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Identifying trade-offs between ecosystem services, land use, and biodiversity: a plea for combining scenario analysis and optimization on different spatial scales

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Research on mitigating land use conflicts is characterized by a variety of projects from the global to various sub-global scales. These projects are aiming at disentangling feedbacks within changing socio-environmental systems to identify strategies for sustainable resource use. Our review shows that any global analysis benefits from systematic synthesis of sub-global research from various scales, while sub-global investigations require embedding in global scenarios. There is an urgent need for improved methods to identify trade-offs at all scales as scenario analysis frequently results in a discrete set of options. We argue that the use of optimization algorithms including Pareto-frontiers combined with scenario analysis can provide efficient options for sustainable land use from global to sub-global scales.

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Introduction

Land is a limited resource that has to fulfil multiple functions. Sustainable management of landscapes requires reconciling demands for settlements and infrastructure (globally approx. 0.5% of the terrestrial earth surface [1]), production for food and fibre (40%), and maintaining ecosystem functions and protection of species (global protection sites: 11% [2]) and water [3]. Land use strategies require therefore the integration of the oftentimes conflicting demands of society on resources. The objective to be achieved is to fulfil the demands and ensure human well-being without impairing biodiversity and ecosystem functions [4,5••]. The related land use decisions, such as the selection of crop rotations, deforestation or reforestation measures, design of protections sites, among others, take place on multiple scales from hectares to several thousand square kilometres [6].

Various processes have to be considered to develop and implement land use strategies. Early, the multi-functionality of landscapes was identified as a key concept for solving resource use conflicts [7]. Maximization of a single function, for instance productivity, can be expected to feedback negatively on several other ecosystem functions and services with consequences on human well-being. Sustainable land use thus requires an analysis of trade-offs to reconcile requirements and demands, which are measured by environmental, economic and social indicators. Further, ecosystem functions should be maintained on the long-term. The focal point of research occurring at the local, regional or continental scale is the development of land use management solutions, which fit the needs of the involved actors and communities (e.g. stakeholders). Although the situation is in principle similar at the global scale, the lack of institutions for management at a world scale implies a different management situation. The global scale has been the focus of synthesis studies on food provisioning [2] or biodiversity conservation [8], for example. The strong links across the scales need to be considered in the analysis of land use management [9,10].

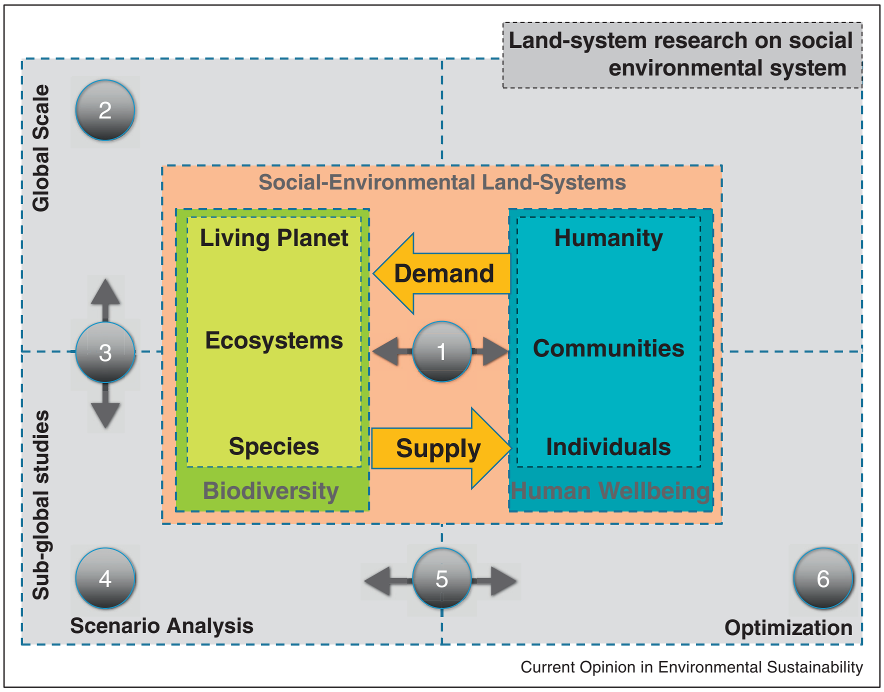
Figure 1 provides a conceptual framework and suggests two complementary lines of thought: (i) the identification of major limiting factors for an improved embedding of sub-global assessments in global scale analysis and vice versa (Figure 1, Labels 2–4), and (ii) the analysis of trade-offs between land use and ecosystem services, as well as among ecosystem services, using a methodology that goes beyond scenario analysis (Figure 1, Labels 4–6).

