

A: The future of ecosystem services: Impacts on ecosystem service values, and global and national scenarios

Lead authors:

Sharolyn Anderson^a, Paul Sutton^{a,c},
Ida Kubiszewski^b, Robert Costanza^b

Author affiliation:

^a University of South Australia.
101 Currie St, Adelaide SA 5001, Australia.
sharolyn.anderson@unisa.edu.au;
paul.sutton@unisa.edu.au

^b Crawford School of Public Policy,
Australian National University.
Canberra ACT 2601, Australia.
ida.kub@gmail.com;
rcostanz@gmail.com

^c University of Denver.
2050 Iliff Ave, Denver, CO, 80208, USA

Impacts of land cover changes degradation on ecosystem service values

The magnitude of the global economic value of ecosystem services dwarfs the value of the global market economy¹. Changes to land cover in the past twenty years have reduced the value of the annual flow of ecosystem services by USD 4–20 trillion/yr². However, these losses do not account for reduced ecosystem function and its impact on the value of ecosystem services. Here, human appropriation of net primary productivity (HANPP)³ was used as a proxy of land degradation to estimate losses of ecosystem services due to land degradation. Two proxy measures of land degradation were used as a measure of impact on ecosystem function; the first is a representation of HANPP derived from population distributions and aggregate national statistics. The second is theoretically derived



from biophysical models and is the ratio of actual net primary productivity (NPP) to potential NPP. Juxtaposition of these measures of land degradation with a map of ecosystem service values (ESV) allows for spatially explicit representation of those lost values that result from land degradation. Resulting estimates of lost ecosystem services is USD 6.3 and 10.6 trillion/yr, using these two approaches respectively. With global gross domestic product (GDP) standing at roughly USD 63 trillion in 2010, all of agriculture represents roughly USD 1.7 trillion (2.8 per cent) of the world's GDP. These estimates of lost ecosystem services represent significantly larger fractions (10–17 per cent) of global GDP. These results demonstrate why the economics of land degradation is more critical than the market value of agricultural products alone.

Introduction

It is becoming increasingly evident that land degradation is expensive, both to local owners and to society in general over multiple time and space scales^{1, 2,4,5,6}. The UNCCD recognises this, and at Rio+20 set a target of *zero net land degradation*⁷, now referred to as land degradation neutrality (LDN, see *Box 1.2*). The need to restore degraded lands and prevent further degradation is especially important now as the demand for accessible productive land is increasing. These changes are projected to affect mainly tropical regions that are already vulnerable to other stresses, including the increasing unpredictability of rainfall patterns and extreme events as a result of climate change^{8,9}.

Land degradation, amongst other drivers, is a consequence of poor management of natural capital (soils, water, vegetation, etc.). Better frameworks are needed to: (1) quantify the scale of the problem globally; (2) calculate the cost of 'business as usual'⁷, and; (3) assess the benefits of restoration. Visionary farmers and business leaders are becoming aware that ecosystem degradation may affect their bottom line and future prosperity¹⁰, however, they lack the decision-making tools to develop robust and effective solutions. In addition, the prevailing political economy encourages rent-seeking activities in which short-term individual gains are more valued than long societal benefits. Nonetheless, modeling and simulation techniques enable the creation and evaluation of scenarios of alternative futures and

other decision-making tools to address these gaps in data and knowledge^{11,12,13,14}.

In this section, methods to assess the degree of land degradation are investigated, based on its effects on NPP globally. Estimates are then used to derive assessments of the loss of ecosystem service values from land degradation.

Data and methods

Land degradation is a complex phenomenon that manifests in many ways. There have been numerous efforts using a variety of approaches to characterise various facets of land degradation over the last few decades. A recent review of various datasets and the approaches to their development (e.g., expert opinion, satellite derived NPP, biophysical models, and abandoned cropland) has been conducted by Gibbs and Salmon¹⁵. The GLASOD project (1987–1990) was a global assessment of human-induced soil degradation based primarily on expert opinion¹. The GLASOD effort separately characterised chemical deterioration, wind erosion susceptibility and damage, physical deterioration, and water erosion severity into categories of low, medium, high, and very high. An influential 1986 study estimated that humans were directly and indirectly appropriating 31 per cent of the earth's NPP¹⁶. A subsequent 2001 study arrived at a similar figure of 32 per cent¹⁷.

The Food and Agriculture Organization of the United Nations (FAO) has developed a map of land degradation represented by a loss of NPP. NPP is measured using a Rainfall Use Efficiency (RUE) adjusted Normalized Difference Vegetation Index (NDVI) derived from MODIS satellites as a proxy of measure land degradation^{ii,18}. There are many challenges associated with using satellite observations of NDVI as a proxy of NPP because of variability of rainfall and spatially varying agricultural and pastoral practices.

Much of the net primary productivity research seeks to determine the human appropriation of such. Imhoff *et al.* made estimates of HANPP using models derived from empirical satellite observations and related statistical data^{19,20,21}. Imhoff's representation spatially allocates the HANPP to the location of its consumption. Haberl *et al.* made a similar assessment of HANPP using process models

ⁱ *Global Assessment of Human-induced Soil Degradation (GLASOD):* www.isric.org/data/global-assessment-human-induced-soil-degradation-glasod

ⁱⁱ *Global NPP Loss In The Degrading Areas (1981–2003):* www.fao.org/geonetwork/srv/en/metadata.show?id=37055

and agricultural statistics that were consistent with the estimates of Imhoff *et al.*³ The Haberl representation spatially allocated the degradation primarily to the agricultural and grazing areas where the land degradation is actually taking place. In some respects, the Haberl representation of land degradation spatially allocates degradation to its actual production location, whereas the Imhoff representation allocates degradation to the spatial location of the consumption of the products that caused the degradation.

Spatially explicit global datasets were sought, that could provide simple and general measures of land degradation to be used as a factor to adjust ESVs on a pixel by pixel basis. The Imhoff data²² was chosen as a demand-based proxy measure and the Haberl data as a supply-based measure informed by agricultural statistics. The Imhoff data were partially derived from empirical satellite observations of NPP using a time series of Advanced Very High Resolution Radiometer (AVHRR) data.

The Haberl *et al.* databases also lent themselves to this purpose and were easy to accessⁱⁱⁱ. These theoretically derived datasets were also used to assess HANPP. They consisted of several datasets including the following:

- 1) **NPP**: A dynamic global vegetation model which is used to represent potential NPP in terms of $gC/m^2/yr$ ^{23,24};
- 2) **NPPact**: an actual NPP layer calculated from harvest statistics in agricultural areas and livestock statistics that are used in grazing areas;
- 3) **NPP_h**: the NPP destroyed during harvest;
- 4) **NPP_t**: the NPP remaining on the land surface after harvest, and;
- 5) **ΔNPP_{ic}**: the impact of human-induced land conversions such as land cover change, land use change, and soil degradation.

