The Value of the World's Ecosystem Services and Natural Capital

by

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We estimated the current economic value of 17 ecosystem services for 16 biomes, based on a synthesis of published studies and a few original calculations. For the entire biosphere, the value (most of which is outside the market) is estimated to be in the range of $16 - 54 trillion/yr., with an average of $33 trillion/yr. Because of the nature of the uncertainties, this must be considered a minimum estimate. Global GNP is around $18 trillion/yr.

The services of ecological systems and the natural capital stocks that produce them are critical to the functioning of the earth's life support system. They contribute significantly to human welfare, both directly and indirectly, and therefore represent a significant portion of the total economic value of the planet. Because these services are not fully captured in markets or adequately quantified in terms comparable with economic services and manufactured capital, they are often given too little weight in policy decisions. This neglect may ultimately compromise the sustainability of humans in the biosphere. The economies of the earth would grind to a halt without the services of ecological life support systems, so in one sense their total value to the economy is infinite. However, it is instructive to estimate the "incremental" or "marginal" value of ecosystem services - the estimated rate of change of value with changes in ecosystem services from their current levels. There have been many studies in the last few decades aimed at estimating the value of a wide variety of ecosystem services. We synthesized this large (but scattered) literature and present it in a form useful for ecologists, economists, policy makers, and the general public. From this synthesis, we estimated values for ecosystem services per unit area by biome, and then multiplied by the total area of each biome and summed over all services and biomes.

While acknowledging the many conceptual and empirical problems inherent in producing such an estimate, we think this exercise is essential in order to (1) make the range of potential values of the services of ecosystems more apparent; (2) establish at least a first approximation of the relative magnitude of global ecosystem services; (3) set up a framework for their further analysis; (4) point out those areas most in need of additional research; and (5) stimulate additional research and debate. Most of the problems and uncertainties we encountered indicate that our estimate represents a minimum value, which would probably increase: (1) with additional effort in studying and valuing a broader range of ecosystem services; (2) with the incorporation of more realistic representations of ecosystem dynamics and interdependence; and (3) as ecosystem services become more stressed and "scarce" in the future.

Ecosystem Functions and Ecosystem Services

Ecosystem *functions* refer variously to the habitat, biological, or systems properties or processes of ecosystems. Ecosystem *goods* (e.g. food) and *services* (e.g. waste assimilation) represent the benefits human populations derive, directly or indirectly, from ecosystem functions. For simplicity, we will refer to ecosystem goods and services together as ecosystem services. A large number of functions and services can be identified.[1-4] Daily[5] provides a detailed recent compendium on describing, measuring, and valuing ecosystem services. For the purposes of this analysis we grouped ecosystem services into 17 major categories. These groups are listed in Table 1. We included only renewable ecosystem services, excluding non-renewable fuels and minerals and the atmosphere. Note that ecosystem services and functions do not necessarily show a one-to-one correspondence. In some cases a single ecosystem service is the product of two or more ecosystem functions whereas in other cases a single ecosystem function contributes to two or more ecosystem services. It is also important to emphasize the interdependent nature of many ecosystem functions. For example, some of the net primary production in an ecosystem ends up as food, the consumption of which generates respiratory products necessary for primary production. Even though these functions and services are interdependent, in many cases they can be added because they represent "joint products" of the ecosystem which support human welfare. To the extent possible, we have attempted to distinguish joint and addable products from products which would represent "double counting" (because they represent different aspects of the same service) if they were added. It is also important to recognize that a minimum level of ecosystem "infrastructure" is necessary in order to allow production of the range of services shown in Table 1. Several authors have stressed the importance of this "infrastructure" of the ecosystem itself as a contributor to its total value.[6,7] This component of the value is not included in the current analysis.

Natural Capital and Ecosystem Services

In general, capital is considered a stock of materials or information which exists at a point in time. Each form of capital stock generates, either autonomously or in conjunction with services from other capital stocks, a flow of services which may be used to transform materials, or the spatial configuration of materials, to enhance the welfare of humans. The human use of this flow of services may or may not leave the original capital stock intact. Capital stock takes different identifiable forms, most notably in physical forms including natural capital, such as trees, minerals, ecosystems, the atmosphere, etc.; manufactured capital, such as machines and buildings; and the human capital of physical bodies. In addition, capital stocks can take intangible forms, especially as information such as that stored in computers and in individual human brains, as well as that stored in species and ecosystems.

