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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 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.

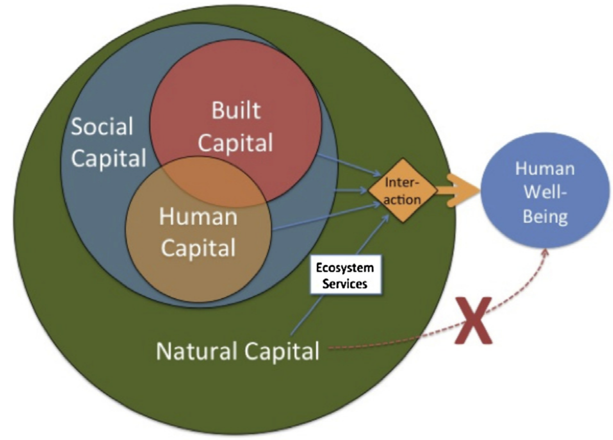

Fig. 1. Interaction between built, social, human and natural capital required to produce human well-being. Built and human capital (the economy) are embedded in society which is embedded in the rest of nature. Ecosystem services are the relative contribution of natural capital to human well-being, they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

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)			Unit values 2007$/ha/yr			Aggregate Global Flow Value e12 2007$/yr				2011-1997 Change in 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)	**E.** Column C - Column A	**F.** Column D - Column B
	1997	2011	Change 2011-1997	1997	2011	Change 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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