Two representations of land degradation were created that varied in value from 0–100 in which a zero corresponded to 100 per cent degradation and 100 corresponded to no degradation at all. With the Imhoff data, the representation of land degradation was simply $100 - \%HANPP$ (Figure 3a.1). The Haberl representation was created using data available at their website (www.uni-klu.ac.at/socec/inhalt/1191.htm). A percentage ratio of the data was created and named as *NPPactual* (tnap_all_gcm) and *NPPo* (tn0_all_gsm) (Figure 3a.2). Note this is not identical to the measure of HANPP. Perusal of these data show significant differences in that India and China are much more degraded in the Imhoff representation than in the Haberl representation. In addition, the mid-west of the USA and central Canada are much more significantly degraded in the Haberl representation. It should be noted that these differences do not suggest inaccuracy on the part of either dataset. These datasets are representative of two correlated but distinct phenomena (e.g., %HANPP and per cent of potential NPP). Both were chosen because their juxtaposition is an interesting exploration of the separation of production and consumption as it manifests as land degradation.

The third dataset used in this analysis was a representation of ESV based on USD/ha/yr for each type of land cover² (Figure 3a.3). For this study, only terrestrial values were used, because the representations of land degradation did not include coastal estuaries, coral reefs, and ocean areas. These figures present the data products as they were obtained (i.e., in an unprojected geographic or platte carre equi-rectangular projection). These calculations assume ESVs are a function of areal extent and consequently the analyses have all been converted to their corresponding area. Two representations of the ESV of degraded lands were created via the very simple process of multiplying three raster representations as follows:

ESV_Imhoff_degradation = ESV(Figure 3a.3 * Imhoff Degradation (Figure 3a.1) * Area in Hectares

ESV_Haberl_degradation = ESV(Figure 3a.3 * Haberl Degradation (Figure 3a.2) * Area in Hectares

