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Ex ante assessment of crop rotations focusing on energy crops using a multi-attribute decision-making method

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ABSTRACT

The cultivation of plants for use as energy resources is an agricultural and industrial sector with potentially synergistic benefits related to protecting the environment and generating income. Against the background of increasing land-use changes and new agricultural approaches to the production of energy crops, we present a method for identifying future-oriented crop rotations that supports both the economic and environmental components of decision-making strategies with respect to agriculture-related policy decisions (regional mission statements). The conflicting aspects of these objectives can be addressed with the analytic hierarchy process (AHP), a multi-attribute decision-making method that was integrated here. Three models are used to generate simulations of the defined objectives over a planning period of 30 years under the current climate scenario and provide input data for the multi-attribute assessment of several crop rotations. Based on the entire evaluation process, dimensionless global priority vectors are used to indicate how well the crop rotations meet the requirements of the defined mission statement. The method is tested in a municipality in NE Germany.

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1. Introduction

The environmental effects of biomass feedstocks are becoming an increasingly common subject of social discussion, political making and scientific research. The increasing use of biomass for energy production is expected to expand and intensify biomass production in the decades ahead (McBride et al., 2011), and the intensification of land use and land use changes could greatly affect the sustainability of agricultural systems. Therefore, some scientists have advocated biomass production, whereas others believe that the production of biomass feedstocks exacerbates a number of environmental problems, such as the depletion of nutrients in soil, soil erosion and biodiversity loss (Jordan et al., 2007; Williams et al., 2009). This debate coincides with an expected increase in bioenergy use and political regulations requiring that bioenergy and biomass not be produced at the expense of the environment (Fritsche et al., 2010); therefore, knowledge of the environmental effects of energy cultivation systems must be made available.

Assessing the effects of cultivation systems is a key issue for the implementation of management practices intended to achieve goal-oriented, sustainable forms of land use (Sulser et al., 2001; Pacini et al., 2003). However, for such assessments to be realistic and effective, they must be capable of handling complex effects while also considering personal and subjective views of the relative importance of priorities (Park and Seaton, 1996; Andreoli and Tellarini, 2000). The assessment of cultivation systems is a typical decision-making problem that requires the use of decision aid methods, and most approaches are based on multi-criteria decision-making methods (MCDM).

The goal of MCDM is to develop decision-making support methods, particularly for selecting, ranking or sorting options (i.e., alternatives, solutions, courses of action) in the presence of multiple and often conflicting criteria (Zanakis et al., 1998; Figueira et al., 2005; Sadok et al., 2008). Multi-attribute decision-making methods (MADM) are a methodological subgroup of MCDM (Hwang and Yoon, 1981) and are used in cases of discrete and limited numbers of alternatives that are characterized by multiple and conflicting

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criteria. MADM methodologies have been used successfully in various assessments on different scales to address problems that involve a range of alternatives. At the farm scale, Arondel and Girardin (2000) used the ELECTRE (*Elimination et choix traduisant la réalité*; Roy, 1968) method to sort cropping systems on the basis of their impact on groundwater quality. Mazzetto and Bonera (2003) developed a multi-criteria software package derived from the ELECTRE method (MEACROS) to identify alternative cropping systems that meet a set of technical, economic and environmental criteria. Other authors have applied the analytic hierarchy process (AHP; Harker and Vargas, 1987; Saaty, 1980) method for selecting crops to determine the optimal allocation of resources (Alphonce, 1997); assess the environmental, economic and social factors relating to the adoption of silvopasture techniques in south-central Florida (Shrestha et al., 2004); evaluate soil productivity (Zhang et al., 2004); and rank alternatives for preserving natural resources, such as forestry management practices (Schmoldt et al., 2001).

The typical multi-dimensional characteristics of crop rotations require the consideration of heterogeneous measurement levels of relevant quantitative and/or qualitative criteria (Munda et al., 1995). To allow an effective ex ante evaluation, Sadok et al. (2008) suggested selecting criteria that take into account specific methodological characteristics of the chosen MADM method. The knowledge and expertise of decision-makers are crucial elements.

