The value of the world's ecosystem services and natural capital

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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 to human welfare, both directly and indirectly, and therefore represent part of the total economic value of the planet. We have estimated the current economic value of 17 ecosystem services for 16 biomes, based on 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 US$16–54 trillion ($10^{12}$) per year, with an average of US$33 trillion per year. Because of the nature of the uncertainties, this must be considered a minimum estimate. Global gross national product total is around US$18 trillion per year.

Because ecosystem services are not fully 'captured' in commercial 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 can be instructive to estimate the 'incremental' or 'marginal' value of ecosystem services (the estimated rate of change of value compared with changes in ecosystem services from their current levels). There have been many studies in the past few decades aimed at estimating the value of a wide variety of ecosystem services. We have gathered together this large (but scattered) amount of information and present it here in a form useful for ecologists, economists, policy makers and the general public. From this synthesis, we have 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.

Although we acknowledge that there are 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 system properties or processes of ecosystems. Ecosystem goods (such as food) and services (such as 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]. Reference 5 provides a recent, detailed 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

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welfare. To the extent possible, we have attempted to distinguish joint and 'addable' products from products that 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 to be a stock of materials or information that 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 that 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 and so on; 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. Although 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

Table 1 Ecosystem services and functions used in this study

Number	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.	Greenhouse 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 (such as irrigation) or industrial (such as 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 stilt 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 overwintering 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.

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 soil infrastructure 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 have an impact on 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, having an impact on 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 problem of valuation and choice 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, although 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 expressed in monetary terms). We can choose to make these valuations explicit or not; we can do them with an explicit acknowledgement of the huge uncertainties involved or not; but as long as we are forced to make choices, we are going through the process of 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 have an impact on human welfare through established markets or through non-market activities. For example, coral reefs provide habitats 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. But other aspects of the value of coral reefs, such as recreational diving and biodiversity conservation, do not show up completely in markets. 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

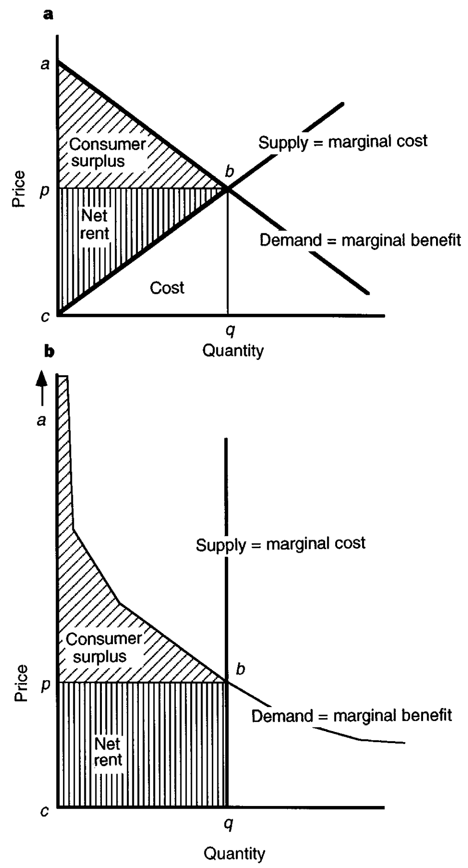

Figure 1 Supply and demand curves, showing the definitions of cost, net rent and consumer surplus for normal goods (**a**) and some essential ecosystem services (**b**). See text for further explanation.

Table 2 Summary of average global value of annual ecosystem services

Biome	Area (ha × 10^6)	Ecosystem serivces (1994 US\$ ha^{-1} yr^{-1}) 1 Gas regulation	2 Climate regulation	3 Disturbance regulation	4 Water regulation	5 Water supply	6 Erosion control	7 Soil formation	8 Nutrient cycling	9 Waste treatment	10 Pollination	11 Biological control	12 Habitat/ refugia	13 Food production	14 Raw materials	15 Genetic resources	16 Recreation	17 Cultural	Total value per ha (\$ ha^{-1} yr^{-1})	Total global flow value (\$ yr^{-1} × 10^9)
Marine	36,302																		577	20,949
Open ocean	33,200	38							118			5		15	0			76	252	8,381
Coastal	3,102			88					3,677			38	8	93	4		82	62	4,052	12,568
Estuaries	180			567					21,100			78	131	521	25		381	29	22,832	4,110
Seagrass/ algae beds	200								19,002						2				19,004	3,801
Coral reefs	62			2,750						58		5	7	220	27		3,008	1	6,075	375
Shelf	2,660								1,431			39		68	2			70	1,610	4,283
Terrestrial	15,323																		804	12,319
Forest	4,855		141	2	2	3	96	10	361	87		2		43	138	16	66	2	969	4,706
Tropical	1,900		223	5	6	8	245	10	922	87				32	315	41	112	2	2,007	3,813
Temperate/boreal	2,955		88		0			10		87		4		50	25		36	2	302	894
Grass/rangelands	3,898	7	0		3		29	1		87	25	23		67		0	2		232	906
Wetlands	330	133		4,539	15	3,800				4,177			304	256	106		574	881	14,785	4,879
Tidal marsh/ mangroves	165			1,839						6,696			169	466	162		658		9,990	1,648
Swamps/ floodplains	165	265		7,240	30	7,600				1,659			439	47	49		491	1,761	19,580	3,231
Lakes/rivers	200				5,445	2,117				665				41			230		8,498	1,700
Desert	1,925																			
Tundra	743																			
Ice/rock	1,640																			
Cropland	1,400										14	24		54					92	128
Urban	332																			
Total	51,625	1,341	684	1,779	1,115	1,692	576	53	17,075	2,277	117	417	124	1,386	721	79	815	3,015		33,268

Numbers in the body of the table are in \$ ha^{-1} yr^{-1}. Row and column totals are in \$ yr^{-1} × 10^9, column totals are the sum of the products of the per ha services in the table and the area of each biome, not the sum of the per ha services themselves. Shaded cells indicate services that do not occur or are known to be negligible. Open cells indicate lack of available information.

value of ecological services would be $120, but 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 diagrammatically. 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 Fig. 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 Fig. 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 Fig. 1b than Fig. 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 behaviour in many cases.