Ecosystem services consist of flows of materials, energy, and information from natural capital stocks which combine with manufactured and human capital services to produce human welfare. While it is possible to imagine generating human welfare without natural capital and ecosystem services in artificial "space colonies," this possibility is too remote and unlikely to be of much current interest. In fact, one additional way to think about the value of ecosystem services is to determine what it would cost to replicate them in a technologically produced, artificial biosphere. Experience with manned space missions and with Biosphere II in Arizona indicates that this is an exceedingly complex and expensive proposition. Biosphere I (the earth) is a very efficient, least-cost provider of human life support services.

Thus we can consider the general class of natural capital as essential to human welfare. Zero natural capital implies zero human welfare because it is not feasible to substitute, in total, purely "non-natural" capital for natural capital. Manufactured and human capital require natural capital for their construction.[7] Therefore, it is not very meaningful to ask the total value of natural capital to human welfare, nor to ask the value of massive, particular forms of natural capital. It is trivial to ask what is the value of the atmosphere to humankind, or what is the value of rocks and soils infrastructures as support systems. Their value is infinite in total.

However, it *is* meaningful to ask how changes in the quantity or quality of various types of natural capital and ecosystem services may impact human welfare. Such changes include both small changes at large scales and large changes at small scales. For example, changing the gaseous composition of the global atmosphere by a small amount may have large scale climate change effects that will affect the viability and welfare of global human populations. Large changes at small scales include, for example, dramatically changing local forest composition. These changes may dramatically alter terrestrial and aquatic ecosystems, impacting the benefits and costs of local human activities. In general, changes in particular forms of natural capital and ecosystem services will alter the costs or benefits of maintaining human welfare.

Valuation of Ecosystem Services

The issue of valuation is inseparable from the choices and decisions we have to make about ecological systems.[6,8] Some argue that valuation of ecosystems is either impossible or unwise, that we cannot place a value on such "intangibles" as human life, environmental aesthetics, or long-term ecological benefits. But, in fact, we do so every day. When we set construction standards for highways, bridges and the like, we value human life (acknowledged or not) because spending more money on construction would save lives. Another frequent argument is that we should protect ecosystems for purely moral or aesthetic reasons, and we do not need valuations of ecosystems for this purpose. But there are equally compelling moral arguments that may be in direct conflict with the moral argument to protect ecosystems; for example, the moral argument that no one should go hungry. Moral arguments translate the valuation and decision problem into a different set of dimensions and a different language of discourse[6]; one that, in our view, makes the valuation and choice problem more difficult and less explicit. But moral and economic arguments are certainly not mutually exclusive. Both discussions can and should go on in parallel.

So, while ecosystem valuation is certainly difficult and fraught with uncertainties, one choice we do not have is whether or not to do it. Rather, the decisions we make as a society about ecosystems *imply* valuations (although not necessarily exchange values expressed in money terms). We can choose to make these valuations explicit or not; we can undertake them using the best available ecological science and understanding or not; we can do them with an explicit acknowledgment of the huge uncertainties involved or not; but as long as we are forced to make choices, we are doing valuation.

The exercise of valuing the services of natural capital "at the margin" consists of determining the differences that relatively small changes in these services make to human welfare. Changes in quality or quantity of ecosystem services have value insofar as they either change the benefits associated with human activities or change the costs of those activities. These changes in benefits and costs either impact human welfare through established markets or through non-market activities. For example, coral reefs provide habitat for fish. One aspect of their value is to increase and concentrate fish stocks. One effect of changes in coral reef quality or quantity would be discernible in commercial fisheries markets, or in recreational fisheries. Other aspects of coral reefs' value, such as recreational diving and biodiversity conservation, do not show up completely in markets, however. Forests provide timber materials through well-established markets, but the associated habitat values of forests are also felt through unmarketed recreational activities. The chains of effects from ecosystem services to human welfare can range from extremely simple to exceedingly complex. Forests provide timber, but also hold soils and moisture, and create microclimates, all of which contribute to human welfare in complex, and generally non-marketed ways.

