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REVIEW PAPER

The influence of temporal variation on relationships between ecosystem services

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Abstract A growing literature aims to identify areas of congruence in the provision of multiple ecosystem goods and services. However, little attention has been paid to the effect that temporal variation in the provision of such services may have on understanding of these relationships. Due to a lack of temporally and spatially replicated monitoring surveys, such relationships are often assessed using data from disparate time periods. Utilising temporally replicated data for indices of freshwater quality and agricultural production we demonstrate that through time the biophysical values of ecosystem services may vary in a spatially non-uniform way. This can lead to differing conclusions being reached about the strength of relationships between services, which in turn has implications for the prioritisation of areas for management of multiple services. We present this first analysis to illustrate the effect that the use of such temporally disparate datasets may have, and to

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highlight the need for further research to assess under what circumstances temporal variation of this sort will have the greatest impact.

Keywords Ecosystem services · Temporal variation · Freshwater · Spatial congruence · Agriculture

Introduction

There is a growing understanding of the benefits that humans derive from ecosystems (Millennium Ecosystem Assessment 2005; TEEB 2010). A rapidly expanding literature seeks to quantify the spatial distribution of ecosystem goods and services (e.g. Eade and Moran 1996; Sutton and Costanza 2002; Chan et al. 2006; Turner et al. 2007; Naidoo et al. 2008; Anderson et al. 2009; Luck et al. 2009; Raymond et al. 2009; Raudsepp-Hearne et al. 2010), often with the objective of identifying areas of high importance for multiple benefits (e.g. Chan et al. 2006; Anderson et al. 2009).

As well as varying spatially, the provision of ecosystem goods and services can vary temporally due both to natural changes in ecosystems and/or those induced by human activity (Nicholson et al. 2009). For example, significant changes in the provision of ecosystem goods and services have occurred in Europe in the last 50 years across broad habitat types (Harrison et al. 2010), while land use change coupled with climate change may have contributed to loss of carbon from soils in the UK (Bellamy et al. 2005; Smith et al. 2007). Similarly, land use changes alone, such as large-scale urbanization (e.g. Tianhong et al. 2010) or deforestation (e.g. Martínez et al. 2009) can lead to dramatic reductions in supplies of ecosystem goods and services. Separate from these biophysical changes the economic values of ecosystem services may also change over time as a consequence of, for example, the reduction of a particular service increasing the value of that which remains (Kreuter et al. 2001) or a service becoming more highly valued as understanding of its importance increases (Farber et al. 2002).

Despite this temporal variability, the limited availability of data on the distribution of ecosystem services often forces researchers to combine temporally disjunct datasets to describe spatial patterns and identify areas with high provision of multiple services. A review of the literature (Table 1) shows that datasets collected over an average time period of 17.25 years have been combined in studies mapping the distribution of multiple ecosystem services over large spatial scales. While various authors have examined the possible effects of land cover changes on ecosystem services (Kreuter et al. 2001; Zongming et al. 2005; Martínez et al. 2009; Tianhong et al. 2010) changes are assumed to be exclusively due to variation in land cover and not temporal variation in the biophysical or economic value of the ecosystem services.

It is difficult to assess the implications of these temporal mismatches in data for the very reason that they occur, namely that there are few large scale spatially explicit and temporally replicated datasets available. Here, we provide a first analysis of the implications of temporal mismatches in data on inferences from ecosystem service mapping exercises using datasets from 1995 and 2000 that provide temporally replicated measures of services associated with river health and agricultural production. Indices of freshwater quality and biodiversity in river systems in England and Wales provide information on ‘biophysical changes’ in ecosystem goods and services. By contrast, our datasets on the spatial distribution of the economic values of agricultural production from 1995 and 2000 represent changes in ecosystem service values brought about principally by changing market prices.

