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Applying a multi-criteria genetic algorithm framework for brownfield reuse optimization: Improving redevelopment options based on stakeholder preferences

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ABSTRACT

The reuse of underused or abandoned contaminated land, so-called brownfields, is increasingly seen as an important means for reducing the consumption of land and natural resources. Many existing decision support systems are not appropriate because they focus mainly on economic aspects, while neglecting sustainability issues. To fill this gap, we present a framework for spatially explicit, integrated planning and assessment of brownfield redevelopment options. A multi-criteria genetic algorithm allows us to determine optimal land use configurations with respect to assessment criteria and given constraints on the composition of land use classes, according to, e.g., stakeholder preferences. Assessment criteria include sustainability indicators as well as economic aspects, including remediation costs and land value. The framework is applied to a case study of a former military site near Potsdam, Germany. Emphasis is placed on the trade-off between possibly conflicting objectives (e.g., economic goals versus the need for sustainable development in the regional context of the brownfield site), which may represent different perspectives of involved stakeholders. The economic analysis reveals the trade-off between the increase in land value due to reuse and the costs for remediation required to make reuse possible. We identify various reuse options, which perform similarly well although they exhibit different land use patterns. High-cost high-value options dominated by residential land use and low-cost low-value options with less sensitive land use types may perform equally well economically. The results of the integrated analysis show that the quantitative integration of sustainability may change optimal land use patterns considerably.

1. Introduction

1.1. The brownfields issue

The scarcity of land for food production, energy crops, living and other uses is becoming a major problem in our world (Böhner, 2006; Lambin and Meyfroidt, 2011). One important aspect in efficiently using available land resources is the reduction of unnecessary land consumption. For example, promoting inner urban development is an essential means for reducing unnecessary sprawl to greenfields. A major challenge is the reuse of derelict land, or brownfields (CABERNET, 2005; Lee et al., 2004; Nuissl and Schroeter-Schlaack, 2009; U.S.EPA, 2002). Especially if these sites are considerably large and contaminated they may represent an economic as well as human and ecological health risk (e.g., Agostini et al., 2007; Apostolidis and Hutton, 2006; Cao and Guan, 2007; De Sousa, 2003; Kaufman et al., 2005). Successful brownfield revitalization benefits from the existing infrastructure and the typically prominent location of the sites. Furthermore, brownfield revitalization can drastically enhance sustainable regional development (Bardos et al., 2000).

1.2. Integrated assessment and decision support

Redeveloping brownfields means dealing with potentially conflicting objectives. Soil and water protection acts, like the German Federal Soil Protection Act and Ordinance, call for appropriate and reliably dimensioned risk mitigation measures, whereas economic goals include the minimization of related efforts and costs. Maximizing the financial benefits that would be derived from reusing a site may lead to reuse visions that contradict societal interests. These societal interests might be sustainable development aimed to optimizing the wellbeing of concerned local parties. For a long time, the search for economically feasible options has shaped the

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decisions of how to redevelop a brownfield. Over the last several years the issues of sustainable development have been catching more and more stakeholders' and researchers' attention (e.g., Jakeman et al., 2008; Hartmuth et al., 2008; Singh et al., 2009). Informed decisions can be made only if advantages and disadvantages of any particular reuse option are carefully weighed against each other, taking into account the often divergent choices and objectives of stakeholders (Linkov et al., 2006). To amend this process, decision support systems (DSS) are required that are based on a formally clear and, if possible, quantitative multi-criteria assessment scheme. These DSS should provide an integrated evaluation of possible options of future use (e.g., Kok et al., 2007; Marcomini et al., 2009; Parker et al., 2002). Decision support is also required to optimally explore the scope of planning for the design of future land use options, i.e., the types of uses considered and their allocation on the site. Revitalization of large brownfields can be successful only if this scope is exploited. In this way, an optimal trade-off between the partly conflicting goals of maximizing land value, minimizing remediation costs, and contributing to sustainable urban and regional development, can be achieved. Furthermore, using a DSS may generate an added value by making the routes to decisions transparent (Pollard et al., 2004). Manifold criteria and characteristics might be relevant for the assessment of a brownfield site, depending on the site's size and former use, its surroundings, and the existence of possible receptors that might be affected by existing contamination. Quantification of these criteria is typically done in different units: monetary cost and benefit units, in physical units such as risk levels, or rather abstract indices (e.g., *social acceptance* or *sustainability index*). Previous studies focusing on integrated assessment of brownfields were focused on their classification, scoring schemes and general success factors (Dasgupta and Tam, 2009; Wedding and Crawford-Brown, 2007; Zavadskas and Antucheviciene, 2006). A recent meta-evaluation of assessment and monitoring tools (Pediaditi et al., 2010) emphasized the need for a DSS to be participatory as well as context-specific, transparent, holistic and sustainability objective-oriented.

