Using “BEAST” to support the local dialogue on lignocellulosic cropping for energy use, climate protection and sustaining ecosystem services

Tool description and case study scenario application for the Göttingen district, Germany

BEAST
Bio-Energy Allocation and Scenario Tool

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1 Introduction

Lignocellulosic crops not only provide woody biomass at low CO_2 avoidance costs [1-3], but also conserve several ecosystem services such as erosion protection [4-6], groundwater protection [7], habitat creation [8-10] and structural enrichment [11-14]. However, lignocellulosic crop production on agricultural land in Europe occupies only a small niche with largest wood production from short rotation coppice (SRC) occurs in the UK, Sweden and Poland [15]. For Germany, literature studies and regional surveys indicate [Boll et al [16]] that apart from economic uncertainties such as the contribution of SRC to income generation, diversification and local added value, the wide range of regulations, laws and perceptions of local authorities creating extended planning-approval time is perceived as a major disadvantage of SRC. Nonetheless, Poplar SRC in Germany can be competitive with annual crops [17-20] but proper site selection as well as a suitable business model for wood chip production is critical for its economic success. Thus, apart from communicating economic success stories [e.g., 20, 21] and transferring scientific knowledge into practice [22], it is crucial to develop participatory communication and decision support strategies with local actors and communities to overcome perception barriers [19, 23]. Given the necessity of an ongoing substitution of biomass sources for fossil fuels [24-27], lignocellulosic crops, either as SRC or agroforestry systems (AFS) or both, provide an excellent opportunity to provide decentralized energy supply accompanied by desired environmental outcomes such as conserving biodiversity, soil fertility or water quality on agricultural land. However, if lignocellulosic cropping should play a larger role in future renewable energy supply and sustainable land-use approaches it is important to identify economically competitive sites and to illustrate how ecosystem services will be hampered or sustained in comparison to region-specific annual cropping.

Local evaluation dialogue and visualization tools are needed to help local communities grasp the associated opportunities and constraints associated with lignocellulosic biomass cropping. To support this need, the “Bio-Energy Allocation and Scenario Tool” (BEAST) was developed to rapidly create, evaluate and visualize scenarios of woody biomass supply and its associated economic and ecological outcomes in a spatial explicit way. BEAST is scale-independent since it serves as a modelling shell for largely pre-processed data [29, 18]. Based on a simple evaluation strategy, BEAST can be applied as a decision support tool during stakeholder workshops, providing the participants with spatially explicit maps, graphs and tables depicting ecological and economic outcomes as well as biomass supply associated with SRC cropping scenarios. The target actors are stakeholders involved in regional development issues, local climate protection policy-makers, renewable energy concerns, land use planning processes, and local farmers and forest owners. In Germany, BEAST was applied on a regional scale (Göttingen district in Lower Saxony) to support the local dialogue on lignocellulosic cropping for energy use, climate protection and sustaining ecosystem services. This report introduces BEAST by outlining the concept of the tool in chapter 2. Chapter 3 addresses a case study example to illustrate scenario generation and results presentation with BEAST. Chapter 4 provides accompanying background information on methods applied and input data used for the case study application in chapter 3.

2 BEAST - An overview

2.1 DEVELOPMENT

Building on concepts of Busch [28], BEAST was developed by the author and Jan C. Thiele, Ecoinformatics, Biometrics and Forest Growth Department, Göttingen University during the BEST project (http://best-forschung.uni-goettingen.de/ - in German). Valuable input and data contribution were provided by Kai Husmann (Northwest German Forest Research Station), Christian Kleinschmit (Forest Economy Department, Göttingen University), Benjamin Krause (Nature Conservation Department, Göttingen University), Norbert Lamersdorf (Soil Science of Temperate Ecosystems Department, Göttingen University), Dominik Seidel (Forest Inventory and Remote Sensing/ Silviculture and Forest Ecology of the Temperate Zones Department, Göttingen University), Stephan Willems (Forest Work Science and Engineering Department, Göttingen University) und Matthias Wolbert-Haverkamp (Department of Agricultural Economics and Rural Development, Göttingen University).

2.2 CONCEPT

BEAST serves as a modelling shell for largely pre-processed data, producing rapid results by calculating and visualizing the effects of user-defined scenarios of woody biomass use [29, 18]. Supporting all kinds of spatial geometries, BEAST currently refers to agricultural field shapes due to the input data provided. In this study BEAST only addresses arable fields (around 20.000 geometries) for the allocation of potential SRC sites (see Figure 2-1).

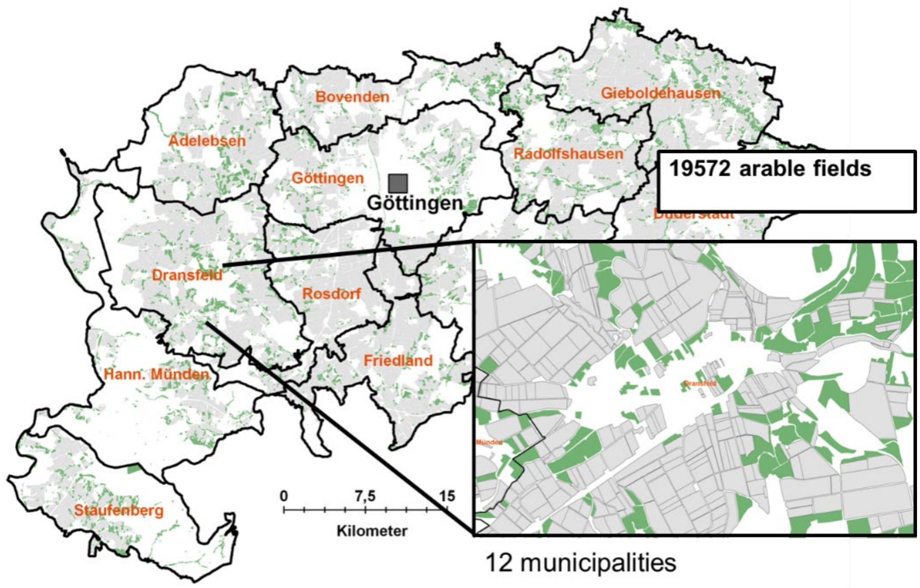


Figure 2-1 Arable (grey) and pasture (green) field geometries as spatial SRC potential in BEAST

BEAST addresses woody biomass supply from three sources: (a) forests, (b) hedgerows and solitary trees, woodlands and shrubs (WoF – Woody biomass outside Forests), and (c) short rotation coppice (SRC) on agricultural land. Only SRC is simulated and visualised in a spatially explicit way. Preferred field locations for SRC can be identified with respect to user-defined scenario objectives and compared to arable reference crops, respectively crop rotations.

BEAST allows the simulation of two separate 20-year periods. In the current version, the base year was set to 2017 and thus, the subsequent periods ranged from 2017-2036 and 2037-2056, respectively. Three main graphical user interfaces, the "Scenario Generator", the "Results Explorer", and the "Map Viewer" are the core elements of BEAST.

Scenario Generator

The "Scenario generator" in BEAST facilitates the expression of scenario objectives by addressing various topics ranging from energy demand over SRC site selection, economic and

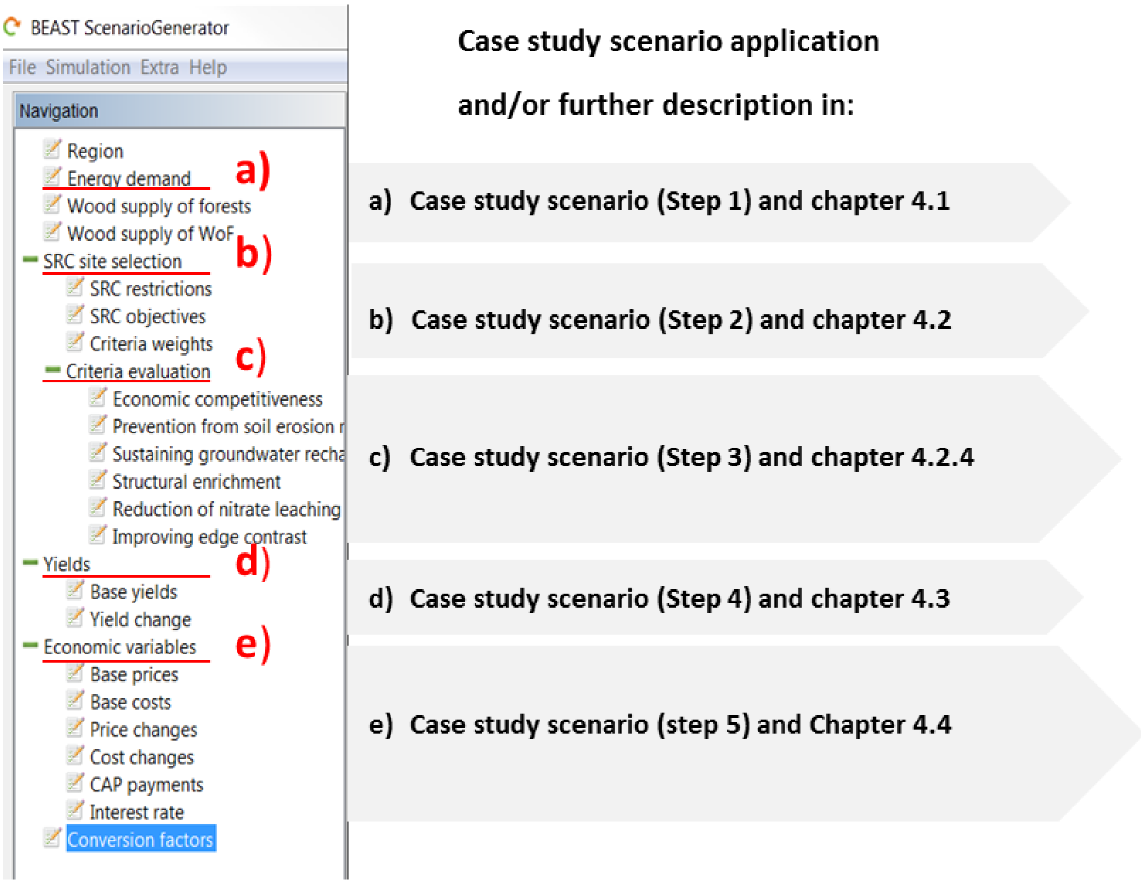


Figure 2-2 Structure of the "Scenario Generator" in BEAST and its cross-references to corresponding information in this report

Energy demand and wood supply (a)

The scenario generation process starts by determining the overall energy demand. BEAST further allows to determine the amount of wood supply originating from (a) forests, and (b) Woody structures outside forests ("WoF"). However, this report focuses on lignocellulosic cropping on agricultural land and therefore Forests and WoF are not addressed.

"SRC site selection" (b)

By using the topic "SRC restrictions" the user can apply spatial filter rules to express his/her preferences with respect to e.g., ecological functions, buffer distance or spatial composition). The section criteria "Criteria objectives" allows to define thresholds for various indicators and thus to filter the spatial selection of suitable SRC fields. Criteria weighting can be used under the topic "Criteria Weights" to (a) express a specific balance of multiple criteria, and/or (b) to exclude selected criteria from the analysis.