Valuation Methods

Various methods have been used to estimate both the market and non-market components of the value of ecosystem services.[9-16] In this analysis, we synthesized previous studies based on a wide variety of methods, noting the limitations and assumptions underlying each.

Many of the valuation techniques used in the studies covered in our synthesis are based, either directly or indirectly, on attempts to estimate the willingness-to-pay of individuals for ecosystem services. For example, if ecological services provided a $50 increment to the timber productivity of a forest, then the beneficiaries of this service should be willing to pay up to $50 for it. In addition to timber production, if the forest offered non-marketed aesthetic, existence, and conservation values of $70, those receiving this non-market benefit should be willing to pay up to $70 for it. The total value of ecological services would be $120, while the contribution to the money economy of ecological services would be $50, the amount that actually passes through markets. In this study we have tried to estimate the total value of ecological services, regardless of whether they are currently marketed.

Figure 1 shows some of these concepts diagramatically. Figure 1a shows conventional supply (marginal cost) and demand (marginal benefit) curves for a typical marketed good or service. The value that would show up in Gross National Product (GNP) is the market price *p* times the quantity *q*, or the area *pbqc*. There are three other relevant areas represented on the diagram, however. The cost of production is the area under the supply curve, *cbq*. The "producer surplus" or "net rent" for a resource is the area between the market price and the supply curve, *pbc*. The "consumer surplus" or the amount of welfare the consumer receives over and above the price paid in the market is the area between the demand curve and the market price, *abp*. The total economic value of the resource is the sum of the producer and consumer surplus (excluding the cost of production), or the area *abc* on the diagram. Note that total economic value can be greater or less than the price times quantity estimates used in GNP.

Figure 1a refers to a human-made, substitutable good. Many ecosystem services are only substitutable up to a point, and their demand curves probably look more like figure 1b. Here the demand approaches infinity as the quantity available approaches zero (or some minimum necessary level of services), and the consumer surplus (as well as the total economic value) approaches infinity. Demand curves for ecosystem services are very difficult, if not impossible, to estimate in practice. In addition, to the extent that ecosystem services cannot be increased or decreased by actions of the economic system, their supply curves are more nearly vertical, as shown in figure 1b.

In this study we estimated the value per unit area of each ecosystem service for each ecosystem type. To estimate this "unit value" we used (in order of preference) either (1) the sum of consumer and producer surplus; or (2) the net rent (or producer surplus); or (3) price times quantity as a proxy for the economic value of the service, assuming that the demand curve for ecosystem services looks more like figure 1b than figure 1a, and that therefore the area *pbqc* is a conservative underestimate of the area *abc*. We then multiplied the unit values times the surface area of each ecosystem to arrive at global totals.

Ecosystem Values, Markets, and GNP

As we have noted, the value of many types of natural capital and ecosystem services may not be easily traceable through well-functioning markets, or may not show up in markets at all. For example, the aesthetic enhancement of a forest may alter recreational expenditures at that site, but this change in expenditure bears no necessary relation to the value of the enhancement. Recreationists may value the improvement at $100, but transfer only $20 in spending from other recreational areas to the improved site. Enhanced wetlands quality may improve waste treatment, saving on potential treatment costs. For example, tertiary treatment by wetlands may save $100 in alternative treatment. Existing treatment may cost only $30. The treatment cost savings does not show up in any market. There is very little relation between the value of services and observable current spending behavior in many cases.

There is also no necessary relation between the valuation of natural capital service flows, even on the margin, and aggregate spending, or GNP, in the economy. This is true even if all capital service flows impacted well-functioning markets. A large part of the contributions to human welfare by ecosystem services are of a purely public goods nature. They accrue directly to humans without passing through the money economy at all. In many cases people are not even aware of them. Examples include clean air and water, soil formation, climate regulation, waste treatment, aesthetic values, and good health, as mentioned above.