1.3. Spatially explicit planning and optimization methods

A multitude of GIS-based approaches has been proposed for facilitating decisions related to land use suitability analysis. It can be used to identify the most appropriate spatial pattern of future land uses according to the specific requirements and preferences. Approaches are usually based on combinations of map overlay modeling, multi-criteria evaluation using landscape metrics, and optimization methods or artificial intelligence techniques (Malczewski, 2004). The different optimization methods include linear programming (e.g., Romanos and Hatmaker, 1980; Zhang and Wright, 2004), tabu search (Qi et al., 2008), simulated annealing (e.g., Aerts et al., 2003; Duh and Brown, 2007; Sante-Riveira et al., 2008), and evolutionary algorithms (e.g., Aerts et al., 2005; Bennett et al., 2004; Holzkämper and Seppelt, 2007; Matthews et al., 2006; Xiao, 2008; Xiaoli et al., 2009). Holzkämper et al. (2006) introduced a map to genome transformation that is based on patches in order to optimize land use patch configurations within an evolutionary algorithm, and a genome to map algorithm that allows for evaluation of individuals on a spatially explicit basis. In urban planning, spatially explicit optimization has been applied for school redistricting (Caro et al., 2004), for efficient utilization of urban space through infill development (Ligmann-Zielinska et al., 2008), for landfill siting (Eskandari et al., 2012) and for future city development (Cao et al., 2012). Most of the spatially explicit methods supporting brownfield revitalization do not provide integration of relevant technical, environmental, economic and social aspects but deal with specific aspects of brownfield revitalization such as risk assessment (e.g., Carlon et al., 2008; McKnight and Finkel, 2012; Semenzin et al., 2009), optimization of remediation (e.g., Bayer et al., 2005; Wang and McTernan, 2002), and remediation cost assessment (e.g., Kaufman et al., 2005). Only recently has an integrated and spatially explicit attempt been made to assess brownfield reuse options (Schädler et al, 2011).

1.4. Objectives

In this paper, we present an assessment optimization framework for the identification of optimum brownfield redevelopment options from a holistic perspective. We develop further the achievements described in Schädler et al. (2011, 2013, 2012b). The consistently quantitative assessment scheme is extended here into a fully automated spatially explicit raster-based evaluation system, making the assessment scheme amenable to multi-objective optimization. By integration of this automated evaluation scheme into a heuristic optimization framework (Holzkämper, 2006; Holzkämper and Seppelt, 2007), and through setting up a novel multi-criteria objective function for evaluation of brownfield-specific assessment aspects, a new framework is created for the identification of optimal land use options. With this framework we wish to answer a recent request for an improved DSS for contaminated land reuse (e.g., Agostini et al., 2007; Agostini and Vega, 2009).

The proposed framework allows for spatial analysis and optimization of mixed land use scenarios (i.e., land use configurations), and accounts for given stakeholder preferences regarding the future use of the brownfield sites. Preferences are expressed through constraints regarding the fraction of individual land use classes and through sets of weightings assigned to the different aspects of integrated assessment. By trading off economic costs (minimization of costs and maximization of benefits) with sustainability (maximization of suitability with respect to sustainable development) optimal land use scenarios can be determined. Using a real-world case study, emphasis is given here to the formulation of the objective function: several functions representing different stakeholder perspectives are compared in order to analyze the significance of the trade-off scheme and given scope of planning.

2. Methods

2.1. Integrated assessment of mixed reuse options

The approach presented in this manuscript is especially designed for sites which, because of their size, have a certain degree of freedom with respect to both composition and configuration of redevelopment plans. We therefore assume the redevelopment to be targeted at a mixed use of the site, allocating different land use classes to multiple planning units. How many and which particular land use classes shall be considered for allocation can be freely defined according to existing demands and suggestions of the stakeholders involved in the planning project. Aiming at an integrated assessment, the selection of assessment criteria shall represent the environmental, economic, and social aspects of brownfield redevelopment (as previously suggested by, e.g., Bleicher and Gross, 2010; Rall and Haase, 2011). Along these lines, each land use class is characterized here by (i) compliance criteria with respect to subsurface contamination i.e., target concentrations (clean-up goals) for the contaminants of concern (CoC) in soil and groundwater, (ii) a reference land value, and (iii) the attribution to one of the use types defined for the assessment of sustainable development (Table 1).

2.2. Problem representation

In order to enable an automated assessment of criteria and to implement this assessment within a heuristic optimization procedure,