“Criteria evaluation” (c)

The “Criteria evaluation” section currently comprises a set of five ecological indicators. From the numerous options to quantify various ecosystem service criteria, these indicators [“Potential soil erosion”, “Reduction of deep percolation water”, “Soil water exchange rate”, “Ecotone density”, “Area Performance”] were selected according to stakeholder’s preferences in the Göttingen district and can be altered or modified according to preferences in other case study regions. Annuities of annual crops (sugar beet, maize, wheat, barley, oilseed rape) and Poplar SRC serve as economic indicators. The annuity difference between the selected annual crops and Poplar SRC is than subject to criteria evaluation. It is the major goal of the “Criteria evaluation“ application to assign an assessment function to a quantitative indicator in order to establish a corresponding criteria evaluation (e.g. evaluate the pot. soil erosion risk with respect to the criterion “Protection from soil erosion”). The crucial part of the “Criteria evaluation” section (and an important part of the participative scenario approach in BEAST) is to allow the user to “design” these qualitative evaluation functions with respect to the corresponding quantitative indicators. This way, expert knowledge as provided e.g., by reference scenarios, can be refined according to specific local conditions. However, with this approach comes great responsibility, e.g. to avoid biased evaluation or misinformation.

Yields (d)

Yield numbers for the reference cops and Poplar SRC originate from spatially explicit yield modelling [18, 30]. These yield numbers can be used in the “Reference yields” section to shift the yield levels according to local conditions or user preferences. Further, crop yield levels can be modified by applying a factor of annual yield increase in the “Yield increase” section. Note, that cost calculation as part of the annuity computation (see next paragraph) is yield-sensitive, and thus, the underlying yield levels of both SRC and annual crops have an impact on costs.

Economic variables (e)

In the corresponding submenus, the user can vary costs and commodity prices as well the annual cost and price changes for the annual reference crops and Poplar as SRC reference crop. Additionally, the amount of CAP-related direct payments (section “CAP payments”) as well as the interest rate and be set as part of the economic calculation.

The resulting economic return is calculated via a dynamic capital budgeting approach as annuity for both, annual reference crops (sugar beet, maize, wheat, barley, oilseed rape - and their specific crop rotations) and poplar SRC in 5-year rotation. Further, it is possible to compare the economic output of annual crops/crop rotations and SRC in terms of annuity differences (see chapter 4.4 for detailed information).

Results Explorer

The Results Explorer shows aggregated tabular and graphic results of the scenario generation process for the study area and for municipality level (see Figure 2-3). Examples are given in chapter 3.5 when showing the results of the case study scenario.

To start off, bar graphs and tables address the overall numbers of primary energy and biomass supply according to the scenario settings. The “SRC section” provides a wide range of tabular and graphic information, starting with a table summarizing the potential suitable area for SRC, the corresponding biomass and energy supply as well as the average indicator values for the study area. Further, results are presented for potential SRC fields showing boxplots figures of (a) Indicator and criteria values, (b), Crop and SRC yields, and (c) Annuities for crops and SRC.

In the "administrative units" section, the same results are presented on a municipality level, enabling the user to search for spatial differences in SRC suitability.

The "Forests" and WoF" sections provide summary tables comprising the information on biomass and energy supply as well as the average annuity resulting from these sources of wood supply (Not addressed in this study!).

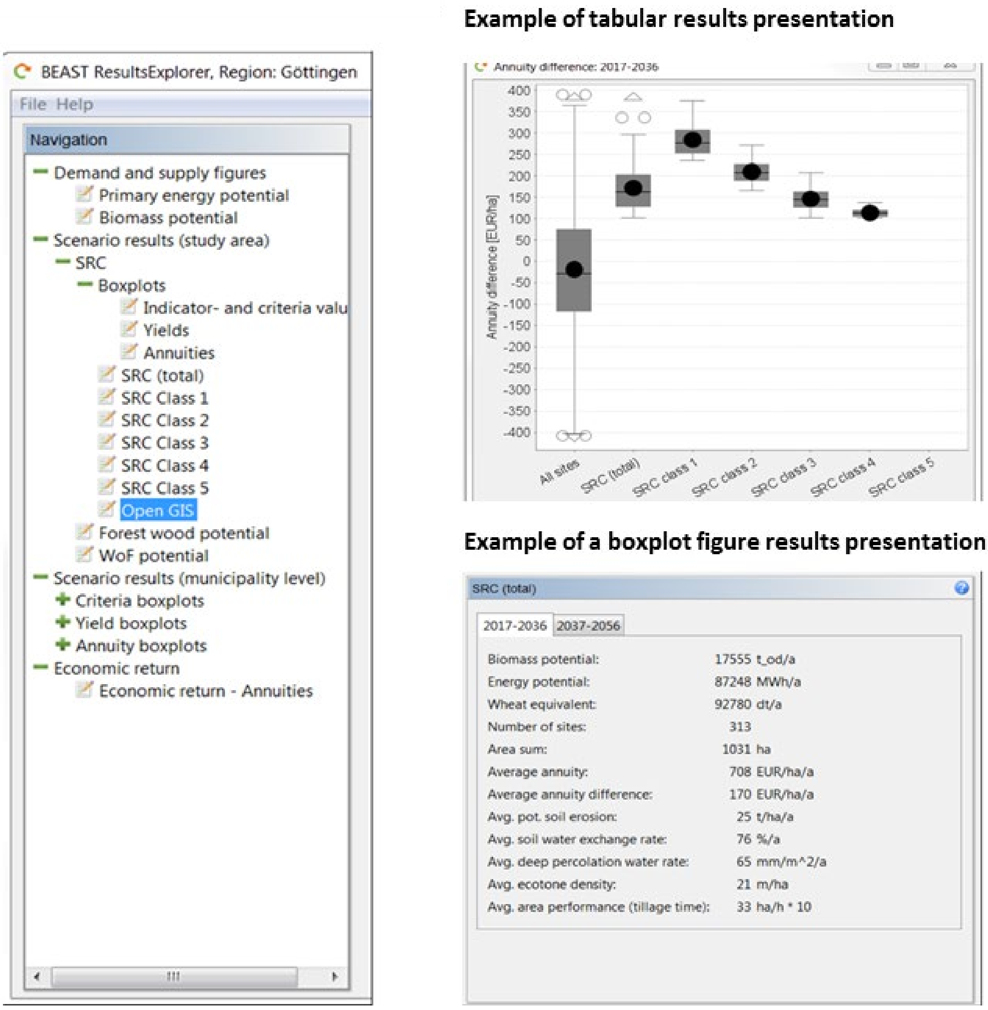


Figure 2-3-Structure of the "ResultsExplorer" and examples of tabular and graphic results presentation

MAP Viewer

While the Results Explorer itself comes up with tables and boxplots showing demand and supply figures as well as information yields, annuities, criteria, and indicator values, the "Map Viewer" interface supplies basic GIS functionalities to spatially analyse the many layers comprising the scenario input information and scenario results (see Figure 2-4). Additionally, the user can load external data sources such as web mapping services, polygon- or raster data. Advanced GIS procedures could be carried out in a GIS like ARCGIS or QGIS by exporting the results as a shapefile (see Chapter 4.5 for details).

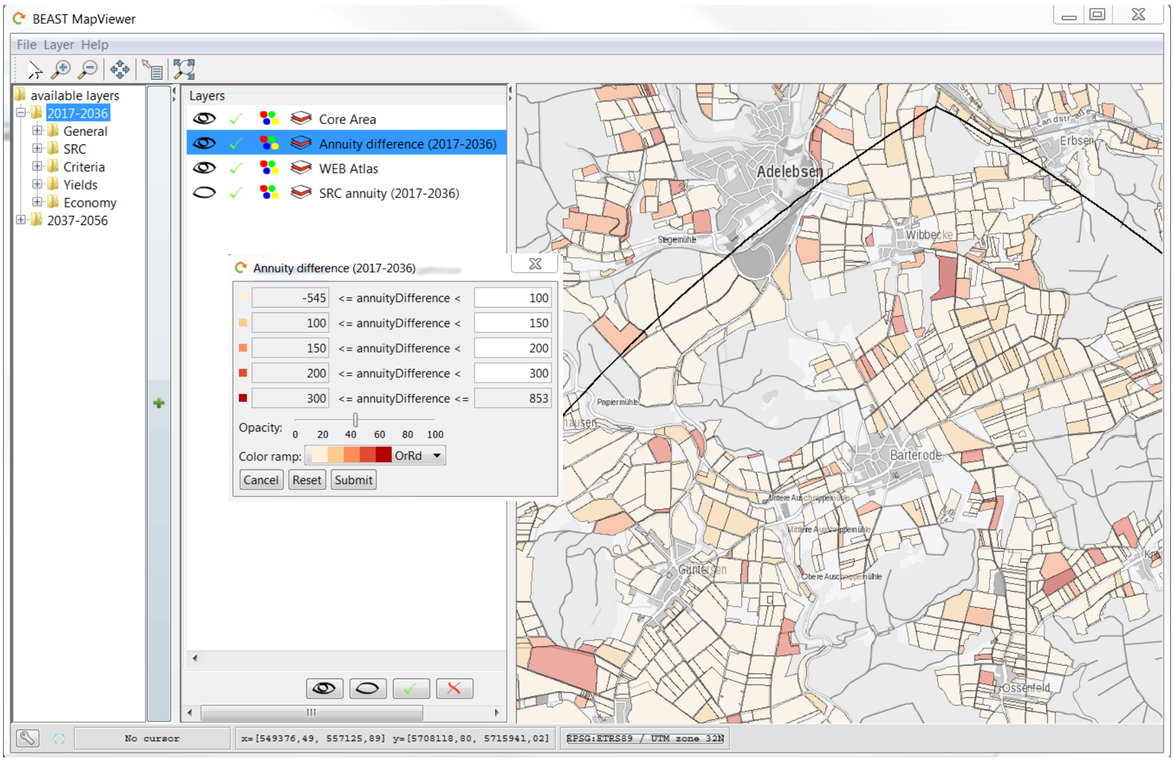


Figure 2-4 Screenshot of the "MapViewer" showing results of the case study scenario application

3 Case study example– wood chip supply for heating public buildings to promote SRC cropping and meet climate protection goals in the Göttingen district, Germany

In many German regions, there are ambitious climate protection goals in place aimed at reducing the energy demand by 30% by 2030 and expanding the local renewable energy supply to cover 60% of the energy demand in 2030 from local and decentralized renewable energy supply [31]. Half of this renewable energy supply is to originate from biomass sources. This provides an opportunity to integrate biomass cropping with spatial planning, regional renewable energy concepts and regional rural development programs such as the EU-funded LEADER initiative in a way that that participatory discussion of the several objectives in place could facilitate the complex negotiation process between various stakeholder groups and local key players [31, 32, 33]. Spatial development scenarios for lignocellulosic crops need to be developed that address suitable areas in terms of both environmental and socio-economic objectives. This case study example of the Göttingen district, Germany (see Figure 2-4), shows how a participative scenario generation could be put to practice with BEAST.