iii Haberl database:
www.uni-klu.ac.at/socec/inhalt/1191.htm

FIGURE 3 A . 1

A representation of land degradation derived from Imhoff data

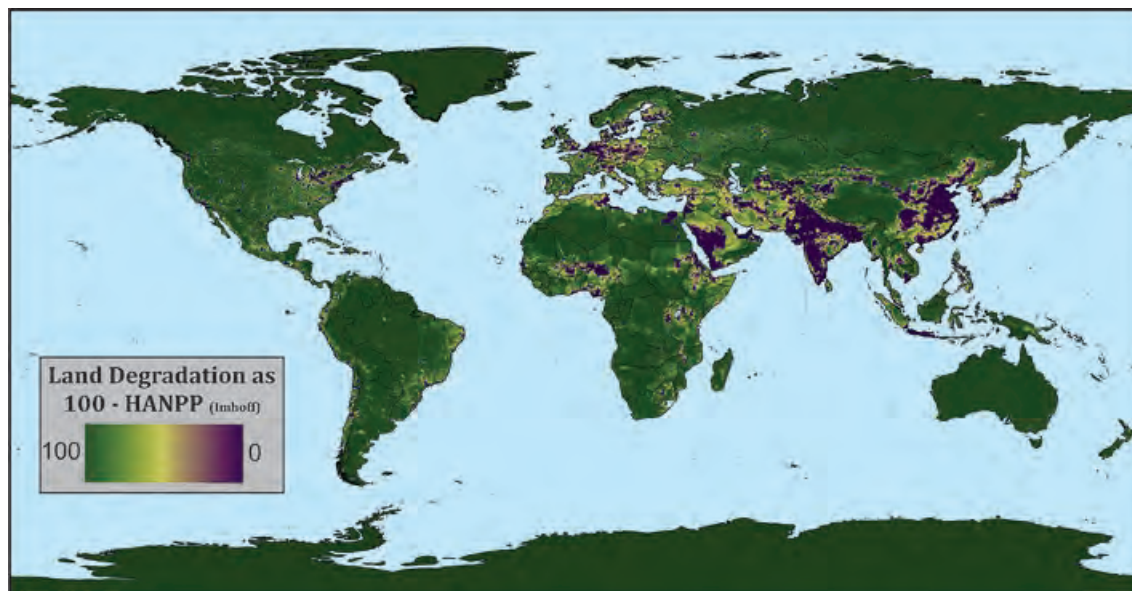


FIGURE 3 A . 2

A representation of land degradation derived from Haberl data

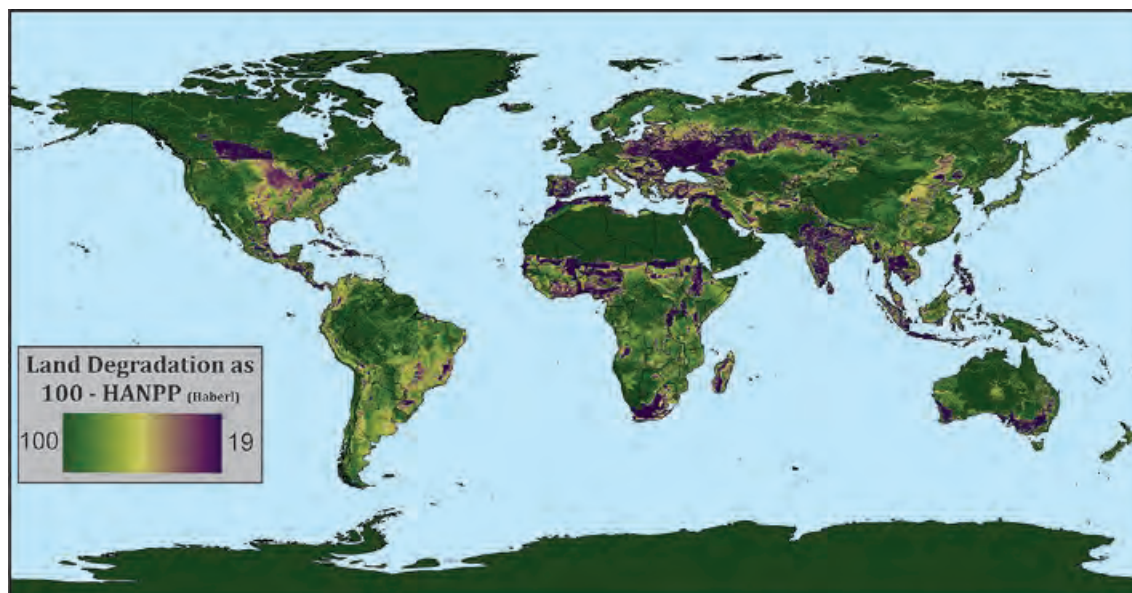
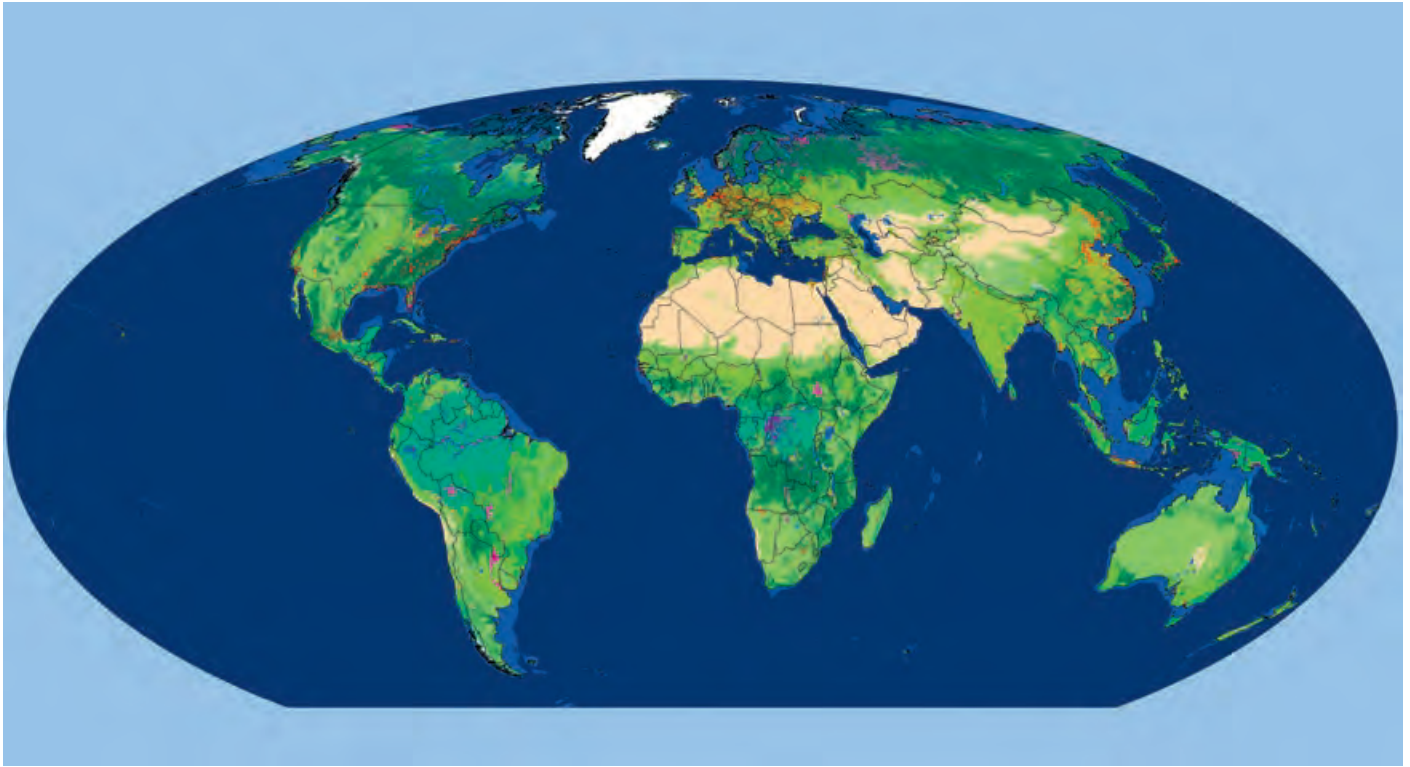


FIGURE 3A.3

Ecosystem service values*(adapted from Costanza et al., 2014²)*

This results in two new spatially explicit representations of ecosystem service values as 'degraded' by the 'Imhoff proxy' and 'Haberl proxy' respectively. The global and national aggregations of these are presented as results. See *Table 4.1* and *4.2*, as well as *Figure 4.1* in *Chapter 4* for similar regional analyses, as well as for per capita and per square kilometre values. The Imhoff representation differs markedly from the Haberl representation. The Imhoff version is really more a map of the location of the driving forces of land degradation, which are a function of population and consumption. The Haberl representation is a more spatially accurate measure of actual land degradation where it takes place; however, it captures agricultural land degradation more effectively than degradation of non-agricultural lands.

Results

The impacts on ecosystem service monetary values that results if proxy measures are linearly proportional to degradation of ecosystem function

are found in *Appendix 3*. Globally, the Haberl and Imhoff proxies produce a 9.2 and 15.2 per cent decrease respectively in the global annual value of ecosystem services. Spatial variation between these representations results in some stark differences in their respective impacts on the value of ecosystem services at national levels. In India, the theoretical Haberl derived representation produces an impact that is a 20.3 per cent loss of ESV, whereas with the Imhoff derived representation produces a 72.8 per cent loss. With China, these differences are 6.6 and 45.2 per cent. In the United States, the differences are not as marked, at 8.0 and 16.0 per cent degraded.

At the national level, the spatial patterns of land degradation and their impacts on the loss of ESVs can be similar or dramatically different between the two approaches.

The island continent of Australia provides an example of striking differences. The total value of terrestrial ecosystem services in Australia is roughly USD 3.2 trillion/yr². The Haberl

representation of land degradation for Australia includes most of Australia's agricultural areas and even some of the central scrublands whereas the Imhoff representation is much more focused on areas of intense human settlement in and around the capital cities (*Figure 3a.4*). The loss of ESV from the Imhoff and Haberl representations are USD 79 and 224 billion/yr respectively. These values differ by roughly a factor of three. The overall losses presented here represent 2 per cent (Imhoff) and 7 per cent (Haberl) annual loss of ESV. These results are a consequence of the highly urbanised and spatially concentrated population of Australia and the fact that they are a net exporter of food and ecosystem service values. The Haberl representation is likely the best actual measure of actual land degradation whereas the Imhoff representation measures the land degradation

associated with the behaviour of the population of Australia.