Synthesising results across scales

Two research topics are key for an analysis across scales: (i) the quantification of off-site effects of regional land management, and (ii) the comparative analysis of regional scale case studies with the quantification of landscape scale processes and trade-offs.

Sub-global studies often do not quantify off-site effects of regional land management, a key element

Figure 1



Conceptual illustration of the review. Identification of land-system as socio-environmental system in the frame of the Millennium Ecosystem Assessment. The organization in space, from local to global analysis, and the application of optimization and scenario analysis are also depicted.

of sustainability [11•,12,13]. These off-site effects become crucial at larger scales as they can lead to sub-optimal solutions at that scale, and can feedback negatively at the local scale (where the initial decisions were taken). For example, land management programmes to protect forests and biodiversity in China have led to an increasing import of timber from countries such as Laos and Cambodia, thereby 'exporting damage' to the ecosystems of these countries [12,13]. Bioenergy decisions made in the EU are likely to have impacts on land systems in Brazil and in Indonesia potentially leading to changes in the climate system which might, in turn, lead to unanticipated consequences for human well-being in Europe [14]. Although it is impossible to involve every potential off-site effect (or trade-off) in a sub-global study at least some bookkeeping should be mandatory: if local/regional land use decisions lead to an increasing or decreasing import of goods and services then this should be monitored and reported. Alternatively, global scale scenarios, which provide information on global exchange of commodities, can be used as constraints or boundary conditions in sub-global analysis [6].

At the global scale, result downscaling to identify priority regions is still lacking for several important indicators. Typically, this leads to general recommendations such as stopping further land conversion, closing the yield gap and the diet gap and improving the distribution of food [2]. However, these studies frequently lack the identification of specific priority or 'hot-spot' regions. Spatially explicit recommendations for conservation actions derived from gap analysis [15], hot-spot regions for crop pollination [16], and the identification of sensitive regions for water provisioning [17] represent exceptions. At a more aggregated level, the characterization of 'anthromes' can form the basis of a map of global human impact [18•].

Comparative analysis of regional case studies allows the derivation of common trends, patterns and relationships. However, the synthesis of regional studies is limited by the fact that the case studies differ significantly in their design, e.g. have different levels of complexity. The synthesis has to be performed either through (i) a qualitative comparison of results of sub-global studies ('story-telling') by systematically describing the most important drivers and results [5••,9], or (ii) a descriptive statistical analyses for identifying common pattern and gaps of information [11•], or finally by (iii) a meta-analysis and hypothesis testing [20•]. Requirements with respect to consistency in common assumptions and common indicators increase from (i) to (iii). Notably, to perform a meta-analysis of sub-global studies consistent global assumptions regarding the structure of the problem and solution are required. This can notably be achieved by referring to the same scenarios [6]. Thus the choice among simple alternatives of land sharing or land sparing (cf. [2]) cannot be optimized in general at the global scale, and is expected to vary for various places and contexts [21]. A second option to identify comparable pattern on a global scale could consist of the identification of syndromes of land management [19•], which would help to identify vulnerable hot-spot areas and support priority setting for further analysis [15].