3.1 CASE STUDY AREA

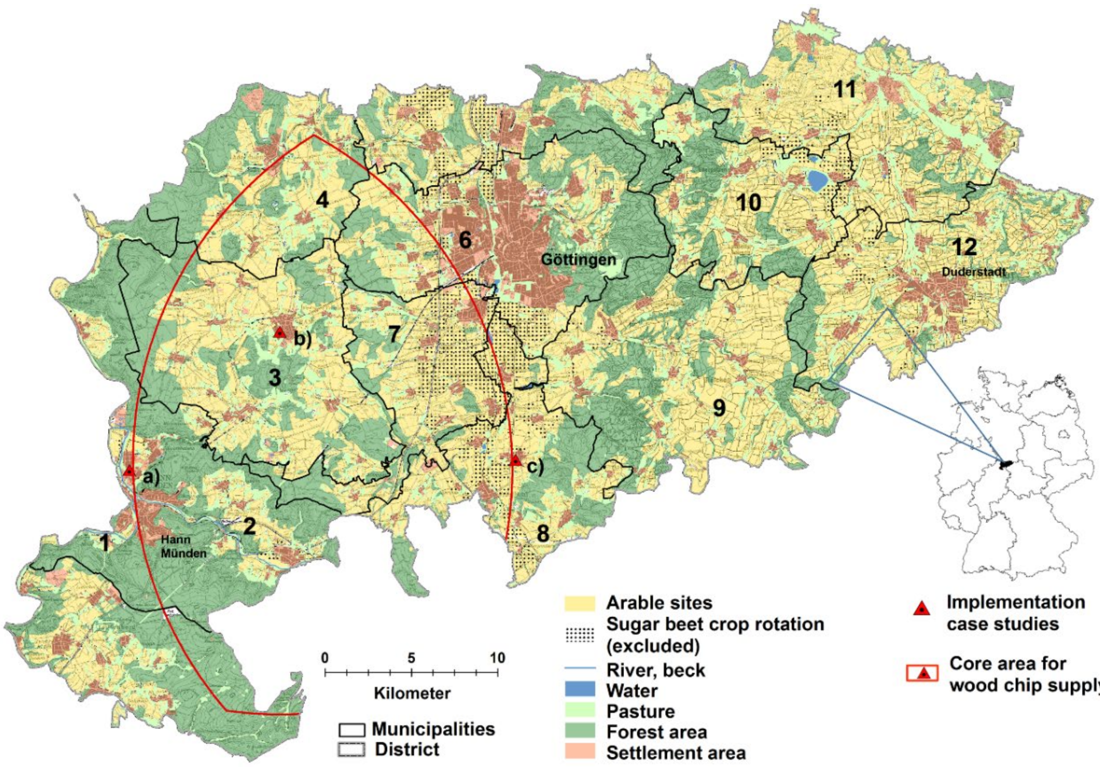


Figure 3-1 The Göttingen district as study area. Right: Overview of Germany depicting the federal states and the study area in black. Left: Map of the study area indicating the various land cover types, municipality borders, and the core zone for wood chip supply according to the intersecting 20km radii surrounding each of the three public building complexes

The total area of the Göttingen district, Germany, is 1.118 km², 55 % of which is used for agriculture. Arable sites account for more than 80 % of the agricultural area (49.000 ha). The land cover pattern is diverse, a mixture of forest, arable land and pasture constitutes a varied set of mosaic landscapes with the central and eastern region dominated by arable land and the western, hilly part is shaped by larger forest patches. Natural growth conditions for SRC are quite suitable in a German context [39], given an average annual precipitation of around 700mm (1981-2010 – derived from DWD 1km grid information), a mean annual temperature of 8.9°C (1981-2010 - derived from DWD 1km grid information) [40], and a majority of medium- to high productive soils [41].

3.2 SCENARIO STORYLINE AND OBJECTIVES

To set incentives for a supply of locally produced biomass from lignocellulosic crops, district capital and local municipalities decided to begin providing wood chip-based heating for public building complexes (letters a, b, and c in Figure 3.1 and Table 3.1) in three municipalities in the Göttingen district. The feasibility of wood chip heating and the corresponding annual heating demand for these particular buildings was evaluated and calculated by 3N (Network Renewable Resources for Lower Saxony, Germany) as contribution to the BEST-project (www.best-forschung.de).

Location	Building types	Heating demand in MWh/a	Wood demand in t_{od} a^{-1}*	Primary energy supply from SRC (corresponding wood supply)**
Hann. Münden **(a)**	Complex of 7 public school buildings	1.400	313	1830 (368)
Dransfeld **(b)**	Complex of five public buildings (schools, kindergarten, coliseum)	1.167	261	1526 (307)
Groß Schneen **(c)**	Complex of public school buildings	584	131	763 (154)
		3151	**705**	**4119 (829)**

*Table 3-1 Heating demand and corresponding wood demand for three public buildings as examples for wood-chip-based heating. *The wood demand calculation considers a heating efficiency of 0.9 [42] and an energy content of 4.97MWh tod^{-1} [43]. **Wood supply, respectively primary energy supply calculation reflects a heating efficiency of 0.9, woodchips storage losses of 15% [79, 102], and an energy content of 4.97MWh tod^{-1} [43]*

To promote local energy production, it is mandatory to identify synergies and conflicts with existing local planning goals as well as address the interests of various local actors. The key players in this scenario are the farmers/land owners who need to be convinced to grow lignocellulosic crops and the owners of the buildings interested in an economically viable energy supply. There interests are addressed with the following scenario objectives:

1. The scenario visualization enables the farmer/land owner to identify suitable arable fields, i.e. fields that show a positive economic return compared to annual reference crops and crop rotations which are typical for the study area (Wheat–Wheat–Sugar beet; Wheat–Barley–Oilseed rape; Maize–Wheat–Maize–Wheat).
2. An average positive annuity difference of 100€ ha^{-1} for SRC is set as threshold to motivate the farmer to switch from annual cropping to SRC on selected fields. The 100€ reflect the upper threshold of revenue losses when wood chips prices drop by 10% compared to the 2008-17 average (see chapter 4.4.4 for details)
3. The most productive sites are excluded from the analysis to address existing scepticism about SRC as a new and perennial crop.
4. For this case study example, a Wheat–Barley–Oilseed rape, and a Maize–Wheat–Maize–Wheat crop rotation are compared to a poplar SRC in 5-year rotation
5. In this scenario the farmer is solely a biomass producer and only provides the harvested (fresh) wood chips in a 20km radius.
6. Municipalities/owners as operating institutions of the buildings will pay end-user prices for wood chips as stated in national statistics.

Existing policy and planning goals, environmental issues as well as stakeholder perceptions and regulations are addressed with the subsequent objectives:

7. Spatial planning objectives [33] are considered with respect to agricultural productivity and structural development (i.e. fields with very high crop productivity are excluded from SRC allocation, homogenous landscape with a lack of woody structure are preferred)
8. Woody biomass supply originates from the core area (i.e. the intersection of 20km supply radii for all three building complexes – numbers a, b, c- in Figure 3-2). Annual wood demand is at least 829 t_{od} a^{-1} (see Table 3.1).
9. Prevention from soil erosion is by preferring arable fields which are prone to soil erosion and subject EU cross compliance regulations [38].
10. Environmental issues are addressed by drawing buffer zones around humid-sensitive areas [34] and excluding SRC from SPA and SAC areas (see chapter 4.2.1 for explanation) [35, 36]. Potential SRC site selection is restricted to arable land since the conversion of pasture

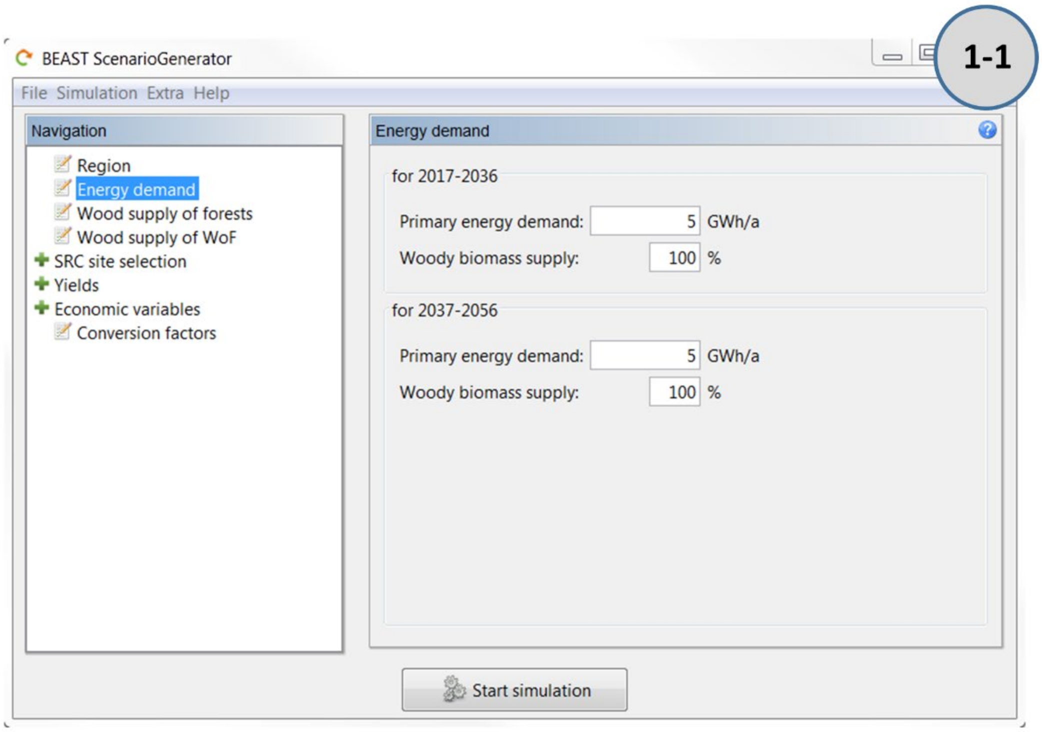
poses potential environmental concerns [36, 37]. Further field selection is limited to a maximum SRC share of 20% for each municipality and to a maximum field size of 10ha to avoid perceived negative effects on scenic beauty and biodiversity [15]

11. Floodplains are excluded from SRC allocation according to federal state flooding regulations [36]

3.3 SCENARIO GENERATION WITH BEAST

The scenario storyline comprises 11 objectives which are subject to the scenario generation with BEAST. There is no pre-defined order for generating a scenario in BEAST – however, for this case study, it is logical to start off with the determination of the energy demand. To fulfil the demanded primary energy supply of the three building compounds (see Table 3-2) an energy demand of 5GWh is used as scenario input.