Table 1 Range of dates used for assessment of ecosystem services in previous studies in which multiple services were mapped and where dates for mapping data could be obtained

Study	Range of data sources	Ecosystem Service	Temporal data used
Eade and Moran (1996)	1977–1992	Non timber products	Valuation for 1989
		Medicinal plants	Valuation for 1992
		Carbon storage	Model and valuation based on 1977 and 1990
		Existence	Valuation for 1991
Chan et al. (2006)	1996–2003	Forage production	Modelled based on data from 2003
		Recreation	Modelled based on data from 2000 to 2002
		Water provision	Modelled based on data spanning 1996–2000
Ingraham and Foster (2008)	1978–2002	Disturbance prevention	Valuation from studies conducted in 1981, 1987, 1997, 2001
		Freshwater regulation and supply	Valuation from studies conducted in 1997
		Nutrient regulation and waste assimilation	Valuation from studies conducted in 1995, 1981, 2000
		Habitat provision	Valuation from studies conducted in 1978, 1987, 1989, 1994, 2000, 2001, 2003
		Carbon sequestration	Valuation from studies conducted in 2002
Naidoo et al. (2008)	1961–2000	Carbon sequestration	Modelled value for the 1980s
		Carbon storage	Estimated as value in 2000
		Grassland production of livestock	Modelled data for 2000
		Water provision	30 year average 1961–1990
Willemen et al. (2008)	2000–2005	Arable production	Modelled from data sources from 2000, 2003, 2004, 2005
		Plant habitat	Modelled based on data sources from 1990, 2000, 2003, 2002, 2004
Anderson et al. (2009)	1981–2005	Biodiversity	Data 1981–1991, 2008
		Carbon	Data for model based on 1984 and 1990 values
		Agricultural production	Modelled based on 2007/2008 values
		Recreation	Modelled based on 2005 values
Raudsepp-Hearne et al. (2010)	1988–2007	Agricultural production (various)	2001 agricultural census
		Drinking water	Average values from data collected 2001
		Deer hunting	Data from 1999 database
		Tourism	Database accessed 2007
		Nature appreciation	Mapped observation of rare species 1988–2007
		Summer cottages	2007 tax valuation database
		Forest recreation	Database accessed 2005
		Carbon sequestration	Modelled data for 2001
		Soil phosphorous retention	Average values from data collected 1995–2001
		Soil organic matter	Average values from data collected 1995–2001

Table 1 continued

Study	Range of data sources	Ecosystem Service	Temporal data used
O'Farrell et al. (2011)	2002–2007	Grazing services	Agricultural census from 2002 plus modelled values
		Tourism	Range of previous studies from 2003 to 2007
		Water	Data from survey published 2006

We examined (i) how the provision and spatial distributions of individual ecosystem services changes through time; (ii) how temporal variation in individual services leads to changing patterns of spatial covariation between services; and (iii) the possible consequences of combining temporally disjunct datasets when evaluating spatial covariation between ecosystem services.

Materials and methods

Data sources

Freshwater quality

We used monitoring data collected as part of the Environment Agency's General Quality Assessment programme for rivers in England and Wales to calculate freshwater quality in both 1995 and 2000. These were mapped at a 10 × 10 km grid resolution to allow comparisons with agricultural production. Freshwater taxa are collected using a standard methodology that involves a three minute kick sample and one minute hand search, full details of which are provided in Murray-Bligh et al. (1997). Results are collated into a central database (BIOSYS), from which we extracted sites that were sampled in both 1995 and 2000. We compare two measures of freshwater quality:

(i) Average Score Per Taxon (ASPT)—this measure is based on the sensitivity of taxa within the community to organic pollution. Each taxon is assigned a score from one to ten, with ten representing the most sensitive. These values are summarized for the community within the sample and then this figure is divided by the number of taxa present. This removes bias associated with differing levels of taxonomic richness within the river continuum. Within each 10 × 10 km grid cell we calculated an average of the ASPT value across all sites. ASPT provides an indication of the health of the aquatic community associated with the provision of supporting services such as decomposition and nutrient cycling (Covich et al. 1999; Baron et al. 2002) that underpin the provision of many other services.

(ii) Freshwater biodiversity (taxon richness)—the number of families of freshwater taxa present within each 10 × 10 km grid cell was calculated based on the taxon's recorded presence in any sampling point within each cell. We used family level data as this was the highest taxonomic level recorded for all taxa; family level data are likely to be indicative of patterns of species richness (Wright et al., 1998). While sampling intensity varied between grid cells, there was no evidence that this biased the measure, with a low correlation between the number of samples per cell and taxon richness (Spearman's Rho = 0.096). Freshwater biodiversity provides resilience and adaptability within the system reducing the variability of the provision of some services (e.g. Schindler et al. 2010) and is thought to play a key role in supporting all ecosystem services (Balvanera et al. 2006; UNEP 2009).

