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Participative dendromass bioenergy modeling in regional dialogs with the open-source BEAST system

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ABSTRACT

Regional participative decision-making processes are becoming increasingly important in the context of climate change mitigation goals and renewable energy production. Dendromass bioenergy plays an important role in climate protection planning at the local and regional levels.
The 'Bio-Energy Allocation and Scenario Tool' (BEAST) is a decision support system designed to assist in stakeholder dialogues, with the goal of developing scenarios of regional wood production through scenario quantification and visualization. While it incorporates wood from forests and outside of forests as bioenergy sources, its main application area is the spatial selection of preference sites for Short Rotation Coppices on arable land, based on the integration of ecological and economic assessments in a multi-criteria analysis with preference selection using Analytic Hierarchy Process (AHP).
This paper provides a comprehensive overview of the purposes of the system, its simulation and software design, and also announces the system's availability as open-source software.

1. Introduction

Climate change, increasing energy demand and shortage of fossil fuels are major global challenges affecting energy usage today and especially in the future (IEA 2016). Thus, the European Union (EU) has been promoting the use of renewable energies, with biomass for energetic use as one important component by mobilization of existing reserves and the development of new systems (EU 2009). For example, it is expected that up to 26 % of Germany's energy demand in year 2050 can be covered by domestic biomass (FNR 2017). In Germany, a financial support for the production of renewable energies including biomass was established with the Act on the Development of Renewable Energy Sources in 2000 and its successors (German Parliament 2000). This stimulated the bioenergy production from 586 GWh in 2000 to 41'016 GWh in 2018 (Federal Ministry for Economic Affairs and Energy 2017). The largest shares of bioenergy in Germany are produced with maize and oilseed rape (Schmidt-Walter & Lamersdorf 2012). For example, the area for energy maize production increased from year 2007 to 2017 by approx. 4.5 times to 1 Million ha (FNR 2017; FNR 2018). However, the production of energy maize needs a relatively high energy input compared to perennial energy crops (Boehmel et al. 2008) and there are indications that the large maize monocultures result in a loss of biologic diversity (Eggers et al. 2009; Sauerbrei et al. 2014). Furthermore, maize and rapeseed production implies high risk of erosion, nutrient inputs in ground and surface water as well as pesticide pollution of soils and water (EEA 2006). Due to these implications, not only annual energy crops should play a significant role in the projected energy mix but also the utilization of dendromass (BirdLife International et al. 2014; Schellnhuber et al. 2009).

In addition to the usage of waste wood, which is already almost exhausted (FNR 2018), there are three possible sources for bioenergy production using wood: forests, wood from outside forests (trees and hedges of open landscapes and roadsides), and plantations of short rotation forests/coppices on

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arable land. In Germany and perhaps in most other Central European countries, there are source-specific restrictions on the usage of such sources as bioenergy, as summarized in the following.

The usage of stem wood from forests as bioenergy competes directly with the material use of stem wood and is therefore ecologically and economically problematic. Bioenergetic utilization of stem wood reduces long-term carbon sequestration and is thus inadequate for green-house gas mitigation (Schulze et al. 2012). Additionally, the usage of residues from forests is under discussion due to questions of nutrient removal and accelerated release of carbon (Vanhala et al. 2013).

Woody biomass from open landscapes, i.e., hedges and trees outside forests or woodland, could be an additional source of woody bioenergy but is often not taken into consideration. However, from this source, Seidel et al. (2015) expects an annual supply of 233 TJ, based on a district in Germany with an area of approx. 1.100 km². A study by Drigo & Veselič (2006) for Slovenia estimates a usable annual non-forest woody biomass volume of approx. 300.000 m³. As trees and hedges in open landscapes must be cut often as part of landscape tending measures, costs could be compensated by energetic usage (Schönbach & Bitter 2015). However, accessibility restrictions on machineries, missing utilization chains, and the reluctance of landowners and stakeholders all limit the usage of this biomass source (Seidel et al. 2015).

Another option is the production of woody bioenergy on arable land with Short Rotation Coppice (SRC). Planting SRC on arable land has many ecological advantages compared to the annual energy crop production. SRC is a low-intensity perennial agricultural system that can support various ecosystem functions and services, such as protection from nitrate leaching (Bredemeier et al. 2015; Schmidt-Walter & Lamersdorf 2012), fragmentation of homogeneous arable landscapes (Baum et al. 2012), increased biodiversity (Rowe et al. 2011; Sage et al. 2006), reduction of soil erosion, lower fertelizer requirement, and sequestration of soil organic carbon (Blanco-Canqui 2010; Don et al. 2012). Due to its positive effects on soil and water quality SRC can also be cultivated on former cropland which has been abandoned due to soil and water issues (Schmidt-Walter & Lamersdorf 2012) and is optimal for the transition of marginal land (Holland et al. 2015). However, there is a strong reluctance of landowners to establish SRC due to the initial investment, the long-term (~20 yrs.) and binding nature of the decision, missing supply chains, as well as a lack of information and experience although SRC is an interesting option for areas of lower site quality (Drittler & Theuvsen 2018; Verwijst et al. 2013; Faasch & Patenaude 2012; Schweier & Becker 2012; Dimitriou et al. 2011). Furthermore, the economically competitive of SRC to annual crops was already proven, when proper sites are selected (Kröber et al. 2015).