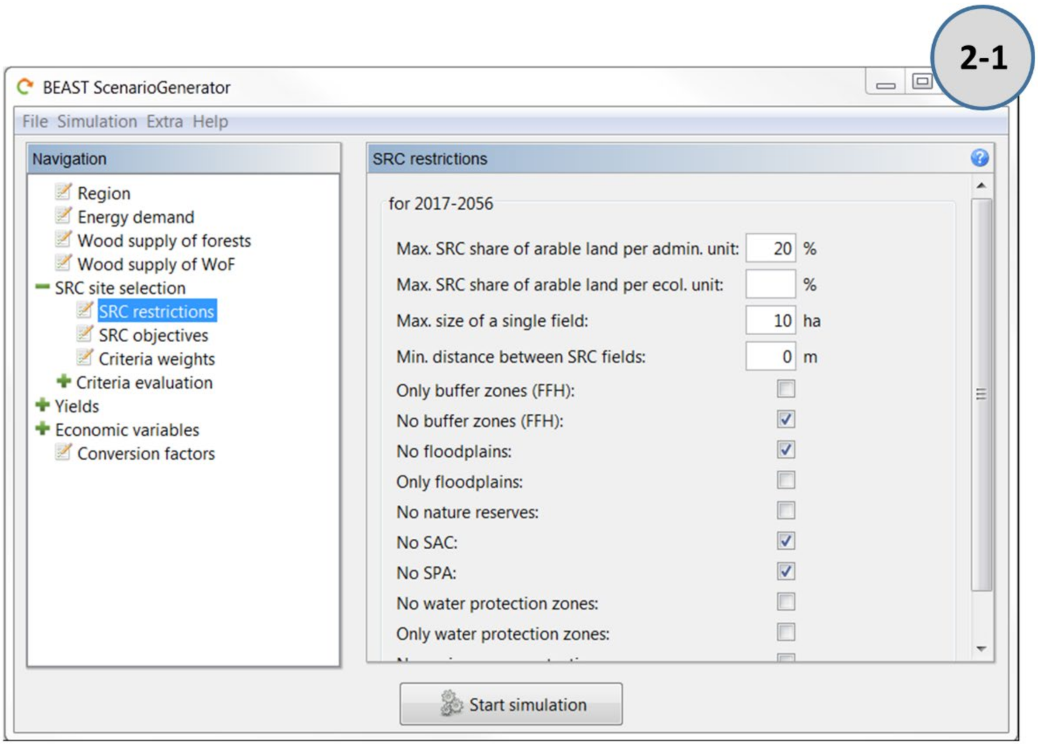
Step 1: Define the energy demand (Scenario objective 8)



Step 2: SRC site selection

2-1-SRC restrictions (Objectives 9, 10)

There are several options to define spatial filters for the SRC selection procedure in BEAST. In this scenario, SRC selection is excluded from SAC, SPA and in buffer zones of humid-sensitive areas to address nature conservation issues. Further, the amount of potential SRC fields is limited to a 20% share of agricultural for each municipality and is restricted to field sizes smaller than 10ha. Finally, flooding areas are excluded from SRC allocation by activating the "No floodplains" button.



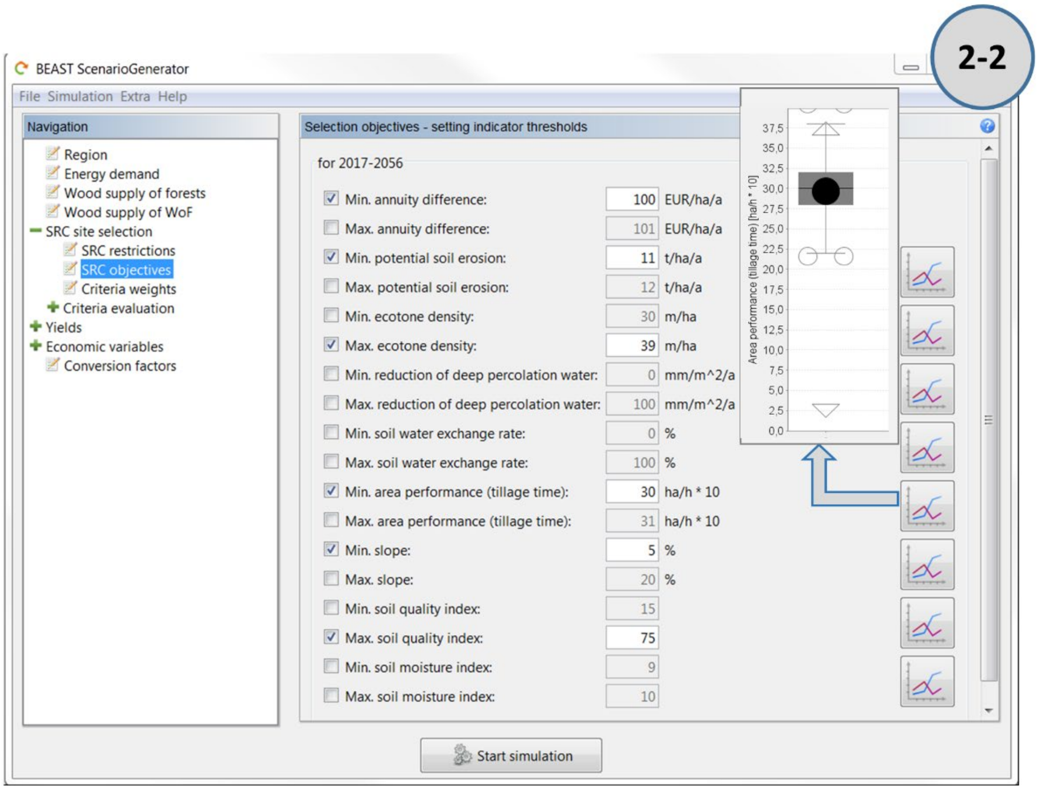
2-2- Objectives selection (Scenario objectives 1, 2, 3, 7, 9, 10, 11)

The objectives selection options in BEAST allow to set min-max thresholds and thus enable the user to fine-tune the spatial restrictions as well as to define suitable indicator value ranges for the multi-criteria evaluation (see step 5).

To meet the scenario objectives 1 and 2, only areas with a positive annuity difference are deemed as suitable. A positive annuity difference expresses that SRC is economically superior to the selected annual crops. To cover the perception of an additional risk when cropping SRC instead of annual crops the threshold is set to +100€ ha^{-1} a^{-1}.

Thresholds for the indicators (a) slope, (b) soil quality, and (c) area performance are set to select the most productive and thus preferable fields for a Wheat-Wheat-Sugar beet rotation and exclude these sites from the SRC selection (scenario objective 3). The threshold setting avoids a selection of flat to slightly inclined fields with high productivity (high soil quality index) and favourable geometries (higher area performance – i.e., lower labour- and machinery costs).

These settings are based on local experience – however, the boxplot graphs allow the user to get an impression of the value range for each indicator and create own threshold corridors.



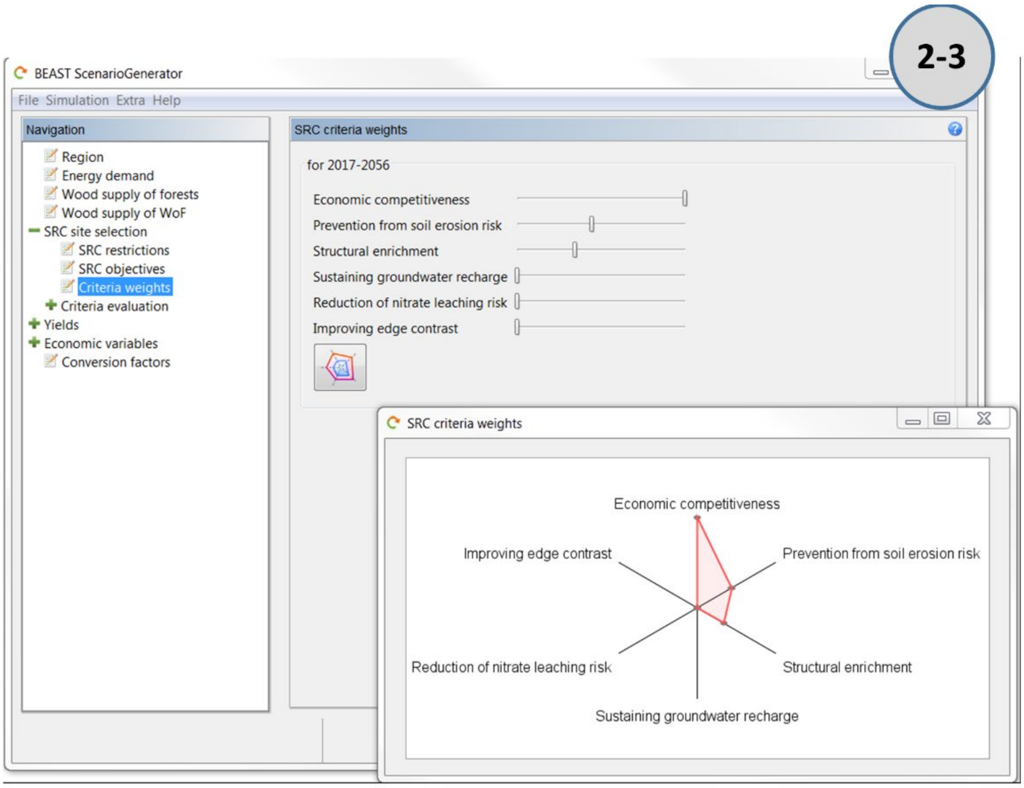
Spatial planning objectives with respect to structural development are met by defining a threshold corridor for the ecotone density. The indicator ecotone density describes the density of woody edges in agricultural landscapes (see chapter 4.2.4 for details). Setting the maximum threshold to 40m ha^{-1}, restricts the selection of potential SRC sites to agricultural fields with an ecotone density lower than the median value of the case study area (scenario objective 7).

Erosion protection (scenario objective 9) is addressed by setting the minimum threshold of potential soil erosion (water-induced) to 11t ha^{-1} a^{-1} which corresponds to EU Cross Compliance regulation (farmers must take protective measures).

Scenario objective 10 is met by excluding SRC from SPA and SAC regions and restrict SRC site selection to arable land. Arable fields with SRC have a maximum share of 20% for each municipality and a maximum field size of 10ha to avoid perceived negative effects on scenic beauty and biodiversity. Floodplains are excluded from SRC allocation to meet scenario objective 11.

2-3 - Criteria weighting (Scenario objectives 3, 9, 10)

The final step of the "SRC restrictions" section is to weigh the selected criteria allowing the user to express his/her preferences for specific criteria. Of the three criteria selected, "Economic competitiveness" was evaluated most important and thus, given the highest weight. Soil protection, i.e. "Prevention from erosion risk", was given a higher weight than "Structural enrichment" because water-induced risk of soil erosion is a widespread phenomenon in the study area [] with many arable fields being subject to EU cross compliance regulations. Criteria weights for the other 3 criteria were set to zero because these criteria were not subject of this scenario.