Agricultural production

We defined agricultural production as the gross margin of major crops and livestock [gross margin = value of output—variable costs, with subsidy payments removed], across England during 1995 and 2000 at 10 × 10 km grid cell resolution, following the methods of Eigenbrod et al. (2009). The gross margins were calculated using data from the Farm Management Handbook for the two time periods (Chadwick, 1995; Beaton et al., 2000) and values standardised to 2000 prices using the Harmonised Index of Consumer Prices. Historical data for crop and livestock production were obtained from the June Agricultural Survey (https://statistics.defra.gov.uk/esg/junesurvey/june_survey.htm) at the ward level (mean area 1912 ha) for 1995 and 2000.

Analysis

We used Spearman's rank correlations to compare the spatial distribution of our indicators of ecosystem services from all possible combinations of time periods and used a bootstrap procedure (10,000 iterations: R 'boot' package; (Canty and Ripley 2009) to calculate 84% confidence intervals for the correlations, as non-overlapping 84% confidence intervals indicate significant ($\alpha = 0.05$) differences between the mean values (Julious 2004) of two bootstrapped rank correlations. Three comparisons of indicators are possible (ASPT with taxon richness, ASPT with agricultural production, taxon richness with agricultural production) and three temporal combinations (1995–1995, 2000–2000, 1995–2000). All statistical analyses were carried out in R 2.9 (R Development Core Team 2009), and all GIS analyses in ArcGIS 9.2 (ESRI, Redlands, California, USA).

Results

The overall average percentage changes in freshwater quality for England and Wales between 1995 and 2000 were very low (1.72% increase in ASPT and -2.85% decrease in taxon richness). However, spatially taxon richness showed marked changes between regions not exhibited by ASPT (Fig. 1) This is reflected in differences in between-year Spearman correlation for taxon richness (Rho = 0.73) compared with ASPT (Rho = 0.95).

There was a significant effect of year of sampling for the spatial relationship between taxon richness and ASPT driven by between-year changes in taxon richness (Table 2). Using ASPT values from 1995 and taxon richness values from 1995 resulted in a correlation coefficient of Rho = 0.6. Using the 2000 data for each variable resulted in a much lower correlation coefficient of Rho = 0.38. This change in taxon richness leads to a strong effect of temporally disjunct datasets. Utilizing taxon richness from 1995 and ASPT from 2000 results in a stronger relationship (Rho = 0.56) than in the reverse situation (Rho = 0.35).

Whilst there was a large (30.4%) overall decrease in the value of agricultural production in England between 1995 and 2000 there was little change in the relative importance of different regions in contributing to this overall total (Fig. 1) (Rho = 0.97). Results from