How to find the best possible options in land management

Scenario analysis is the most frequently used tool for assessing options and characterize possible futures, see Figure 1, Labels 2 and 4. For global land systems, this approach was a core element of several assessments studies such as the Millennium Ecosystem Assessment [21,22], the global environmental outlook GEO4 [23], and various sub-global investigations. As scenarios require providing projections of socio-economic as well as environmental indicators, 'next generation' scenarios acknowledge this by developing scenario data sets on the global scale independently [24].

Sub-global investigations, on the other hand, are driven to a certain degree by assumptions of global scenarios and make use of a 'down-scaling' approach [25–27], for instance for biodiversity on a European scale [28,29] and for biofuel demand in Brazil [30]. Generally, quantified storylines with the respected simulations results at the global scale are mapped to sub-global scale regions. This downscaling is done based on appropriate models, that incorporate the required finer scale specifications. With this approach, sub-global scale scenarios and their storylines can simultaneously consider larger scale and regional constraints in addition to requirements incorporated through stakeholder consultations.

Scenario based impact analysis provides information on the dependency of selected environmental indicators and a specific mix of measures or — for sake of simplicity — invested money for a certain land management, usually by applying an appropriate model or model system [31•], cf. Figure 2, left. However, because of the multifunctionality of landscapes maximizing one ecosystem function or service might reduce others (i.e. trade-offs). This was acknowledged by applying the ecosystem service indicator framework [21,22], which provides an exhaustive characterization of ecosystem properties. Such a common indicator framework [32,33] represents the basis of a comprehensive analysis which identifies unexpected trade-offs. Although case studies on ecosystem services show weaknesses [11•], they provide knowledge about the effect of land use intensity to biodiversity [34,35], and about the role that biodiversity plays for ecosystem services provisioning [36–38]. However, at the global scale the positive relationship between ecosystem services and human well-being is debated [39].

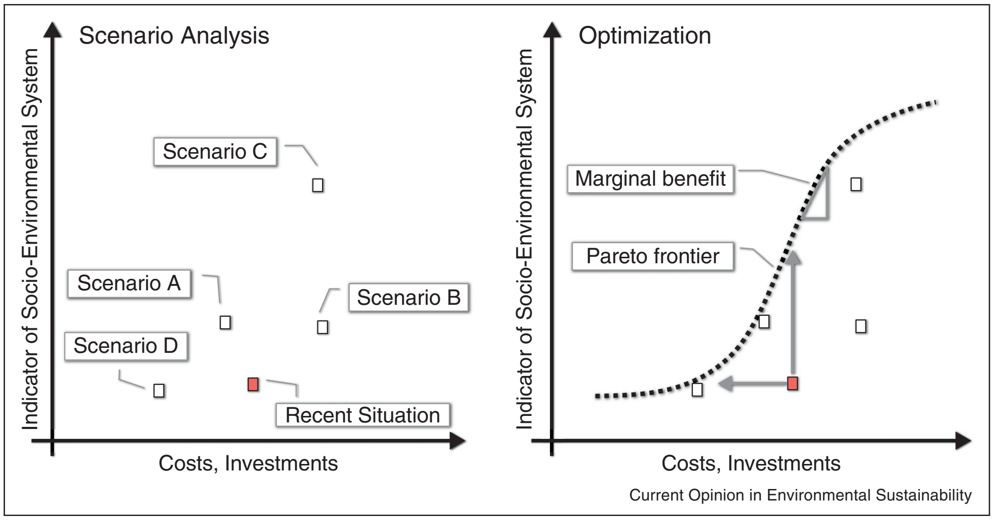
Several case studies used ecosystem service indicators for quantifying trade-offs and synergies in a spatially explicit manner at the landscape scale [40]. These approaches need to fully capture ecosystem functioning and need to go beyond the scenario assumptions. Thus a functional understanding of feedbacks between land use and management is required, Figure 1, Label 6. This can be achieved by linking models with optimization algorithms, which combine the assessment of ecosystem functions and search through the space of possible, spatially explicit, management options. A possible solution of sustainable land management might be located 'between' two distinct scenarios, cf. Figure 2, left.

