Environmental Modelling & Software 48 (2013) 98–112

Contents lists available at SciVerse ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

Optimization-based trade-off analysis of biodiesel crop production for managing an agricultural catchment

Sven Lautenbach [a,b,*], Martin Volk [b], Michael Strauch [c,b], Gerald Whittaker [d], Ralf Seppelt [b,e]

[a] University Bonn, Institute for Geodesy and Geoinformation, Nußallee 1, 53115 Bonn, Germany
[b] UFZ – Helmholtz Centre for Environmental Research, Department of Computational Landscape Ecology, Permoserstr. 15, 04318 Leipzig, Germany
[c] Dresden University of Technology, Institute of Soil Science and Site Ecology, Pienner Str. 19, 01737 Tharandt, Germany
[d] USDA, ARS, National Forage Seed Production Research Center, 3450 SW Campus Way, Corvallis, OR 97331-7102, USA
[e] Martin-Luther University Halle-Wittenberg, Faculty of Natural Sciences III, Institute of Geosciences, Germany

ARTICLE INFO

Article history:
Received 13 December 2012
Received in revised form
15 June 2013
Accepted 19 June 2013
Available online 16 July 2013

Keywords:
River basin management
Water quality
Bioenergy
Land use
Genetic algorithm
Crop rotation schemes

ABSTRACT

Political agendas worldwide include increased production of biofuel, which multiplies the trade-offs among conflicting objectives, including food and fodder production, water quantity, water quality, biodiversity, and ecosystem services. Quantification of trade-offs among objectives in bioenergy crop production is most frequently accomplished by a comparison of a limited number of plausible scenarios. Here we analyze biophysical trade-offs among bioenergy crop production based on rape seed, food crop production, water quantity, and water quality in the Parthe catchment in Central Germany. Based on an integrated river basin model (SWAT) and a multi-objective genetic algorithm (NSGA-II), we estimated Pareto optimal frontiers among multiple objectives. Results indicate that the same level of bioenergy crop production can be achieved at different costs with respect to the other objectives. Intermediate rapeseed production does not lead to strong trade-offs with water quality and low flow if a reduction of food and fodder production can be accepted. Compared to solutions focused on maximizing food and fodder yield, solutions with intermediate rapeseed production even improve with respect to water quality and low flow. If rapeseed production is further increased, negative effects on low flow prevail. The major achievement of the optimization approach is the quantification of the functional trade-offs for the feasible range of all objectives. The application of the approach provides the results of what is in effect an infinite number of scenarios. We offer a general methodology that may be used to support recommendations for the best way to achieve certain goals, and to compare the optimal outcomes given different policy preferences. In addition, visualization options of the resulting non-dominated solutions are discussed.

1. Introduction

Increasing energy demand together with fluctuating oil prices and concerns about the negative effects of climate change have focused attention on alternative energy resources. Bioenergy plants designed for biofuel production offer one of the major alternatives (Graham-Rowe, 2011; Robbins, 2011; Zinoviev et al., 2011). The Renewable Energy Roadmap of the European Union (European Commission, 2007) sets the goals of a 20% share of European energy consumption by 2020 and a binding 10% share of renewable energy use in the fuel sector. Within that framework, the member states define their own national targets. 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). Supported by tax exemptions and quota obligations, the use of biofuels in the German transport sector has already increased from 3.8% in 2005 to 7% in 2007 (German Environmental Ministery, 2009). In 2008, the largest share (69%) of renewable energy production in Germany was from biomass (German Environmental Ministery, 2009).

While the target for bioenergy production has already been set by legislation, a quantitative evaluation of the costs and benefits of bioenergy production is just starting. At present, the first generation bioenergy crops compete with food and fodder production on arable land. Negative effects of increasing bioenergy production are

* Corresponding author. University Bonn, Institute for Geodesy and Geoinformation, Nußallee 1, 53115 Bonn, Germany.
E-mail address: sven.lautenbach@uni-bonn.de (S. Lautenbach).

1364-8152/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.envsoft.2013.06.006

expected (Fargione et al., 2010; Gasparatos et al., 2011; Tilman et al., 2009), including effects on biodiversity (Fitzherbert et al., 2008; Fletcher et al., 2010), biological control (Landis et al., 2008) and water (Gerbens-Leenes et al., 2009a,b; Gerbens-Leenes et al., 2009a,b; Martin, 2011; Yeh and Studies, 2011). However, quantification of the trade-offs among objectives in bioenergy crop production is problematic, and only few results have been published. The trade-offs that have been quantified usually report a comparison of plausible scenarios (e.g. Donner and Kucharik, 2008; Meehan et al., 2010; Engel et al., 2012), but do not consider whether the reported trade-offs are optimal or not. Unless at least approximately optimal trade-offs are calculated, it is quite possible that the results from any given scenario could be achieved at lower cost with better environmental results, and the stakeholders have no way of knowing. The goal of the study was the identification and quantification of functional trade-offs between bioenergy and food crop production with regard to water quality and water quantity in a meso-scale agricultural basin. We aimed at providing information on biophysical trade-offs at the regional scale for stakeholders. The results contribute to informing decision makers, and help to identify better compromise solutions. The identification of functional trade-offs was done based on the calculation of the Pareto frontier. We started with the hypothesis that the choice and the spatial allocation of crop rotation schemes allow different solutions with respect to four objectives: food and fodder crop yield, bioenergy crop yield, discharge at low flow conditions and water quality. We focused on rapeseed, which is by far the most important source of biodiesel in the EU, especially in Germany (Deutscher Bundestag, 2012; Spencer et al., 2011). The use of soybean and palm oil for biodiesel production, which are important in the USA, is limited by the EU biodiesel standard DIN EN 14214. Biodiesel can be expected to play an important role as a renewable energy source at intermediate time scales (Isermayer et al., 2012). The work presented here builds on the analysis of Strauch (2008) and Strauch et al. (2010), who used a scenario approach to study the effects of climate change and different bioenergy production options in the Parthe basin. The work has been extended (Lautenbach et al., 2012) to quantify and map the nitrogen retention ecosystem service in the case study region.