There is also no necessary relationship 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 had an impact on 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 2 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

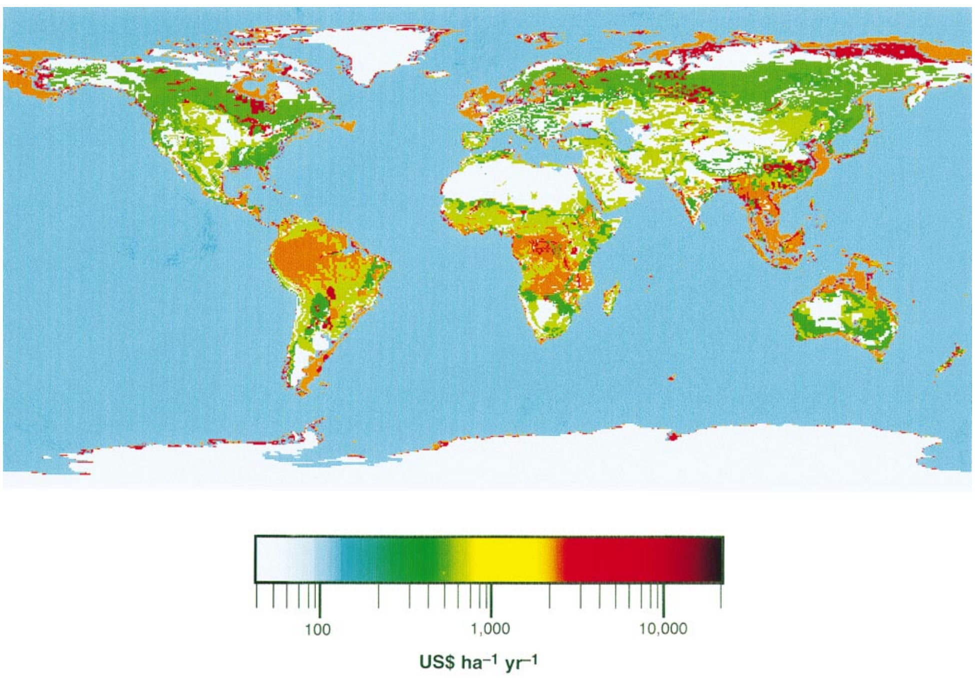

Figure 2 Global map of the value of ecosystem services. See Supplementary Information and Table 2 for details.

data were from ref. 17 as summarized in ref. 4 with additional information from a number of sources[18–22]. We also used data from ref. 23, as a cross-check on the terrestrial estimates and refs 24 and 25 as a check on the marine estimates. The 32 landcover types of ref. 17 were recategorized for Table 2 and Fig. 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. Supplementary Information lists the primary results for each ecosystem service and biome. Supplementary Information 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 USA consumer price index and other conversion factors as needed. These are listed in the notes to the Supplementary Information. 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 USA. 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 the Supplementary Information 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 Supplementary Information 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 ref. 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) Although we have attempted to include as much as possible, our estimate leaves out many categories of services, which have not yet been adequately studied for many ecosystems. In addition, we could identify no valuation studies 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 labour and the informal economy. In addition to this, there are differences between total value, consumer surplus, net rent (or producer surplus) and $p \times q$, all of which are used to estimate unit values (see Fig. 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 Fig. 1a. In reality, supply curves for many ecosystem services are more nearly inelastic vertical lines, and the demand curves probably look more like Fig. 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 used in this study (see below).

(8) Values for individual ecosystem functions should be based on sustainable use levels, taking account of both the carrying capacity for individual functions (such as 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 because of 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) Inter-country 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 USA, 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 interdependencies between the services. The estimate could also change drastically as the system moved through critical non-linearities or thresholds. Although 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 Supplementary Information 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 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 2 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 hectare basis) of the estimated values of the 17 ecosystem services we have identified from Supplementary Information, 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 US$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 (US$1.3 trillion yr^{-1}), disturbance regulation (US$1.8 trillion yr^{-1}), waste treatment (US$2.3 trillion yr^{-1}) and nutrient cycling (US$17 trillion yr^{-1}). About 63% of the estimated value is contributed by marine systems (US$20.9 trillion yr^{-1}). Most of this comes from coastal systems (US$10.6 trillion yr^{-1}). About 38% of the estimated value comes from terrestrial systems, mainly from forests (US$4.7 trillion yr^{-1}) and wetlands (US$4.9 trillion yr^{-1}).