Achieving ambitious political goals for the increase in woody biomass supply for energetic usage requires involving various stakeholders in discussion and participation processes in order to implement regional strategies. Several constraints, including aspects of ecological sustainability and economic advantageousness, are restricting the increased usage of existing biomass sources. Furthermore, the replacement of annual energy crop production on arable land by ecological advantageous SRC could be a further goal.

As governmental authorities own only small shares of land, private sector land owners need to be motivated to increase biomass supply for energetic usage. The government could stimulate the production of ecological advantageous bioenergy production by, for example, the establishment of financial incentives for landowners to shift to SRC and include landowners and further stakeholders, e.g. from nature conservation, in political strategy planning processes. Typically, participation takes place on the regional scale, where the integration of stakeholders can be most successful (Butler Manning et al. 2015). Those political participation and group-decision processes can be improved by using participative modelling and corresponding tools for scenario definition, modelling, and visualization. However, there is a gap between already existing paper-and-pencil DSS frameworks, simple spreadsheet-based end-user DSS and highly complex scientific bioenergy simulation systems. Stakeholders should be enabled to define and adjust scenarios participative and directly quantify and visualize the results.

The purpose of this paper is to present a methodology, modelling concept, and reference software implementation of a tool tailored to fill the described gap to support regional participation and group-decision processes for dendromass production by software-based scenario definition, quantification and visualization. Furthermore, it announces the public availability of the resulting software product under an open-source license to foster its application and to provide the software's source code as a starting point for further developments.

2. Methodology

To support regional discussion and participation processes, participatory modeling is a useful approach to assist stakeholders in visualizing the consequences of specific decisions scenarios and to help in collective decision-making (La Rosa et al. 2014; Voinov & Bousquet 2010). For this purpose, the development of "Bio-Energy Assessment and Simulation Tool" (BEAST) was started in the context of the joint research project "Strengthening Bioenergy Regions" (German: "BioEnergie-Regionen stärken", BEST). The tool integrates ecological assessments (ecosystem functions and services) with economic calculations as a basis for regional participative dialogs and participatory modeling (Figure 1). It considers wood from forests, open landscapes and short rotations. However, the focus is on the spatial selection of preference areas for SRC under user-defined ecological and economic restrictions and selection criteria. The BEAST uses preprocessed input data of a study region, which makes it independent from specific growth-modeling approaches; the BEAST also provides easy-to-use graphical user interfaces to define goals, restrictions and parameters for creating and analyzing scenarios of wooden bioenergy utilization. The selection of preferred SRC areas is processed – in a multi-criteria evaluation – based on stakeholders' perceptions with respect to ecosystem functions and services as well as economic returns compared to certain annual field crops. The scenario results are processed for two 20-year periods: 2011 to 2030 and 2031 to 2050. This creates the possibility of incorporating climate change effects into the scenario assessment via the input data.

The BEAST system ideally complements existing approaches in the field of bioenergy modeling and participation process support, as those approaches and the BEAST can be applied side-by-side or integrated into regional participation processes. Such existing approaches comprise the following (GBEP - Global Bioenergy Partnership 2011; for a list of tools; see, e.g., Milbrandt & Uriarte 2012):

- Specific simulation models, which can serve as producers of input data for the BEAST. Examples of such models are detailed forest wood supply models (e.g., Sacchelli et al. 2013) and SRC growth models (e.g., De Groote et al. 2015; Tallis et al. 2013).
- Participation framework models, which can serve as discussion guidelines in which the application of the BEAST can be embedded, as these frameworks do not include computer simulations for (spatial) scenario visualization (e.g., FAO & UNEP 2010; Lezberg et al. 2010).
- Related simulation approaches for identification of potential areas for production (e.g., Aust et al. 2014; Bauen et al. 2010; Wu et al. 2012), fitomass energy calculations (e.g., Bai et al. 2016), CO_2 calculations for different biomass sources (e.g., Bai et al. 2017), holistic renewable energy calculations (e.g., Benedek et al. 2018), and impact assessments of land-use changes (e.g., Meehan et al. 2013; Schulze et al. 2016) with different application domains and, therefore, without an integration into a user-friendly open-source tool applicable for participatory modeling in regional participation processes. Nevertheless, those approaches can serve as a technical basis for input generation or as a methodological basis for the extension of BEAST.