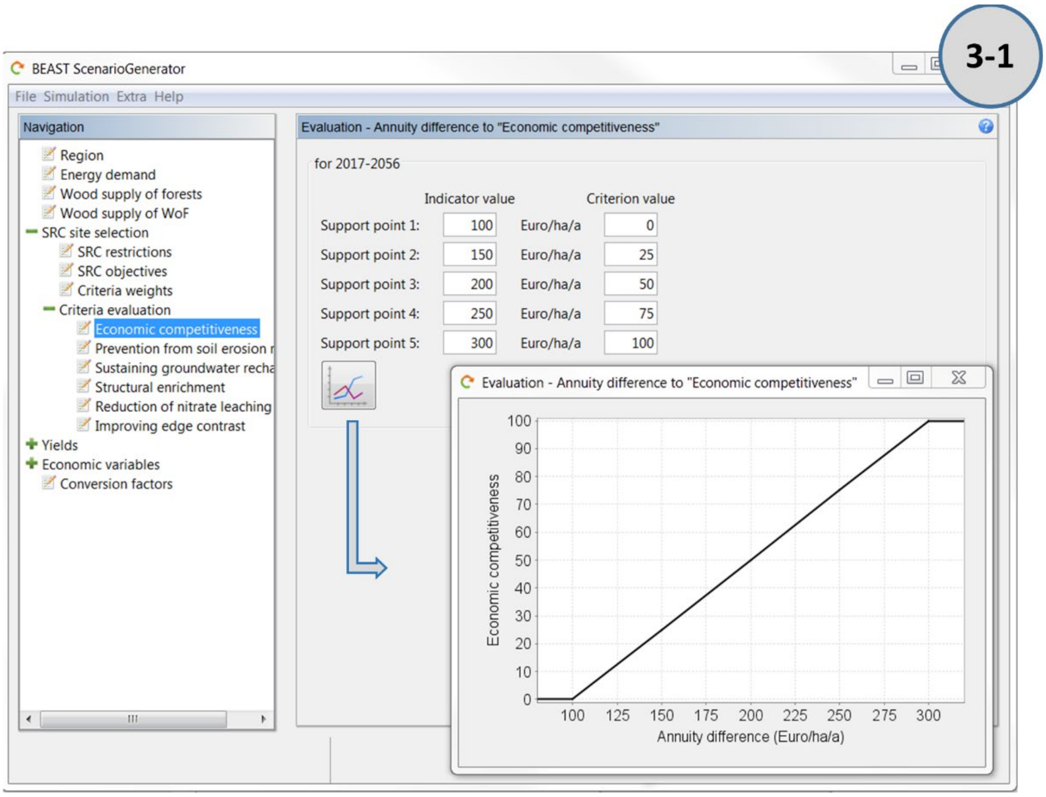
Step 3: Criteria evaluation (Scenario objectives 2, 7, 9, 10)

For this scenario three criteria and their corresponding indicators are selected: (a) Economic competitiveness, (b) Prevention of soil erosion risk, (c) Structural enrichment.

To allow for a multi-criteria calculation, all criteria values are scaled to fit in a range from 0 to 100. To do so, the user defines a function representing the evaluation of the criterion-specific quantitative indicator value. Five support points enable the user to create various shapes of functions. For the indicator evaluation of the three selected criteria simple ramp functions were created with the thresholds of the corresponding indicators (see step 2-2) used as minimum values (0). More information on the indicators and their corresponding criteria evaluation can be found in chapter 4.2.4.

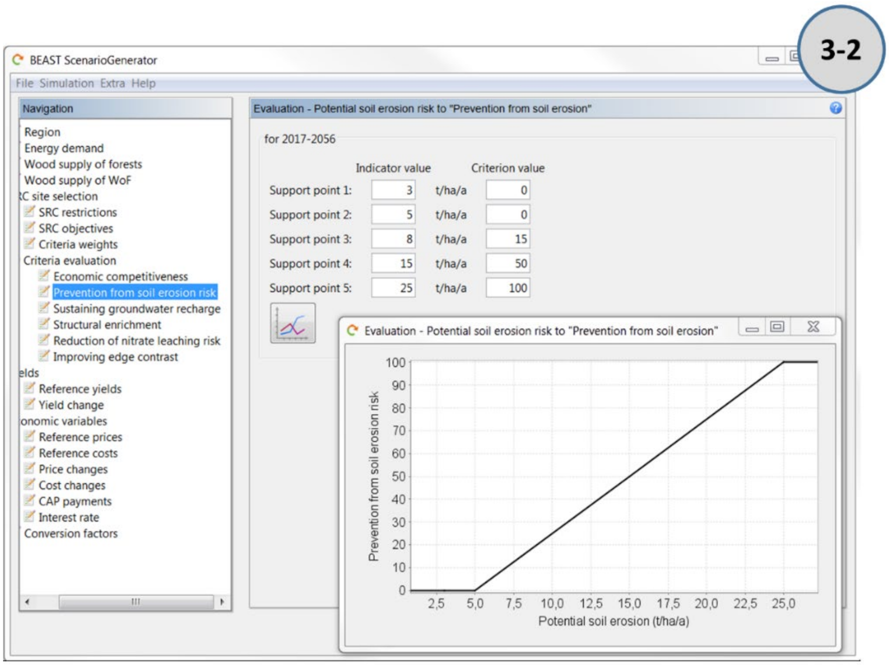
3-1 - Evaluating "Economic competitiveness"

The "economic competitiveness" was set to the maximum value of 100 for annuity differences higher than 300€ ha^{-1} a^{-1} because sensitivity results revealed this as threshold of positive economic return from SRC with costs at the higher end and both prices and yields at the lower end (see chapter 4.2.4 and chapter 4.4.4 for details). The minimum value (0) was set to an annuity difference of 100€ (scenario objective 2)



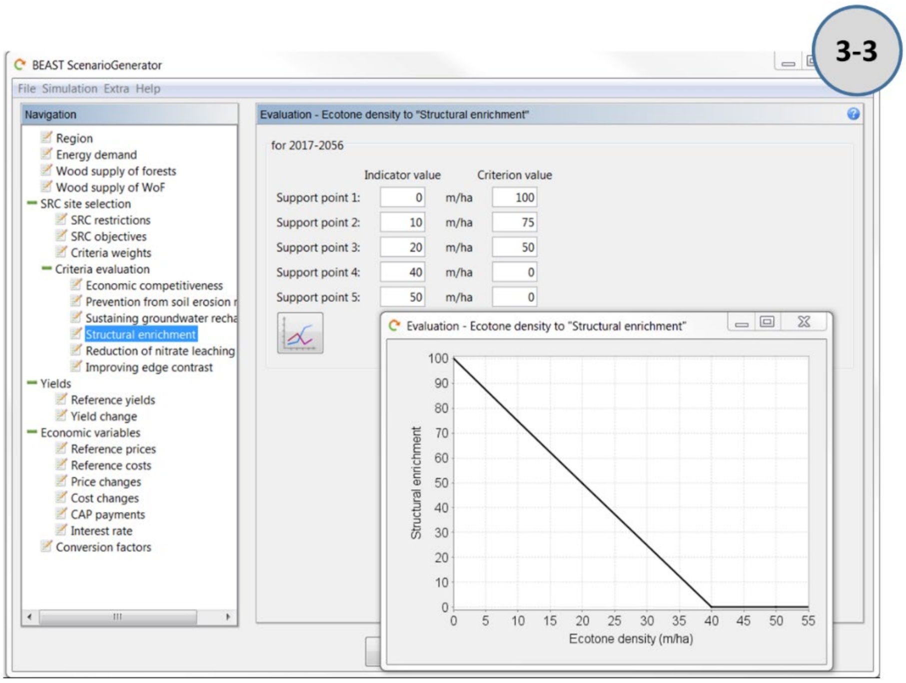
3-2 – Evaluating "Prevention from soil erosion risk"

The evaluation function follows the EU Cross Compliance classification of soil erosion risk [38, 45, 46]. The maximum value of 100 for "Prevention from soil erosion" was assigned to a "Potential soil erosion risk" value of 25 t ha^{-1} since this is the threshold of the highest priority for taking protective measures according to EU Cross Compliance regulations. Accordingly, the minimum value of zero was assigned to values smaller than 5 t ha^{-1}.



3-3 – Evaluating "Structural enrichment"

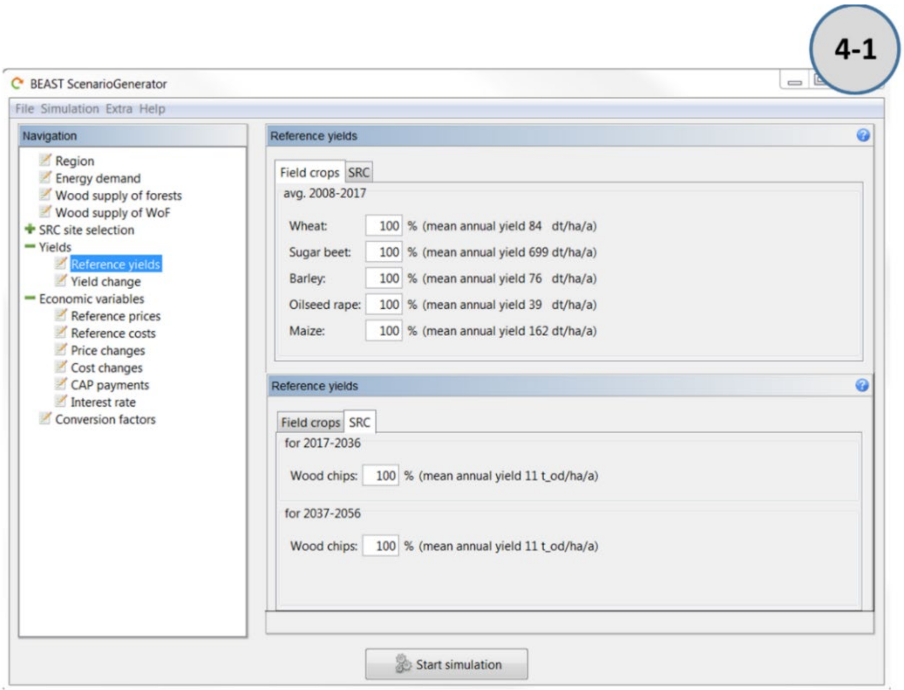
The indicator "Ecotone density" measures woody edges in the agricultural landscape (for details see chapter 4.2.4). The average ecotone density for the study area is 40m ha^{-1}. Thus, for all indicator values between 0m ha^{-1} and 40m ha^{-1} structural enrichment of the agricultural landscape was deemed to be important. Accordingly, the evaluation function for the "structural enrichment criterion was linearly interpolated between these two values, with the ecotone density of 0m ha^{-1} a as minimum value and the ecotone density of 40m ha^{-1} as maximum value.