We estimated a range of values whenever possible for each entry in Supplementary Information. Table 2 reports only the average values. Had we used the low end of the range in Supplementary Information, the global total would have been around US$19 trillion. If we eliminate nutrient cycling, which is the largest single service, estimated at US$17 trillion, the total annual value would be around US$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 US$54 trillion. So the total range of annual values we estimated were from US$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 used 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 in to 9 commodities or product groups and 9 processes, two of which were 'economic' (urban and agriculture) and 7 of which were 'ecological', 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 input–output format is far superior to the partial equilibrium format we used 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 US$9.4 trillion in 1972. Converted to 1994 US$ this is about $34 trillion, surprisingly close to our current average estimate. This estimate broke down into US$11.9 trillion (or 35%) from terrestrial ecosystem processes and US$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 labour and manufactured capital. Their estimates ranged from US$3.4 to US$17.6 trillion yr^{-1}, depending on various assumptions. This approach assumed that the total value of ecosystem services is limited to that which has an impact on marketed value, either directly or indirectly, and thus cannot exceed the total world GNP of about US$18 trillion. But, as we have pointed out, only a fraction of ecosystem services affects private goods traded in existing markets, which would be included in measures such as 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.

Discussion

What this study makes abundantly clear is that ecosystem services provide an important portion of the total contribution to human welfare on this planet. We must begin to give the natural capital stock that 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 US$16–54 trillion, with an estimated average of US$33 trillion. The real value is almost certainly much larger, even at the current margin. US$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 US$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 because 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 from what it is today. The price of commodities using 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 levelling 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 outweight 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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Changes in the global value of ecosystem services

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ABSTRACT

In 1997, the global value of ecosystem services was estimated to average $33 trillion/yr in 1995 $US ($46 trillion/yr in 2007 $US). In this paper, we provide an updated estimate based on updated unit ecosystem service values and land use change estimates between 1997 and 2011. We also address some of the critiques of the 1997 paper. Using the same methods as in the 1997 paper but with updated data, the estimate for the total global ecosystem services in 2011 is $125 trillion/yr (assuming updated unit values and changes to biome areas) and $145 trillion/yr (assuming only unit values changed), both in 2007 $US. From this we estimated the loss of eco-services from 1997 to 2011 due to land use change at $4.3–20.2 trillion/yr, depending on which unit values are used. Global estimates expressed in monetary accounting units, such as this, are useful to highlight the magnitude of eco-services, but have no specific decision-making context. However, the underlying data and models can be applied at multiple scales to assess changes resulting from various scenarios and policies. We emphasize that valuation of eco-services (in whatever units) is not the same as commodification or privatization. Many eco-services are best considered public goods or common pool resources, so conventional markets are often not the best institutional frameworks to manage them. However, these services must be (and are being) valued, and we need new, common asset institutions to better take these values into account.

1. Introduction

Ecosystems provide a range of services that are of fundamental importance to human well-being, health, livelihoods, and survival (Costanza et al., 1997; Millennium Ecosystem Assessment (MEA), 2005; TEEB Foundations, 2010; TEEB Synthesis, 2010). Interest in ecosystem services in both the research and policy communities has grown rapidly (Braat and de Groot, 2012; Costanza and Kubiszewski, 2012). In 1997, the value of global ecosystem services was estimated to be around US$ 33 trillion per year (in 1995 $US), a figure significantly larger than global gross domestic product (GDP) at the time. This admittedly crude underestimate of the welfare benefits of natural capital, and a few other early studies (Daily, 1997; de Groot, 1987; Ehrlich and Ehrlich, 1981; Ehrlich and Mooney, 1983; Odum, 1971; Westman, 1977) stimulated a huge surge in interest in this topic.

In 2005, the concept of ecosystem services gained broader attention when the United Nations published its Millennium Ecosystem Assessment (MEA). The MEA was a four-year, 1300-scientist study for policymakers. Between 2007 and 2010, a second international initiative was undertaken by the UN Environment Programme, called the Economics of Ecosystems and Biodiversity (TEEB) (TEEB Foundations, 2010). The TEEB report was picked up extensively by the mass media, bringing ecosystem services to a broader audience. Ecosystem services have now also entered the consciousness of mainstream media and business. The World Business Council for Sustainable Development has actively supported and developed the concept (WBCSD, 2011, 2012). Hundreds of projects and groups are currently working toward

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better understanding, modeling, valuation, and management of ecosystem services and natural capital. It would be impossible to list all of them here, but emerging regional, national, and global networks, like the Ecosystem Services Partnership (ESP), are doing just that and are coordinating their efforts (Braat and de Groot, 2012; de Groot et al., 2011).

Probably the most important contribution of the widespread recognition of ecosystem services is that it reframes the relationship between humans and the rest of nature. A better understanding of the role of ecosystem services emphasizes our natural assets as critical components of inclusive wealth, well-being, and sustainability. Sustaining and enhancing human well-being requires a balance of all of our assets—individual people, society, the built economy, and ecosystems. This reframing of the way we look at "nature" is essential to solving the problem of how to build a sustainable and desirable future for humanity.

Estimating the relative magnitude of the contributions of ecosystem services has been an important part of changing this framing. There has been an on-going debate about what some see as the "commodification" of nature that this approach supposedly implies (Costanza, 2006; McCauley, 2006) and what others see as the flawed methods and questionable wisdom of aggregating ecosystem services values to larger scales (Chaisson, 2002). We think that these critiques are largely misplaced once one understands the context and multiple potential uses of ecosystem services valuation, as we explain further on.

In this paper we (1) update estimates of the value of global ecosystem services based on new data from the TEEB study (de Groot et al., 2012, 2010a,b); (2) compare those results with earlier estimates (Costanza et al., 1997) and with alternative methods (Boumans et al., 2002); (3) estimate the global changes in ecosystem service values from land use change over the period 1997–2011; and (4) review some of the objections to aggregate ecosystem services value estimates and provide some responses (Howarth and Farber, 2002).