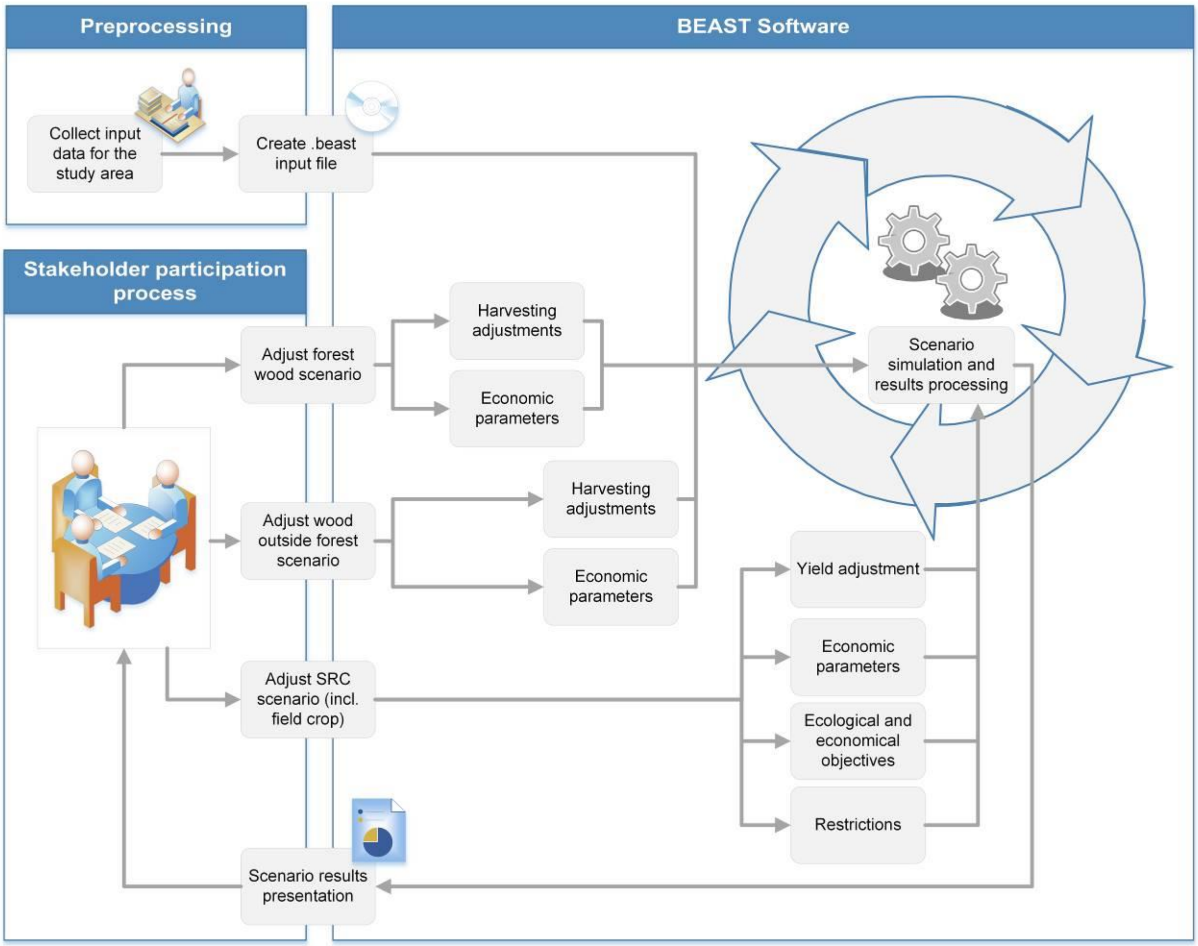

Figure 1. Use case visualization of the "Bio-Energy Assessment and Simulation Tool" (BEAST). The flow chart depicts the processes of input data preprocessing, iterative software usage in the stakeholder participation process by adjusting scenario settings, and the production of simulation results. Scenario adjustments are discussed in the stakeholder workshops on the basis of the simulation results and can be immediately entered into the forms of the BEAST software to request a new scenario simulation.

A first version of the BEAST tool was applied to the Göttingen district in Central Germany. This version was far away from being applicable independently from the system developers although the backend model system was equivalent. The results of that case study can be found in Busch & Thiele (2015). The paper presents a methodology to generate the necessary input data and parameter values for the tool, including advice on data sources, which can be adapted for system application to other study areas. In the meantime, the software has been further developed to be applicable in participative process independently from the system developers, e.g. by adding Saaty's Analytic Hierarchy Process (AHP) (Saaty 1990; Saaty 1987) to support the group-decision making process.

The application software development cycle followed the spiral model by developing prototypes in several iterations. The prototypes were presented in stakeholder groups of regional actors of the Göttingen district for feedbacks which have been incorporated in the next version.

The development of the upstream backend model concept followed also the spiral model. The simulation model concept was developed by interviewing domain experts, transforming the interview results into algorithmic simulation model descriptions and requesting feedback on the descriptions by the domain experts.

3. Simulation Model Concept

The simulation model concept delivers an impression of the internal processes of the BEAST software, i.e., which inputs are used and how results are processed. The description follows the ODD (Overview, Design concepts, Details) protocol for simulation models (Grimm et al. 2006; Grimm et al. 2010).

3.1. Overview

3.1.1. Purpose

BEAST is designed to define and evaluate scenarios of woody biomass on a regional scale. It supports stakeholder participation regarding ecological and economic aspects via participatory modeling. The system considers different sources of woody biomass and delivers biomass and energy potentials. It also discloses preference areas suitable for establishment of SRC on arable land based on multiple criteria. It enables users to compare scenario-based biomass availability to a politically targeted amount. Thus, the system identifies, for example, the necessity of political actions to foster the attractiveness of woody biomass production.