Step 4: Yields

4-1 Reference yields

For this scenario the average crop yield levels of the last decade (2008-17) were used as input for the reference crops Wheat, Oilseed rape, Maize, Barley (see chapter 4.3.1 for further details). Poplar SRC in 5-year rotation and 7000 cuttings serves as SRC reference system. The reference SRC yield level of 11t_{od} ha^{-1} a^{-1} reflects the area-weighted average yield level over a 20year management period on arable sites in the study area (see [16], and chapter 4.3.2 for further details).



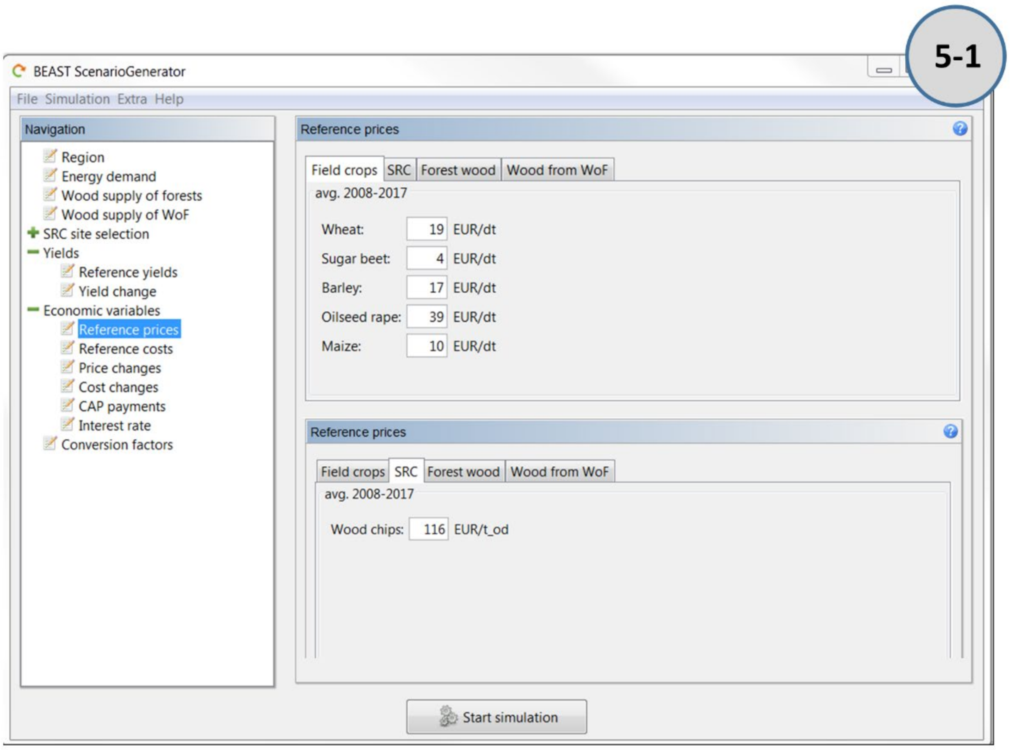
4-2 Crop yield changes

Yield changes for annual crops were set to 1.1 % a^{-1} reflecting the average yield increase for the selected annual crops oilseed rape, wheat, barley, and maize over the last decade (2008-17) and the 40year period between 1978 and 2017. For details, refer to chapter 4.3.

Step 5 Economic variables

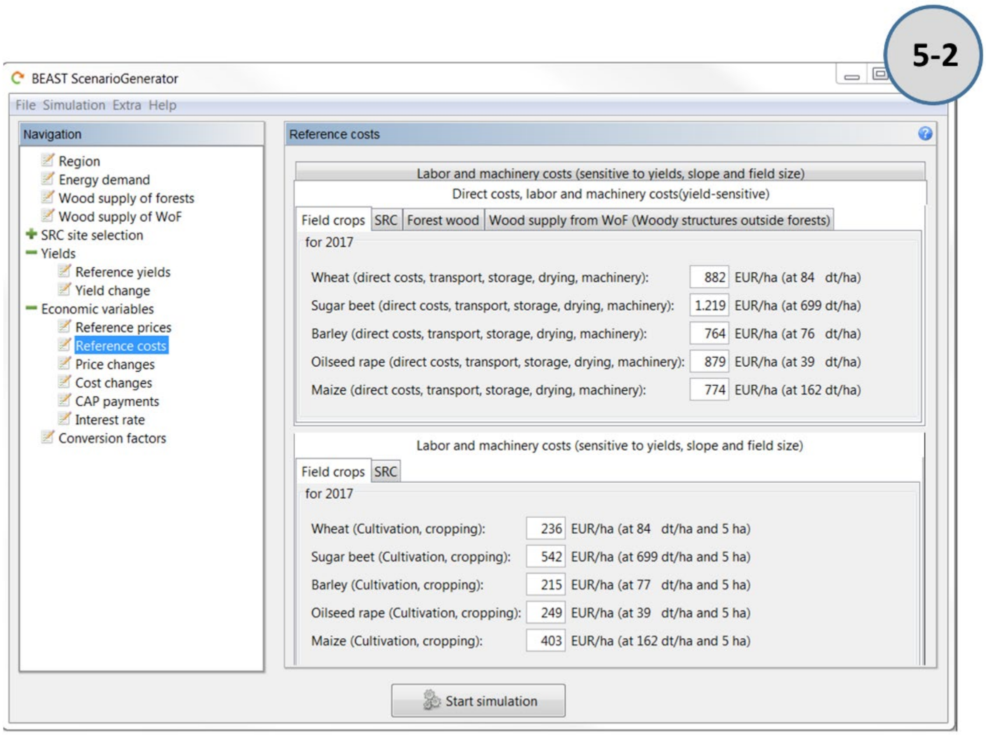
5-1 Reference prices

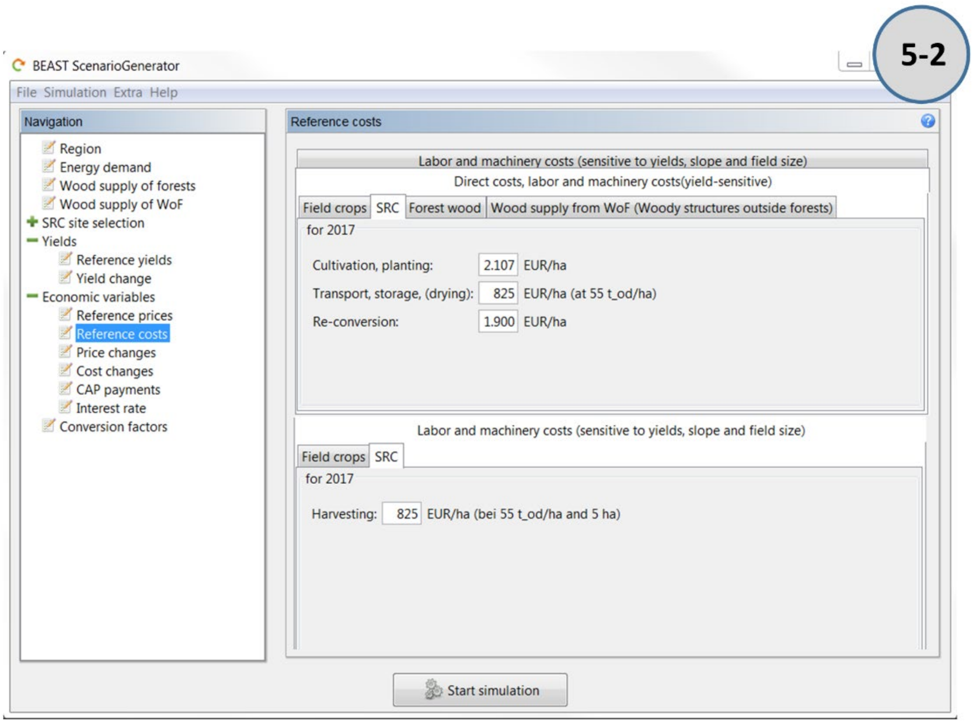
Starting with prices, net prices for this scenario refer to inflation-adjusted decadal averages (2008-17) from national statistics [47, 48]. See chapter 4.4.1 for further details.



5-2 "Reference costs"

Cost inputs reflects the 2017 costs [47]. Costs can be defined for two cost categories. The first cost category aggregates yield-sensitive costs while the second cost category refers to costs which are additionally shaped by slope and field geometry. A detailed description of the underlying cost calculation functions can be found in chapter 4.4.2.





5-3 "Price and cost changes"

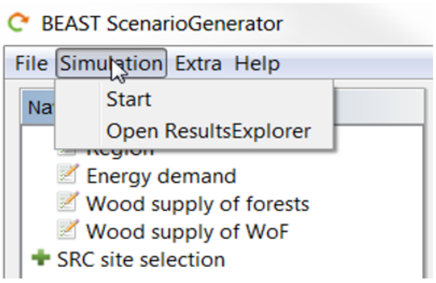
To allow for a better comparison of the scenario results with the current situation no price- and cost changes over time were assumed.

5-4 "Interest rate"

The interest rate was set to 3.5%, reflecting the assumption of future increase in interest rates.

Step 6 Start simulation and open the "Results Explorer", respectively the "Map Viewer"

As a final step of the scenario generation process, the input information is processed ("Start simulation") and the simulation results can be examined by opening the "Results Explorer" and the "MapViewer".



3.4 SCENARIO FACT SHEET

Scenario element	Value or type	Scenario step and further description in chapter	Key references [reference numbers]
Energy demand			
	5GWh a^{-1}	Step 1, chapter 4.1	
SRC restrictions			
- SPA, SAC	Exclusion	Step 2, chapter 4.2.1	[35, 36]
- Humid-sensitive areas	Exclusion		[34, 11]
- Arable fields	<10ha and max SRC share of 20%		[36, 37, 14]
SRC objectives			
- Min. annuity difference	100€ ha^{-1} a^{-1}	Step 2, chapter 4.2.2	Chapter 4.4.4
- max ecotone density	39m ha^{-1}		Chapter 4.4.4
- Min. tillage time	3ha ha^{-1}		[61]
- Min slope	5%		[45, 46, 103]
- Max SQI	75		[18, 55]
Crop reference yields			
- Wheat	84€ dt^{-1}	Step 4, chapter 4.3.1	[18, 55, 63]
- Maize	162€ dt^{-1}		[18, 55, 63]
- Barley	76€ dt^{-1}		[18, 55, 63]
- Oilseed rape	39€ dt^{-1}		[18, 55, 63]
- Sugar beet	699€ dt^{-1}		[18, 55, 63]
Crop yield changes			
- All crops	1.1% a^{-1}		[18, 55, 63]
Poplar reference yield			
	11t_{od} ha^{-1} a^{-1}	Step 4, chapter 4.3.2	[18, 55, 64-67]
Crop prices			
- Wheat	19€ dt^{-1}	Step 5, chapter 4.4.1	[47, 48, 70]
- Maize	10€ dt^{-1}		[47, 48, 70]
- Barley	17€ dt^{-1}		[47, 48, 70]
- Oilseed rape	39€ dt^{-1}		[47, 48, 70]

