Quantifying Ecosystem Service Trade-offs

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Abstract: The ecosystem services concept evaluates ecosystem functions from a human perspective, e.g. the concept focuses on the contribution of ecosystem functions, ecosystem goods and services or human well-being. An evaluation allows the analysis of trade-offs between different ecosystem services as well as between ecosystem services and other components of human well-being. We will test three options to compare trade-offs between ecosystem services, namely map comparison, scenario analysis and trade-off analysis using optimized landscapes. While map comparison and scenario analysis are valuable tools to study ecosystem service trade-offs we emphasize the use of optimized landscapes for trade-off analysis. Overall, analysis of trade-offs between ecosystem services seems to be in its infancy and more enhanced tools are required.

Keywords: Ecosystem services, trade-offs, simulation models.

1. Introduction

1.1 Where it all begins: a brief summary of the background

The environment supports human existence and human well-being with numerous goods and services. These are for instance products like food, fiber and fuel but also services like water retention, pollination, pest control or cultural values. These functions are summarized as ecosystem services (ESS; see MA 2003). As these environmental processes get their value by the benefit people obtain from them (MA 2005, Diaz et al. 2007) it is a clear anthropocentric concept: without a benefit there is no service. This involvement of beneficiaries for human life is the key feature that distinguishes the services from ecosystem functions or processes (Chan et al. 2006). Since the value of ESS is typically external to the valuation framework of decision-makers suboptimal decisions and allocations of sparse resources are made. ESS assessments can help to incorporate the value of ESS into decisions and help thereby to achieve better decisions. While process studies at the field and landscape level are important, for assessments of ESS and their trade-offs complementary tools and methods are needed. Due to the multi-functionality of the landscape ESS assessments should aim at studying several ESS in parallel (Seppelt et al., Bennett et al. 2009). To be most cost efficient, regional assessments should build on indicators derived from available data. Indicators based on land use or land cover data seem fit for this purpose and have been recently the focus of parts of the research community.

1.2 State of the art

The quantity of published studies on ESS shows an exponential trend over the last years. Just a few studies, however, aim at producing results applicable for decision support and - at the same time - involve practitioners that are supposed to benefit from the information and knowledge compiled in the study (Plummer 2009). A significant number of studies

uses land use data to assess the state of ESS. Land cover data are often applied in the context of a benefit transfer approach. This approach focuses on the valuation of ESS by seeking for similar ESS whose values are similar and are known. An improved process understanding cannot be expected by applying this procedure. The approach can be understood as a lookup table approach: values once assigned to objects with specific characteristics and later used to assign values for objects with similar properties. Rodriguez et al. (2006) provide a detailed discussion of the benefit transfer approach.

On top of the problems of such simplified approaches to valuate single ESS a crucial challenge remains, namely to analyze trade-offs and interrelations between different ESS. ESS are not independent of one another and policies targeting one service may well affect spatio-temporal patterns of others (Nelson et al. 2008). This points to the potential existence of trade-offs, where a policy to increase one ESS may lead to the loss or decrease of another (Swallow et al. 2009). In general, ESS may trade-off against each other simply because they compete for space (e.g. between forest and crop field), or because they are causally linked (e.g. removal of vegetation on slopes increases erosion and hence leads to a loss of soil fertility). The former trade-off can easily be represented e.g. through GIS-based approaches (Chan et al. 2006). The latter require a process-based description of the system to detect and quantify them (Jakeman and Letcher 2003).

Published studies on trade-offs between ESS have used rather simple approaches to quantify the trade-offs. Common tools are boxplots (Anderson et al. 2009) and scatterplots – sometimes used to plot the efficiency frontier (Nelson et al. 2008, Bennett et al. 2009) -as well as correlation analysis based on the spearman rank correlation coefficient (Raudsepp-Hearne et al. 2010). Correlations are calculated based on maps for the different ESS, which are sometimes split into smaller blocks (Anderson et al. 2009) or sub-basins for detailed analysis. Swallow et al. (2009) use a linear regression analysis as well as some basic descriptive statistic measures to quantify trade-offs.