Nations in and around the Mekong Delta in Southeast Asia diverge from the findings for Australia. The total annual value of ecosystem services for this region is roughly USD 1 trillion/yr². The overall spatial patterns of degradation for the Haberl and Imhoff representations in the Mekong Delta are more similar because these countries have significant rural populations; however, the Imhoff values tend to show higher levels of degradation than the Haberl values. Here, the Imhoff representation produces a much larger loss of ESV (USD 275 billion/yr) than the Haberl representation (USD 100 billion/yr) (*Figure 3a.5*). In fact, the Imhoff representation produces a larger loss of ecosystem services for all of these nations except for Laos, in which the two numbers are USD

FIGURE 3A.4

Representations of land degradation and land cover for Australia

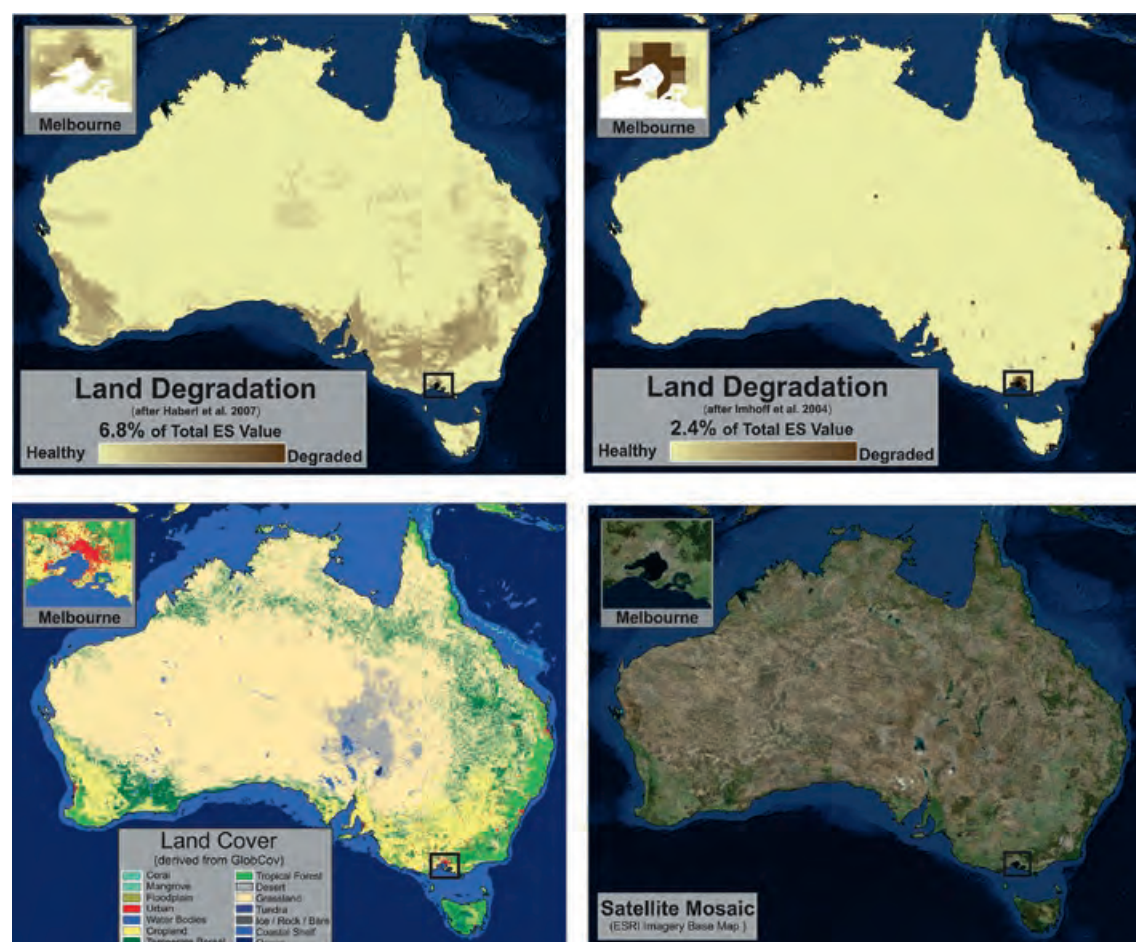
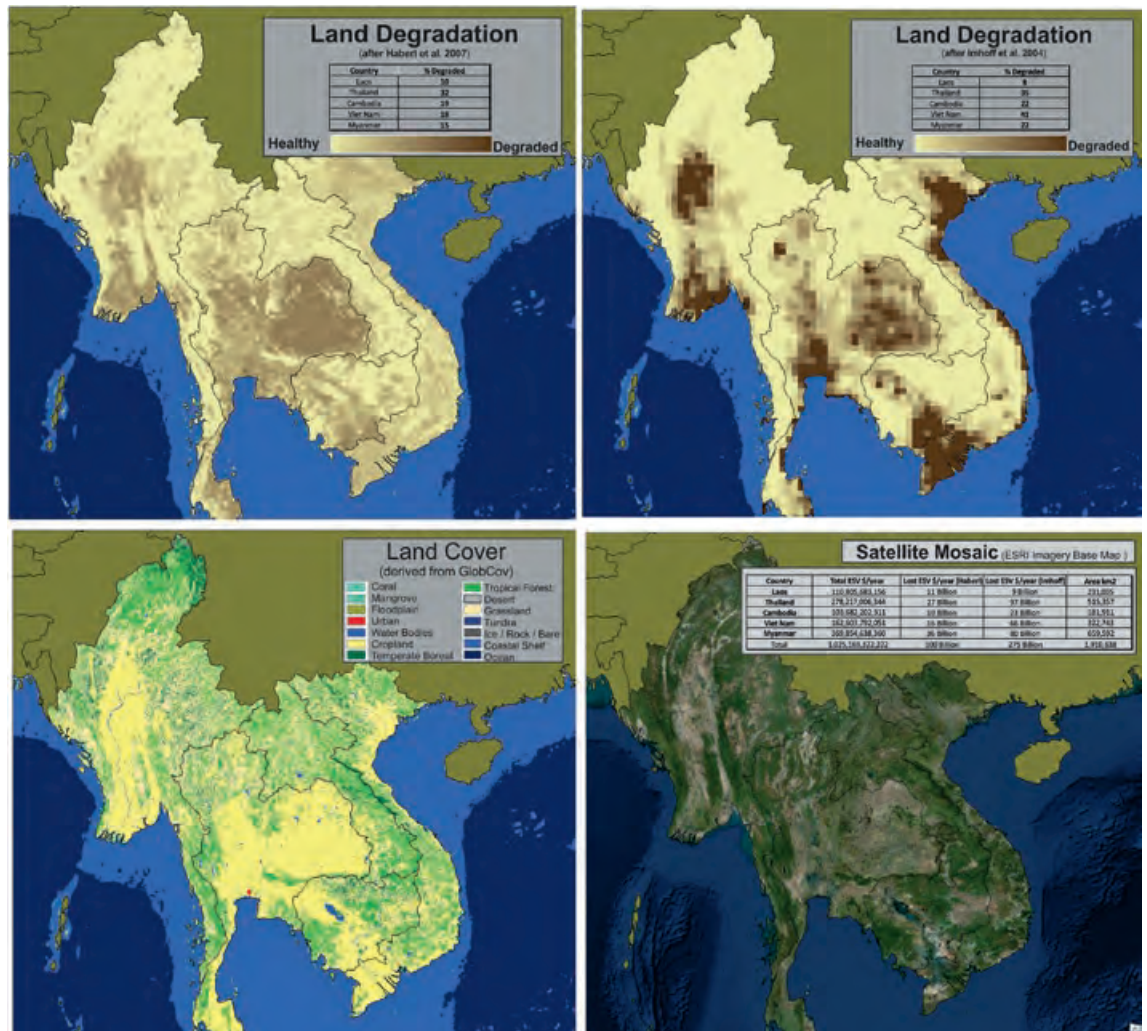