Compared to a scenario analysis that tests a few possible options, typically selected before the analysis is run, an optimization approach tests many possible land use configuration options and is able to identify non-dominated solutions (Seppelt et al., 2013). The use of the concept of domination to compare and select solutions provides a major advantage over Monte-Carlo or other sampling based procedures. The aim of the study is not to sample the whole range of possibilities or to identify the average behavior of the system – such as a regression type of analysis based on sampling based model runs would describe. In contrast, the study aims to identify the approximately optimal trade-offs between land use decisions: How much does the decision to increase bioenergy crop production cost the society in terms of food crop production and with respect to water quality and quantity? Since optimization is computationally intensive and as complexity increases exponentially with the number of available control options, we constrain our analysis here in several dimensions, e.g. by focusing only on biodiesel crop production based on rapeseed. In a sense, we are identifying non-dominated solutions available within the specifications of a generalized scenario. Following Coello et al. (2007), we considered the multi-objective optimization approach as a posteriori decision support tool. The identified trade-offs can be presented to decision makers before they express their preference for one or more selected solutions.

This is the first application of a multi-objective optimization approach for the biophysical trade-offs associated with bioenergy crop production. Optimization algorithms have been widely used in environmental modeling. Reed et al. (2013) and Nicklow et al. (2010) provide an overview about the many different applications of evolutionary algorithms in water related research. Applications of multi-objective evolutionary algorithms in domains outside environmental modeling can be found in Coello et al. (2007). A number of approaches have been based on economic optimization models with respect to land use, such as linear programming, compromise programming or goal programming. For water related assessments, many studies have linked economic optimization with simulation models of groundwater leaching to specify groundwater quality/farm income trade-offs. Meyer et al. (2009), for example, used SWAT and GIS models together with goal programming to identify trade-offs between farm income based on agricultural production and nitrogen leaching. Darradi et al. (2012) used a comparable tool chain to study the trade-offs between water yields, sediment loads, nitrogen concentrations and crop yields. Seppelt and Voinov (2002, 2003) as well as Seppelt and Lautenbach (2010)used single-objective genetic algorithms to optimize land use patterns with respect to costs and benefits of the different land use types under varying shadow prices for nitrate leaching. Polasky et al. (2008) used a heuristic search algorithm to study trade-offs between biodiversity and economic returns of land use. Holzkämper et al. (2006) as well as Holzkämper and Seppelt (2007) optimized land use with respect to habitat requirements of birds and the value of arable land using a single-objective genetic algorithm together with weighing schemes for the different objectives. Rabotyagov et al. (2010) employed SWAT together with the multi-objective genetic algorithm SPEA2 (E. Zitzler, 1999) to study trade-offs between costs and nutrient emissions. The model chain that we employed here, SWAT and NSGA-II, has been applied before in different contexts and with different aims. Maringanti et al. (2009) and Rodriguez et al. (2011) used SWAT and NSGA-II to identify the spatial allocation of best management practices (combinations of pasture management, buffer zones, and poultry litter application practices). Selection and placement of these best management practices were analyzed under different cost solutions. Panagopoulos et al. (2012) used SWAT and NSGA-II to optimize the placement of fifty different best management practices (livestock, crop, soil and nutrient application management in alfalfa, corn and pastureland fields) with respect to cost, phosphorus and nitrogen emissions. Whittaker (2005) applied the model chain for the analysis of trade-offs between agriculture and salmon habitat protection. In this study, alternative policies (command and control regulation and tax incentives) to reduce non-point emissions of nitrogen from agriculture were evaluated with respect to the environmental efficiency and effects on profits were compared. Groot et al. (2007) used an optimization approach related to NSGA-II to study the trade-offs between plant species number, nitrogen loss, and landscape value. The study used land-use intensity and hedgerow presence as control variables.

2. Data and case study

2.1. Case study

The Parthe catchment (cf. Fig. 1) was chosen as study area. The catchment has been used as the study area for predicting the impact of alternative management practices on water quality and quantity (Ullrich and Martin Volk, 2009) and analyzing the influence of different nitrate–N monitoring strategies on load estimation and model calibration (Ullrich and Martin Volk, 2010). It is located in the State of Saxony in Central Germany and drains an area of about 315 km.[2] It is a sub-basin of the Weisse Elster catchment in the Elbe river system. The topography of the basin is