Global Land Use and Land Cover

In order to estimate the total value of ecosystem services, we needed estimates of the total global extent of the ecosystems themselves. We devised an aggregated classification scheme with 16 primary categories as shown in Table 3 to represent current global land use. The major division is between Marine and Terrestrial systems. Marine was further subdivided into Open Ocean and Coastal, which itself includes Estuaries, Seagrass/Algae Beds, Coral Reefs, and Shelf systems. Terrestrial systems were broken down into two types of Forest (Tropical and Temperate/Boreal), Grasslands/Rangelands, Wetlands, Lakes/Rivers, Desert, Tundra, Ice/Rock, Cropland, and Urban. Primary data were from Matthews[17] as summarized in de Groot[4] with additional information from a number of sources.[18-22] We also used data from Bailey,[23] as a cross-check on the terrestrial estimates and Houde & Rutherford[24] and Pauly & Christensen,[25] as a check on the marine estimates. The 32 landcover types of Matthews were re-categorized for Table 3 and figure 2. The major assumptions were: (1) chaparral and steppe were considered rangeland and combined with grasslands; and (2) a variety of tropical forest and woodland types were combined into "tropical forests."

Synthesis

We conducted a thorough literature review and synthesized the information, along with a few original calculations, during a one-week intensive workshop at the new National Center for Ecological Analysis and Synthesis (NCEAS) at the University of California at Santa Barbara.

Table 2 (with accompanying notes and references) lists the primary results for each ecosystem service and biome. It is voluminous and could not be included in the printed version, but is available directly from the first author, and is also posted at Nature's web site - http://www.america.nature.com. Table 2 includes all the estimates we could identify from the literature (from over 100 studies), their valuation methods, location, and stated value. We converted each estimate into 1994 US$ ha^{-1} yr^{-1} using the US consumer price index and other conversion factors as needed. These are listed in the notes to Table 2. For some estimates we also converted the service estimate into US$ equivalents using the ratio of purchasing power GNP per capita for the country of origin to that of the US. This was intended to adjust for income effects. Where possible the estimates are stated as a range, based on the high and low values found in the literature, and an average value, with annotated comments as to methods and assumptions. We also included in Table 2 some estimates from the literature on "total ecosystem value," mainly using energy analysis techniques.[10] We did not include these estimates in any of the totals or averages given below, but only for comparison with the totals from the other techniques. Interestingly, these different methods showed fairly close agreement in the final results.

Each biome and each ecosystem service had its special considerations. Detailed notes explaining each biome and each entry in Table 2 are given in notes following the table. More detailed descriptions of some of the ecosystems, their services, and general valuation issues can be found in Daily.[5] Below we briefly discuss some general considerations that apply across the board.

Sources of Error, Limitations, and Caveats

Our attempt to estimate the total current economic value of ecosystem services is limited for a number of reasons, including:

1. While we have attempted to be as comprehensive and inclusive as possible, our estimate leaves out many categories of services, which, for one reason or another, have not yet been adequately studied for many ecosystems. In addition, we could identify no valuation studies at all for some major biomes (desert, tundra, ice/rock, and cropland). As more and better information becomes available, we expect the total estimated value to increase.
2. Current prices, which form the basis (either directly or indirectly) of many of the valuation estimates, are distorted for a number of reasons, including the fact that they exclude the value of ecosystem services, household labor, the informal economy, and many other problems. In addition to this, there are differences between total value, consumer surplus, net rent (or producer surplus), and *p**q*, all of which are used to estimate unit values (see figure 1).
3. In many cases the values are based on the current willingness-to-pay of individuals for ecosystem services, even though these individuals may be ill-informed and their preferences may not adequately incorporate social fairness, ecological sustainability, and other important goals.[16] In other words, if we actually lived in a world that was ecologically sustainable, socially fair, and where everyone had perfect knowledge of their connection to ecosystem services, both market prices and surveys of willingness-to-pay would yield very different results than they currently do, and the value of ecosystem services would probably increase.
4. In calculating the current value, we generally assumed that the demand and supply curves look something like figure 1a. In reality, supply curves for many ecosystem services are more nearly inelastic vertical lines, and the demand curves probably look more like figure 1b, approaching infinity as quantity goes to zero. Thus the consumer and producer surplus and thereby the total value of ecosystem services would also approach infinity.
5. The valuation approach taken here assumes that there are no sharp thresholds, discontinuities, or irreversibilities in the ecosystem response functions. This is almost certainly not the case. Therefore this valuation yields an underestimate of the total value.
6. Extrapolation from point estimates to global totals introduces error. In general, we estimated unit area values for the ecosystem services (in $ ha^{-1} yr^{-1}) and then multiplied by the total area