A decision-support method is required to assess the long-term effects of energy crop cultivation while also considering regional development objectives. Such a method must be capable of linking indicator-based models with regional development objectives based on the region's mission statement. The mission statement is based on the economic and environmental aspects of agriculture-related policy decisions. A multitude of indicator-based models can be applied at the regional level (e.g., MODAM – Sattler et al., 2010, Seamless – Van Ittersum et al., 2008). Nevertheless, no existing model is capable of being integrated in a mission statement-oriented regional development process, and most lack the decisive step of weighting the pros and cons of possible impacts at the local or small-scale level. However, this step is required to effectively assist local decision-makers in enacting appropriate decisions (Malkina-Pykh, 2002).

The aim of this paper is to present a method that is suitable for the ex ante assessment of crop rotation in energy crop cultivation. A suitable methodological approach must be developed that meets the following requirements:

- Includes a regionally defined mission statement as a prerequisite for the assessment.
- Compares, rates and assesses a large number of crop rotations for their development over a simulation period.
- Evaluates conventional market fruit and energy crops.
- Addresses the ecological consequences and economic efficiency of crop sequences.
- Merges existing and future applicable simulation models in the methodological approach.
- Considers quantitative and qualitative criteria in the evaluation.
- Includes assessment unit on a small scale to consider local spatial conditions at an adequate scale.

The method was applied to the municipality of Ziethen (Brandenburg). Because of its small-scale climatic and geological variability, this region offers a variety of potential land uses and landscape functions. In addition, the municipality has long benefited from vigorous cooperation with the Leibniz Centre for Agricultural Landscape Research in Müncheberg. This cooperation has resulted in a vast array of basic spatial data, monitoring data and research results (Lutze et al., 2006a).

Weighting of the pros and cons of the possible impacts of applying various crop rotations was conducted using an MADM method. Based on the selection criteria determined by Sadok et al. (2008), the AHP was identified as a suitable weighting method. The AHP is particularly suitable for linking a region's mission statement-oriented planning process with the possibilities offered by indicator-based model simulations. A decision hierarchy was created to structure the aims of the project and generate suitable criteria. The highest hierarchy level contains the region's mission statement, which was subdivided hierarchically into criteria (objectives and indicators). With the objective of optimally achieving the mission statement, the AHP was used by experts to weight the defined objectives and indicators. In addition, the crop rotations were simulated over a period of several years using process-based ecosystem models. The results were also weighted using the AHP. At the end of the assessment process, the impacts of each crop rotation were presented using a dimensionless preference value (global priority vector) by aggregating individual weighting values. It was then possible to rank the investigated crop rotations according to the mission statement. This ranking provides information about the crop rotations that are best suited for achieving the mission statement.

Based on methodological test runs over a simulation period of 30 years, the ability of the method to provide credible information was tested to determine whether it could be used in the next project phase for deriving specific regional cultivation recommendations. To this end, the simulation results were randomly tested to verify whether they are comparable to regional conditions; however, the objective was not to verify the calculations of the applied models, and the actual models were not evaluated in this way. The individual models have been previously published and discussed a number of times, and for the purpose of this study, their validity was assumed. Random sampling checks were conducted to verify the calculations of global priority vectors of single grid cells. The results for a selected mission statement are presented and discussed in this paper.

2. Materials and methods

2.1. The study area

The municipality of Ziethen is located at 52°58′0″ N and 13°55′0″ E in NE Germany (Fig. 1). The total area of the municipality is 24.33 km^2, 80% of which is used for agricultural crop production and permanent grassland. The remaining 20% is covered by forest, water and residential areas. The municipality is characterized by a highly heterogeneous landscape, and its land use patterns are typical of a morainal landscape in the NE German Lowlands (see explanations in Werner et al., 2008). The variable geomorphologic conditions justify variable soil parameters and soil types, and sandy soils are predominant (Lutze et al., 2006b). With regard to climate, the region is characterized by subcontinental conditions. With a relatively low annual precipitation rate below 540 mm a^{-1}, it is one of the driest landscapes in Germany (Mirschel et al., 2006a). The annual mean temperature in the region is 8.6 °C. Two gradients in the average rainfall (from west to east) and mean temperature (from north to south) prevail in the area and reflect the influence of spatial variations of geomorphologic conditions (Mirschel et al., 2006a).

The influence of agricultural policy and economic frameworks is reflected very clearly in the region, particularly after the German Renewable Energy Sources Act (EEG) was introduced in 2000. A growing trend can be seen in the increased cultivation of profitable crops, such as winter wheat, oleiferous crops (rape) and maize. In the future, the economic pressure of the market will require the

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