

Quantifying Trade-offs between Bioenergy Production, Food Production, Water Quality and Water Quantity Aspects in a German Case Study

Sven Lautenbach^{1,4}, Martin Volk¹, Michael Strauch², Gerald Whittaker³, Ralf Seppelt¹

¹ Helmholtz Centre for Environmental Research – UFZ, Department for Computational Landscape Ecology, Permoserstr. 15, 04318 Leipzig, Germany

² Institute of Soil Science and Site Ecology, Dresden University of Technology, Piennner Str. 19, 01737 Tharandt, Germany

³ USDA, ARS, National Forage Seed Production Research Center, 3450 SW Campus Way, Corvallis, OR 97331-7102, USA

⁴ University of Bonn, Institute of Geodesy and Geoinformation, Nussallee 1, 53115 Bonn, Germany
sven.lautenbach@ufz.de

Abstract: Worldwide increasing bioenergy production is on the political agenda. It is well known that bioenergy production comes at a cost – several trade-offs with food production, water quality and quantity issues, biodiversity and ecosystem services are known but a quantification of these trade-offs is missing. Hence, we show in this study an analysis of trade-offs between bioenergy production, food production, water quality and water quantity aspects in the Parthe catchment in Central Germany. The analysis is based on using SWAT and a multi-objective genetic algorithm (NSGA II). The genetic algorithm is used to find Pareto-optimal configurations of crop rotation schemes. The Pareto-optimality describes solutions in which an objective cannot be improved without decreasing other objectives. This allows us to quantify the costs at which several levels of increase in bioenergy production come and to derive recommendations for policy makers.

Keywords: *Ecosystem services; trade-offs; optimization; bioenergy, agriculture, water quality*

1 INTRODUCTION

Increasing energy demand in addition to fluctuating oil prices and concerns about the negative effects of climate change move alternative energy resources into focus. Bioenergy plants especially for biofuel production play thereby a major role in the international discussion [Robbins, 2011, Zinoviev et al., 2011]. Germany aims at increasing its share of energy from renewable resources in final consumption from 5.8% in 2005 to 18% in 2020 [Fräss-Ehrfeld, 2009]. The use of biofuels in the German transport sector - supported by tax exemptions and quota obligations - increased already from 3.8% in 2005 to 7% in 2007 [Umweltpolitik, 2009]. In the year 2008 Biomass had with 69% the greatest share of the renewable energy production in Germany [Umweltpolitik, 2009].

While the target on bioenergy production is set by the legislation, challenges still exist with regard to finding suitable and sustainable regions for bioenergy production considering arising costs and trade-offs with other land uses and ecosystem services. It is assumed that spatial as well as temporal aspects play an important role for bioenergy production and its side-effects. Therefore, classical life

cycle assessments have to be supported by approaches that are capable to include dynamic and spatial interactions [Bryan et al., 2010].

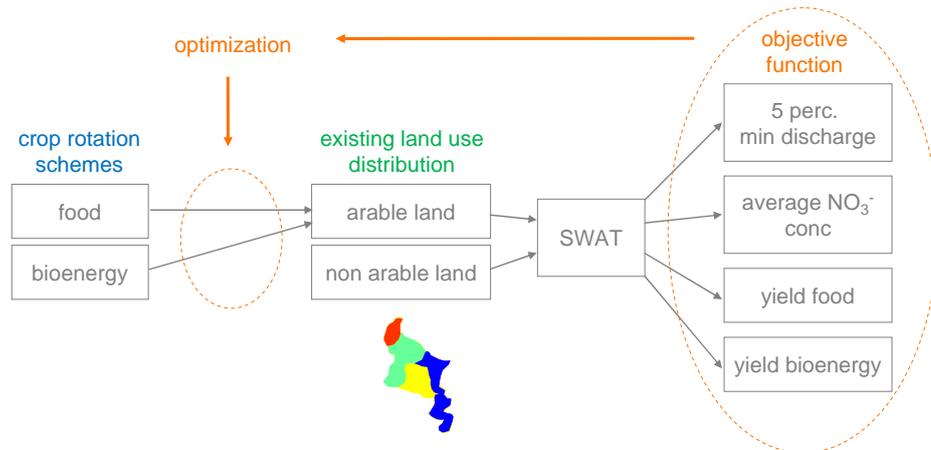


Figure 1. Overview about the optimization approach.