We do not claim that these estimates are the only, or even the best way, to understand the value of ecosystem services. Quite the contrary, we advocate pluralism based on a broad range of approaches at multiple scales. However, within this range of approaches, estimates of aggregate accounting value for ecosystem services in monetary units have a critical role to play in heightening awareness and estimating the overall level of importance of ecosystem services relative to and in combination with other contributors to sustainable human well-being (Luisetti et al., 2013).

2. What is valuation?

Valuation is about assessing trade-offs toward achieving a goal (Farber et al., 2002). All decisions that involve trade-offs involve valuation, either implicitly or explicitly (Costanza et al., 2011). When assessing trade-offs, one must be clear about the goal. Ecosystem services are defined as the benefits people derive from ecosystems – the support of sustainable human well-being that ecosystems provide (Costanza et al., 1997; Millennium Ecosystem Assessment (MEA), 2005). The value of ecosystem services is therefore the *relative* contribution of ecosystems to that goal. There are multiple ways to assess this contribution, some of which are based on individual's perceptions of the benefits they derive. But the support of sustainable human well-being is a much larger goal (Costanza, 2000) and individual's perceptions are limited and often biased (Kahneman, 2011). Therefore, we also need to include methods to assess benefits to individuals that are not well perceived, benefits to whole communities, and benefits to sustainability (Costanza, 2000). This is an on-going challenge in ecosystem services valuation, but even some of the existing valuation methods like avoided and replacement cost estimates

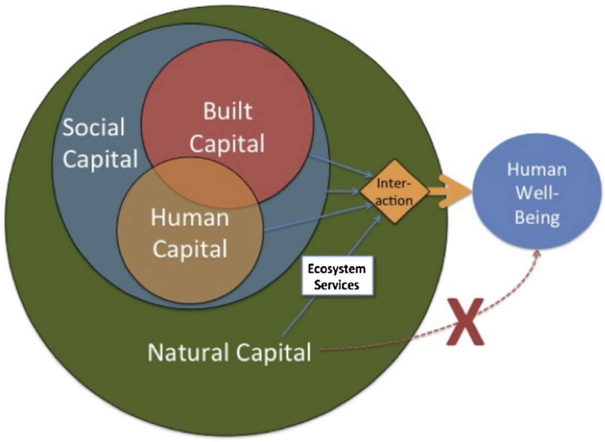

Fig. 1. Interaction between built, social, human and natural capital required to produce human well-being. Built and human capital (the economy) are embedded in society which is embedded in the rest of nature. Ecosystem services are the relative contribution of natural capital to human well-being, they do not flow directly. It is therefore essential to adopt a broad, transdisciplinary perspective in order to address ecosystem services.

are not dependent on individual perceptions of value. For example, estimating the storm protection value of coastal wetlands requires information on historical damage, storm tracks and probability, wetland area and location, built infrastructure location, population distribution, etc. (Costanza et al., 2008). It would be unrealistic to think that the general public understands this complex connection, so one must bring in much additional information not connected with perceptions to arrive at an estimate of the value. Of course, there is ultimately the link to built infrastructure, which people perceive as a benefit and value, but the link is complex and not dependent on the general public's understanding of or perception of the link.

It is also important to note that ecosystems cannot provide any benefits to people without the presence of people (human capital), their communities (social capital), and their built environment (built capital). This interaction is shown in Fig. 1. Ecosystem services do not flow directly from natural capital to human well-being – it is only through interaction with the other three forms of capital that natural capital can provide benefits. This is also the conceptual valuation framework for the recent UK National Ecosystem Assessment (http://uknea.unep-wcmc.org) and the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES – http://www.ipbes.net). The challenge in ecosystem services valuation is to assess the relative contribution of the natural capital stock in this interaction and to balance our assets to enhance sustainable human well-being.

The relative contribution of ecosystem services can be expressed in multiple units – in essence any of the contributors to the production of benefits can be used as the "denominator" and other contributors expressed in terms of it. Since built capital in the economy, expressed in monetary units, is one of the required contributors, and most people understand values expressed in monetary units, this is often a convenient denominator for expressing the relative contributions of the other forms of capital, including natural capital. But other units are certainly possible (i.e. land, energy, time, etc.) – the choice is largely about which units communicate best to different audiences in a given decision-making context.

3. Valuation is not privatization

It is a misconception to assume that valuing ecosystem services in monetary units is the same as privatizing them or commodifying them for trade in private markets (Costanza, 2006; Costanza et al., 2012; McCauley, 2006; Monbiot, 2012). Most ecosystem services are public goods (non-rival and non-excludable) or common pool resources (rival but non-excludable), which means that privatization and conventional markets work poorly, if at all. In addition, the non-market values estimated for these ecosystem services often relate more to *use* or *non-use* values rather than *exchange* values (Daly, 1998). Nevertheless, knowing the value of ecosystem services is helpful for their effective management, which in some cases can include economic incentives, such as those used in successful systems of payment for these services (Farley and Costanza, 2010). In addition, it is important to note that valuation is unavoidable. We already value ecosystems and their services every time we make a decision involving trade-offs concerning them. The problem is that the valuation is implicit in the decision and hidden from view. Improved transparency about the valuation of ecosystem services (while recognizing the uncertainties and limitations) can only help to make better decisions.