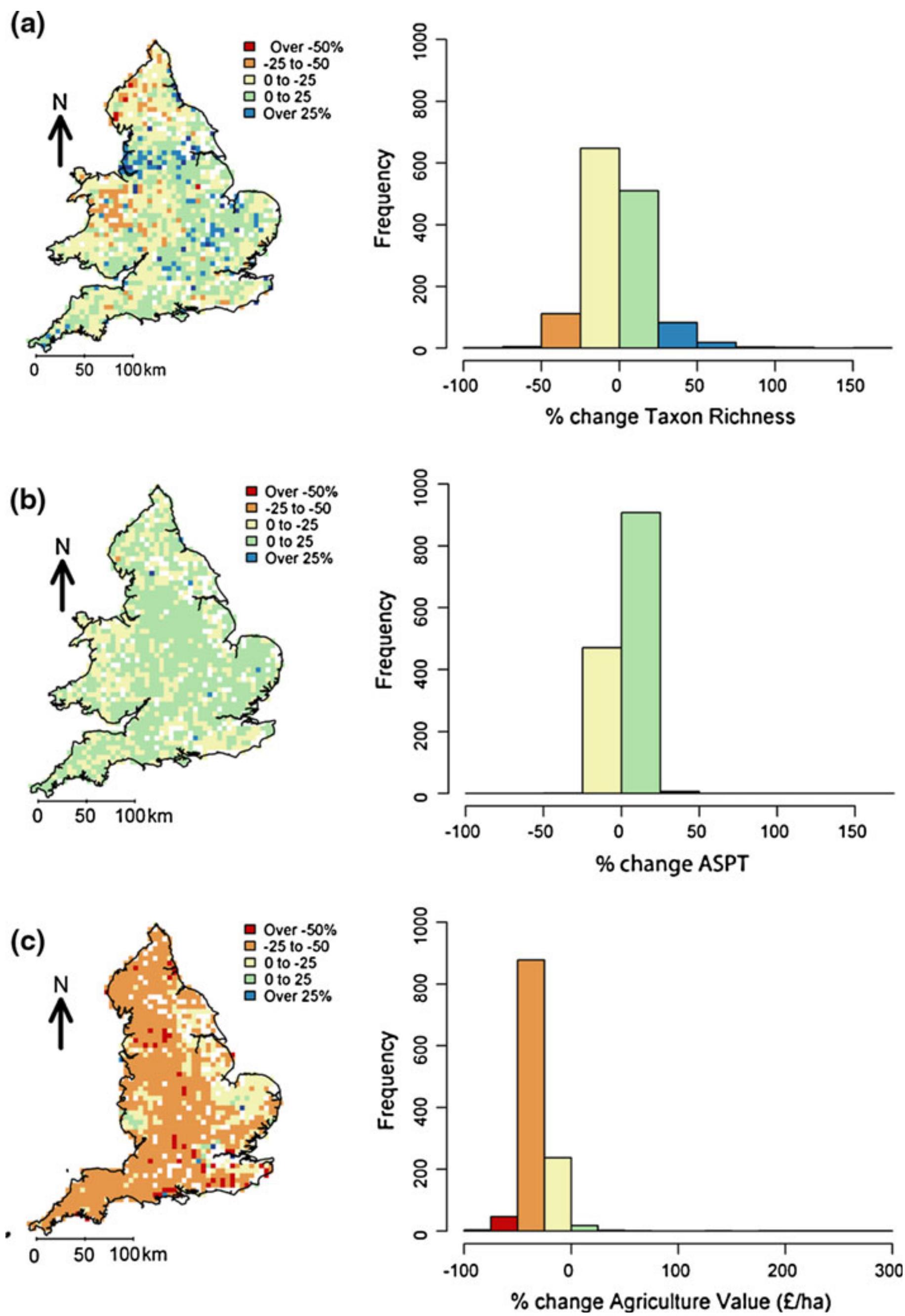

Fig. 1 Percentage change in ecosystem service provision between 1995 and 2000 for **a** freshwater taxon richness, **b** ASPT and **c** for agriculture production (£/ha). Histograms show the distribution in the percentage change for each service

Table 2 The effect of year of sampling on Spearman's rank correlations (with bootstrapped upper and lower 84% confidence intervals) between freshwater taxon richness, ASPT and agricultural production

Comparison	Years	Spearman's rho	Lower 84% CI	Upper 84% CI
Taxon richness vs. ASPT	1995–1995	0.6	0.57	0.62
	2000–2000	0.38	0.34	0.42
	1995–2000	0.56	0.53	0.59
	2000–1995	0.35	0.31	0.38
Taxon richness vs. agricultural production	1995–1995	0.18	0.14	0.22
	2000–2000	0.15	0.11	0.19
	1995–2000	0.17	0.13	0.21
	2000–1995	0.16	0.12	0.20
ASPT vs. agricultural production	1995–1995	0.04	0.00	0.09
	2000–2000	0.00	−0.04	0.04
	1995–2000	0	−0.04	0.04
	2000–1995	0.05	0.00	0.09

the other comparisons provided no evidence of an effect of temporal variation either within or between years (Table 2).

Discussion

Our results provide an initial analysis of the effect that temporally disjunct data can have on the assessment of ecosystem services. The measure of freshwater biodiversity showed marked changes in the locations that one would identify as experiencing high or low values over the 5-year period. This variation led to changing patterns in the spatial relationship between the two freshwater indices using data from concordant years, and has implications for efforts to identify priority areas for conservation based on the provision of multiple ecosystem services (e.g. Table 1; see review Seppelt et al. 2011) or to evaluate the contribution made by existing conservation measures such as protected areas for safeguarding ecosystem goods and services (e.g. Ingraham and Foster 2008; Eigenbrod et al. 2009).