Scenario element	Value or type	Scenario step and further description in chapter	Key references [reference numbers]
- Sugar beet	4€ dt^{-1}		[47, 48, 70]
Wood chip prices			
	116€ t_{od}^{-1} a^{-1}		[55, 68, 69, 71]
Interest rate			
	3.5% a^{-1}		[70]
SRC reference costs			
Total costs (initial + per rotation period (rot)	4007€ + 1650€ rot^{-1}	Step 5, chapter 4.4.2	[18, 55, 72-102]
Crop reference costs			
Total costs Wheat	1118€ ha^{-1} a^{-1}	Step 5, chapter 4.4.2	[18, 55, 72-102]
Total costs Maize	1177€ ha^{-1} a^{-1}		[18, 47, 48, 55]
Total costs Barley	979€ ha^{-1} a^{-1}		[18, 47, 48, 55]
Total costs Oilseed rape	1128€ ha^{-1} a^{-1}		[18, 47, 48, 55]
Total costs Sugar beet	1761€ ha^{-1} a^{-1}		[18, 47, 48, 55]

3.5 SCENARIO RESULTS VISUALIZATION WITH THE "RESULTSEXPLORER", AND THE "MAPVIEWER"

The objective of this exemplary results visualization is to:

- Check if the demand can be met according to the scenario objectives
- Show spatial distribution of suitable SRC fields in the study area and in the core supply area
- Show possible differences and commonalities between the allocation patterns, criteria scores and ecological synergy effects of suitable SRC sites related to a Wheat-Barley-Oilseed rape (W-B-OR) and a Maize-Wheat-Maize-Wheat (M-W-M-W) crop rotation

3.5.1 Suitability of SRC in comparison to a Wheat-Barley- Oilseed rape crop rotation

To start off with a first visual impression, the selected SRC sites are illustrated in the "Map Viewer". In combination with the "ResultsExplorer", it is possible to get a quick overview on the overall results of the scenario generation. As depicted by the map, suitable SRC sites are distributed all over the district but with increasing number in the Eastern agricultural areas and larger gaps in the central municipalities due the exclusion of the most productive arable sites (see Figure 3.2 and scenario objective 3).

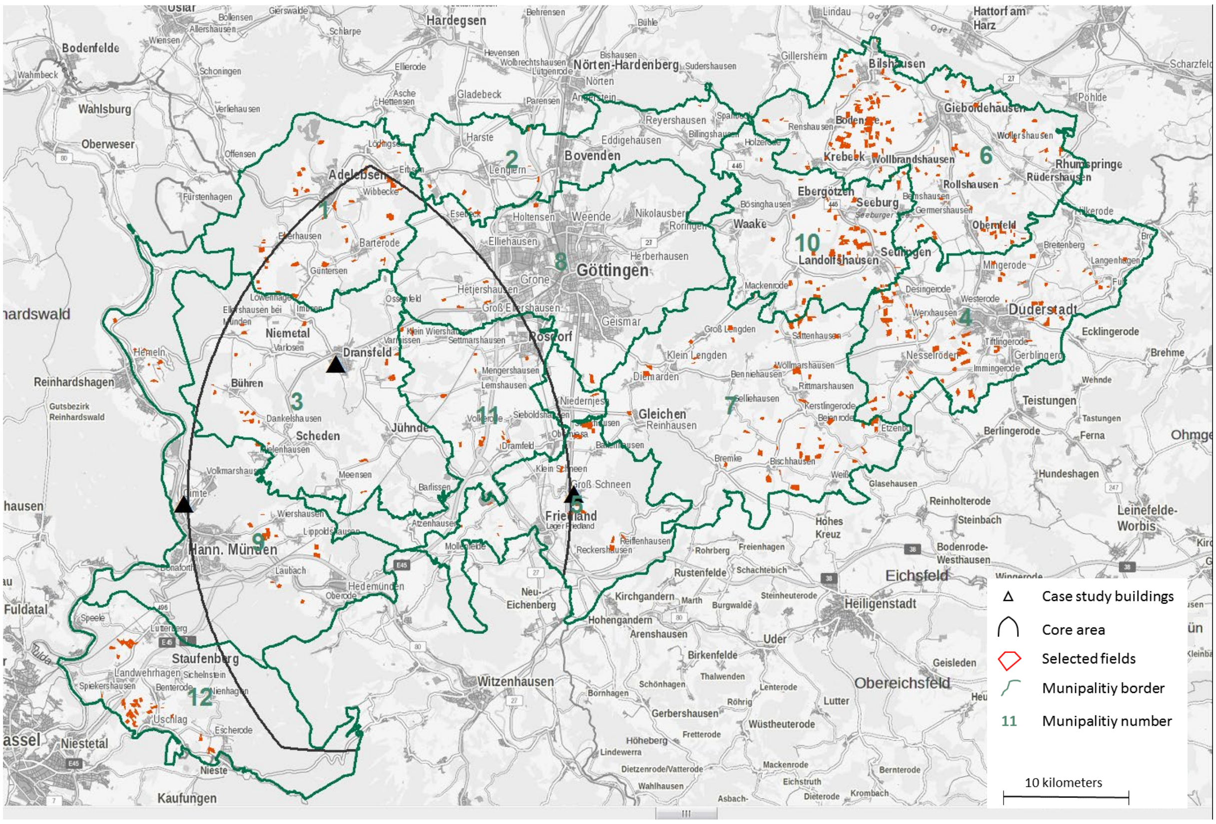
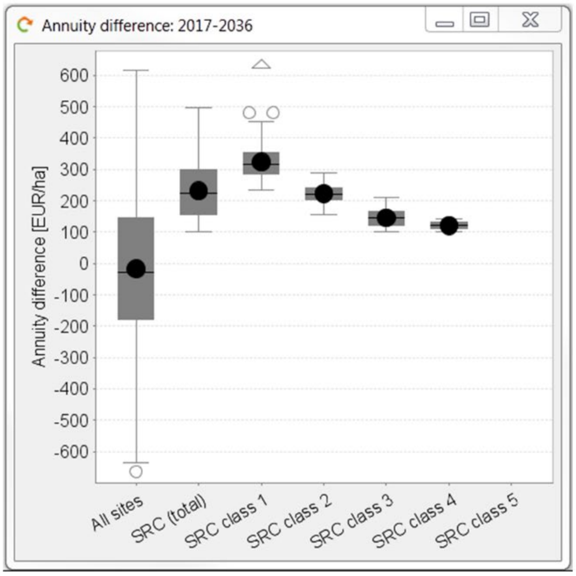
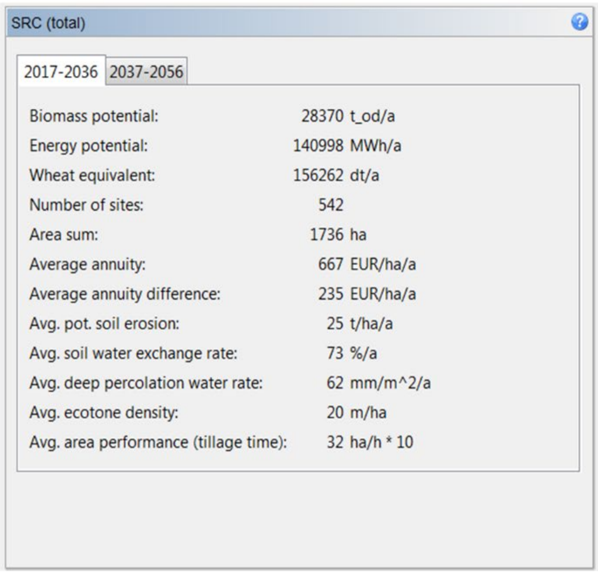


Figure 3-2 Suitable arable SRC fields (in comparison to a W-B-OR crop rotation) in the Göttingen district

In total, 542 arable fields were selected as suitable fields for potential SRC cropping according to the scenario settings – i.e., being economically competitive and meeting the environmental goals of erosion protection and structural enrichment of agricultural landscapes. These arable fields comprise an area of 1736ha which is around 3.9% of the arable area in the district. The demand and supply figures, results show that these fields could provide a biomass supply of 28353t$_{od}$ a^{-1}, respectively a corresponding energy supply of 141GWh a^{-1} which exceeds the demand by far.

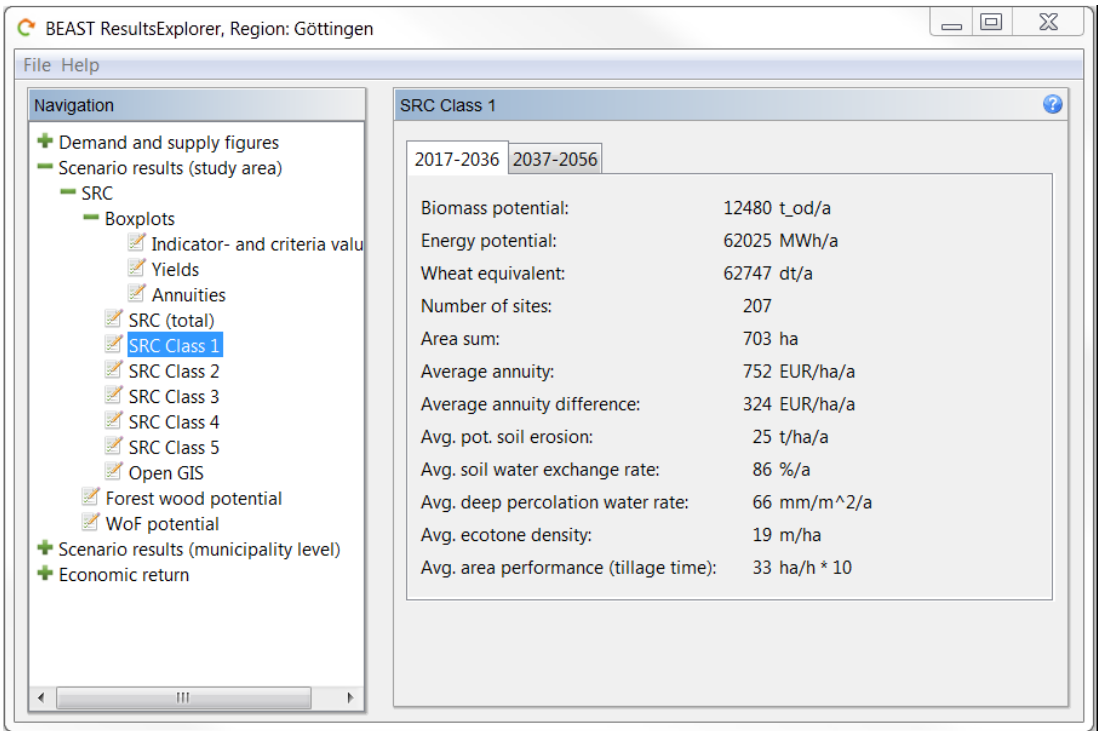




The annuity difference figure (left) reveals how important a proper site selection is because the median annuity difference from SRC on all arable sites in the Göttingen district is negative. On the contrary, the selected suitable arable SRC fields [SRC (total)] illustrate a remarkable positive annuity difference. SRC classes1 to 5 reflect five equal classes of the multi-criteria score range (0-

100), i.e., SRC class 1 represents multi-criteria scores >80 indicating both, high economic and high ecological suitability values.