It is also incorrect to suggest (McCauley, 2006) that conservation based on protecting ecosystem services is betting against human ingenuity. Recognizing and measuring natural capital and ecosystem services in terms of stocks and flows is a prime example of enlightened human ingenuity. The study of ecosystem services has merely identified the limitations and costs of 'hard' engineering solutions to problems that in many cases can be more efficiently solved by natural systems. Pointing out that the 'horizontal levees' of coastal marshes are more cost-effective protectors against hurricanes than constructed vertical levees (Costanza et al., 2008) and that they also store carbon that would otherwise be emitted into the atmosphere (Luisetti et al., 2011) implies that restoring or recreating them for this and other benefits is only using our intelligence and ingenuity, not betting against it.

The ecosystem services concept makes it abundantly clear that the choice of "the environment versus the economy" is a false choice. If nature contributes significantly to human well-being, then it is a major contributor to the *real* economy (Costanza et al., 1997), and the choice becomes how to manage all our assets, including natural and human-made capital, more effectively and sustainably (Costanza et al., 2000).

4. Uses of valuation of ecosystem services

The valuation of ecosystem services can have many potential uses, at multiple time and space scales. Confusion can arise, however, if one is not clear about the distinctions between these uses. Table 1 lists some of the potential uses of ecosystem services valuation, ranging from simply raising awareness to detailed analysis of various policy choices and scenarios. For example, Costanza et al. (1997) was clearly an awareness raising exercise with no specific policy or decision in mind. As its citation history verifies, it was very successful for this purpose. It also pointed out that ecosystem service values could be useful for several of the other purposes listed in Table 1, and it stimulated subsequent research and application in these areas. There have been thousands of subsequent studies addressing the full range of uses listed in Table 1.

5. Aggregating values

Ecosystem services are often assessed and valued at specific sites for specific services. However some uses require aggregate values over larger spatial and temporal scales (Table 1). Producing such aggregates suffers from many of the same problems as producing any aggregate estimate, including macroeconomic aggregates such as GDP. Table 2 lists a range of possible approaches for aggregating ecosystem service values (Kubiszewski et al., 2013a). Basic benefit transfer, the technique used in Costanza et al. (1997) assumes a constant unit value per hectare of ecosystem type and multiplies that value by the area of each type to arrive at aggregate totals. This can be improved somewhat by adjusting values using expert opinion of local conditions (Batker et al., 2008). Benefit transfer is analogous to the approach taken in GDP accounting, which aggregates value by multiplying price times quantity for each sector of the economy. Our aggregate is an accounting measure of the quantity of ecosystem services (Howarth and Farber, 2002). In this accounting dimension the measure is based on virtual non-market prices and incomes, not real prices and incomes. We return to this point later when we examine some of the criticisms of the original 1997 study.

While simple and easy, this approach obviously glosses over many of the complexities involved. This degree of approximation is appropriate for some uses (Table 1) but ultimately a more spatially explicit and dynamic approach would be preferable or essential for some other uses. These approaches are beginning to be implemented (Bateman et al., 2013; Boumans et al., 2002; Burkhard et al., 2013; Costanza et al., 2008; Costanza and Voinov, 2003; Crossman et al., 2012; Goldstein et al., 2012; Nelson et al., 2009) and this represents the cutting edge of research in this field.

Regional aggregates are useful for assessing land use change scenarios. National aggregates are useful for revising national income accounts. Global aggregates are useful for raising awareness and emphasizing the importance of ecosystem services relative to other contributors to human well-being. In this paper, we provide some updated global estimates, recognizing that this is only one among many potential uses for ecosystem services valuation, and that this use has special requirements, limitations, and interpretations.

6. Estimates of global value

Costanza et al. (1997) estimated the value of 17 ecosystem services for 16 biomes and an aggregate global value expressed in monetary units. This estimate was based on a simple benefit transfer method described above.

Notwithstanding the limitations and restrictions in benefit transfer techniques (Brouwer, 2000; Defra, 2010; Johnston and

Table 1
Range of uses for ecosystem service valuation.

Use of valuation	Appropriate values	Appropriate spatial scales	Precision needed
Raising awareness and interest	Total values, macro aggregates	Regional to global	Low
National income and well-being accounts	Total values by sector and macro aggregates	National	Medium
Specific policy analyses	Changes by policy	Multiple depending on policy	Medium to high
Urban and regional land use planning	Changes by land use scenario	Regional	Low to medium
Payment for ecosystem services	Changes by actions due payment	Multiple depending on system	Medium to high
Full cost accounting	Total values by business, product, or activity and changes by business, product, or activity	Regional to global, given the scale of international corporations	Medium to high
Common asset trusts	Totals to assess capital and changes to assess income and loss	Regional to global	Medium

Table 2
Four levels of ecosystem service value aggregation (Kubiszewski et al., 2013a,b).

Aggregation method	Assumptions/approach	Examples
1. Basic value transfer	Assumes values constant over ecosystem types	Costanza et al. (1997), Liu et al. (2010a,b)
2. Expert modified value transfer	Adjusts values for local ecosystem conditions using expert opinion surveys	Batker et al. (2008)
3. Statistical value transfer	Builds statistical model of spatial and other dependencies	de Groot et al. (2012)
4. Spatially explicit functional modeling	Builds spatially explicit statistical or dynamic systems models incorporating valuation	Boumans et al. (2002), Costanza et al. (2008), Nelson et al. (2009)

Rosenberger, 2010) it is an attractive option for researchers and policy-makers facing time and budget constraints. Value transfer has been used for valuation of environmental resources in many instances. Nelson and Kennedy (2009) provide a critical overview of 140 meta-analyses.

