an increase in the fish stock is worth nothing. This example shows that valuation of ecosystem services must be seen in an institutional context. Accounting for ecosystem services is, thus, very closely connected with the institutions that determine the management of the ecosystems.

6 Mangrove Forests and Fisheries

The carrying capacity of the fish stock in the previous example is in general determined by the physical and biological environment in which the fish reproduce. One example of that is the importance of mangrove forests for fisheries. Thus, let us assume that the carrying capacity $\bar{x}$ is a function of the size of the mangrove forest. Once again, we have to face the problem of how we should define size. Possibly, the best way is to simply define it as the area covered by the forest. For our purpose, the

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[7] See Aniyar (2002).

[8] See Aniyar (2002) for details.

exact definition is of importance. Of course, the mangrove forest offers many more services (wood for charcoal production, wood for construction, recreational area, protection of coastal land, etc.) but we will neglect them here and concentrate on the regulating services. Thus, we postulate

$$\overline{x}_s = \overline{x}(M_s) \tag{11}$$

where M_s is the size of the forest.

While keeping the Schaeffer model, we could also have assumed that the intrinsic growth rate is affected by the size of the mangrove forest. However, the case we are going to study is enough to show the general principles. The dynamics of the fish stock can as in the previous section be written

$$x_{s+1} - x_s = rx_s\left(1 - \frac{x_s}{x(M_s)}\right) - h_s \tag{12}$$

We also need to know the dynamics of the mangrove forest. The simplest (but perhaps erroneous) assumption is that the logistic model describes the forest growth sufficiently well.

$$M_{s+1} - M_s = r_M M_s\left(1 - \frac{M_s}{\overline{M}}\right) - h_{M,s} \tag{13}$$

where M_s is the harvest of forest products in period s.

We now have two different equations, and it is not possible to derive closed form solutions to them. However, the accounting price for both mangrove and fish stocks (given the price of fish catch) can be obtained by using, for example, Stella simulation software. Note that the accounting price for the regulating service of the mangrove forest is derived from the price of the fish catch.

7 Plaice Fishery and Environmental Disservice[9]

The surplus model, discussed in the previous section, is based on the idea that food is the limiting factor for growth. However, the assumptions behind the surplus model are not always correct.

Plaice (a fish belonging to the flounders) is an important fish in the North Atlantic. Its reproduction requires bare bottoms (hard or sandy bottoms). Thus, the really scarce factor determining the biomass of plaice is the suitable breeding areas.

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[9] This section is based on a chapter in Dr. Sandra Silva Paulsen PhD thesis (Paulsen 2007).

The size of the breeding area determines the annual production of juveniles. After almost a year, the juveniles are recruited into the adult population. Every individual in a generation is assumed to consume the same amount of food, but the food consumption will increase with the age of the individual (of course up to a certain limit). The food consumption (and therefore the growth of the fishes in that cohort) is given by the von Bertalanffy growth function (VBGF) equation where total biomass of one cohort in 1 year is determined by multiplying the weight of the average individual (given by VBGF) with the number of individuals in the surviving generation and then summed overall cohorts.

The biology of plaice is such that the Schaeffer model is not a good choice for describing the dynamics of this species population because it is based on the idea that food is what is scarce and limits the population growth. For plaice, this is not the case; what limits population growth is breeding space. Reproduction areas are threatened by eutrophication (e.g. due to runoff of nitrogen from agricultural land or discharge of sewage). When the bottom has been covered by algae, it can no longer be used for reproduction. Thus, the growth of algae can be seen as a regulatory disservice, and suitable reproduction areas are an asset which has an accounting price. This accounting price can be estimated as follows.

The Beverton–Holt model is most appropriate for describing the dynamics of plaice population. It is a classic discrete-time population model which gives the expected number (or density) of individuals in one generation as a function of the number of individuals in the previous generation. The model focuses on the growth of individuals over time.

This growth is described by the so-called von Bertalanffy growth function (VBGF) equation,[10] where total biomass of one cohort in 1 year is determined by multiplying the weight of the average individual (given by VBGF) with the number of individuals in the surviving generation, then summed over all cohorts. The model is complicated, and it is impossible to derive mathematical solutions except in some extremely simple cases. Instead, one can use GAMS (General Algebraic Modelling System) to simulate the fishery and thereby estimate the accounting price on suitable reproduction areas.

