Environmental Modelling & Software 97 (2017) 287–302

Contents lists available at ScienceDirect

Environmental Modelling & Software

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

How a Pareto frontier complements scenario projections in land use change impact assessment

Judith A. Verstegen [a, b, *], Jan Gerrit Geurt Jonker [b], Derek Karssenberg [c], Floor van der Hilst [b], Oliver Schmitz [c], Steven M. de Jong [c], André P.C. Faaij [d]

[a] *Institute for Geoinformatics, University of Münster, Germany*
[b] *Copernicus Institute for Sustainable Development, Utrecht University, The Netherlands*
[c] *Department of Physical Geography, Utrecht University, The Netherlands*
[d] *Energy and Sustainability Research Institute Groningen, University of Groningen, The Netherlands*

ARTICLE INFO

Article history:
Received 5 May 2017
Received in revised form
1 August 2017
Accepted 14 August 2017

Keywords:
Pareto frontier
Ethanol
Optimization
Brazil
Genetic algorithm
GHG emissions

ABSTRACT

To evaluate the sustainability of potential agricultural land developments, scenario projections with land use change models are often combined with environmental impact assessments. Although this allows inter-scenario comparison of impacts, it does not permit interpretation of scenarios in the light of theoretically optimal impacts. A Pareto frontier provides this information. We demonstrate this for ethanol production in Goiás, Brazil, in 2030. For a Business-as-Usual scenario projection, the spatial configuration, production costs, and GHG emissions of the production chain are compared with those obtained from spatial optimization and summarized by the Pareto frontier. Projected production costs are 729 $\$/m^3$ ethanol, with GHG emissions of 40 kg CO_2-eq/m^3 ethanol. The Pareto frontier indicates an improvement potential of ~50 $\$/m^3$ ethanol when keeping emissions fixed, or ~250 kg CO_2-eq/m^3 ethanol when keeping costs fixed. Robust locations having low costs and emissions show where and how improvements are reached, offering instruments for policy (re)design.

1. Introduction

Intensifying pressure on land, by e.g., requirements for producing food, feed, fibre and bioenergy, has stimulated debates about sustainable land use (e.g. Lambin and Meyfroidt, 2011; Seppelt et al., 2014). The spatial expansion of multiple land use types can be projected by using land use change models, given expected future demands for commodities (e.g. Fargione et al., 2010; Verstegen et al., 2016b). In such spatially explicit projections, it is common to use scenarios that allow for divergent future story lines, where each line is represented by a particular set of future trends in system drivers. We refer to this modelling approach as 'scenario projection'. Scenario projections are combined with environmental impact assessments of the projected land use changes to quantify the effects of the different story lines on the indicators associated with the impacts of interest. Examples of such indicators are greenhouse gas (GHG) emissions for climate impact, employment for socio-economic impact, and mean species abundance for ecologic impact.

Although scenario projection allows for comparing impacts among a set of scenarios, it has a distinct limitation: it gives no information on the overall optimality of the projection. In other words, a scenario projection does not indicate its position in the total indicator solution space (Seppelt et al., 2013). Thereby, it remains unclear if it is possible to attain lower impacts than those evaluated by the scenario(s), and, if so, how much lower (Fig. 1a). Our aim here is to show how adding spatial optimization to a spatial scenario projection allows for the assessment of how much a scenario can potentially be improved for a given set of impact indicators.

Spatial optimization is a contrasting method to assess the impact of land use change: it involves designing an optimal land use configuration with respect to one or more impact indicators of interest (e.g., GHG emissions, employment, and/or mean species abundance) given a range of boundary conditions (e.g. Almeida et al., 2016). Thus, this approach does not actually apply any land use change model. When optimizing multiple impact indicators (objectives) simultaneously, there is typically a very large number

* Corresponding author. Institute for Geoinformatics, University of Münster, Germany.
E-mail address: j.a.verstegen@uni-muenster.de (J.A. Verstegen).