1.3 Aim and scope

This paper aims at a comparison of existing approaches regarding their potential to analyse trade-offs between different ESS. We have selected three different approaches and applied them to case study regions. For the first approach (map comparison), InVest (Tallis et al. 2008) has been chosen to represent GIS based approaches that can be used to study trade-offs by comparing ESS provisioning maps – similar approaches are followed e.g. by (Lautenbach et al. under review). The second approach (scenario analysis), an application of the watershed model SWAT (Arnold et al. 1998) has been selected as an example of the use of simulation models to assess trade-offs between ESS and water quality. Thirdly (trade-offs using optimized landscapes), the enhanced analysis of the output of the Patuxent watershed model (Seppelt and Voinov 2002, 2003) sheds light on the possibilities that a combination of simulation models and optimization approaches can offer for trade-off analysis. All approaches evaluate different ESS on different case studies. This induces no problem as we do not want to compare specific trade-offs between certain ESS, but rather focus on demonstrating the principle differences between these three approaches in the capability to analyse trade-offs between ESS.

2.   Methods

Our analysis has been set up in a way that aims at the comparison of the amount of ESS provisioning given different land use systems. We focused on the analysis of the trade-offs in biophysical units instead of monetary values. From our point of view, monetary values assigned to ESS come at the cost of increased uncertainty. Particularly as values assigned to ESS would differ significantly at different levels of service provisioning, and price elasticity would have to be assumed as non constant.

Service provisioning can be assessed by white box, grey box and black box models. Assessments on the regional scale – which is in our focus here – typically have to rely on black box or grey box models (Seppelt 2003). These models will calculate maps or time series of service provisioning indicators which can then be used to calculate trade-offs between services.

The analysis of trade-offs based on map comparison of ESS provisioning has been performed in two ways: first, by calculating the bivariate spearman rank correlation for each pair of ESS. Second, we used the following approach to check for each pair of ESS if the overall correlation varies at different levels of service provisioning: We sorted a pair of ESS by their rank of levels of the first ESS over all grid cells. Then we used a moving window approach and calculated the spearman rank correlation for windows sizes of 100 data points over all data points. This was redone now ordered by the ranks of the levels of the second ESS. Finally we took the mean of both analyses and plotted the spearman value over the total range.

Obviously, the results of both analyses are valid for a single land use system or for a subset of it. To assess trade-offs that result from changes in land use we have to compare the service provisioning of different land use realizations. This could be done by generating a random land use pattern - a permutation of the existing land use pattern - or by changing the land use following scenario assumptions or by applying land use models (e.g. Nelson et al. 2008). All three options might lead to sub-optimal land use pattern – i.e. a reconfiguration of the obtained landscape might increase the provisioning of all ESS (cf. figure 1). To avoid this, one has to compare optimal land use patterns which can be generated by optimization approaches like genetic algorithms (Seppelt and Voinov 2002, 2003, e.g. Holzkamper et al. 2006, e.g. Holzkamper and Seppelt 2007) or simulated annealing (Chan et al. 2006).
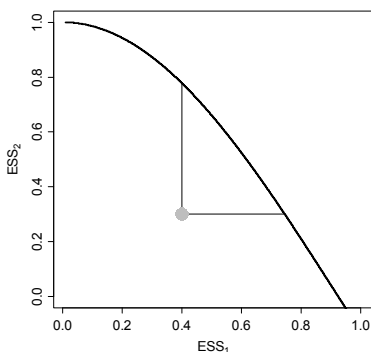

Figure 1 Optimal and suboptimal solutions. The bold line represents optimal land use configurations regarding two ESS. The grey point represents a suboptimal solution which might result from scenario assumptions. It is possible for both services to improve the provisioning of one service without reducing the provisioning of the other service.