Such an estimate of the accounting price is obviously needed for accounting for the changes in hard bottoms. However, it is also important for social cost-benefit analysis. If we are contemplating a project aiming at a reduction of the flow of nutrients to the breeding areas in order to reduce eutrophication. The benefits of such a project is then equal to the value of the increased area of hard bottoms, where the value is defined by the accounting price! This is a general result. The accounting prices we have been discussing are exactly the prices that are the correct prices to use in social cost-benefit analysis.[11]

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[10] The von Bertalanffy growth function (VBGF) equation was introduced by von Bertalanffy to predict the length of a shark as a function of its age (Bertalanffy 1938).

[11] See Arrow et al. 2003 for a general analysis of this issue.

8 Pollination Services from Wild Bumblebees

This is based on a study that we carried out on the sustainable development of the Stockholm County parts of which is to be found in Mäler et al. (2008, 2010).

Many types of rapeseed (Canola), a major cash crop in North America, are pollinator dependant. For certain Canola lines, the seed weight per plant can increase over 80% with bumblebee's pollination (Steffan-Dewenter et al. 2002). The growing demand for urban development has significant impacts on terrestrial ecosystems (McYntyre et al. 2000) and on habitat fragmentation (Sala et al. 2000), which represents a major threat to wild pollinators (Allen-Wardel et al. 1998). In this context, it is relevant to assess the pollination ecosystem services. In our Stockholm Country Project, we attempted to estimate the accounting price for the pollination-regulating service by calculating how the pollination potential of Canola can vary due to land-use change, in an urban development.

It has shown that the availability of mass-flowering crops (as Canola) has strong positive effects on bumblebee densities, and the strongest correlation between the proportion of mass-flowering crops and bumblebee (*B. terrestris*, *B. lucorum*, *B. lapidaries*, *B. pascuarum*) densities was found for landscape sectors with 3,000 m radius (Westphal et al. 2003).

The bumblebees also require a 2% area of semi-natural habitat within the circles surrounding the canola fields, to obtain adequate nesting sites. By using a GIS (ArcView) and information on area and geographical location of Canola fields, we could then place circles (3,000 m radius) around the canola fields of the study area (Stockholm County, Sweden) and calculate the pollination potential in each circle. By changing land use according to a regional development plan (Stockholm Regional Planning Office 2001) of the study area, we can then estimate the change in the pollination potential of the Canola. The parameters upon which our estimates of pollination potential changes are based on the proportion of mass-flowering crops within the circle and the minimum requirement of semi-natural habitat.

As there is also a correlation between bumblebee density and harvest index (30), the change in pollination potential can be linked to crop output. The change in crop output can then, in turn, be translated into monetary units through a market price method. Using a similar approach, it has been shown (Rickettes et al. 2004) that forest-based pollinators increased coffee yield in plantations in Costa Rica by 20% and estimated that during 2000–2003 pollination services from two forest fragments translated into about USD 60,000.

Furthermore, the scales of operation of ecosystem services are essential consideration when valuing ecosystem services (Hein et al. 2006). The scale of operation of solidarity wild bees as well as some long-tongued bumblebees (Walter-Hellwig and Frankl 2000) is in the realm of hundreds of metres, as opposed to several thousand metres, as is the case for the included generalist bumblebees; in our example, there are potentially several scales of operation to consider.

The distribution of resources at the landscape is an important issue to consider in the context of mobile organisms contributing to ecosystem services (Kremen 2007). Landscape connectivity is needed for different pollinators and potentially also for relevant pest control species, the freedom of choice to switch between different crops, in the face of, for example, climate change, is enhanced. This freedom allows adaptation to future environmental and other changes and should also be considered an option value, at least partly ascribed to the pollination service.

The dynamics of the interactions between the wild pollinators needs therefore at least two capital stocks, the size of the canola plantation and the size of the natural and semi-natural habitat. The bee population seems to adjust very quickly to changes in the canola cultivation; thus, there is a very fast positive feedback from increases in the canola area to the increase in stock of bees and the following increase in canola production. On the other hand, the increase in impacts on the size of the natural or semi-natural habitat seems to reach a saturation point with regard to impacts on the size of the bee populations. If the habitat is smaller than saturation size, a decrease of habitat will result in lower bee population and therefore lower harvest of canola.