At present, it is the first generation of bioenergy crops competing with food production on arable land. Negative effects of increasing bioenergy production are expected [Tilman et al., 2009, Fargione et al., 2010], namely effects on biodiversity [Fletcher et al., 2010], ecosystem services [Landis et al., 2008, Gasparatos et al., 2011] and water [Gerbens-Leenes et al., 2009, Yeh et al., 2011]. The actual carbon savings are debated for bioenergy crops of the first generation for which N₂O emissions might outweigh CO₂ savings [Crutzen et al., 2007]. Net effects clearly depend on where the bioenergy production takes place and whether land has to be cleared directly or indirectly [Fargione et al., 2008].

This study aims especially at identifying the effect of spatial configuration on trade-offs of bioenergy production. The goal of the study is the identification of functional trade-offs between the ecosystem services bioenergy and food production with regard to water quality and water quantity aspects in a meso-scale agricultural basin. This is done based on the identification of the pareto front which we derive from an optimization approach. Our hypothesis is that choice and spatial allocation of crop rotation schemes allow for different solutions with respect to four objectives: food yield [tons], bioenergy yield [tons], low flow [m³/sec] and water quality [mg N/l]. We focused our analysis on the currently dominant bioenergy crops of the first generation.

2 METHODS

To assess the functional relationships we employed land use optimization tools that aim at identifying optimal land use patterns with regard to an objective function (cf. Figure 1). Since the objective function cannot be assumed to be sufficiently continuous we had to employ a genetic algorithm as a gradient free search algorithm. Optimization algorithms in environmental modelling have been used in the domain of nature conservation and water quality issues [Seppelt et al., 2003, Whittaker, 2005, Holzkamper et al., 2007, Polasky et al., 2008, Lautenbach et al., 2010]. Compared to scenario analysis, this approach tests many more possible land use configuration options and is able to identify non-dominated solutions. The possibility to identify non-dominated solutions is an improvement compared to Monte-Carlo or sampling based procedures, which would lead to a large number of dominated solution making it impossible to identify trade-offs. The aim of the study is neither to sample the whole range of possibilities nor to identify the average behaviour of the system, e.g. from regression-type analyses using sampling-based model runs. Our study aims at quantifying the functional trade-offs between land use decisions. To give an example, a typical question to answer in our case study

would be “How much does the decision to increase bioenergy production by x tons cost us in terms of food and of water quality and quantity aspects?”

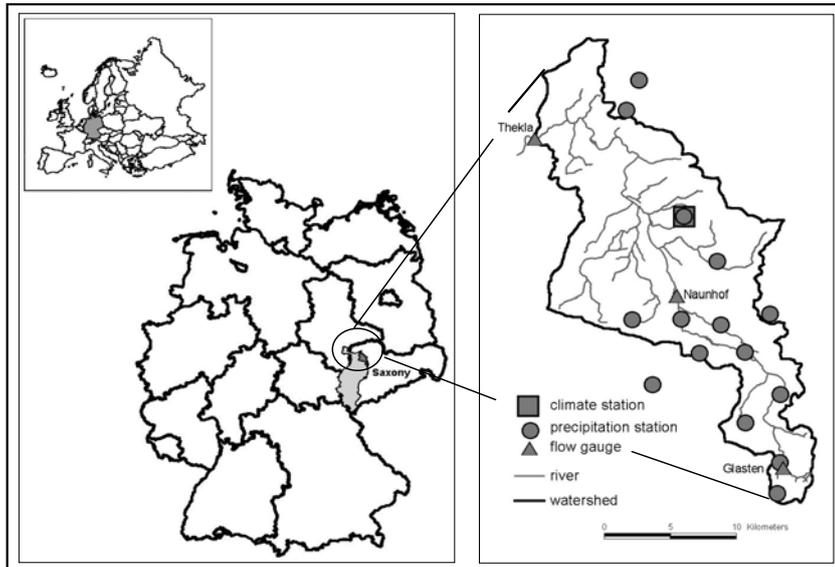


Figure 2. The Parthe case study region is located in Eastern Germany, close to the city of Leipzig.