3. Case studies and related services assessments

3.1 Map comparison

Case study one investigates ESS trade-offs in the Willamette Basin, Oregon, USA using the sample data coming with the InVest package[1]– for a detailed description of the data and approaches for specific ESS see Tallis et al. 2008. To give a clearer impression of how trade-offs could be studied, we limited our analysis to three ESS – namely, biodiversity, carbon sequestration and pollination. Each EES assessment in InVest consists of a number of GIS operations which process GIS layers like land use or elevation together with user supplied information – e.g. on the threat of roads on nearby habitats. The result is presented in form of one or more maps.

The biodiversity assessment model uses the relative extent of different types of habitat or vegetation types in a region and the relative degradation of those types to produce maps of sensitivity towards the threats. The following factors are considered: 1. the relative impact of each threat on each habitat, 2. the relative sensitivity of each threat for each habitat, the distance between a location and the threat source cell and 4. the level of legal protection in each cell.

For carbon sequestration, InVest estimates carbon storage on a given parcel in the landscape based on the sizes of four fundamental carbon "pools": aboveground biomass, belowground biomass, soil, and dead organic matter. Values for each pool have to be given by the user together with information on the amount of harvest, the harvesting frequency, the amount of carbon that is stored in harvested woods products (HWP) and the decay rate for the different HWPs.

The pollination model uses information on the availability of nesting sites and flower resources as well as flight ranges of bees, to map an index of bee abundance across the landscape. The bee abundance information is then combined with bee flight ranges and the

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[1] We used version 1.003 for our analysis.

locations of pollination dependent or pollination profiting crops to calculate visitation probabilities that are used as a proxy for the actual pollination service.

3.2   Scenario analysis

The last years have seen a jumping demand for bio-fuels which rose questions about related trade-offs. In our second case study we focus on the analysis of trade-offs between food production, energy-crop production water supply and water quality. The analysis is based on the application of the watershed model SWAT (Arnold et al. 1998) in a medium sized lowland basin in Eastern Germany (Strauch 2008, Strauch et al. 2009). The analysis of the trade-offs is based on the following scenarios: 1. reference situation with some bio-fuel cultivation, 2. a food-only scenario without bio-fuel cultivation, 3. increasing rapeseed cultivation for biodiesel production, 4. increasing cultivation of biogas crops (e.g. maize) and 5. increasing cultivation of short rotational poplars (energy forest). The scenarios 3 to 5 each come with two realizations: one 30% increase scenario – in which 30 % of total crop land are used for energy cropping - and an extreme scenario with exclusive production of the specific energy crop(s) (see Strauch 2008 for details).

Effects on the water supply and water quality originate from the different water and nutrient demands of the crops. In case of the biogas scenarios, production residues are also used as fertilizers. Since the processes in SWAT are described at the level of hydrological response units (HRUs), this spatial aggregation level defines the lower limit for a spatial trade-off analysis. As discharge and substance concentrations in the river network integrate all upstream areas, trade-offs for related indicators should also be analysed only along points at the river network. For practical reasons these comparisons might be additionally limited to gauging stations where calibration and validation of the model is possible.

3.3   Trade-offs using optimized landscapes

The third case study is based on Seppelt and Voinov (2002, 2003) which studied in a mainly agricultural region the nutrient (N) balance as a function of different land use and land cover schemes. The landscape model uses a grid structure to calculate water- and matter-dynamics in a spatially explicit way. In other words, flow of water and matter is calculated from cells to neighboring cells for surface, subsurface and groundwater according to the flow network and conductivities, to soil properties and land use. We are focusing here on the generation of optimum land use maps and fertilizer application maps for the Patuxent watershed (2365 km^2).

For this purpose optimization tasks were formulated. This required the definition of performance criteria which compare economic aspects, such like farmer's income from harvest A, costs for fertilization B, with ecologic aspects, such like nutrient loss out of the watershed C. As A and B can be quantified by monetary units and C is given in non-monetary terms, for instance by mass per area, a weight c_N (shadow price) was introduced in the performance criterion J that is to be maximized:

$$J = A - B - c_N\,C \qquad (1)$$

The maxima of the criterion J were calculated based on numerical optimization in spatially explicit dynamic ecosystem simulation models and tests performed by Monte-Carlo's simulations and gradient free optimization procedures. Here, we focus on optimizing nitrogen loss out of the watershed. In other words, we study the trade-off between agricultural production and nutrient retention capability of a landscape including the inner-regional dependencies, given by the topography and the spatial configuration of the landscape. The core idea of the investigation is, to study optimum land use patterns as a function of the unknown weight c_N in Eqn. (3). Increasing c_N nutrient loss out of the watershed is "punished" (compared to economic income by agriculture).