We will try to summarise the above description by the following model structure. Let

x_t be the stock of bumblebees in the beginning of period t
y_t be the canola production
N_t be the size of natural habitat for the bumblebees
L_t be the land used for canola cultivation

Then we could represent the dynamics of the bumblebees by

$$x_{t+1} - x_t = rx_t\left(1 - \frac{x_t}{\overline{x}_t}\right) \tag{14}$$

Here, we have assumed that there is no predation of bumblebees. However, it is possible to change that assumption without difficulties. This is a logic growth model with carrying capacity given by

$$\overline{x}_t = \overline{x}\left(N_t, L_t\right) \tag{15}$$

The canola production y_t is described by

$$y_t = \psi\left(L_t\right) \tag{16}$$

Here, we have assumed that the Canola production is determined by the size of land allocated to its growth. Of course, labour, fertiliser, etc. and other inputs will affect the production, but we will disregard such factors in this presentation. The production of canola seeds (S_t) is given by

$$S_t = \varnothing\left(y_t, x_t\right) \tag{17}$$

Finally, the value of the seed production in year *t* is

$$v_t = q_t S_t - C(L_t) \tag{18}$$

where $C(L_t)$ is the cost of cultivating the land L_t.

Finally, the accounting prices for the stocks of natural land *N*, cultivation land *L* and bumblebees are defined as the partial derivatives with respect to these variables of objective function

$$\sum_{s=\tau}^{\infty} \frac{v_\tau}{(1+r)s-t} \tag{19}$$

If the dynamics of the bumblebees are fast enough, then Eq. 14 can be simplified to

$$x_t = \bar{x}(N_t, L_t) \tag{20}$$

This substantially simplifies the estimation of the accounting prices.

In flow accounting, the only quantity of interest is v_t, as it is done in the standard system of national accounts (SNA). This v_t can easily be found from agricultural statistics. However, here, we are interested in the value of changes in capital stocks, and therefore, we are interested in the value of the change in the stock of bumblebees during the time period considered. The change in the stock of bumblebees is, however, determined by changes in other stocks – stock of rapeseed (food for bumblebees) – as well of the stock of suitable habitat for the bees. For an analysis sustainability – which focuses on future rapeseed production – this is much more interesting than the current harvest of rapeseed. The contributions from the bumblebees do not need to be accounted for, as these are already, implicitly accounted for in v_t.

9 Forests and Water

In all previous examples, the value of a regulating service has been calculated from an assumed knowledge of the value of a provisional service. We will in this example study a case where we first have to estimate the marginal value of the provisional service before we can estimate the value of the regulating service.

It seems to be accepted that a forest will retain water in greater quantities and for longer periods than a corresponding area in which all trees have been removed. In particular, the transport of water in the soil will be much slower in forested area, which means a higher quality, both of ground water as well as surface water. This can be studied by using detailed hydrological models.

We will thus assume that we do have such a model that relates changes in forested area to changes in water flow, to changes in the variance of the water flow and to changes in the quality of the water flow.

Thus, associated with a change ΔF of forested area, there are corresponding changes in the average water flow, ΔW, in the variance in the flow, $\Delta\sigma$, and in the quality (measured e.g. by its turbidity), ΔQ. If we can value these changes, we will be able to estimate the accounting price, p, for the forested area.

Assume now that this water will be used for irrigation. Then turbidity does not matter, but the variance of the flow does matter. An increase in the variance of the flow will mean a waste of water which otherwise could have been used for increased productivity of the land, and vice versa.

10 Accounting Price for Resilience

Ecosystems are often characterised by positive feedbacks which imply that external disturbances will be reinforced and the system may switch to a completely different equilibrium. Such equilibrium may have totally different characteristics with a different supply of ecosystem services. A collection of studies dealing with this situation were put together in Dasgupta and Mäler (2004).

This is the case when there will exist thresholds, and when reaching such a threshold would cause a substantial change in the supply of ecosystem services. However, the present situation for the ecosystem may be that only large disturbances will cause the system to move to the threshold. The largest disturbance the system can manage without undergoing a major change is known as *resilience*. The larger the resilience is, the smaller is the probability that a disturbance will be large enough to move the system to the threshold. Thus, resilience has a value to society and should therefore be accounted for.

In Mäler and Li (2010), an analysis was done using a model with continuous time. In line with the general approach in that paper, we should present a derivation of the accounting price in a model with discrete time. However, we have not accomplished this as yet.

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