Our study took place in the Parthe basin, an agricultural watershed of 320 sqkm close to the city of Leipzig in Central Germany (cf., Figure 2). The Soil and Water Assessment Tool (SWAT) [Arnold et al., 2005] was chosen as an integrated model which simulates crop yields, discharge and water quality aspects. SWAT is a physically-based, conceptual, continuous-time river basin model with spatially distributed parameters operating on a daily time step. It was designed to simulate broader scale patterns of discharge and water quality in the spatial and temporal domain [Neitsch et al., 2005]. The SWAT model integrates all relevant eco-hydrological processes including water flow, nutrient transport and turnover, vegetation growth, land use, and water management at the sub-basin scale. The area was divided into 4 sub-basins which are defined by a gauging station which allows for a comparison between modelled and observed discharge as well as water quality data. SWAT uses the concept of hydrological response units (HRU) to further subdivide the sub-basins. The HRUs are characterized by containing similar terrain, soil and land use conditions. For our application, the area was divided into 53 HRUs. Other model input data such as on climate was gathered from local stations, information on land management was provided by farmer interviews and agricultural statistics.

We used a multi-objective genetic algorithm, the non-dominated sorting algorithm (NSGA-II) [Deb, 2001, Deb et al., 2002], for optimizing our four-dimensional goal function. Genetic or evolutionary algorithms [Goldberg, 1989] code the parameters to be optimized in a genome and evaluate the fitness of an individual (which carries one genome) based on a fitness function. The fitness function is defined based on the SWAT simulation output which is evaluated with respect to food and bioenergy yield, minimum discharge at the basin outlet and the average nitrogen concentration at the basin outlet.

In our application, the genome consisted of the crop rotation schemes applied to the agricultural HRUs – we did not modify the non-arable land HRUs during the optimization. The set of crop rotation schemes used in the optimization consisted of two parts: first, crop rotations that have been estimated based on available agricultural statistics and second, crop rotations in which rapeseed for biodiesel production had been added. Known constraints on crop rotations were considered:

Maximum rapeseed share of a crop rotation is 33% and rapeseed cannot be mixed with related crops like fodder beets or rutabaga due to increased pest risk.

A number of individuals form a population from which individuals get selected for mating. The probability of mating depends on the fitness functions. Mating takes place due to a crossover operator, which randomly combines the genomes of the two mating partners. For our application the cross-over operator combines the crop rotation scheme to HRU mapping of two individuals. This is done by splitting the genome at a randomly chosen point and by combining the part of the genome of individual A left of the chosen point with that of individual B to the right of that chosen point and vice versa for the second offspring. In addition, mutation operators randomly change the genome of the offspring to increase the search space. The mutator operator in our case picks on HRU from the genome and assigns a randomly chosen crop rotation scheme from the set of available crop rotation schemes. Since the objective function is 4-dimensional, ranks are assigned to the individuals based on a non-dominated sorting scheme: an individual is dominated by another individual if the other individual has a better fitness value in one dimension of the objective function while having the same or better fitness value in the other dimensions. Each individual gets a score based on the number of individuals it is dominated by. All individuals that have the same number of dominating individuals are said to belong to one front (F_i). The final most outer front describes the Pareto-front. For each individual on that front, objective one cannot be improved without losing some quantity of the other objectives – this describes the trade-offs between the objectives.