3.1.2. Entities, state variables and scales

BEAST handles three sources of biomass: wood from forests, wood from outside of forests and SRC on arable land. For comparative purposes, field crops are also processed. Whereas wood from forests as well as from outside of forests is taken into account only as aggregated biomass pools in the system, SRC and field crops are modeled spatially explicitly on arable field geometries.

The basic state variables of the different sources are the biomass potentials.

The minimum time scale of internal processing is one year. The output is presented in two periods with lengths of 20 years each. The spatial scale of calculations for wood from forests and wood from outside forests is the study region, determined by the input data. The scale for the processing of SRC and reference field crops is the single field, determined by the input data as well. Thus, the system itself is virtually scale-independent.

3.1.3. Process overview and scheduling

The simulation begins by loading the inputs and parameters from a selected input file and updating the parameter values using user inputs from the Graphical User Interface (GUI). Then, the simulation runs separately for the two simulation periods of 20 years each. Within a simulation period, the different biomass sources are simulated independently from each other. The biomass and energy potential from forest wood and wood from outside of forests is calculated distinctly for different compartments (forest: stem, industrial/fire wood, residues; outside of forest: stock, yield) but is spatially aggregated for the study area. In contrast, the calculations for arable reference crops and Short Rotation Coppices are performed spatially explicitly. Therefore, yield and resulting economic return are calculated for all fields. The economic return of a reference field crop rotation is calculated and compared to the economic return of SRC as an annuity difference value. This value serves as an area selection criterion in addition to other criteria or objectives, mostly ecological ones: susceptibility to (water) erosion, landscape diversity, rate of water percolation, potential nitrate leaching, area complexity, slope, soil quality index, and soil moisture index. A check of each field area against the selected restrictions and objectives is performed, as well as a calculation of the criteria sum based on criteria values, scaling and weightings is done. Then, the list of potential SRC areas is reduced to those that conform to the selected restrictions and objectives. This subset is sorted by decreasing value of the scaled criteria sum, which serves as a proxy for selection preference. Next, areas are selected as preference areas based on their criteria sums and by checking restrictions regarding the max. area of SRC within administrative and ecological units simultaneously. If the minimum distance option is selected, the minimum distance between two SRC fields is also checked by buffering and subsequent intersection test against all fields selected so far. If an intersection is found, the candidate area is rejected and not put on the list of preference areas. At the end of the SRC calculations, the areas on the preference list are further classified.

The inputs, parameters and results for all wood sources and the reference crops are aggregated and stored. If another simulation period is pending, parameters with annual change factors, i.e., yields, prices and costs, are prolongated to the next period and the next iteration is started. If the last simulation period is reached, there is an option of writing the results to a file and loading the results into the ResultsExplorer tool, which visualizes the results in tables, plots and maps.

A visualization of the process schedule is attached in Digital Supplement A.

3.2. Model design concepts

Basic principles. The data- and model-driven system serves as a shell for scenario analysis and decision support. High flexibility and fast processing are guaranteed by using as many input data as possible from pre-processed import files. Even changing the study area by loading a different input file is a simple task. Simultaneously, the system itself is independent from yield and growth models and corresponding modeling approaches. Its rapid response to changed parameters encourages users to play with values and learn how they affect the results.

Emergence. Scenario results, especially the pattern of spatial distribution of potential SRC fields, emerge from user-defined scenario settings, such as restrictions, objectives, criteria scaling and weighting.

Objectives. The system captures and visualizes the stakeholder's perceptions of regional renewable energy goals for woody biomass.

Stochasticity. The system includes no random effects.

Observation. Figures of biomass demand and supply, primary energy equivalents and annuities are stored during the simulation for all sources of wood supply. Annuities for all field crops and crop rotation composition are also captured. Moreover, scaled criteria values, scaled criteria sums and flags reflecting (a) the fulfillment of restrictions and objectives, (b) the selection of potential SRC fields and (c) the SRC classification are stored for further analysis.

3.3. Details

Detailed descriptions of initialization, inputs, and processes are beyond the scope of this paper and can be found in the documentation accompanying the software bundle and in the online repository (https://beast.sourceforge.io/).

4. Software Design Principles

The following five principles guide the software design and implementation.

1. *Easy to install and use:* The target audience of the software is stakeholders in regional energy policy participation processes as well as consultants in such discussion processes. Therefore, the software needs to be easy to install and should come with a generally self-explanatory and easy-to-use GUI. The level of detail has to be selectable.

2. *Integration of ecological, political and economic aspects:* To mediate the interests of different stakeholders, the system has to integrate perceptions about different ecological, political and economic aspects of woody biomass production for energy usage.

3. *Fast output generation:* To support participation processes, the software should not only be useable in back-offices after discussion processes but also should be applicable simultaneously with the meetings. The scenario settings should be definable via the GUI and should guide the discussion. Testing and analyzing different variants of parameter adjustments should be possible during the meetings. Therefore, the processing of intensive calculations needs to be either avoided or optional in order to keep the software's response-time as short as possible so as not to interrupt discussions for too long. Instead of using equation-based modeling on

demand in every scenario simulation, base data could be pre-processed, but they need to be modifiable during scenario processing.