de Groot et al. (2012) estimated the value of ecosystem services in monetary units provided by 10 main biomes (Open oceans, Coral reefs, Coastal systems, Coastal wetlands, Inland wetlands, Lakes, Tropical forests, Temperate forests, Woodlands, and Grasslands) based on local case studies across the world. These studies covered a large number of ecosystems, types of landscapes, different definitions of services, different areas, different levels of scale, time and complexity and different valuation methods. In total, approximately 320 publications were screened and more than 1350 data-points from over 300 case study locations were stored in the Ecosystem Services Value Database (ESVD) (http://www.fsd.nl/esp/80763/5/0/50). A selection of 665 of these value data points were used for the analysis. Values were expressed in terms of 2007 'International' $/ha/year, i.e. translated into US$ values on the basis of Purchasing Power Parity (PPP) and contains site-, study-, and context-specific information from the case studies. We added some additional estimates for this paper, notably for urban and cropland systems (see Supporting Material for details).

A detailed description of the ESVD is given in van der Ploeg et al. (2010). de Groot et al. (2012) provides details of the results. Below, we provide a comparison of the de Groot et al. (2012) results with the Costanza et al. (1997) results in order to estimate the changes in the flow of ecosystem services over this time period.

After some consolidation of the typologies used in the two studies we can compare the de Groot et al. (2012) estimates per service and per biome with the Costanza et al. (1997) estimates in Table 3, and in more detail in Supporting Material, Table S1. Table S1 lists the mean value for each service and biome for both 1997 and 2011. Table 4 is a summary of the number of estimates, mean, standard deviation, median, and minimum and maximum values used in de Groot et al. (2012). All values are in international $/ha/yr and were derived from the ESV database. Note that there is a wide range of the number of studies for each biome, ranging from 14 for open ocean to 168 for inland wetlands. This is a significantly larger number of studies than were available for the Costanza et al. study (less than 100). One can also note the wide variation and high standard deviation for several of the biomes. For example, values for coral reefs varied from a low of 36,794 $/ha/yr to a high of 2,129,122 $/ha/yr. Given a sufficient number of studies, some of this variation can be explained by other variables. For example, De Groot et al. performed a meta-regression analysis for inland wetlands using 16 independent variables in a model with an adjusted R^2 of 0.442. Variables that were significant in explaining the value of inland wetlands included the area of the study site, the type of inland wetland, GDP/capita, and population of the country in which the wetland occurred, the proximity of other wetlands, and the valuation method used for the study. If this number of studies were available for the other biomes in our global assessment, we could use this type of meta-regression to produce more accurate estimates. However, for the current estimate, we must continue to rely on global averages.

Global averages per ha may vary between the two time periods we are comparing for three distinct reasons: (1) new (and generally more numerous and complete) estimates of the unit values of ecosystem services per ha; (2) changes in the average functionality of ecosystem per ha; and (3) changes in value per ha due to changes in human, social, or built capital. The actual estimates conflate these causes and we see no way of disentangling them at this point. However, since global population only increased by 16% between 1997 and 2011 (from 5.83 to 7 billion), and, if anything, ecosystems are becoming more stressed and less functional, we can attribute most of the increase in unit values to more comprehensive, value estimates available in 2011 than in 1997.

Table 3 shows that values per ha estimated by de Groot et al. (2012) are an average of 8 times higher than the equivalent estimates from Costanza et al. (1997) (both converted into $2007). Only inland wetlands and estuaries did not show a significant increase in estimated value per ha, but these were among the best studied biomes in 1997. Some biomes showed significant increases in value. For example, tidal marsh/mangroves increased from abound 14,000 to around 194,000 $/ha/yr. This is largely due to new studies of the storm protection, erosion control, and waste treatment values of these systems. Coral reefs also increased tremendously in estimated value from around 8000 to around 352,000 $/ha/yr due to additional studies of storm protection, erosion protection, and recreation. Cropland and urban system also increased dramatically, largely because there were almost no studies of these systems in 1997 and there have subsequently been several new studies (Wratten et al., 2013).

Table 3 also shows the aggregate global annual value of services, estimated by multiplying the land area of each biome by the unit values. Column A uses the original values from Costanza et al. (1997) converted to 2007 dollars (total = $45.9 trillion/yr). If we assume that land areas did not change between the two time periods, the new estimate, shown in column B is $145 trillion/yr, are more than 3 times larger than the original estimate. This is due solely to updated unit values. However, land use *has* changed significantly between the two years, changing the supply (the flow) of ecosystem services. If we use the new land use estimates shown in Table 3 (see Supporting Material for details) and the 1997 unit values, we get the estimates in column C – a total of $41.6 trillion/yr. Column E is the change in value due to land use change using the 1997 unit values. Marine systems show a slight increase in value, while terrestrial systems show a large decrease. This decrease is largely due to decreases in the area of high value per ha biomes (tropical forests, wetlands, and coral reefs – shown in red in Table 3) and increases in low value per ha biomes. The total net decrease is estimated to be $4.3 trillion/yr. It is almost certain that the functionality of ecosystems per ha has also declined in many cases so the supply effects are surely greater than this. Column D

Table 3
Changes in area, unit values and aggregate global flow values from 1997 to 2011 (green are values that have increased, red are values that have decreased).