Optimizing land use patterns with respect to multifunctional use [41–49] provides useful information and solutions to problems beyond the region of study. The analysis offers functional relations, such as possible trade-offs given as the simulated Pareto-frontier. These results also provide the gradient or — as economists denote — the marginal costs/benefits. This is obtained by the (derivative of the) Pareto-frontier as a result of the optimization-based analysis of land management measure, Figure 2, right. In the given application, a Pareto-frontier provides a set of multiple optimum land use management solutions, which all cannot be improved and thus span the possible solution space under all given constraints. This comprises more information than just a limited number of scenarios.

In a simple scenario analysis, the solution found might be sub-optimal with respect to other land management options that have not been studied in the limited set of scenario options. On the other hand, an optimized landscape might not be reachable given the current land system and the existing policy instruments. Thus, whether a point on the Pareto-frontier is accessible and whether current existing political instruments are sufficient to 'navigate' towards accessible points remains an open question. This is where scenarios come into play again.

Indeed, scenarios capture information on underlying storylines and assumptions, and these are mapped to quantitative simulations. Then an analysis, of which assumptions need to be modified to navigate closer to any points of the solution of the optimized land management given by the Pareto-frontier, is performed, Figure 1, Label 5. Modern developments of optimization tools and smart coding of land use models allows a broader application of these approaches. However, their spatial scale is currently focused on at the regional level, Figure 1, Label 6.

Figure 2



Based on a scenario analysis there is only information on distinct relations linking investments or costs with an environmental indicator (left). No functional dependency is available. There might be an optimum or even an area, which is desirable, but not reachable with the given constraints. This can only be identified by the pareto-frontier (right). It shows that even for the most cost-efficient scenarios (A, C) there are even better situations for which none of the considered variables (costs, investments, socio-environmental indicator) can be improved while not decreasing the other. Given the Pareto-frontier the arrows denote possible strategies of improving the socio-environmental indicator without changing investments or costs, or the reduction of costs while maintaining the recent state of the socio-environmental system.

In summary, an application of optimization methods in model-based environmental impact assessment studies can perform two major tasks

(1) It provides the basis for systematic exploratory simulations, e.g. implementation of a systematic search through the space of possible scenarios which define the alternative land management. This can be a static but spatially explicit task of studying trade-offs given by different land use configurations (such as land use structure, intensity, among others) but also within dynamic models that offer possible control strategies and change over time, which reveals tipping-points or threshold in the state-space of the dynamic human-environmental system.
(2) Given specific constraints, optimization can also be used to identify optimum combinations and offer the basis for optimum policy mixes. This, however, requires a sufficient understanding of the decision making process and the feedbacks in the socio-environmental system.

Discussion

We showed that an analysis across scales is key for an in-depth analysis of land use and management assessments. Sub-global assessments can and should be performed under consideration of land use archetypes or syndromes identified at the global scale [50,51•]. Such an analysis benefits from a consistent definition of a scenario framework since this eases comparisons [6], Figure 1, Label 3. This has been implemented in a range of sub-global projects such as sub-global assessments (SGA[a]), the Natural Capital Project[b], the Programme on Ecosystem Change and Society (PECS[c]) of the Sustainable Land Management Programme (GLUES[d]). It provides ground for any meta-analysis and synthesis based on available results of sub-global land management projects, see for instance the effectiveness of ecosystem service based land management [20•]. This could be a key element that helps to define optimization tasks, which seeks for an optimum combination of different policy instruments that aim at sustainable of land management [52].