of each biome. This can only be considered a crude first approximation and can introduce errors depending on the type of ecosystem service and its spatial heterogeneity.

7. To avoid double counting, a general equilibrium framework that could directly incorporate the interdependence between ecosystem functions and services would be preferred to the partial equilibrium framework employed in this study (see 12 below for more on this).

8. Values for individual ecosystem functions should be based on sustainable use levels, taking account of both the carrying capacity for individual functions (e.g. food-production or waste recycling) and the combined effect of simultaneous use of more functions. Ecosystems should be able to provide all the functions listed in Table 1 simultaneously and indefinitely. This is certainly not the case for some current ecosystem services due to overuse at existing prices.

9. We have not incorporated the "infrastructure" value of ecosystems, as noted above, leading to an underestimation of the total value.

10. Intercountry comparisons of valuation are affected by income differences. We attempted to address this in some cases using the relative purchasing power GNP per capita of the country relative to the US, but this is a very crude way to make the correction.

11. In general, we have used annual flow values and have avoided many of the difficult issues involved with discounting future flow values to arrive at a net present value of the capital stock. But a few estimates in the literature were stated as stock values, and it was necessary to assume a discount rate (we used 5%) in order to convert them into annual flows.

12. Our estimate is based on a static "snapshot" of what is, in fact, a complex, dynamic system. We have assumed a static and "partial equilibrium" model in the sense that the value of each service is derived independently and added. This ignores the complex interdepencies between services. The estimate could also change drastically as the system moved through critical non-linearities or thresholds. While it is possible to build "general equilibrium" models in which the value of all ecosystem services are derived simultaneously with all other values, and to build dynamic models that can incorporate non-linearities and thresholds, these models

have rarely been attempted at the scale we are discussing. They represent the next logical step in deriving better estimates of the value of ecosystem services.

We have tried to expose these various sources of uncertainty wherever possible in Table 2 and its supporting notes, and state the range of relevant values. In spite of the limitations noted above, we believe it is very useful to synthesize existing valuation estimates, if only to determine a crude, initial "ballpark" magnitude. In general, because of the nature of the limitations noted, we expect our current estimate to represent a minimum value for ecosystem services.

Total Global Value of Ecosystem Services

Table 3 is a summary of the results of our synthesis. It lists each of the major biomes along with their current estimated global surface area, the average (on a per ha basis) of the estimated values of the 17 ecosystem services we have identified from Table 2, and the total value of ecosystem services by biome, by service type, and for the entire biosphere.

We estimated that at the current margin, ecosystems provide at least $33 trillion dollars worth of services annually. The majority of the value of services we could identify is currently outside the market system, in services such as gas regulation ($1.3 trillion/yr), disturbance regulation ($1.8 trillion/yr), waste treatment ($2.3 trillion/yr), and nutrient cycling ($17 trillion/yr). About 63% of the estimated value is contributed by marine systems ($20.9 trillion/yr). Most of this comes from coastal systems ($10.6 trillion/yr). About 38% of the estimated value comes from terrestrial systems, mainly from forests ($4.7 trillion/yr) and wetlands ($4.9 trillion/yr).