The optimization process was terminated based on the number of generations, which were chosen based on pilot simulations. The implementation of the algorithm was based on the ECsPy (Evolutionary Computations in Python, <http://code.google.com/p/ecspy/>) library, which was parallelized by using the mpi4py library for Python 2.6 (<http://mpi4py.scipy.org/>).

3 RESULTS

As our optimization results are Pareto fronts in the 4 dimensional space, we used five two-dimensional projections to display the solution space. In the lower dimensional projection solutions might look dominated, while the real four-dimensional representation indicates no domination of the solution. Figure 3 shows a scatterplot matrix of these two-dimensional projections. The cell in the first row, second column for example displays the average nitrogen concentration at the basin outlet [mg N/l] at the x-axis and the lower five-percentile of the discharge at the basin outlet [m^3/sec] at the y-axis. The figure in row four, column three shows food yield [tons] at the x-axis versus bioenergy yield [tons] at the y-axis.

The production of biodiesel based on rapeseed involves a clear trade-off with water quality. Since nitrogen fertilizer uptake of rapeseed is relatively less efficient compared to other crops, increasing biodiesel production involves higher nitrogen concentrations in the river system (cf. Figure 3, second row, fourth column). Since we fixed the agricultural area, water quality improved with increasing food production (cf. Figure 3, second row, third column). As expected, bioenergy yield and food yield show a clear trade-off. The functional form of the upper part of this projection of the trade-off curve (cf. Figure 3, third row, fourth column) resembles a broken stick model. While the food yield costs are relatively low up to a certain amount of rapeseed yield, a further increase of rapeseed yield leads to unequally higher losses of food yield. This pattern might be explained with the different soil properties in the catchment: while a part of the catchment consists of highly fertile soils, the soil fertility for the rest of the catchment is significantly lower. On high fertile soils, we lose a lot of food production and gain a lot in bioenergy production while the trade-off is less pronounced on the less fertile sandy soils. A similar – but less pronounced – change of slope can be seen for the trade-off between bioenergy production and nitrogen concentration: if rapeseed is cultivated on

sandy soils this leads to increasing nitrogen leaching due to the relatively poor nitrogen uptake of rapeseed. Minimum discharge is generally reduced if we increase either food yield or bioenergy yield, assumable due to increasing transpiration (cf. Figure 3, first row, third/fourth column). But this trade-off is not as strong as the trade-off between nitrogen concentration and bioenergy or food yield – different allocations of the crop rotation schemes to the HRUs allow a larger choice of options between minimum discharge and yield combinations. While a simple hypothesis would expect increasing nitrogen concentrations with decreasing minimum discharge due to a lower average dilution, this trade-off does not show up very clearly (cf. Figure 3, first row, second column).