4. *Visual result presentation and export:* To be usable in participation processes, the results should be presented visually. Because it focuses on the discussion of locations for Short Rotation Coppice, the system should present preference areas on a spatial map. Export functions could create the possibility of further analysis of results in external software, such as statistical analysis programs and Geographical Information Systems (GIS).
5. *Foster re-usage and further development:* To increase its reliability, the system should not appear as a black box, and it should come without costs and without usage of proprietary libraries in order to increase its distribution and re-usage. Furthermore, the source code should be available to allow community development and improvement of the software.

5. Implementation

The first design goal is addressed by providing ready-to-use Windows executables and by implementing a navigation tree separating and structuring the different input forms. Several supporting visualizations of input data help in finding reasonable parameter settings. Weights of criteria for multi-criteria analysis are derived from pairwise importance comparisons using Saaty's Analytic Hierarchy Process (AHP) (Saaty 1990; Saaty 1987). The resulting weights are visualized in a spider diagram, and user-defined criteria scaling are given by defining support points, which are visualized in a line graph. Where possible, form entries are validated for plausibility.

The second design goal is fulfilled by implementing the described simulation model concept, which ensures that ecological and economic aspects are integrated into the assessment, thus reflecting different political goals and stakeholder perceptions.

The requirement of short response times of the scenario simulation (3rd design goal) is addressed by shifting time-consuming operations as much as possible into preprocessing, as well as by loading and changing the input data from lightweight files packaged in a single archive file with the .beast extension. Furthermore, the tool is implemented as Desktop software instead of as a Web application to ensure usability everywhere, even without Internet access.

The 4th design principle is addressed with the ResultsExplorer tool, which provides functionality to load results stored in a .beast file or immediately processed with the ScenarioGenerator tool. The ResultsExplorer produces interactive bar charts and boxplots of all ecological and economic criteria for all biomass sources. A MapViewer application is integrated into the ResultsExplorer, which provides the possibility of analyzing the inputs and results of the SRC/field crop scenario simulations spatially and of combining them with external maps from local files and/or WebMapping Services.

The software is built upon established open-source libraries and comes under an open-source license to meet the 5th design goal. As a program written in the Java language (Gosling et al. 2015), it is implemented platform-independent and executable on various platforms. Table 1 gives an overview of the libraries used for implementing the software. BEAST is developed using the Eclipse IDE (The Eclipse Foundation 2017) with Maven build tool (The Apache Software Foundation 2017a) support. In conjunction with the launch4j plugin (Kowal 2015), a full-fledged automatic production ecosystem for executables is realized. Directions for setting up the project with Maven in Eclipse IDE, as well as the source code itself, are documented in a development guide, which accompanies the usage guide and documentation.

Table 1. Open-source libraries used for implementing BEAST.

Library	Domain	Reference
Swing	Basic GUI components	Oracle (2015)
JGoodies	Advanced look and feel as well as form layout for Swing panels	Lentzsch (2016)
JFreeChart	Interactive and non-interactive charts including bar charts, spider web as	Gilbert (2014)

	well as box and whisker plots	
Apache Commons Lang	Multi-language GUI support	The Apache Software Foundation (2017b)
EclipseLink MOXy	XML-file mapping	The Eclipse Foundation (2015)
Opencsv	.csv file parser	Smith et al. (2017)
GeoTools	Geoprocessing and map viewing functions	GeoTools (2016)

So far, the tool and its foundations were briefly introduced by describing the simulation model concept, the software design principles, and the implementation. The software product is available as open-source software, which is an important step towards more open and reproducible science and towards lowering the boundary between science and government by means of transparency (Pfenninger et al. 2017).

To foster re-usability, a comprehensive usage guide, documentation and development guide were added, and the software as well as its source code can be downloaded from a publically available repository (https://beast.sourceforge.io/). Being freely available, it can be applied to any region after input data preprocessing. Furthermore, as an open-source software, the source code can be modified, thus, the software can be extended to additional use-cases, or parts of the code can serve as starting points for different tasks with similar functional requirements.

Next, a brief impression of the software's GUIs is given (Figure 2). A comprehensive overview can be found in the usage guide. When starting the software the ScenarioGenerator opens and the user can select a study region. The delivered software package comes with a dummy input dataset of an imaginary example region as well as with a tool to create input files from pre-processed data. The ScenarioGenerator opens the possibility to modify the default model parameters and delivers manigfold options to adjust the input values, e.g. the field specific growth rates of the different field crops. Several plots visualize the input data to support such customizations of the input data. Furthermore, the constraints for the potential SRC fields as well as the selection criteria based on the AHP are defined in the ScenarioGenerator. The settings can be stored in the same or a new scenario input file.