Recent publications show that systematic variation of input variables, that usually quantify scenarios, provides important and detailed knowledge on trade-offs of certain ecosystem functions and services. If used within an optimization framework, this systematic variation also helps identifying Pareto-frontiers [41,42,44–49]. This

[a] cf. http://www.millenniumassessment.org/en/Multiscale.html and http://www.ecosystemassessments.net.
[b] cf. http://www.naturalcapitalproject.org.
[c] cf. http://www.stockholmresilience.org/21/research/research-programmes/pecs.html.
[d] cf. http://modul-a.nachhaltiges-landmanagement.de/en/scientific-coordination-glues/.

approach shows the limits but also further potential of several ecosystem services of a region. Thus the use of Pareto-frontiers results in more information than provided by scenario analysis. Although, these tasks are computationally far more intensive, the burden can be reduced by the identification of more efficient modelling techniques or computational algorithms. For none of the case studies referenced here, computational effort was a real limitation.

Thus the exploration of trade-offs and optimization at the global scale might be developed in the near future. There are promising developments of global scale ecological models capturing the essentials dynamics of multi-trophic systems. These models might be the foundation of the global-scale optimization [53,54]. It is possible to conduct studies occurring 'in the upper right corner' of Figure 1, which can result in a clearer picture of possible global non-linear patterns, tipping points or limits of recent development. The more information one can obtain from sub-global studies and from global hot-spots, the more specific such a 'global explorative optimization' can be.

Finally, the synthesis of place-based studies and global analysis using simultaneous optimization of several criteria within environmental models can theoretically result in the identification of optimum combination of measures and 'policy mixes' for sustainable land management. In achieving this goal, such a synthesis also quantifies the trade-offs between possible objectives and specifies quantitative relationships between possible contrasting objectives. This requires a sufficient understanding of the feedbacks between humans and the environmental systems, and the different decisions taken given certain policy measures. With such a system encoded, one obtains realistic Pareto-frontiers which include real-world constraints. Optimization is still understood as a tool for exploratory modelling rather for normative priority setting. Results can provide however aggregated information, which is not obtained by scenario analysis, and — if presented accordingly — these results will be valuable for stakeholders: for instance such as hot-spot or risk maps of certain ecosystem services (for static spatial explicit optimization) [43], as well as identification of thresholds or tipping-points (for dynamic optimization). This kind of exercise, performed at the global scale, can be the object of future studies.

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References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. Seto KC, Güneralp B, Hutyra LR: **Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools**. *Proc Natl Acad Sci USA* 2012, **109**:16083-16088.

2. Foley JA, Ramankutty N, Brauman KA, Cassidy ES, Gerber JS, Johnston M, Mueller ND, O'Connell C, Ray DK, West PC *et al.*: **Solutions for a cultivated planet**. *Nature* 2011, **478**:337-342.

3. Vörösmarty CJ, McIntyre PB, Gessner MO, Dudgeon D, Prusevich a, Green P, Glidden S, Bunn SE, Sullivan CA, Liermann CR *et al.*: **Global threats to human water security and river biodiversity**. *Nature* 2010, **467**:555-561.

4. Loreau M, Naeem S, Inchausti P, Bengtsson J, Grime JP, Hector A, Hooper DU, Huston M, Raffaelli D, Schmid B *et al.*: **Biodiversity and ecosystem functioning: current knowledge and future challenges**. *Science* 2001, **294**:804-808.

5. •• Cardinale BJ, Duffy JE, Gonzalez A, Hooper DU, Perrings C, Venail P, Narwani A, Mace GM, Tilman D, Wardle DA *et al.*: **Biodiversity loss and its impact on humanity**. *Nature* 2012, **486**:59-67.

Important meta-analysis and excellent summary of the state of the art of local scale and experimental findings on the impact of biodiversity to ecosystem functioning and ecosystem services.

6. Eppink FV, Werntze A, Mäs S, Popp A, Seppelt R: **Land management and ecosystem services**. *Gaia Ecol Perspect Sci Soc* 2012, **21**:55-63.