We estimated a range of values whenever possible for each entry in Table 2. Table 3 reports only the average values. Had we used the low end of the ranges in Table 2, the global total would have been around $19 trillion. If we eliminate nutrient cycling, which is the largest single service, estimated at $17 trillion, the total annual value would be around $16 trillion. Had we used the high end for all estimates, along with estimating the value of Desert, Tundra, and

Ice/Rock as the average value of Rangelands, the estimate would be around $54 trillion. So the total range of annual values we estimated were from $16 - $54 trillion. This is not a huge range, but other sources of uncertainty listed above are much more critical. It is important to emphasize, however, that despite the many uncertainties included in this estimate, it is almost certainly an underestimate for several reasons, as listed above.

There have been very few previous attempts to estimate the total global value of ecosystem services with which to compare these results. We identified two, based on completely different methods and assumptions, both from each other and from the methods employed in this study. They thus provide an interesting check.

One was an early attempt at a static general equilibrium input-output model of the globe, including both ecological and economic processes and commodities.[26,27] This model divided the globe into 9 commodities or product groups and 9 processes, two of which were "economic" (urban and agriculture) and 7 of which were "ecologic," including both terrestrial and marine systems. Data were from about 1970. Although this was a very aggregated breakdown and the data was of only moderate quality, the model produced a set of "shadow prices" and "shadow values" for all the flows between processes, as well as the net outputs from the system which could be used to derive an estimate of the total value of ecosystem services. The I-O format is far superior to the partial equilibrium format we employed in this study for differentiating gross from net flows and avoiding double counting. The results yielded a total value of the net output of the 7 global ecosystem processes equal to the equivalent of 9.4 trillion 1972 US$. Converted to 1994 US$ this is about $34 trillion - surprisingly close to our current average estimate. This estimate broke down into $11.9 trillion (or 35%) from terrestrial ecosystem processes and $22.1 trillion (or 65%) from marine processes, also very close to our current estimate. World GNP in 1970 was about $14.3 trillion (in 1994 US$), indicating a ratio of total ecosystem services to GNP of about 2.4 to 1. The current estimate has a corresponding ratio of 1.8 to 1.

A more recent study[28] estimated a "maximum sustainable surplus" value of ecosystem services by considering ecosystem services as one input to an aggregate global production function along with labor and manufactured capital. Their estimates ranged from $3.4 to $17.6 trillion/year, depending on various assumptions. This approach assumed that the total value of ecosystem services is limited to that which impacts marketed value, either directly or indirectly, and thus cannot exceed the total world GNP of about $18 trillion. But, as we have pointed out, only a fraction of ecosystem services affect private goods traded in existing markets which would be included in measures like GNP. This is a subset of the services we estimated, so we would expect this estimate to undervalue total ecosystem services.

The results of both of these studies indicate, however, that our current estimate is at least in approximately the same range. As we have noted, there are many limitations to both the current and these two previous studies. They are all only static snapshots of a biosphere that is a complex, dynamic system. The obvious next steps include building regional and global models of the linked ecological economic system aimed at a better understanding of both the complex dynamics of physical/biological processes and the value of these processes to human well-being.[29,30] But we do not have to wait for the results of these models to draw the following conclusions.

Conclusions

What this study makes abundantly clear is that ecosystem services provide a significant portion of the total contribution to human welfare on this planet. We must begin to give the natural capital stock which produces these services adequate weight in the decision-making process, otherwise current and continued future human welfare may drastically suffer. We estimate in this study that the annual value of these services is $16 - 54 trillion, with an estimated average of $33 trillion. The real value is almost certainly much larger, even at the current margin. $33 trillion is 1.8 times the current global GNP. One way to look at this comparison is that if one were to try to replace the services of ecosystems at the current margin, one would need to increase global GNP by at least $33 trillion, partly to cover services already captured in existing GNP and partly to cover services that are not currently captured in GNP.

This impossible task would lead to no increase in welfare since we would only be replacing existing services, and it ignores the fact that many ecosystem services are literally irreplaceable.