FIGURE 3A.5

Representations of land degradation and land cover for South-east Asia



11 and 9 billion/yr respectively. The overall values presented here respectively represent a 27 per cent (Imhoff) and 10 per cent (Haberl) annual loss of ESV. This suggests that this region of the world is in some sort of ecological deficit^{25,26}.

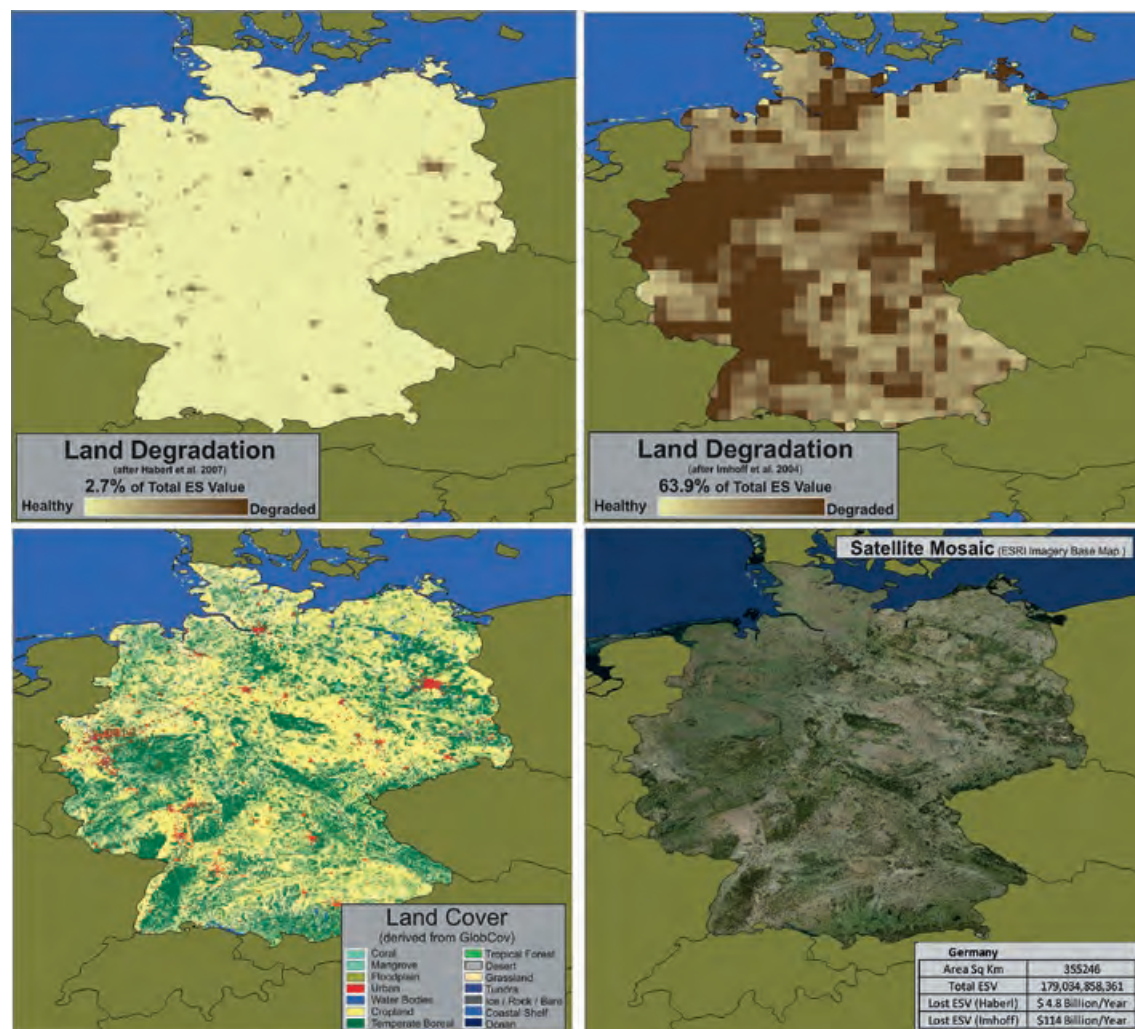
Germany also provides a striking contrast to the patterns of degradation seen in Australia. In Germany, the Imhoff representation shows land degradation as widespread throughout the nation, while the Haberl representation shows degradation as much more concentrated in and around the urban centers (*Figure 3a.6*). The annual value of ecosystem services from German lands is estimated to be USD 179 billion². Here the empirical Imhoff representation of degradation produces a

much larger percentage loss in annual ecosystem service value (64 per cent or USD 114 billion) than the Haberl representation (3 per cent or USD 4.8 billion). Here, the degradation represented in the Imhoff representation is a result of the high levels of consumption characteristic of the population of a western European nation. The Haberl representation is much less extensive and severe likely as a result of significant soil inputs and a highly regulated agricultural industry.

Bolivia is a nation that appears to have navigated the challenges of land degradation fairly well so far. The annual value of ecosystem services in Bolivia was estimated at USD 1.27 trillion². Here, the Haberl and Imhoff representations of land degradation

FIGURE 3A.6

Representations of land degradation and land cover for Germany



look much the way they did in Australia, in that the degraded areas in the population based Imhoff measure are concentrated in and around human settlements, whereas the agricultural representation derived from Haberl data is more widespread throughout the agricultural areas. The percentage loss of annual ESVs for Bolivia are 4 per cent (USD 53 billion) and 2 per cent (USD 21 billion) from the Imhoff and Haberl versions respectively.