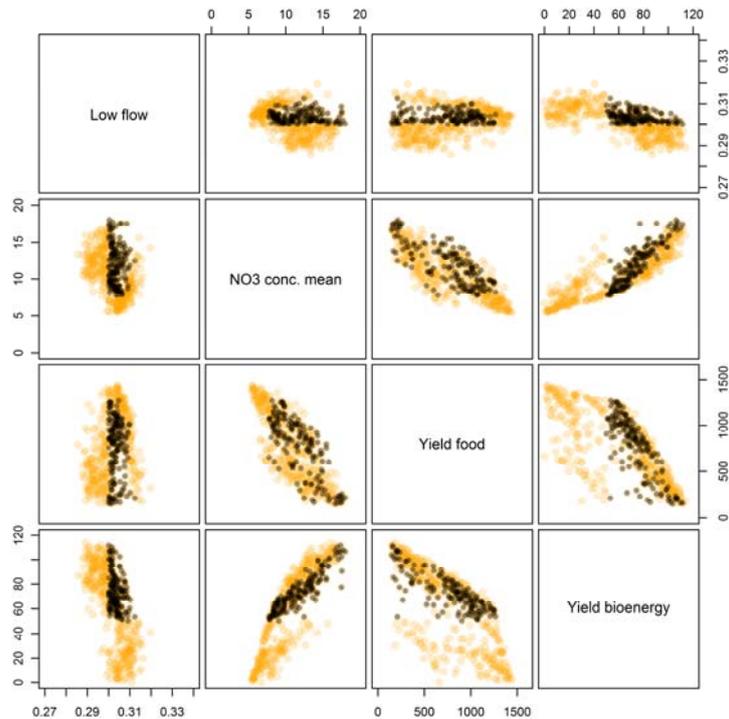


Figure 3. Scatterplot matrix of the Pareto front. Each point represents a complete model run. Black points are solutions selected on potential policy constraints.

Expected political decisions might define certain constraints – the minimum discharge might be limited due to irrigation demand or ecological reasoning, for water quality indicators minimum requirements might be set by legislative regulations and bioenergy production might be set to a desired minimum standard. To satisfy such demands, it is possible to select satisfying solutions from the Pareto front. In Figure 3, we selected solutions that ensure a minimum discharge of $0.3 \text{ m}^3/\text{sec}$ and a minimal bioenergy production of 60 tons. The related solutions have been marked in black.

5 CONCLUSIONS AND RECOMMENDATIONS

The current analysis has shown that optimization approaches are useful to calculate a Pareto front based on a process model. This Pareto front describes functional relationships between different objectives. Such a trade-off analysis of ecosystem services is an alternative to management planning based solely on monetary valuation of the services and it provides a much better theoretical basis compared to a multi criteria analysis which is based on a very limited set of options. We have also shown that in principle it is possible to include policy constraints. A necessary next step will be an incorporation of stakeholders and an in depth analysis of regulations to get input on policy constraints.

We used biodiesel production based on rapeseed as an example. We are aiming at extending this analysis to different bioenergy options such as biogas production based on corn, high biodiversity grassland systems or short rotation forestry. Identifying the trade-offs associated with these different options will enable better informed policy decisions.

To improve the reliability of the results, a comprehensive uncertainty analysis will be necessary. Therefore, the optimization needs to be run inside an uncertainty framework – e.g. by using different model parameterizations or different climate time series.

It will also become necessary to include more ecosystem services like pollination or bio-control which link crop production and spill-over effects from natural habitats. These services have to be modelled at a different spatial scale – new approaches in model integration are necessary to link across these scales.

Monetary aspects for food and bioenergy production might be included in future applications of the approach by including the contribution margin of the crop. This would allow a better representation of value of the different crops for the farmers. Results would differ due to changing prices - this would allow a better representation of farmer's likelihood. Clearly, this would also move the focus away from the analysis of the biophysical trade-offs to monetary trade-offs which tend to reflect the biases introduced by the market economy.

With respect to more applied applications in the direction of decision support for spatial planning it will become necessary to include the effects of policy instruments on land use practice. Therefore, it will be also necessary to include a more explicit representation of farmer behaviour e.g. by incorporating simplified agent-based models. Our analysis so far is only a first step in the direction of policy support. Nevertheless, we moved an important step forward with respect to trade-off analysis which is still dominated by relatively simple GIS operations.

ACKNOWLEDGEMENTS

A part of the work was funded the Helmholtz Program "Terrestrial Environmental Research".