Patterns of covariation between services will be influenced by spatio-temporal dynamics of both the biophysical processes involved in producing ecosystem services and the socio-economic processes that affect valuation of services. Using temporally disjunct datasets therefore has the potential to influence conclusions about relationships between services. It seems likely that changes in biophysical processes are a common driver of variation in the provision of ecosystem services. Those associated with land-use change are common and represent a major driver (Kreuter et al. 2001; Zongming et al. 2005; Martinez et al. 2009; Tianhong et al. 2010). But such variation can also come about due to intrinsic properties of the systems that make them prone to large fluctuations through time (e.g. Barbier et al. 2008; Koch et al. 2009; sea grasses for wave attenuation), climate change (e.g. Thomas et al. 2004; for biodiversity), or intensive agriculture (e.g. Emmett et al. 2010; loss of soil carbon in cropped land). In addition, valuation estimates of ecosystem services using WTP can also exhibit significant changes through time. Although values remain relatively stable over time periods up to 5 years, over longer periods consistent with the examples provided in Table 1, this stability is lost as preferences evolve (Skourtos et al. 2009).

We chose to quantify ecosystem services in natural units for each service, which meant comparing an economic measure for agricultural production with a biophysical measure for freshwater services. For our results, we do not consider the mixing of biophysical and socioeconomic processes in the agricultural layer presents a problem, because patterns of spatial variation in gross margins are consistent through time (Rho = 0.97), despite large changes in gross margin at any given location between the two time periods. Instead, the spatio-temporal changes that we observe are playing out primarily in the freshwater quality data (specifically taxon richness). An alternative approach would have been to compare just the biophysical elements of agricultural production to our biophysical measures of freshwater services, for example, by using yield based measures of output (e.g. tons of protein or grain). This approach introduces a number of other problems. Without recourse to market prices (as per Naidoo and Iwamura 2007), there is no obvious way to aggregate the diversity of agricultural products into a single metric, and focussing on a single or a small set of agricultural products would lead to large spatial distortions in yield estimates because of regional specialization of agricultural production systems. Yield-based measures also fail to account for whether output is high because the ecosystem itself is productive or because the farmers are applying large quantities of fertilisers or other inputs. A second alternative approach would be to transform the purely biophysical measures used in the current study into economic units. As freshwater quality is a non-market good, such an approach would have to rely on non-market valuation measures to ascertain people's Willingness to Pay (WTP). Whilst it would be extremely interesting to repeat our study design using temporally replicated, spatially disaggregated layers of WTP for freshwater quality, a review of the available data resource of WTP estimates for freshwater quality in England and Wales suggests that sufficient data are not available for such an analysis. The main problems lie in (1) the small number of studies relative to the biophysical variation in river ecosystems; (2) the studies that do exist tend to consider different endpoints (some studies focus on increasing amounts of flow; other on increasing water quality for wildlife or 'ecological improvement'; others on obtaining water quality suitable for swimming); and (3) units in existing studies are inconsistent (i.e. WTP per km of river versus a single river versus the entire UK freshwater supply).

Our study highlights the benefits of spatially and temporally replicated monitoring surveys of ecosystem services that employ consistent reporting metrics and sampling methodologies through time. Future studies mapping the distributions of multiple ecosystem services should aim to minimize the range of dates during which the data used to assemble the ecosystem services layers were collected. If some temporal mismatches are unavoidable, then some discussion is required of the degree of temporal change, of its spatial distribution, perhaps drawn from smaller scale replicated studies, and of its potential effects on inferences drawn.

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References

Anderson BJ, Armsworth PR, Eigenbrod F, Thomas CD, Gillings S, Heinemeyer A, Roy DB, Gaston KJ (2009) Spatial covariance between biodiversity and other ecosystem service priorities. J Appl Ecol 46:888–896