4.   Results

4.1   Map comparison

The overall cell by cell spearman rank correlation for case study one shows a strong positive correlation between pollination and carbon sequestration (spearman rank correlation coefficient: 0.9) as well as light negative correlations between biodiversity and pollination (spearman rank correlation coefficient: -0.2) as well as between carbon sequestration and biodiversity (spearman rank correlation coefficient: -0.3).

Applying the second approach described in section 2 uncovers some more details about the structure of the correlation (cf. figure 2): All three ESS show oscillating correlation patterns which include changes of sign. The high positive correlation between carbon sequestration and pollination for example can be attributed to the very high correlation between areas with high pollination service and high carbon sequestration service – good nesting habitats at forest edges which also are productive in storing carbon.
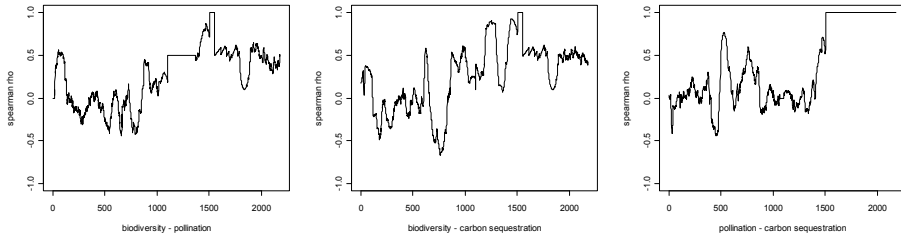

Figure 2. Correlation on a cell by cell basis between the three ESS in the map comparison case study(from left to right: biodiversity and pollination, biodiversity and. carbon sequestration, pollination and carbon sequestration). A moving window approach has been used to calculate the Spearman rank correlation coefficient for the rank ordered cells.

4.2   Scenario analysis

The results of the SWAT simulations indicate clearly that increasing bio-fuel production comes at a cost (cf. figure 3): increasing biodiesel production leads to increasing NO_3-N concentrations which can be related to decreasing runoff due to the higher water demand of the related crop rotation. The trade-offs related to water supply and water quality are less negative for biogas. While the extreme scenario (100% biodiesel or biogas) comes at the cost of increasing NO_3-N concentrations and decreasing runoff, the 30% scenarios lead to a slight runoff surplus. All biogas scenarios lead to a significant higher total yield – but since we have not considered market prices we are unable to tell if this leads to increasing income for farmers.
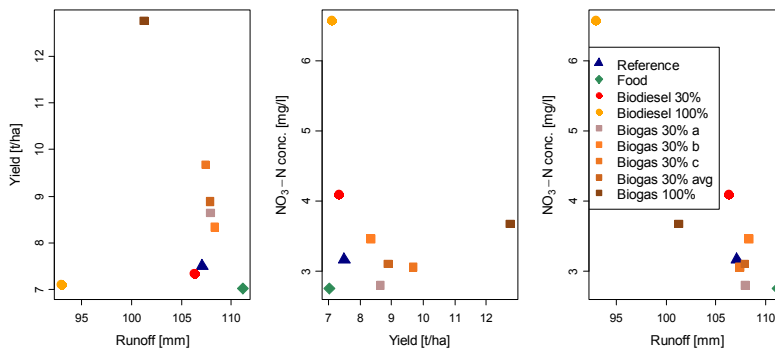

Figure 3. Trade-offs between average yield [t/ha], runoff [mm] and NO_3-N concentrations at the catchment outlet (scenario analysis case study).