Biome	Area (e6 ha)		Change	Unit values 2007$/ha/yr		Change	Aggregate Global Flow Value e12 2007$/yr: A. Original (Assuming 1997 area and 1997 unit values)	B. Change unit values only (Assuming 1997 area and 2011 unit values)	C. Change area only (Assuming 2011 area and 1997 unit values)	D. Change both unit values and area (Assuming 2011 area and 2011 unit values)	2011-1997 Change in Value e12 2007$/yr: E. Column C - Column A	F. Column D - Column B
	1997	2011	2011-1997	1997	2011	2011-1997	1997	2011	2011	2011	1997 unit values	2011 unit values
Marine	**36,302**	**36,302**	0	796	1,368	572	**28.9**	**60.5**	**29.5**	**49.7**	0.6	(10.9)
Open Ocean	**33,200**	**33,200**	0	348	660	312	11.6	21.9	11.6	21.9	-	-
Coastal	**3,102**	**3,102**	0	5,592	8,944	3,352	17.3	38.6	18.0	27.7	0.6	(10.9)
Estuaries	180	**180**	0	31,509	28,916	-2,593	5.7	5.2	5.7	5.2	-	-
Seagrass/Algae Beds	200	**234**	34	26,226	28,916	2,690	5.2	5.8	6.1	6.8	0.9	1.0
Coral Reefs	62	**28**	-34	8,384	352,249	343,865	0.5	21.7	0.2	9.9	(0.3)	(11.9)
Shelf	2,660	**2,660**	0	2,222	2,222	0	5.9	5.9	5.9	5.9	-	-
Terrestrial	**15,323**	**15,323**	0	1,109	4,901	3,792	**17.0**	**84.5**	**12.1**	**75.1**	(4.9)	(9.4)
Forest	**4,855**	**4,261**	-594	1,338	3,800	2,462	6.5	19.5	4.7	16.2	(1.8)	(3.3)
Tropical	1,900	**1,258**	-642	2,769	5,382	2,613	5.3	10.2	3.5	6.8	(1.8)	(3.5)
Temperate/Boreal	2,955	**3,003**	48	417	3,137	2,720	1.2	9.3	1.3	9.4	0.0	0.2
Grass/Rangelands	**3,898**	**4,418**	520	321	4,166	3,845	1.2	16.2	1.4	18.4	0.2	2.2
Wetlands	**330**	**188**	-142	20,404	140,174	119,770	6.7	36.2	3.4	26.4	(3.3)	(9.9)
Tidal Marsh/Mangroves	165	**128**	-37	13,786	193,843	180,057	2.3	32.0	1.8	24.8	(0.5)	(7.2)
Swamps/Floodplains	165	**60**	-105	27,021	25,681	-1,340	4.5	4.2	1.6	1.5	(2.8)	(2.7)
Lakes/Rivers	**200**	**200**	0	11,727	12,512	785	2.3	2.5	2.3	2.5	-	-
Desert	**1,925**	**2,159**	234	-	-	0	-	-	-	-	-	-
Tundra	**743**	**433**	-310	-	-	0	-	-	-	-	-	-
Ice/Rock	**1,640**	**1,640**	0	-	-	0	-	-	-	-	-	-
Cropland	**1,400**	**1,672**	272	126	5,567	5,441	0.2	7.8	0.2	9.3	0.0	1.5
Urban	**332**	**352**	20	-	6,661	6,661	-	2.2	-	2.3	-	0.1
Total	**51,625**	**51,625**	0				**45.9**	**145.0**	**41.6**	**124.8**	**(4.3)**	**(20.2)**

shows the combined effects of both changes in land areas and updated unit values. The net effect yields an estimate of $124.8 trillion/yr – 2.7 times the original estimate. For comparison, global GDP was approximately 46.3 trillion/yr in 1997 and $75.2 trillion/yr in 2011 (in $2007).

The difference between columns D and B is the estimated loss of ecosystem services based on land use changes and using the 2011 unit value estimates. This is shown in column F. In this case marine systems show a large loss ($10.9 trillion/yr), due mainly to a decrease in coral reef area and the substantially larger unit value for coral reef using the 2011 unit values. Terrestrial systems also show a large loss, dominated by tropical forests and wetlands, but countered by small increases in the value of grasslands, cropland, and urban systems. Overall, the total net decrease is estimated to be $20.2 trillion in annual services since 1997. Given the more comprehensive unit values employed in the 2011 estimates, this is a better approximation than using the 1997 unit values, but certainly still a conservative estimate. The present value of the discounted flow of ecosystem services consumed would represent part of the stock of inclusive wealth lost/gained over time (UNU-IHDP, 2012).

As we have previously noted, basic value transfer is a crude first approximation at best. We could put ranges on these numbers based on the standard deviations shown in Table 4, but there are other sources of error and caveats as well, as described in Costanza et al. including errors in estimating land use changes. However, we think that solving these problems will most likely lead to even larger estimates. For example, one problem is the limited number of valuation studies available and we expected that as more studies became available from 1997 to 2011 the unit value estimates would increase, and they did.

We also anticipate that more sophisticated techniques for estimating value will lead to larger estimates. For example, more sophisticated integrated dynamic and spatially explicit modeling

Table 4
Summary of the number of estimates, mean, standard deviation, median, minimum and maximum values used in de Groot et al. (2012). Values are in international $/ha/yr, derived from the ESV database.