REFERENCES

- Arnold, J.G., Fohrer, N., SWAT2000: current capabilities and research opportunities in applied watershed modelling. *Hydrological Processes* 19, 563-572 2005.
- Bryan, B. a., King, D., Wang, E., Biofuels agriculture: landscape-scale trade-offs between fuel, economics, carbon, energy, food, and fiber. *GCB Bioenergy* 2, 330-345 2010.
- Crutzen, P.J., Mosier, a. R., Smith, K. a., Winiwarter, W., N₂O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. *Atmospheric Chemistry and Physics Discussions* 7, 11191-11205 2007.
- Deb, K., Multi-objective optimization using evolutionary algorithms. Wiley 2001.
- Deb, K., Pratap, A., Agarwal, S., Meyarivan, T., A fast and elitist Multi-Objective Genetic Algorithm: NSGA-II. *IEEE Transactions on Evolutionary Computation* 6, 182-197 2002.
- Fargione, J., Hill, J., Tilman, D., Polasky, S., Hawthorne, P., Land clearing and the biofuel carbon debt. *Science* 319, 1235-1238 2008.
- Fargione, J.E., Plevin, R.J., Hill, J.D., The Ecological Impact of Biofuels. *Annual Review of Ecology, Evolution, and Systematics* 41, 351-377 2010.
- Fletcher, R.J., Robertson, B. a, Evans, J., Doran, P.J., Alavalapati, J.R., Schemske, D.W., Biodiversity conservation in the era of biofuels: risks and opportunities. *Frontiers in Ecology and the Environment* 9, 161–168 2010.

- Fräss-Ehrfeld, C., Renewable energy sources: a chance to combat climate change. Kluwer Law Intl 2009.
- Gasparatos, A., Stromberg, P., Takeuchi, K., Biofuels, ecosystem services and human wellbeing: Putting biofuels in the ecosystem services narrative. *Agriculture, Ecosystems & Environment* 1-18 2011.
- Gerbens-Leenes, W., Hoekstra, A.Y., van der Meer, T.H., The water footprint of bioenergy. *Proceedings of the National Academy of Sciences of the United States of America* 106, 10219-10223 2009.
- Goldberg, D.E., Genetic algorithms in search, optimization, and machine learning 1989.
- Holzkamper, A., Seppelt, R., Evaluating cost-effectiveness of conservation management actions in an agricultural landscape on a regional scale. *Biological Conservation* 136, 117-127 2007.
- Landis, D. a, Gardiner, M.M., van der Werf, W., Swinton, S.M., Increasing corn for biofuel production reduces biocontrol services in agricultural landscapes. *Proceedings of the National Academy of Sciences of the United States of America* 105, 20552-7 2008.
- Lautenbach, S., Volk, M., Gruber, B., Dormann, C.F., Strauch, M., Seppelt, R., Quantifying Ecosystem Service Trade-offs. In: David A. Swayne, Yang, W., Voinov, A.A., Rizzoli, A., Filatova, T. [Eds.], *International Environmental Modelling and Software Society (iEMSs) 2010 International Congress on Environmental Modelling and Software Modelling for Environment's Sake*. Ottawa, Canada 2010.
- Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., Soil and Water Assessment Tool - Documentation, Version 2005 2005.
- 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. *Biological Conservation* 141, 1505-1524 2008.
- Robbins, M., Fuelling politics. *Nature* 474, S22-S24 2011.
- Seppelt, R., Voinov, A., Optimization methodology for land use patterns—evaluation based on multiscale habitat pattern comparison. *Ecological Modelling* 168, 217-231 2003.
- Tilman, D., Socolow, R., Foley, J.A., Hill, J., Larson, E., Lynd, L., Pacala, S., Reilly, J., Searchinger, T., Somerville, C., Williams, R., Beneficial Biofuels—The Food, Energy, and Environment Trilemma. *Science* 325, 270-271 2009.
- Umweltpolitik, R., Langfristszenarien und Strategien für den Ausbau erneuerbarer Energien in Deutschland _ Leitszenario 2009 2009.
- Whittaker, G., Application of SWAT in the evaluation of salmon habitat remediation policy. *Hydrological Processes* 19, 839-848 2005.
- Yeh, S., Studies, T., Evaluation of water use for bioenergy at different scales. *Biofuels Bioproducts & Biorefining* 5, 361-374 2011.
- Zinoviev, S., Müller-Langer, F., Das, P., Bertero, N., Fornasiero, P., Kaltschmitt, M., Centi, G., Miertus, S., Next-generation biofuels: Survey of emerging technologies and sustainability issues. *Nature* 474, S2-S5 2011.