4.3   Trade-offs using optimized landscapes

In contrast to the other two case studies, case study number three compared trade-offs based on optimized land use patterns. With increasing shadow price c_N for nitrogen loss the number of agricultural areas decreases leading to different optimum land use patterns (results not shown). The striking result is that sensitive regions can be identified based on the presented method.

Figure 4 shows the trade-offs between net primary productivity, crop yield, and nitrogen loss for different shadow prices and climatic conditions. Each point in the scatter plots represents a land use pattern that has been optimized for a specific shadow price. Since yields, net primary production and nitrogen loss depend on climatic conditions, simulations were performed separately for the climatic conditions of the years 1985 to 1995. The strong correlation between net primary production and yield is obvious. However, for low yields variation can be identified which is due to the diversity of crops. The other plots show strong non-linearities between the analyzed variables. These are due to the nonlinearities of the processes, the structure of the landscape, and spatial interrelations. Above a certain threshold, yield and net primary production cannot be increased by further fertilization (if external cost of nitrogen loss is ignored). This just increases nitrogen loss.
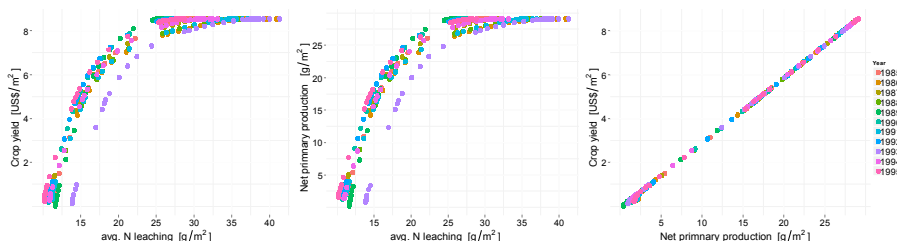

Figure 4. Trade-offs in optimally configured landscapes. The plots show trade-offs between net primary production, crop yield, and nitrogen loss for the trade-offs using optimized landscapes case study. Each point represents a land use pattern that has been optimized for a specific shadow price c_N. The different point symbols represent different years.

Since the optimization has been performed only on the basis of crop yield and nitrogen loss -weighted by c_N -, external effects can still be present. We analyzed the effect of pollination on crop yields as an example for these external costs (cf. figure 5). Since soya bean yield profits by pollination (Klein et al. 2007) we can calculate expected yield losses due to insufficient pollination. We used therefore the approach of Lautenbach et al. (in review) who relate forest edges as a primary nesting habitat for wild bees with distances to pollination dependent crops. The distance dependent visitation probability is calculated based on the formula given by Ricketts et al. (2008). To include external costs like that, the optimization function has to be extended.
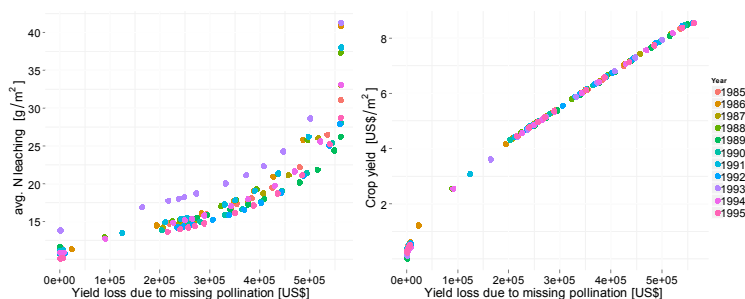

Figure 5. External effects by pollination on crop yields for the trade-offs using optimized landscapes case study. The different colours represent the simulation results for the different years.

5. Conclusions and Recommendations

The focus of our work has been on the analysis of trade-offs. Nevertheless, the validity of the applied models has to be checked. For the case of the Patuxent watershed model and the SWAT case study, models have been calibrated and validated with independent data. However, the calibration and validation depends on data that do not cover land use configurations that are used as scenarios or as optimization results. Therefore, results should be considered with some caution. InVest on the other hand offers very limited options for a validation of the results, so extra care should be taken – simpler approaches do not necessarily coincident with robust results.