7. Seppelt R, Müller F, Schröder B, Volk M: **Challenges of simulating complex environmental systems at the landscape scale: a controversial dialogue between two cups of espresso**. *Ecol Model* 2009, **220**:3481-3489.

8. Turner W, Brandon K, Brooks T, Costanza R: **Global conservation of biodiversity and ecosystem services**. *Bioscience* 2007.

9. Lambin EF, Turner BL, Geist HJ, Agbola SB, Angelsen A, Bruce JW, Coomes OT, Dirzo R, Fischer G, Folke C *et al.*: **The causes of land-use and land-cover change: moving beyond the myths**. *Global Environ Chang* 2001, **11**:261-269.

10. *MA: Ecosystems and Human Well-being: Multiscale Assessments. Findings of the Sub-global Assessments Working Groups*. Island Press; 2005.

11. • Seppelt R, Dormann CF, Eppink FV, Lautenbach S, Schmidt S: **A quantitative review of ecosystem service studies: approaches, shortcomings and the road ahead**. *J Appl Ecol* 2011, **48**: 630-636.

Synthesis of more than 100 place-based studies on ecosystem service assessments deriving four important facets for future research: improvement of biophysical realism of ecosystem service models, identification of trade-offs and off site effects and test on the robustness of results given stakeholder involvement.

12. Liu JG, Li SX, Ouyang ZY, Tam C, Chen XD: **Ecological and socioeconomic effects of China's policies for ecosystem services**. *Proc Natl Acad Sci* 2008, **105**:9477-9482.

13. Meyfroidt P, Lambin EF: **Forest transition in Vietnam and displacement of deforestation abroad**. *Proc Natl Acad Sci* 2009, **106**:16139-16144.

14. Meyfroidt P, Rudel TK, Lambin EF: **Forest transitions, trade, and the global displacement of land use**. *Proc Natl Acad Sci USA* 2010, **107**:20917-20922.

15. Rodrigues ASL, Akçakaya HR, Andelman SJ, Bakarr MI, Boitani L, Gaston KJ, Hoffmann M, Marquet PA, Pilgrim JD, Pressey RL *et al.*: **Global gap analysis: priority regions for expanding the global protected-area network**. *Bioscience* 2004:54.

16. Lautenbach S, Seppelt R, Liebscher J, Dormann CF: **Spatial and temporal trends of global pollination benefit**. *PLoS ONE* 2012, **7**:e35954.

17. Oki T, Kanae S: **Global hydrological cycles and world water resources**. *Science* 2006, **313**:1068-1072.

18. • Ellis E: **Putting people in the map: anthropogenic biomes of the world**. *Front Ecol* 2008, **6**:439-447.

Synthesis study based on global land use data for characterizing anthropogenic biomes, so called 'anthromes'.

19. • Goldman RL, Tallis H, Kareiva P, Daily GC: **Field evidence that ecosystem service projects support biodiversity and diversify options**. *Proc Natl Acad Sci* 2008, **105**:9445-9448.

Synthesis of case studies showing that biodiversity as well as ecosystem service based land management strategies aim at the same objectives but have different options for funding sources.

20. • Phalan B, Onial M, Balmford A, Green RE: **Reconciling food production and biodiversity conservation: land sharing and land sparing compared**. *Science* 2011, **333**:1289-1291.

Intensely discussed paper on the effects of land sharing vs. land sparing strategies for sustainable land use.