http://dx.doi.org/10.1016/j.envsoft.2017.08.006
1364-8152/

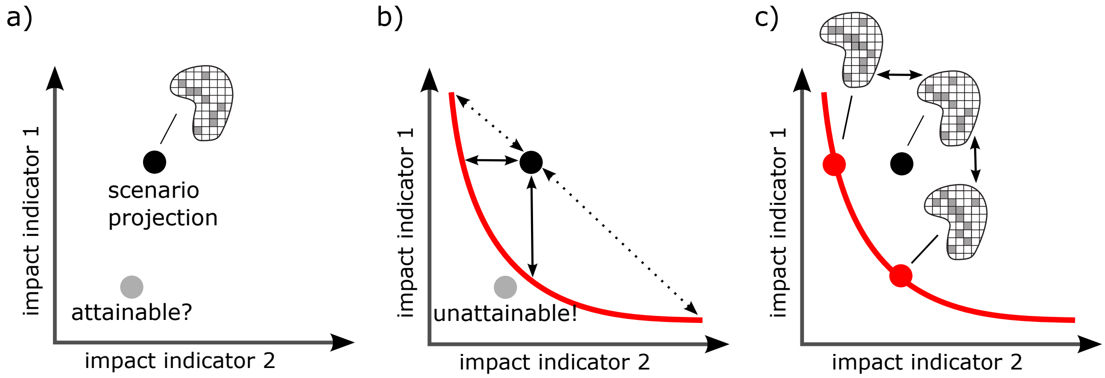

Fig. 1. A hypothetical land use change scenario projection for which two impact indicators are assessed, 1 and 2. For both impact indicators, low values are desired. (a) Scenario projection with spatial configurations projected by the land use change model (maps), the impact indicator values (black dot) derived from these, and the question of if (and by how much) lower impact indicator values are attainable (grey dot). (b) Scenario projection and calculation of Pareto frontier (red line) with an assessment of the maximum impact reduction (dotted arrows) and constrained impact reduction (solid arrows). (c) Comparison of spatial land use configurations associated with points on the Pareto frontier and calculated by the scenario projection, to identify required spatial reorganization of scenario projections to minimize impacts. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of optimal land use configurations (solutions); together, these optimal solutions form a Pareto frontier (Seppelt et al., 2013). Because for all these solutions it is impossible to improve one objective without impairing another, the best solution from the Pareto frontier depends on the weighting of the impact indicators. As such, the Pareto frontier shows trade-offs between the different impact indicators.

It is hypothesized that combining spatial scenario projection and spatial optimization would provide deeper insights in the solution space of future land use, because it enables the scenario projections to be interpreted in the context of the optimal solutions given by the Pareto frontier. In particular, this approach is expected to provide information on:

1. The performance of a scenario is in terms of impact indicators, and how much each impact indicator value of the scenario projection can theoretically be improved. The maximum and constrained improvement can be calculated, where 'constrained improvement' is calculated by keeping the other impact indicator(s) at the same value as in the scenario projection (Fig. 1b) and;
2. Where and how the land use projected by the scenario should be reorganized to reach these improvements (and where it should not be reorganized) (Fig. 1c).

These two aspects are beneficial for policy making, because they assist in developing scenarios with an increased performance by quantifying improvement opportunity and identifying land use characteristics that lead to these improvements. On the other hand, a Pareto frontier alone, without scenario projection results, does not provide information about the feasibility of reaching these improvements given the current land use system dynamics and current policy instruments captured in the scenario. For example, Cotter et al. (2014), used spatial optimization to design a sustainable land use scenario, but they did not have a Business-as-Usual (BAU) scenario of land use change, thereby missing information on which part of the optimal future configuration is likely to be attained by current dynamics and policies. If it is known to what extent the BAU is sustainable, then one can assess in what way policies should be *re*designed.

Some recent studies have used spatial optimization to optimize certain parameters of scenarios (e.g. Arancibia et al., 2016; Law et al., 2017), whereby this integration of optimization and scenario projection allowed for selection of the optimal scenario. However, such integration still cannot ascertain if the retrieved impacts are the lowest attainable, as the lowest impacts might not be attainable using any of the options defined as the scenario parameters. Seppelt et al. (2013) agree with this sentiment: they argue that it is not the integration but the combination of scenario projection and optimization that can strengthen efficient decision making for sustainable land use. Yet, as a very limited number of case studies exists with which to investigate this approach (e.g. Gaddis et al., 2014), and none exists in land use change, our paper aims to provide such a case study.

At this time, biofuels are, rightly or unrightly so, at the centre of the debate around sustainable land use (Tempels and Van den Belt, 2016). Because of this, we performed an impact assessment of ethanol production from sugar cane for 2030, in Goiás, Brazil, a region with a large expected increase in ethanol production (e.g. Lapola et al., 2010). In line with other biofuel impact assessments (e.g. Akgul et al., 2012; Arancibia et al., 2016), we consider two impact indicators: ethanol production costs, as an indicator of economic competitiveness, and greenhouse gas (GHG) emissions, as an indicator of the potential to mitigate climate change. Our research questions for this case study are: What is the performance of and improvement potential for a BAU scenario projection in terms of impact indicator values? How can an assessment of the spatial differences between the projected and optimized land use configurations explain the performance of the BAU scenario projection? How can these spatial differences be used to (re)design land use policies?

We evaluated the way in which the configuration of the ethanol production chain impacts ethanol production costs and GHG emissions for the sum of the ethanol production chain's four main components: acquisition and preparation of land for sugar cane production, sugar cane cultivation and harvest, sugar cane transport to the production facilities (mills), and conversion from sugar cane to ethanol. First, we performed an impact assessment on a BAU scenario projection of the expansion of sugar cane fields and mills for 2030, using an existing land use change model (Verstegen et al., 2016b; Jonker et al., 2016); the impact indicators were calculated through a post-analysis on the configuration of sugar cane fields and mills for 2030. Next, we performed a separate impact assessment via the Pareto frontier for the two impact indicators, calculated through spatial optimization, also for 2030. In this assessment, we optimized the locations of the sugar cane fields