In the best of all worlds we would have full knowledge about the underlying processes of each ESS and therefore we could simply model and calculate the trade-offs between ESS under different (optimized) land-use scenarios and decide on our management actions based on these results. Unfortunately we do only have very limited and simplified approaches to estimate ESS due to a lack of data and knowledge on the identity of the relevant processes. Intensified research on evaluation of ESS and monitoring actions are needed to bridge this gap. Until then we have to deal with the problem that an ecosystem is something like a black box and reports on interactions and trade-offs of its processes and services remain correlative and not causal. Moreover the correlation between ESS can completely reverse when the ecosystem (landscape) is changed and therefore we need a more causal approach. A first step towards a more causal description is to establish a typology that describes the interaction of ESS based on common parameters as suggested by Bennett et al. 2009. In our view their idea can be further formalized in such a way that for each ESS a function can be stated for example:

ESS(pollination) = f(distant to forest edge, amount of nesting habitat, dispersal distances)

ESS(carbon sequestration) = f(amount of forest, timber production).

From these functions one can immediately see that a negative trade-off may be expected due to simply surface competition between forest and nesting habitat, but positive effect is expected due to the relationship of distance to forest edge and amount of forest. So common parameters in the ESS function give hints about potential trade-offs between ESS. A simple description and analysis of these ESS functions would be a first step towards a more process based understanding of trade-offs. Hopefully the functions to calculate single ESS can be improved due to better models on ESS and therefore the approach could be refined over time.

For the analysis of trade-offs for decisions on management actions, the gold standard for standalone trade-off analysis is the use of optimized landscapes which include all relevant processes and services in the goal function – otherwise, results might be biased due to external effects. However, it might be unfeasible to integrate all services and processes particularly when socio-economic factors need to be integrated. The reason why we favour these optimized landscapes is that scenarios as well as real land use patterns represent suboptimal situations which inflate trade-off relationships between ESS. A clever reconfiguration might solve a trade-off or at least improve the situation. Still, scenario analysis and ESS assessments are important scientific tools but care should be taken for policy recommendations based solely on these tools. Scenario analysis for the investigation of ESS trade-offs might be improved by using multiple realisations of the scenarios to cover the variability. This is especially relevant for socio-economic processes which are even harder to parameterize than bio-physical processes. In any case, analysis of trade-offs between ESS seems to be in its infancy and more enhanced tools that e.g. incorporate spatial autocorrelation in the analysis are required.

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REFERENCES

Anderson, B. J., P. R. Armsworth, F. Eigenbrod, C. D. Thomas, S. Gillings, A. Heinemeyer, D. B. Roy, and K. J. Gaston. Spatial covariance between biodiversity and other ecosystem service priorities. *Journal of Applied Ecology* 46, 888–896 2009.

Arnold, J. G., R. Srinivasan, R. S. Muttiah, and J. R. Williams. Large area hydrologic modeling and assessment. I. Model development. 1998.

Bennett, E. M., G. D. Peterson, and L. J. Gordon. Understanding relationships among multiple ecosystem services. *Ecology Letters* 12, 1394-1404 2009.

Chan, K., D. Cameron, E. Underwood, and G. Daily. Conservation Planning for Ecosystem Services. *PLoS Biol* 4, 2138-2152 2006. .

Diaz, S., S. Lavorel, F. de Bello, F. Quétier, K. Grigulis, and T. M. Robson. Incorporating plant functional diversity effects in ecosystem service assessments. *Proceedings of the National Academy of Sciences* 104, 20684 2007. .

Holzkamper, A., A. Lausch, and R. Seppelt. Optimizing landscape configuration to enhance habitat suitability for species with contrasting habitat requirements. *Ecological Modelling* 198, 277-292 2006. .

Holzkamper, A., and R. Seppelt. Evaluating cost-effectiveness of conservation management actions in an agricultural landscape on a regional scale. *Biological Conservation* 136, 117-127 2007. .

Jakeman, A. J., and R. A. Letcher. Integrated assessment and modelling: features, principles and examples for catchment management. *Environmental Modelling and Software* 18, 491–501 2003. .