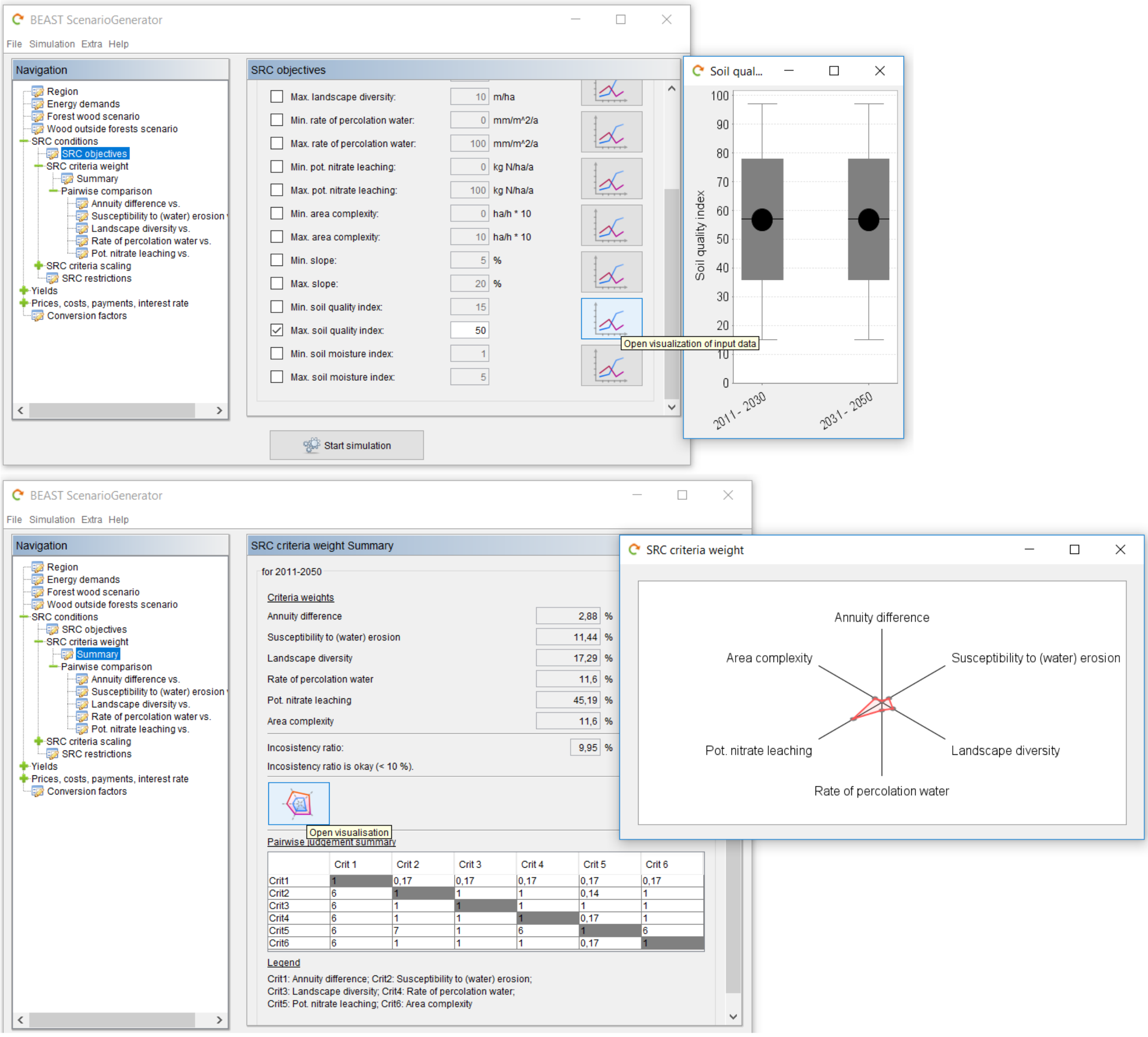

Figure 2. Two example views of the ScenarioGenerator of BEAST tool. On top of the figure: SRC objectives selection. Here, only field with a low soil quality (index < 50) should be selected. The plot on the right shows the distribution of the soil quality index in the study area, which is given as orientation of meaningful values. As the soil quality index of a field is assumed to be invariable over time, the value distributions are identical for both simulation periods (could be changed via the input data). On bottom of figure: The summary view of criteria weightings based on AHP. The spider graph on the right delivers a visual representation of the importance ranking of the different selection criteria. In this example, pot. nitrate leaching has the highest importance, i.e. areas which get out most of SRC regarding nitrate leaching will be prioritized.

Once the scenario is defined the simulation can be requested. Depending on the number of polygons and the settings the processing takes some seconds till some minutes. When the simulation is finished the results can be stored in the same or a new scenario file and the scenario results can be opened in the ResultsExplorer (Figure 3). There are many fold options for analyzing the results. The interactive demand vs. supply plot shows, if the predefined demand of dendromass can be delivered under the defined scenario settings and, if so, which dendromass sources are required. The results are presented in several tables, barcharts and boxplots and can be analyzed by manifold criteria. Furthermore, they can be explored spatially with the MapViewer component (Figure 4) and it is possible to export the data in tables and maps to be further analyzed in external software.