21. Ash N, Blanco H, Brown C, Garcia K, Heinrichs T, Lucas N, Raudsepp-Hearne C, Simpson RD, Scholes R, Tomich T *et al.*: *Ecosystems and Human Well-Being*. Island Press; 2010.
22. Raskin PD: **Global scenarios: background review for the Millennium Ecosystem Assessment**. *Ecosystems* 2005, **8**:133-142.
23. UNEP: *Global Environmental Outlook. GEO4*. 2007.
24. Moss RH, Edmonds JA, Hibbard KA, Manning MR, Rose SK, Van Vuuren DP, Carter TR, Emori S, Kainuma M, Kram T *et al.*: **The next generation of scenarios for climate change research and assessment**. *Nature* 2010, **463**:747-756.
25. Vanvuuren D, Lucas P, Hilderink H: **Downscaling drivers of global environmental change: enabling use of global SRES scenarios at the national and grid levels**. *Global Environ Chang* 2007, **17**:114-130.
26. Strengers B, Leemans R, Eickhout B, Vries B, Bouwman L: **The land-use projections and resulting emissions in the IPCC SRES scenarios as simulated by the IMAGE 2.2 model**. *GeoJournal* 2004, **61**:381-393.
27. Rounsevell M, Reginster I, Araujo MTR: **A coherent set of future land use change scenarios for Europe**. *Agric Ecosyst Environ* 2006, **114**:57-68.
28. Thuiller W, Lavorel S, Araújo MB, Sykes MT, Prentice IC: **Climate change threats to plant diversity in Europe**. *Proc Natl Acad Sci* 2005, **102**:8245-8250.
29. Levinsky I, Skov F, Svenning J-C, Rahbek C: **Potential impacts of climate change on the distributions and diversity patterns of European mammals**. *Biodiversity Conserv* 2007, **16**:3803-3816.
30. Lapola DM, Schaldach R, Alcamo J, Bondeau A, Koch J, Koelking C, Priess JA: **Indirect land-use changes can overcome carbon savings from biofuels in Brazil**. *Proc Natl Acad Sci* 2010, **107**:3388-3393.
31. • Heistermann M, Müller C, Ronneberger K: **Land in sight? Achievements, deficits and potentials of continental to global scale land-use modeling**. *Agric Ecosyst Environ* 2006, **114**:141-158.

Very concise review and overview of modelling aproaches for global scale land use change modeling.