Balvanera P, Pfisterer AB, Buchmann N, He J-S, Nakashizuka T, Raffaelli D, Schmid B (2006) Quantifying the evidence for biodiversity effects on ecosystem functioning and services. Ecol Lett 9:1146–1156
Barbier EB, Koch EW, Silliman BR, Hacker SD, Wolanski E, Primavera J, Granek EF, Polasky S, Aswani S, Cramer LA, Stoms DM, Kennedy CJ, Bael D, Kappel CV, Perillo GME, Reed DJ (2008) Coastal ecosystem-based management with nonlinear ecological functions and values. Science 319:321–323
Baron JS, Poff NL, Angermeier PL, Dahm CN, Gleick PH, Hairston NG, Jackson RB, Johnston CA, Richter RD, Steinman AD (2002) Meeting ecological and societal needs for freshwater. Ecol Appl 12:1247–1260
Beaton C, Catto J, Kerr G (2000) The farm management handbook 2000/2001. Scottish Agricultural College, Edinburgh, UK
Bellamy PH, Loveland PJ, Bradley RI, Lark RM, Kirk GJD (2005) Carbon losses from all soils across England and Wales 1978–2003. Nature 437:245–248
Canty A, Ripley B (2009) Boot: bootstrap R (S-Plus) functions. R package version 1.2-41
Chadwick L (1995) The farm management handbook 1995/1996. Scottish Agricultural College, Edinburgh, UK
Chan KMA, Shaw MR, Cameron DR, Underwood EC, Daily GC (2006) Conservation planning for ecosystem services. PLoS Biol 4:2138–2152
Covich AP, Palmer MA, Crow TA (1999) The role of benthic invertebrate species in freshwater ecosystems: zoobenthic species influence energy flows and nutrient cycling. Bioscience 49(2):119–127
Eade JDO, Moran D (1996) Spatial economic valuation: benefits transfer using geographical information systems. J Environ Manag 48:97–110
Eigenbrod F, Anderson BJ, Armsworth PR, Heinemeyer A, Jackson SE, Parnell M, Thomas CD, Gaston KJ (2009) Ecosystem service benefits of contrasting conservation strategies in a human-dominated region. Proc R Soc B 276:2903–2911
Emmett BA, Reynolds B, Chamberlain PM, Rowe E, Spurgeon D, Brittain SA, Frogbrook Z, Hughes S, Lawlor AJ, Poskitt J, Potter E, Robinson DA, Scott A, Wood C, Woods C (2010) Countryside survey—soils report from 2007. Centre for Ecology and Hydrology
Farber SC, Costanza R, Wilson MA (2002) Economic and ecological concepts for valuing ecosystem services. Ecol Econ 41:375–392
Harrison PA, Vandewalle M, Sykes MT, Berry PM, Bugter R, de Bello F, Feld CD, Granndin U, Harrington R, Haslett JR, Jongman RHG, Luck GW, Da Silve PM, Moora M, Settele J, Sousa JP, Zobel M (2010) Identifying and prioritising services in European terrestrial and freshwater ecosystems. Biodivers Conserv 19:2791–2821
Ingraham MW, Foster SG (2008) The value of ecosystem services provided by the US National Wildlife Refuge System in the contiguous US. Ecol Econ 67:608–618
Julious SA (2004) Using confidence intervals around individual means to assess statistical significance between two means. Pharma Stat 3:217–222
Koch EW, Barbier EB, Silliman BR, Reed DJ, Perillo GME, Hacker SD, Granek EF, Primavera JH, Muthiga N, Polasky S, Halpern BS, Kennedy CJ, Kappel CV, Wolanski E (2009) Non-linearity in ecosystem services: temporal and spatial variability in coastal protection. Front Ecol Environ 7:29–37
Kreuter UP, Harris HG, Matlock MD, Lacey RE (2001) Change in ecosystem service values in the San Antonio area, Texas. Ecol Econ 39:333–346
Luck GW, Chan KMA, Fay JP (2009) Protecting ecosystem services and biodiversity in the world's watersheds. Conserv Lett 2:179–188
Martínez ML, Pérez-Maqueo O, Vázquez G, Castillo-Campos G, García-Franco J, Mehltreter K, Equihua M, Landgrave R Effects of land use change on biodiversity and ecosystem services in tropical montane cloud forests of Mexico. For Ecol Manag (in press) Corrected Proof
Millennium Ecosystem Assessment (2005) Ecosystems and human well-being: synthesis. Island Press, Washington DC
Murray-Bligh JAD, Furze MT, Jones FH, Gunn RJM, Dines RA, Wright JF (1997) Procedure for collecting and analysing macro-invertebrate samples for RIVPACS. Institute of Freshwater Ecology and Environment Agency
Naidoo R, Iwamura T (2007) Global-scale mapping of economic benefits from agricultural lands: implications for conservation priorities. Biol Conserv 140:40–49
Naidoo R, Balmford A, Costanza R, Fisher B, Green RE, Lehner B, Malcolm TR, Ricketts TH (2008). Global mapping of ecosystem services and conservation priorities. Proc Natl Acad Sci USA 105:9495–9500
Nicholson E, Mace GM, Armsworth PR, Atkinson G, Buckle S, Clements T, Ewers RM, Fa JE, Gardner TA, Gibbons J, Grenyer R, Metcalfe R, Mourato S, Muuls M, Osborn D, Reuman DC, Watson C,