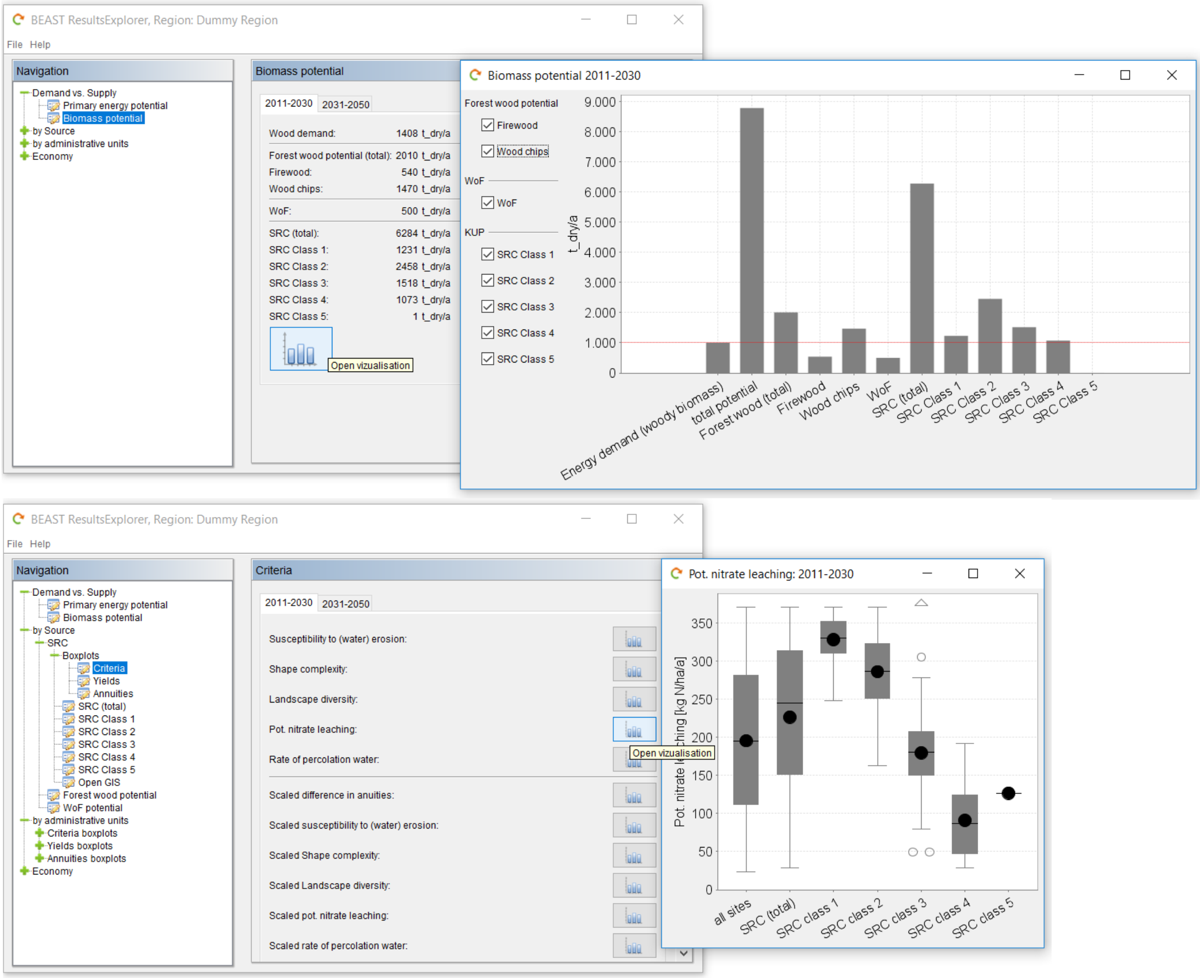

Figure 3. Two example screenshots of the ResultsExplorer for the example given in Figure 2. On top the woody biomass demand is compared to the biomass potential for the selected scenario. In the figure on the right, the different sources can be switched on and off and the necessary mix of sources to meet the demand can be explored. On bottom the distribution of the pot. nitrate leaching of the potential SRC fields are given – as total over the whole study region as well as total over all SRC preference locations and for each preference class. The effect of the high weight of this criteria is indicated by the strong decrease over the different preference classes.