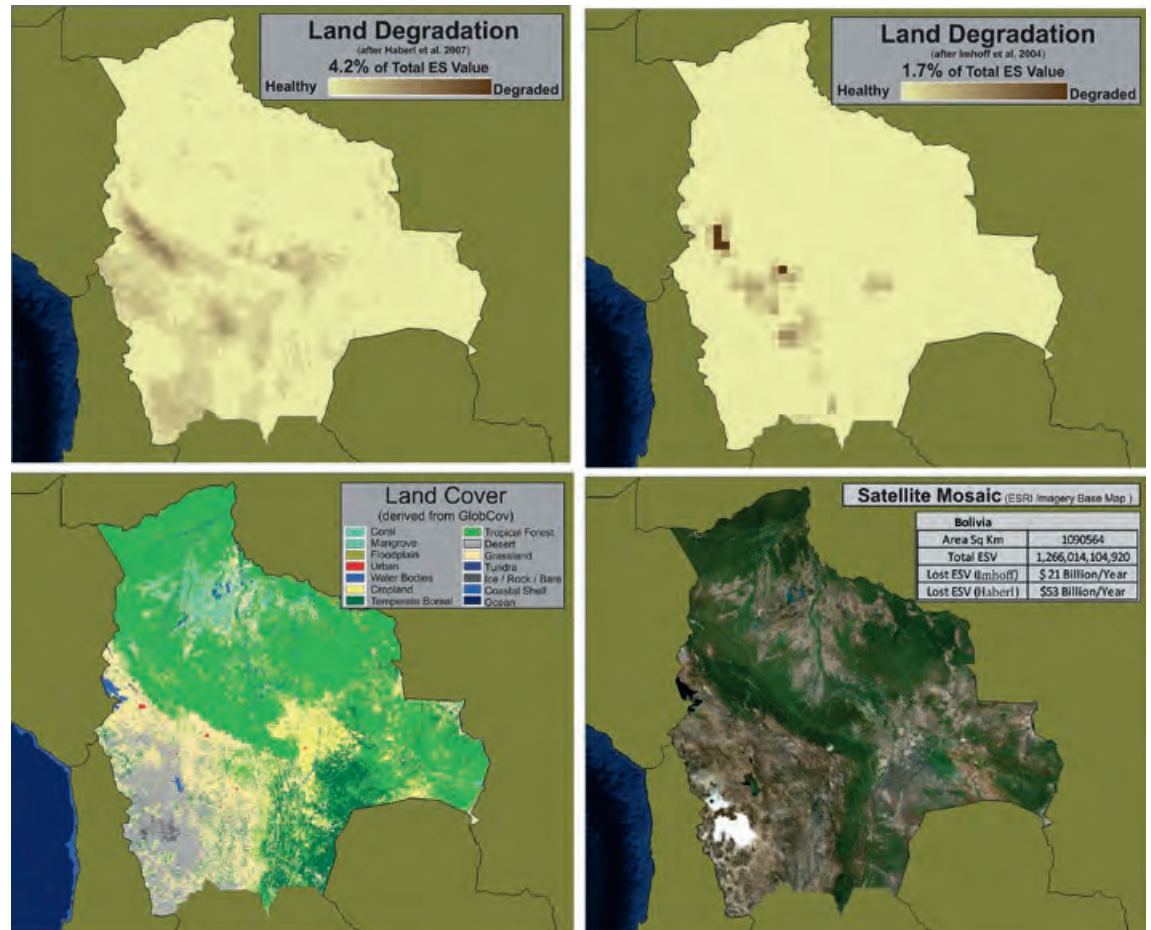
The aforementioned variation between these proxy measures of land degradation warrant some exploration and characterisation. Nations vary significantly in areal extent and human impacts which can distort interpretation of scatterplots in which a point for the small island nation of Samoa

has the same influence as the point for China. To test for a measure of consilience between these measures, authors looked at a Log – Log scatterplot of the ‘effective area of degraded land’ for both the Haberl and Imhoff proxy measures (*Figure 3a.8*).

‘Effective area of degraded land’ was calculated by simply multiplying the percent degraded layer for each proxy measure (i.e., the Haberl and Imhoff) by the area layer and summing up for each nation or territory. A simple linear scatterplot does show increasing variance with much fewer points at higher values. The essence of this exercise is to simply demonstrate that these two approaches show consilience with one another. Nonetheless, it was expected to see significant differences

FIGURE 3A.7

Representations of land degradation and land cover for Bolivia



between these measures of land degradation because one is spatially allocated to, and based primarily on, agricultural practices and yields (Haberl); whereas, the other is spatially allocated to, and based on, the number and behaviour of the population of the country (Imhoff).

It should also be noted that the differences between these two approaches result in profoundly different measures of 'percentage of land degraded' for the nations of the world. The 'percentage of land degraded' is simply calculated as 'effective area of degraded land' divided by 'total area of land' for each country. This does not adjust or account for the value of the ecosystem services of those lands (e.g., a 50 per cent degraded grassland will count the same as a 50 per cent degraded wetland, etc.) (Figure 3a.9).

Discussion and conclusion

Characterising, measuring, and mapping land degradation has long been recognised as a challenging task. Here, authors have presented a simplifying approach to collapse the multivariate phenomena of land degradation into a single spatially varying number. Just as an SAT score and an IQ test both measure intelligence, they do not perfectly correlate nor do they capture all the complexity of what is generally regarded as intelligence. This simplification of land degradation was used to estimate the impact on ecosystem function and convert it into loss of ecosystem service value.

The Haberl and Imhoff datasets were both originally used to estimate HANPP in terms of Pg C/yr (Haberl 15.6 Pg or 24 per cent of NPP, vs. Imhoff