	No. of estimates	Total of service means (TEV)	Total of St. Dev. of means	Total of median values	Total of minimum values	Total of maximum values
Open oceans	14	491	762	135	85	1664
Coral reefs	94	352,915	668,639	197,900	36,794	2129,122
Coastal systems	28	28,917	5045	26,760	26,167	42,063
Coastal wetlands	139	193,845	384,192	12,163	300	887,828
Inland wetlands	168	25,682	36,585	16,534	3018	104,924
Rivers and lakes	15	4267	2771	3938	1446	7757
Tropical forest	96	5264	6526	2355	1581	20,851
Temperate forest	58	3013	5437	1127	278	16,406
Woodlands	21	1588	317	1522	1373	2188
Grasslands	32	2871	3860	2698	124	5930

techniques have been developed and applied at regional scales (Barbier, 2007; Bateman et al., 2013; Bateman and Jones, 2003; Costanza and Voinov, 2003; Goldstein et al., 2012; Nelson et al., 2009). However, few have been applied at the global scale. One example is the Global Unified Metamodel of the Biosphere (GUMBO) that was developed specifically to simulate the integrated earth system and assess the dynamics and values of ecosystem services (Boumans et al., 2002). GUMBO is a 'metamodel' in that it represents a synthesis and simplification of several existing dynamic global models in both the natural and social sciences at an intermediate level of complexity. It includes dynamic feedbacks among human technology, economic production, human welfare, and ecosystem goods and services within and across 11 biomes. The dynamics of eleven major ecosystem goods and services for each of the biomes have been simulated and evaluated. A range of future scenarios representing different assumptions about future technological change, investment strategies and other factors, have been simulated. The relative value of ecosystem services in terms of their contribution to supporting both conventional economic production and human well-being more broadly defined were estimated under each scenario. The value of global ecosystem services was estimated to be about 4.5 times the value of Gross World Product (GWP) in the year 2000 using this approach. For a current global GDP of $75 trillion/yr this would be about $347 trillion/yr, or almost three times the column D estimate in Table 3. This is to be expected since the dynamic simulation can include a more comprehensive picture of the complex interdependencies involved. It is also important to note that this type of model is the only way to potentially assess more than marginal changes in ecosystem services, including irreversible thresholds and tipping points (Rockström et al., 2009; Turner et al., 2003).

7. Caveats and misconceptions

We want to make clear that expressing the value of ecosystem services in monetary units does not mean that they should be treated as private commodities that can be traded in private markets. Many ecosystem services are public goods or the product of common assets that cannot (or should not) be privatized (Wood, 2014). Even if fish and other provisioning services enter the market as private goods, the ecosystems that produce them (i.e. coastal systems and oceans) are common assets. Their value in monetary units is an estimate of their benefits to society expressed in units that communicate with a broad audience. This can help to raise awareness of the importance of ecosystem services to society and serve as a powerful and essential communication tool to inform better, more balanced decisions regarding trade-offs with policies that enhance GDP but damage ecosystem services.

Some have argued that estimating the global value of ecosystem services is meaningless, because if we lost all ecosystem services human life would end, so their value must be infinite (Chaisson, 2002). While this is certainly true, as was clearly pointed out in the 1997 paper (Costanza et al., 1997), it is a simple misinterpretation of what our estimate refers to. Our estimate is more analogous to estimating the total value of agriculture in national income accounting. Whatever the fraction of GDP that agriculture contributes now, it is clear that if all agriculture were to stop, economies would collapse to near zero. What the estimates are referring to, in both cases, is the *relative* contribution, expressed in monetary units, of the assets or activities at the current point in time. Referring to Fig. 1, human well-being comes from the interaction of the four basic types of capital shown. GDP picks up only a fraction of this total contribution (Costanza et al., 2014; Kubiszewski et al., 2013b). What we have estimated is the relative contribution of natural capital now, with the current balance of asset types. Some of this contribution is already included in GDP, embedded in the contribution of natural capital to marketed goods and services. But much of it is not captured in GDP because it is embedded in services that are not marketed or not fully captured in marketed products and services. Our estimate shows that these services (i.e. storm protection, climate regulation, etc.) are much larger in relative magnitude right now than the sum of marketed goods and services (GDP). Some have argued that this result is impossible, wrongly assuming that all of our value estimates are based on willingness-to-pay and that that cannot exceed aggregate ability-to-pay (i.e. GDP). But for it to be impossible, one would have to argue that *all* human benefits are marketed and captured in GDP. This is obviously not the case. Another example is the many other types of goods and services traded on "black markets" that in some countries far exceed GDP. Moreover, our estimate is an accounting measure based on virtual not real prices and incomes and it is these virtual total expenditures that should not be exceeded (Costanza et al., 1998; Howarth and Farber, 2002). It is also important for policy to evaluate gains/losses in stocks and consequent service flows (analogous to net GDP). The discounted present value of such stock/flow changes is a measure of a component of inclusive wealth or wellbeing.

8. Conclusions

The concepts of ecosystem services flows and natural capital stocks are increasingly useful ways to highlight, measure, and value the degree of interdependence between humans and the rest of nature. This approach is complementary with other approaches to nature conservation, but provides conceptual and empirical tools that the others lack and it communicates with different audiences for different purposes. Estimates of the global accounting value of ecosystem services expressed in monetary units, like those in this paper, are mainly useful to raise awareness about the magnitude of these services relative to other services provided by human-built capital at the current point in time. Our estimates show that global land use changes between 1997 and 2011 have resulted in a loss of ecosystem services of between $4.3 and $20.2 trillion/yr, and we believe that these estimates are conservative. One should not underestimate the importance of the change in awareness and worldview that these global estimates can facilitate – it is a necessary precursor to practical application of the concept using changes in the flows of services for decision-making at multiple scales. It allows us to build a more comprehensive and balanced picture of the assets that support human well-being and human's interdependence with the well-being of all life on the planet.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gloenvcha.2014.04.002.

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