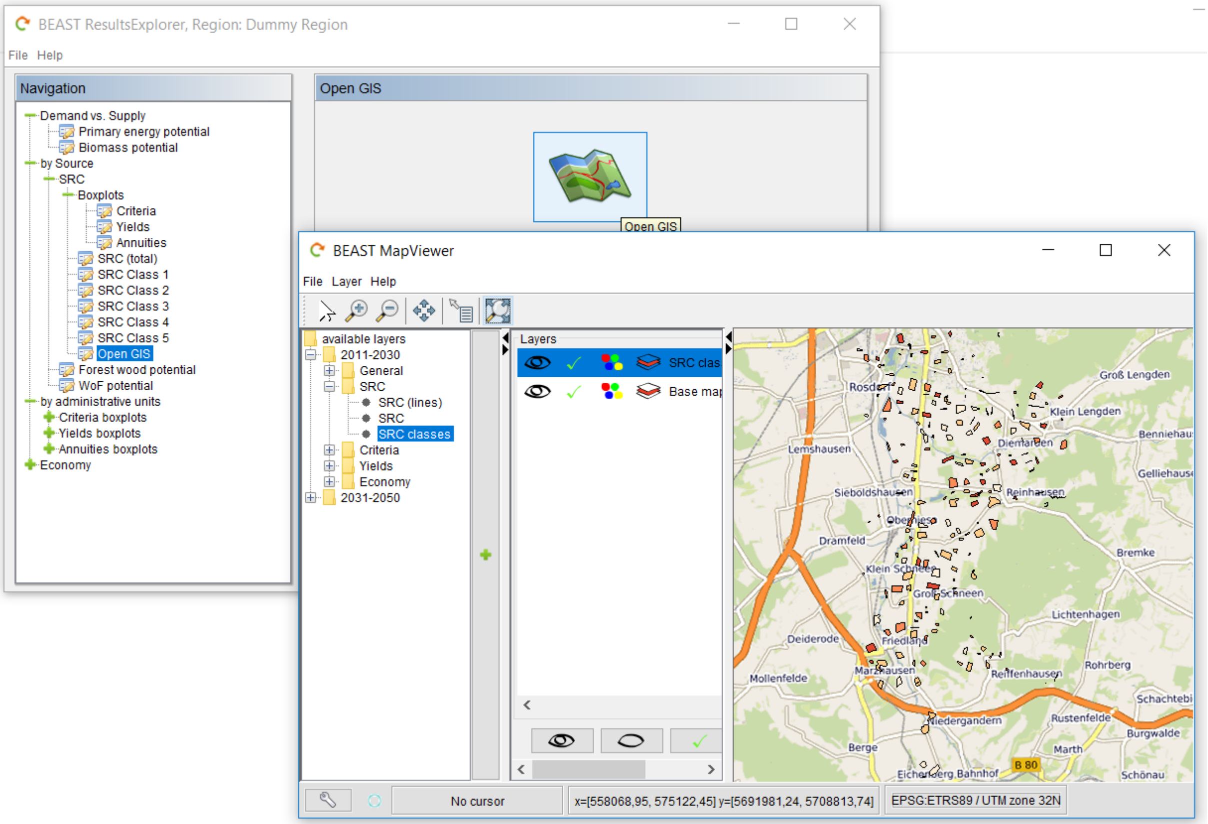

Figure 4. Screenshot of MapViewer to analyze the scenario results of potential SRC fields spatially. Red colored polygons indicate selected potential SRC fields. The different colors represent the different preference classes. A minimum distance between two SRC field of 100 meters was specified in the ScenarioGenerator, which explains the scattered spatial pattern.

6. Conclusion

The BEAST system presented here allows users to integrate economic returns with ecological assessments of the utilization of woody biomass on local and regional levels. It was developed to facilitate participatory scenario generation and analysis in stakeholder dialogues. During the tool's development, the concept and prototypes were presented to stakeholders, and their feedback has been incorporated into the development of the system.

The system was applied to the Göttingen district in Central Germany (Busch & Thiele 2015); however, the system has been implemented as a scenario simulation shell and is, therefore, generic enough to be applied to other study regions. It is possible to replace criteria sets without rebuilding the system architecture. Therefore, Hübner et al. (2016) adapted the BEAST to a second study area with a focus on landscape metrics, and a report about the general methodology is currently under review by the International Energy Agency (Busch 2017).

Furthermore, the range of applications could be extended. For example, Bredemeier et al. (2015) and Busch (2017) used the BEAST methodology for purely scientific purposes instead of for stakeholder dialogs by running multiple scenario simulations – with cost and price values drawn from statistical distributions – as Monte Carlo simulations manually. The BEAST software could be extended to run and analyze those Monte Carlo simulations automatically.

However, key factors for the long-term success of any such simulation system are continuous adaptation, improvement and support. Therefore, the system is now released under an open-source license and placed into the hands of the scientific community for usage and further development. It comes with a usage guide, documentation, and a development guide.

If governments want to foster the production and use of wooden bioenergy as one key part of a renewable energy mix, first, a realistic estimation of available biomass potentials is needed, and second, governmental energy planning needs to reflect the interests of various stakeholders, such as land owners and nature conservators, which usually results in regional participation processes. Tools such as the one presented can support such political participation processes with participative modeling techniques using scenario quantifications and visualizations and, therefore, should become an integral part of such participation processes. However, even if such tools are developed in a scientific framework, as is the case with the BEAST software, they can only be successful if they do not appear as black boxes. Thus, they should always be available as open source software.

Digital Supplement

A. Process Map of BEAST

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Appendix A – Process map of BEAST

The figure sketches the process flow implemented in the BEAST software with four main blocks for the three wooden bioenergy sources and the reference crop rotation. Processing of Short Rotation Coppices is distinguished into three consecutive sub-blocks: the first one runs independently for each arable field geometry, the second one takes the results of the reference crop rotation into account, and the last one selects the preference sites according to the dependence of the other geometries.

Note: The document is in DIN A1 format. Printing it on DIN A4 paper scales the figure down to 33%, which makes it extremly small.