If ecosystem services were actually paid for, in terms of their value contribution to the global economy, the global price system would be very different than it is today. The price of commodities utilizing ecosystem services directly or indirectly would be much greater. The structure of factor payments, including wages, interest rates, and profits would change dramatically. World GNP would be very different in both magnitude and composition if it adequately incorporated the value of ecosystem services. One practical use of the estimates we have developed is to help modify systems of national accounting to better reflect the value of ecosystem services and natural capital. Initial attempts to do this paint a very different picture of our current level of economic welfare than conventional GNP, some indicating a leveling of welfare since about 1970 while GNP has continued to increase.[31-33] A second important use of these estimates is for project appraisal, where ecosystem services lost must be weighed against the benefits of a specific project.[8] Because ecosystem services are largely outside the market and uncertain, they are too often ignored or undervalued, leading to the error of constructing projects whose social costs far outweigh their benefits.

As natural capital and ecosystem services become more stressed and more "scarce" in the future, we can only expect their value to increase. If significant, irreversible thresholds are passed for irreplaceable ecosystem services, their value may quickly jump to infinity. Given the huge uncertainties involved, we may never have a very precise estimate of the value of ecosystem services. Nevertheless, even the crude initial estimate we have been able to assemble is a useful starting point (we stress again that it is *only* a starting point). It demonstrates the need for much additional research and it also indicates the specific areas that are most in need of additional study. It also highlights the relative importance of ecosystem services and the potential impact on our welfare of continuing to squander them.

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Table 1. Ecosystem services and functions used in this study.

#	ECOSYSTEM SERVICE*	ECOSYSTEM FUNCTIONS	EXAMPLES
1	**Gas regulation**	Regulation of atmospheric chemical composition.	CO_2/O_2 balance, O_3 for UVB protection, and SO_x levels.
2	**Climate regulation**	Regulation of global temperature, precipitation, and other biologically mediated climatic processes at global or local levels.	Green-house gas regulation, DMS production affecting cloud formation.
3	**Disturbance regulation**	Capacitance, damping, and integrity of ecosystem response to environmental fluctuations.	Storm protection, flood control, drought recovery, and other aspects of habitat response to environmental variability mainly controlled by vegetation structure.
4	**Water regulation**	Regulation of hydrological flows.	Provisioning of water for agricultural (e.g., irrigation) or industrial (e.g., milling) processes or transportation.
5	**Water supply**	Storage and retention of water.	Provisioning of water by watersheds, reservoirs, and aquifers.
6	**Erosion control and sediment retention**	Retention of soil within an ecosystem.	Prevention of loss of soil by wind, runoff, or other removal processes, storage of silt in lakes and wetlands.
7	**Soil formation**	Soil formation processes.	Weathering of rock and the accumulation of organic material.
8	**Nutrient cycling**	Storage, internal cycling, processing, and acquisition of nutrients.	Nitrogen fixation, N, P, and other elemental or nutrient cycles.
9	**Waste treatment**	Recovery of mobile nutrients and removal or breakdown of excess or xenic nutrients and compounds.	Waste treatment, pollution control, detoxification.
10	**Pollination**	Movement of floral gametes.	Provisioning of pollinators for the reproduction of plant populations.
11	**Biological control**	Trophic-dynamic regulations of populations.	Keystone predator control of prey species, reduction of herbivory by top predators.
12	**Refugia**	Habitat for resident and transient populations.	Nurseries, habitat for migratory species, regional habitats for locally harvested species, or over wintering grounds.
13	**Food production**	That portion of gross primary production extractable as food.	Production of fish, game, crops, nuts, fruits by hunting, gathering, subsistence farming, or fishing.
14	**Raw materials**	That portion of gross primary production extractable as raw materials.	The production of lumber, fuel, or fodder.
15	**Genetic resources**	Sources of unique biological materials and products.	Medicine, products for materials science, genes for resistance to plant pathogens and crop pests, ornamental species (pets and horticultural varieties of plants).
16	**Recreation**	Providing opportunities for recreational activities.	Eco-tourism, sport fishing, and other outdoor recreational activities.
17	**Cultural**	Providing opportunities for non-commercial uses.	Aesthetic, artistic, educational, spiritual, and/or scientific values of ecosystems.

*We include ecosystem “goods” along with ecosystem services.