Milner-Gulland EJ (2009) Priority research areas for ecosystem services in a changing world. J Appl Ecol 46:1139–1144
O'Farrell PJ, De Lange WJ, Le Maitre DC, Reyers B, Blignaut JN, Milton SJ, Atkinson D, Egoh B, Maherry A, Colvin C (2011) The possibilities and pitfalls presented by a pragmatic approach to ecosystem service valuation in an arid biodiversity hotspot. J Arid Environ 75:612–623
R Development Core Team (2009) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria
Raudsepp-Hearne C, Peterson GD, Bennett EM (2010) Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. Proc Nat Acad Sci 107:5242–5247
Raymond CM, Bryan BA, MacDonald DH, Cast A, Strathearn S, Grandgirard A, Kalivas T (2009) Mapping community values for natural capital and ecosystem services. Ecol Econ 68:1301–1315
Schindler DE, Hilborn R, Chasco B, Boatright CP, Quinn TP, Rogers LA, Webster MS (2010) Population diversity and the portfolio effect in an exploited species. Nature 465:609–612
Seppelt R, Dormann CF, Eppink FV, Lautenbach S, Schmidt S (2011) A quantitative review of ecosystem service studies: approaches, shortcomings and the road ahead. J Appl Ecol 48(3):630–636
Skourtos M, Kontogianni A, Harrison PA (2009) Reviewing the dynamics of economic values and preferences for ecosystem goods and services. Biodivers Conserv 19:2855–2872
Smith P, Chapman SJ, Scott WA, Black HIJ, Wattenbach M, Milne R, Campbell CD, Lilly A, Ostle N, Levy PE, Lumsdon DG, Millard P, Towers W, Zaehle S, Smith JU (2007) Climate change cannot be entirely responsible for soil carbon loss observed in England and Wales, 1978–2003. Glob Change Biol 13(12):1365–2486
Sutton PC, Costanza R (2002) Global estimates of market and non-market values derived from nighttime satellite imagery, land cover, and ecosystem service valuation. Ecol Econ 41:509–527
TEEB (2010) Mainstreaming the economics of nature: a synthesis of the approach, conclusions and recommendations of TEEB. The Economics of Ecosystems and Biodiversity (TEEB)
Thomas JA, Telfer MG, Roy DB, Preston CD, Greenwood JJD, Asher J, Fox R, Clarke RT, Lawton JH (2004) Comparative losses of British butterflies, birds, and plants and the global extinction crisis. Science 303:1879–1881
Tianhong L, Wenkai L, Zhenghan Q (2010) Variations in ecosystem service value in response to land use changes in Shenzhen. Ecol Econ 69(7):1427–1435
Turner WR, Brandon K, Brooks TM, Costanza R, da Fonseca GAB, Portela R (2007) Global conservation of biodiversity and ecosystem services. Bioscience 57:868–873
UNEP (2009) Water security and ecosystem services. United Nations Environment Program, Nairobi, Kenya
Willemen L, Verburg PH, Hein L, van Mensvoort MEF (2008) Spatial characterization of landscape functions. Landsc Urb Plan 88:34–43
Wright JF, Furse MT, Moss D (1998) River classification using invertebrates: RIVPACS applications. Aquat Conserv Mar Freshw Ecosyst 8:617–631
Zongming W, Bai Z, Shuqing Z, Kaishan S, Hongtao D (2005) Estimates of loss in ecosystem service values of Songnen plain from 1980 to 2000. J Geograph Sci 15:80–86