FIGURE 3A.8

Log-log scatterplot of national effective degraded land area

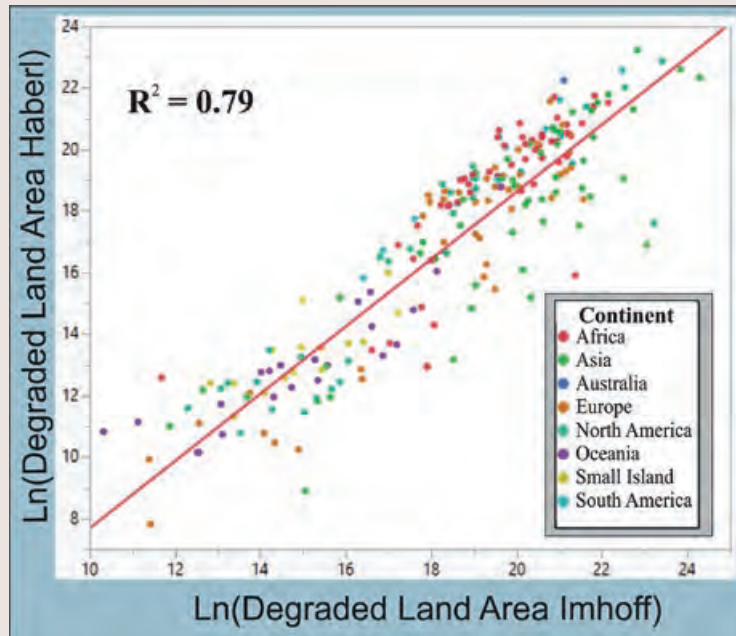
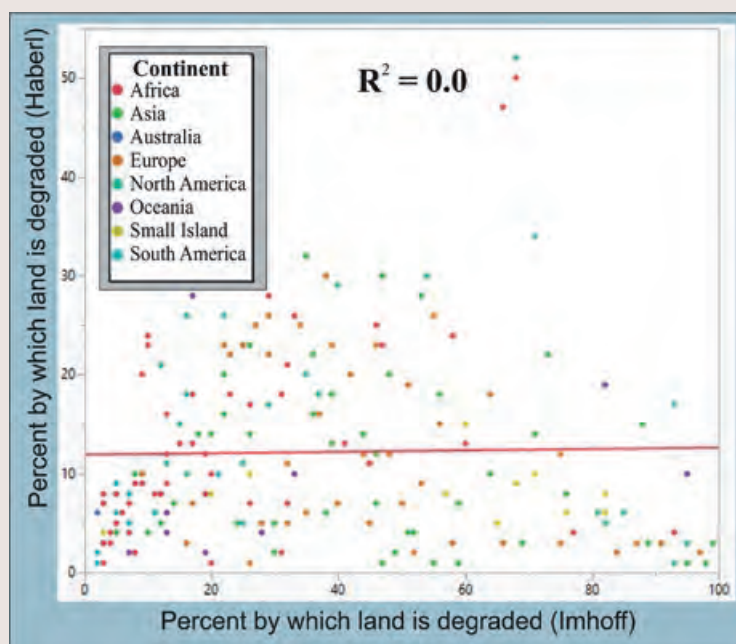


FIGURE 3A.9

Scatterplot of percentage of land degraded for 208 nations



11.5 Pg or 20 per cent of NPP). The Haberl estimate is significantly higher than the Imhoff estimate³, yet when incorporated into these proxy measures of land degradation, the Haberl representation resulted in a lower global degradation rate of 10 per cent, whereas the Imhoff representation was higher at 20 per cent.

Although they are both a reasonable and useful measure of land degradation, these representations of land degradation do not measure the same thing. The Haberl measure is simply the percentage of potential NPP that is actually taking place (e.g., Actual NPP/Potential NPP), which is representative of the fundamental efficiency of an ecosystem from the perspective of energy transformation via photosynthesis. The Imhoff representation is derived from an allocation of harvest processing and efficiency multipliers applied to national level FAO data from seven categories (vegetal foods, meat, milk, eggs, wood, paper, and fibre) and spatially allocated to a global representation of the population distribution. The Haberl representation is the most valid 'map' of land degradation in terms of spatial patterns; however, the Imhoff representation augments this assessment from the perspective of separating production from consumption. A country that imports food is contributing to land degradation in the agricultural areas of the countries it imports food from.

These representations of land degradation are nonetheless relevant to our understanding of the economics of land degradation. Agricultural lands provide a significant output of ecosystem services not accounted for if only dollar values of agricultural products are included (roughly USD 1.7 trillion/yr, or 2.8 per cent of the global annual GDP). The simplifying assumption was made here that these representations of land degradation can be used as linear factors that reduce ecosystem function and consequently the dollar value of the ecosystem services provided that are not part of agricultural product markets. This approach produces an estimate of lost ecosystem services that result from land degradation of USD 6.3 trillion/yr (Haberl representation) and USD 15.2 trillion/yr (Imhoff representation). The spatial patterns of the Haberl representation are most characteristic of actual land degradation resulting from agriculture and forestry. However, the magnitude of this

damage may be better represented by the Imhoff data for several reasons:

- 1) the Imhoff estimates are likely low because they do not include components of NPP lost due to land transformation;
- 2) the Imhoff measures are closer to other estimates of HANPP produced by Vitousek *et al.* (1986)¹⁶ and Rojstaczer *et al.* (2001)¹⁷;
- 3) neither approach captures aspects of land degradation associated with climate change (e.g. melting glaciers that might ultimately disappear and impact land productivity in their watershed), and;
- 4) other ongoing forms of land degradation are not being accounted for (e.g., the potential extinction of pollinating species that are another serious manifestation of land degradation).

How species extinction interacts with land degradation, which in turn interacts with biogeochemical cycles, are questions raised with respect to 'planetary boundaries'²⁷.

The earth is a beautiful, complex, and awe-inspiring chunk of natural (and other types of) capital that annually generates ecosystem services valued at more than twice the size of the world's global GDP. In 1997, authors estimated the value of these ecosystem services to be USD 33 trillion/year¹. This estimate of the global value of the world's ecosystem services was updated to a value of USD 145 trillion/yr in 2014² based on the assumption that the world's land surfaces and associated ecosystems were all functioning at 100 per cent, given the land cover distribution of the earth in 1997. Sadly, the world's land surfaces and associated ecosystems do not have the same distribution they had in 1997 (e.g., roughly half the world's coral reefs are gone) nor are all these ecosystems functioning at 100 per cent. Changes in land cover that have occurred in the last 15 years have resulted in a reduced estimate of the total value of the world's ecosystem services to USD 125 trillion/yr. This represents a loss of roughly USD 20 trillion annually due to land cover change alone. ESV has also been lost as a function of reduced or impaired ecological function. In this chapter, authors prepared a simplified representation of land degradation as a proxy measure of impaired or reduced ecological function to make an estimate of the reduced value



of ecosystem services caused by land degradation using a very simplified average benefits transfer approach. Resulting estimates based on two proxy measures of land degradation are USD 6.3 and 10.6 trillion annually. This suggests that the dollar value of ESV losses from land degradation is roughly 50 to 75 per cent of the dollar value of losses from land cover changes over the last 15 years. These measures of land degradation are mostly associated with changes to agricultural lands around the world. The lower estimate of lost ESV of USD 6.3 trillion/yr is more than five times larger than the entire value of agriculture in the market economy. The ecological economics of land degradation thus indicates that the economics of land degradation is about a lot more than agriculture, and supports the emphasis of the ELD Initiative on total economic valuation inclusive of all land and land-based ecosystem services.