Klein, A., B. E. Vaissière, J. H. Cane, I. Steffan-Dewenter, S. A. Cunningham, C. Kremen, and T. Tscharntke. Importance of pollinators in changing landscapes for world crops. *Proceedings of the Royal Society B: Biological Sciences* 274, 303-313 2007.

Lautenbach, S., C. Kugel, A. Lausch, and R. Seppelt (in review): History teach us nothing? An ecosystem service assessment in the district of Leipzig. *Ecological Indicators*.

MA (Millenium Ecosystem Assessment), M. E. Ecosystems and human well-being: a framework for assessment 2003.

MA (Millenium Ecosystem Assessment), M. E. Ecosystems and Human Well-Being: Multiscale Assessments. Findings of the Sub-global Assessments Working Group. Washington, DC: Island Press 2005. .

Nelson, E., S. Polasky, D. J. Lewis, A. J. Plantinga, E. Lonsdorf, D. White, D. Bael, and J. J. Lawler. Efficiency of incentives to jointly increase carbon sequestration and species conservation on a landscape. *PNAS* 105, 9471–9476 2008. .

Plummer, M.Assessing benefit transfer for the valuation of ecosystem services. *Frontiers in Ecology and the Environment* 7, 38-45 2009.

Raudsepp-Hearne, C., G. D. Peterson, and E. M. Bennett. Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. *Proceedings of the National Academy of Sciences* 107, 5242-5247 2010.

Ricketts, T., J. Regetz, I. Steffan-Dewenter, S. Cunningham, C. Kremen, A. Bogdanski, B. Gemmill-Herren, S. Greenleaf, A. Klein, M. Mayfield, L. Morandin, A. Ochieng, and B. Viana. Landscape effects on crop pollination services: are there general patterns? *Ecology Letters* 11, 499-515 2008.

Rodriguez, J. P., T. D. Beard Jr, E. M. Bennett, G. S. Cumming, S. Cork, J. Agard, A. P. Dobson, and G. D. Peterson.Trade-offs across space, time, and ecosystem services. *Ecology and Society* 11, 28 2006.

Seppelt, R., F. Eppink, S. Lautenbach, S. Schmidt, and C. Dormann. (in review) Zen and the art of ecosystem services. *Ecology and Society*.

Seppelt, R., I. Kuhn, S. Klotz, K. Frank, M. Schloter, H. Auge, S. Kabisch, C. Goerg, and K. Jax. Land Use Options - Strategies and Adaptation to Global Change Terrestrial Environmental Research. *GAIA-Ecological Perspectives for Science and Society* 18, 77-80 2009. .

Seppelt, R.Computer-based environmental management. VCH-Wiley, Weinheim, New York, 2003.

Seppelt, R., and A. Voinov. Optimization methodology for land use patterns using spatially explicit landscape models. *Ecological Modelling* 151, 125-142 2002.

Seppelt, R., and A. Voinov. Optimization methodology for land use patterns--evaluation based on multiscale habitat pattern comparison. *Ecological Modelling* 168, 217-231 2003.

Strauch, M., A. Ulrich, and M. Volk. Simulating the effects of climate change and energy crop production on catchment hydrology and water quality using SWAT. *in* International SWAT Conference Proceedings 2009.

Strauch, M.Effects of climate change and energy crop production on the water supply and water quality in the Parthe Basin (in German). Diploma thesis, TU Dresden 2008.

Swallow, B., J. Sang, M. Nyabenge, D. Bundotich, A. Duraiappah, and T. Yatich.Tradeoffs, synergies and traps among ecosystem services in the Lake Victoria basin of East Africa. *Environmental Science & Policy* 12, 504-519 2009.

Tallis, H. T., T. Ricketts, E. Nelson, K. Vigerstol, G. Mendoza, S. Wolny, N. Olwero, J. Aukema, J. Foster, J. Forrest, and others. InVEST 1.0 beta User's Guide. The Natural Capital Project. Stanford 2008.