32. Haines-Young R, Potschin M, DeGroot D: *Towards a Common International Classification of Ecosystem Services (CICES) for Integrated Environmental and Economic Accounting*, 2010.
33. Seppelt R, Fath B, Burkhard B, Fisher JL, Grêt-Regamey A, Lautenbach S, Pert P, Hotes S, Spangenberg J, Verburg PH *et al.*: **Form follows function? Proposing a blueprint for ecosystem service assessments based on reviews and case studies**. *Ecol Ind* 2012, **21**:145-154.
34. Billeter R, Liira J, Bailey D, Bugter R, Arens P, Augenstein I, Aviron S, Baudry J, Bukacek R, Burel F *et al.*: **Indicators for biodiversity in agricultural landscapes: a pan-European study**. *J Appl Ecol* 2008, **45**:141-150.
35. Dormann CF, Schweiger O, Augenstein I, Bailey D, Billeter R, De Blust G, DeFilippi R, Frenzel M, Hendrickx F, Herzog F *et al.*: **Effects of landscape structure and land-use intensity on similarity of plant and animal communities**. *Global Ecol Biogeogr* 2007, **16**:774-787.
36. Isbell F, Calcagno V, Hector A, Connolly J, Harpole WS, Reich PB, Scherer-Lorenzen M, Schmid B, Tilman D, Van Ruijven J *et al.*: **High plant diversity is needed to maintain ecosystem services**. *Nature* 2011, **477**:199-202.
37. Balvanera P, Pfisterer AB, Buchmann N, He J-S, Nakashizuka T, Raffaelli D, Schmid B: **Quantifying the evidence for biodiversity effects on ecosystem functioning and services**. *Ecol Lett* 2006, **9**:1146-1156.
38. Mace GM, Norris K, Fitter AH: **Biodiversity and ecosystem services: a multilayered relationship**. *Trends Ecol Evol* 2011 http://dx.doi.org/10.1016/j.tree.2011.08.006.
39. Raudsepp-Hearne C, Peterson GD, Tengö M, Bennett EM, Holland T, Benessaiah K, MacDonald GK, Pfeifer L: **Untangling the environmentalist's paradox: why is human well-being increasing as ecosystem services degrade?** *Bioscience* 2010, **60**:576-589.
40. Ziv G, Baran E, Nam S, Rodríguez-Iturbe I, Levin SA: **Trading-off fish biodiversity, food security, and hydropower in the Mekong River Basin**. *Proc Natl Acad Sci USA* 2012:109.
41. Seppelt R, Voinov AA: **Optimization methodology for land use patterns using spatially explicit landscape models**. *Ecol Model* 2002, **151**:125-142.
42. Seppelt R, Voinov AA: **Optimization methodology for land use patterns—evaluation based on multiscale habitat pattern comparison**. *Ecol Model* 2003, **168**:217-231.
43. Holzkämper A, Seppelt R: **Evaluating cost-effectiveness of conservation management actions in an agricultural landscape on a regional scale**. *Biol Conserv* 2007, **136**:117-127.
44. Rabotyagov S, Campbell T, Jha M, Gassman PW, Arnold J, Kurkalova L, Secchi S, Feng H, Kling CL: **Least-cost control of agricultural nutrient contributions to the Gulf of Mexico hypoxic zone**. *Ecol Appl* 2010, **20**:1542-1555.
45. Polasky S, Nelson E, Camm J, Csuti B, Fackler P, Lonsdorf E, Montgomery C, White D, Arthur J, Garberyonts B: **Where to put things? Spatial land management to sustain biodiversity and economic returns**. *Biol Conserv* 2008, **141**:1505-1524.
46. Nelson E, Polasky S, Lewis DJ, Plantinga AJ, Lonsdorf E, White D, Bael D, Lawler JJ: **Efficiency of incentives to jointly increase carbon sequestration and species conservation on a landscape**. *Proc Natl Acad Sci* 2008, **105**:9471-9476.
47. Watts ME, Ball IR, Stewart RS, Klein CJ, Wilson K, Steinback C, Lourival R, Kircher L, Possingham HP: **Marxan with Zones: software for optimal conservation based land- and sea-use zoning**. *Environ Model Software* 2009, **24**:1513-1521.
48. Probert WJM, Hauser CE, McDonald-Madden E, Runge MC, Baxter PWJ, Possingham HP: **Managing and learning with multiple models: objectives and optimization algorithms**. *Biol Conserv* 2011, **144**:1237-1245.
49. Chauvenet ALM, Baxter PWJ, McDonald-Madden E, Possingham HP: **Optimal allocation of conservation effort among subpopulations of a threatened species: how important is patch quality?** *Ecol Appl* 2010, **30**:789-797.
50. Ellis EC, Klein Goldewijk K, Siebert S, Lightman D, Ramankutty N: **Anthropogenic transformation of the biomes, 1700 to 2000**. *Global Ecol Biogeogr* 2010 http://dx.doi.org/10.1111/j.1466-8238.2010.00540.x.
51. • Asselen S, Verburg PH: **A land system representation for global assessments and land-use modeling**. *Global Change Biol* 2012, **18**:3125-3148.

Synthesis study based on global land use data for characterizing new land system representations as input for model applications.

52. Seppelt R: **Applications of optimum control theory to agroecosystem modelling**. *Ecol Model* 1999, **121**:161-183.
53. Purves D, Scharlemann J, Harfoot M, Newbold T, Tittensor DP, Hutton J, Emmott S: **Time to model all life on Earth**. *Nature* 2013, **493**:295-297.
54. Kleidon A, Mooney HA: **A global distribution of biodiversity inferred from climatic constraints: results from a process-based modelling study**. *Global Change Biol* 2000, **6**:507-523.