References

- 1 Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., & van den Belt, M. (1997). The value of the world's ecosystem services and natural capital. *Nature*, *387*(6630): 253–260.
- 2 Costanza, R., de Groot, R., Sutton, P., van der Ploeg, S., Anderson, S., Kubiszewski, I., Farber, S., & Turner, R.K. (2014). Changes in the global value of ecosystem services. *Global Environmental Change*, *26*: 152–158.
- 3 Haberl, H., Erb, K.H., Krausmann, F., Gaube, V., Bondeau, A., Plutzer, C., Gingrich, S., Lucht, W., & Fischer-Kowalski, M. (2007). Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. *PNAS*, *104*(31): 12942–12947.
- 4 Bateman, I.J., Harwood, A.R., Mace, G.M., Watson, R.T., Abson, D.J., Andrews, B., Binner, A., Crowe, A., Day, B.H., Dugdale, S., Fezzi, C., Foden, J., Hadley, D., Haines-Young, R., Hulme, M., Kontoleon, A., Lovett, A.A., Munday, P., Pascual, U., Paterson, J., Perino, G., Sen, A., Siriwardena, G., van Soest, D., & Termansen, M. (2013). Bringing ecosystem services into economic decision-making: Land use in the United Kingdom. *Science*, *341*(6141): 45–50.
- 5 TruCost. (2013). *Natural Capital at risk: The top 100 externalities of business*. London, U.K.: TEEB for Business Coalition.
- 6 von Braun, J., Gerber, N., Mirzabaev, A., & Nkonya, E. (2013). *The economics of land degradation*. ZEF Working Paper Series, Working paper 109. Bonn, Germany: University of Bonn.
- 7 ELD Initiative. (2013). *The rewards of investing in sustainable land management*. Scientific Interim Report for the Economics of Land Degradation Initiative: A global strategy for sustainable land management. Available at: www.eld-initiative.org.
- 8 Intergovernmental Panel on Climate Change (IPCC). (2007). *IPCC Fourth Assessment Report (AR4)*. Cambridge, U.K.: Intergovernmental Panel on Climate Change.
- 9 Foley, J., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockstrom, J., Sheehan, J., Siebert, S., Tilman, D., & Zaks, D.P.M. (2011). Solutions for a cultivated planet. *Nature*, *478*: 337–342.
- 10 Association of Chartered Certified Accountants (ACCA), Fauna & Flora International (FFI) & KPMG. (2012). *Is natural capital a material issue? An evaluation of the relevance of biodiversity and ecosystem services to accountancy professionals and the private sector*. Retrieved on [2015, 15/07] from [www.accaglobal.com/content/dam/accaglobal/PDF-technical/environmental-publications/natural-capital.pdf].
- 11 Farley, J., & Costanza, R. (2002). Envisioning shared goals for humanity: A detailed, shared vision of a sustainable and desirable USA in 2100. *Ecological Economics*, *43*: 245–259.
- 12 Costanza, R., Mitsch, W., & Day, J.W. (2006). A new vision for New Orleans and the Mississippi delta: applying ecological economics and ecological engineering. *Frontiers in Ecology and the Environment*, *4*(9): 465–472.
- 13 Jarchow, M.E., Kubiszewski, I., Larsen, G., Zdorkowski, G., Costanza, R., Gailans, S.R., Ohde, N., Dietzel, R., Kaplan, S., Neal, J., Petrehn, M.R., Gunther, T., D'Adamo, S.N., McCann, N., Larson, A., Damery, P., Gross, L., Merriman, M., Post, J., Sheradin, M., & Liebman, M. (2012). The future of agriculture and society in Iowa: four scenarios. *International Journal of Agricultural Sustainability*, *10*: 76–92.
- 14 Costanza, R., Alperovitz, .G, Daly, H., Farley, J., Franco, C., Jackson, T., Kubiszewski, I., Schor, J., & Victor, J. (2013). *Building a sustainable and desirable economy-in-society-in-nature*. Canberra, Australia: Australia National University E-Press.
- 15 Gibbs, H.K., & Salmon, J.M. (2015). Mapping the world's degraded lands. *Applied Geography*, *57*: 12–21.
- 16 Vitousek, P. M., Ehrlich, P., Ehrlich, A., & Matson, P.M. (1986). Human appropriation of the products of photosynthesis. *BioScience*, *36*: 368–373.

- 17** Rojstaczer, S., Sterling, S.M., & Moore, N.J. (2001). Human appropriation of photosynthesis products. *Science*, *294*: 2549–2552.
- 18** Bai, Z.G., Dent, D.L., Olsson, L., & Schapeman, M.E. (2008). Proxy global assessment of land degradation. *Soil use and management*, *24*(3): 223–234.
- 19** Imhoff, M.L., Bounoua, L., Ricketts, T., Loucks, C., Hariss, R., & Lawrence, W.T. (2004). Global patterns in human consumption of net primary production. *Nature*, *429*: 870–873.
- 20** Cramer, W., Kicklighter, D.W., Bondeau, A., Moore, B., Churkina, G., Nemry, B., Ruimy, A., Schloss, A.L., & the participants of the Potsdam NPP Model Incomparision. (1999). Comparing global models of terrestrial primary productivity (NPP): Overview and key results. *Global Change Biology*, *5*(S1): 1–15.
- 21** Potter, C.S., Randerson, J., Field, C., Matson, P.A., Vitousek, P., Mooney, H.A., & Klooster, S.A. (1993). Terrestrial ecosystem production: a process model based on global satellite and surface data. *Global Biogeochemical Cycles*, *7*: 811–841.
- 22** Imhoff, M.L., & Bounoua, L. (2006). Exploring global patterns of net primary production carbon supply and demand using satellite observations and statistical data. *Journal of Geophysical Research*, *11*(D22).
- 23** Gerten, D., Schaphoff, S., Haberland, U., Lucht, W., & Sitch, S. (2004). Terrestrial vegetation and water balance – hydrological evaluation of a dynamic global vegetation model. *Journal of Hydrology*, *286*: 249–270.
- 24** Sitch, S., Smith, B., Prentice, I.C., Arneth, A., Bondeau, A., Cramer, W., Kamplan, J.O., Levis, S., Lucht, W., Sykes, M.T., Thonicke, K., & Venevsky, S. (2003). Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. *Global Change Biology*, *9*: 161–185.
- 25** Wackernagel, M., Schulz, N.B., Deumling, D., Linares, A.C., Jenkins, M., Kapos, V., Monfreda, C., Lohll, J., Myers, N., Norgaard, R., & Randers, J. (2002). Tracking the ecological overshoot of the human economy. *PNAS*, *99*: 9266–9271.
- 26** Sutton, P.C., Anderson, S.J., Tuttle, B.T., & Morse, L. (2012). The real wealth of nations: Mapping and monetizing the human ecological footprint. *Ecological Indicators*, *16*: 11–22.
- 27** Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E.F., Lenton, T. M., & Scheffer, M. (2009). A safe operating space for humanity. *Nature*, *461*(7263): 472–475.