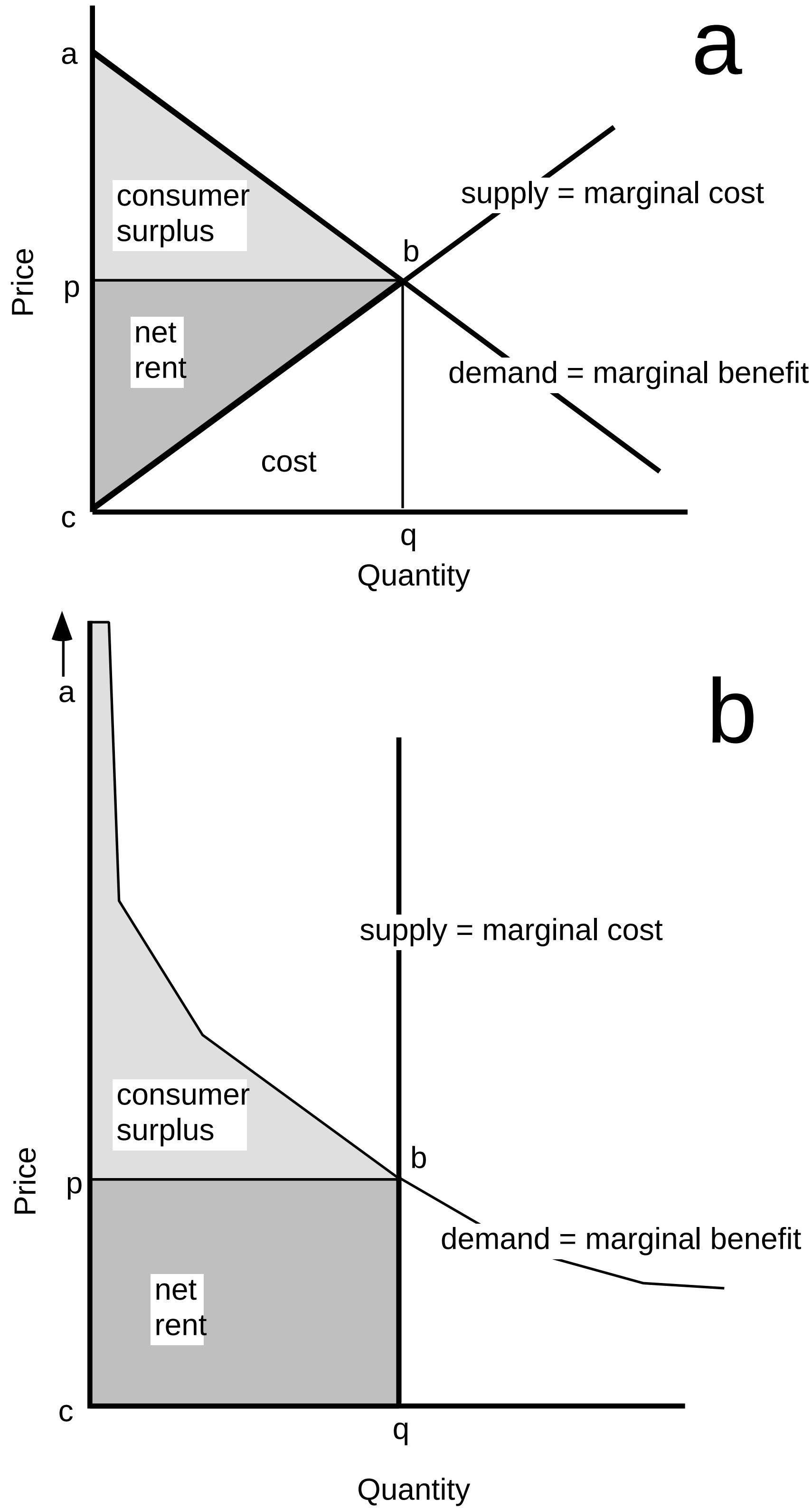

Figure 1. Supply and demand curves, showing the definitions of cost, net rent, and consumer surplus for normal goods (a) and some essential ecosystem services (b). See text for further explanation.