Results show that SRC class 1 alone (see figure below) is more than capable to fulfil the wood chips demand of the case study buildings while providing considerable economic return and creating many opportunities to prevent from soil erosion and to enrich landscape structure. Thus, the first two scenario goals, (1) to check if the wood supply is adequate, and (2) to identify economic competitive arable fields for SRC cropping while creating ecological synergies, are accomplished. However, the question remains, if sufficient energy supply could be generated within the "core area".



Core area results

The necessary analysis was carried out by exporting the scenario results to a GIS (see chapter 4.5.4 for details). Results from the GIS analysis revealed that an area of 284ha was assessed as suitable for SRC cropping. The average positive annuity difference accounts for 240€ ha^{-1} a^{-1} and is very similar to the district average. While providing a substantial energy supply, erosion protection and structural enrichment could be addressed very well.

Again, the selected arable fields of "SRC class1" alone could provide sufficient energy supply for the case study buildings while providing the desired ecological synergies (see Table 3-2). Even when considering a lower biomass production during the first rotation period (around 65% of the average biomass production – see chapter 4.3.2), the corresponding energy supply of 5.5GWh a^{-1} would suffice.

	SRC total	SCR class1
Area (ha)	284	95
Annuity difference (€ ha^{-1} a^{-1})	240	335
Energy supply (GWh a^{-1})	22.9	8.6
Soil erosion risk (t ha^{-1} a^{-1})	25	25
Ecotone density (m ha^{-1})	27	25

Table 3-2 Core area results for suitable SRC fields in comparison to a W-B-Or crop rotation

3.5.2 Suitability of SRC in comparison to a Maize – Wheat – Maize - Wheat crop rotation

The selected arable fields are scattered over the district (see Figure 3-3) but with lower density and a smaller total compared to the sites selected with respect to a W-B-OR crop rotation. The total suitable SRC area accounts for 1031ha or 2.2% of the arable land in the study area.

The 17541t_{od} of annual biomass supply from the selected sites correlates with a primary energy production of 87GWh a^{-1}. This is a reduction by about 39% compared to the W-B-OR-related selection. As for the W-B-OR crop rotation, the selected SRC sites provide ecological synergy effects in combination with a positive economic return.

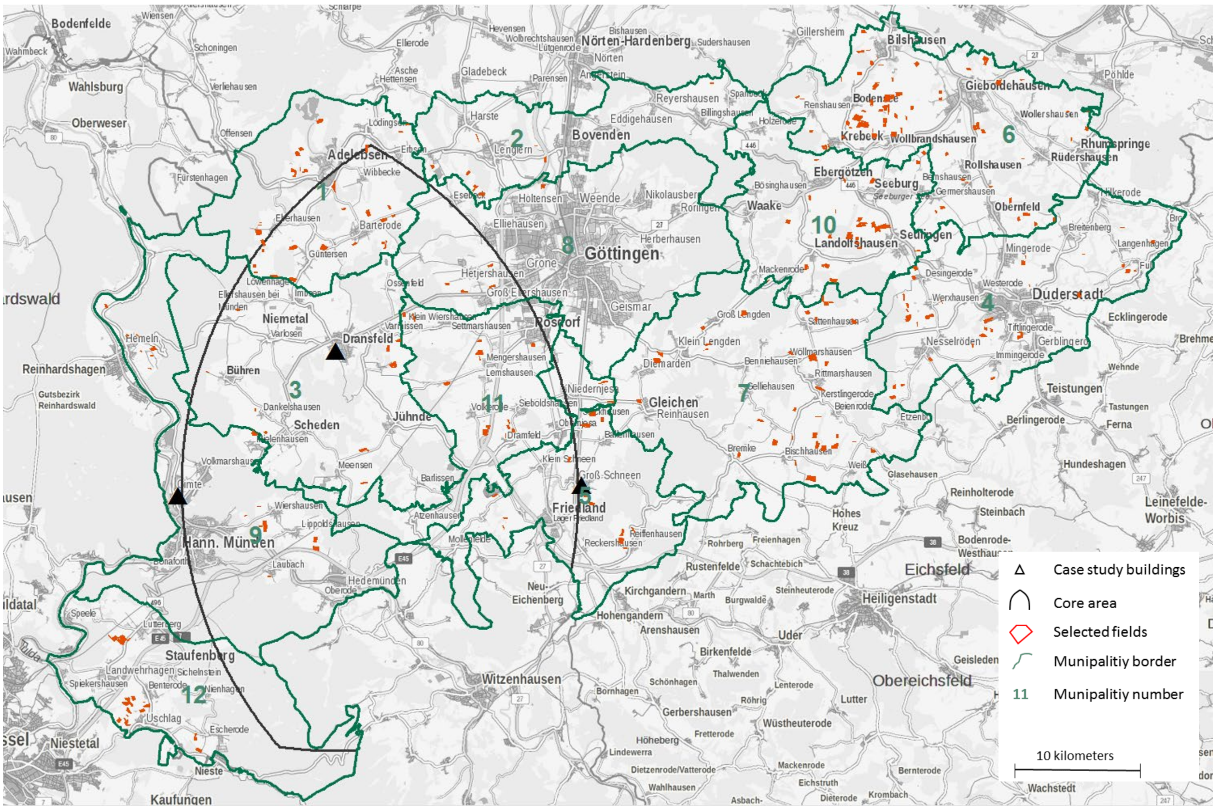
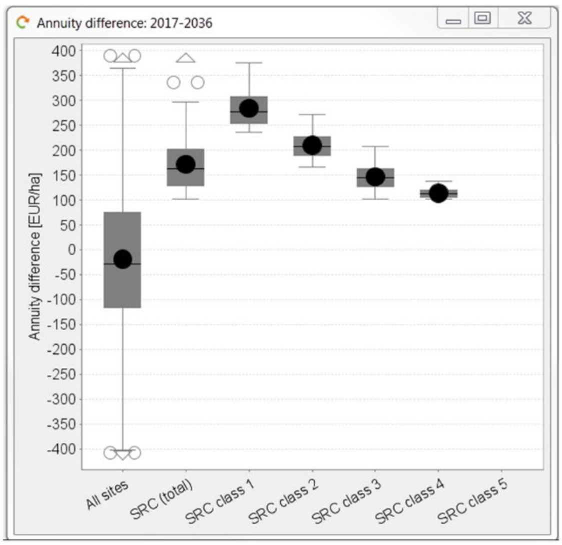
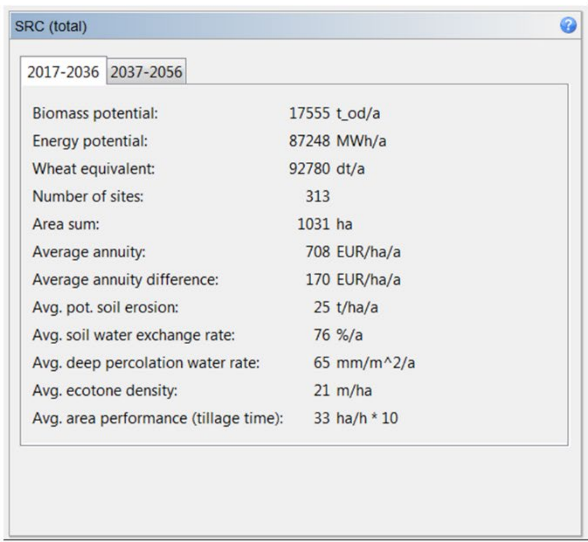


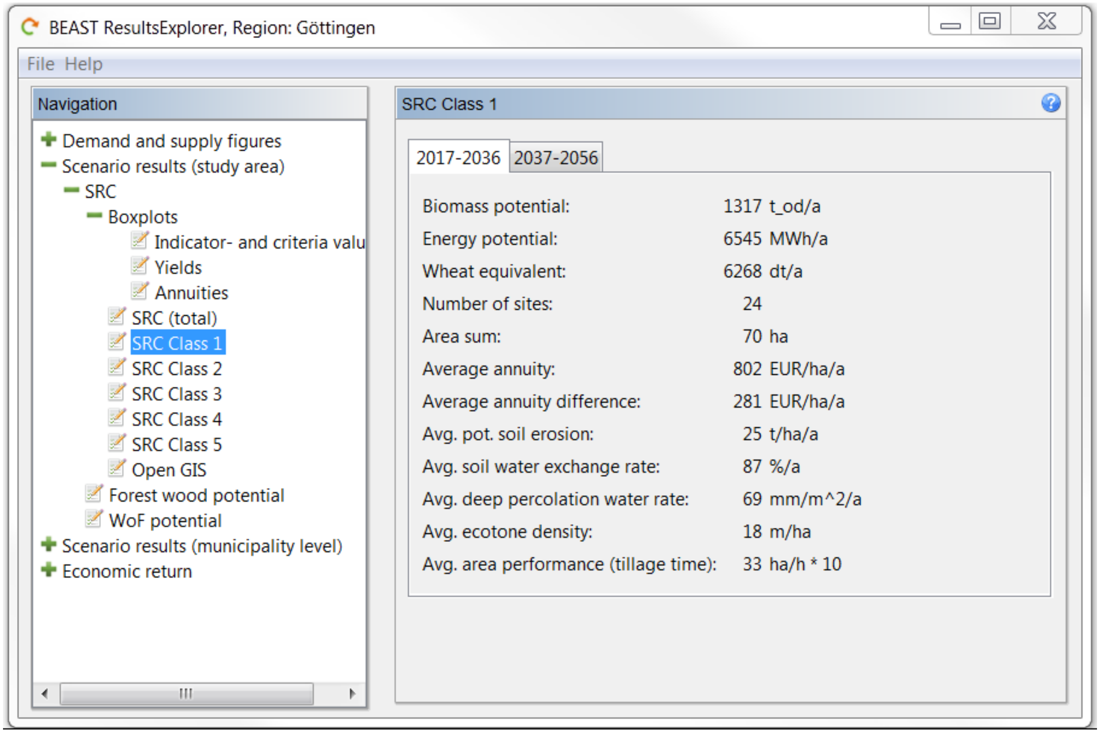
Figure 3-3 Suitable arable SRC fields (in comparison to a M-W-M-W crop rotation) in the Göttingen district

Again (see figure below), the average annuity difference between SRC and the annual crop rotation (M-W-M-W) is negative (-28€ ha^{-1} a^{-1}) and ranges between -403€ ha^{-1} a^{-1} and +364€ ha^{-1} a^{-1}. However, the pool of suitable arable SRC fields shows an average annual annuity difference of 170€ ha^{-1} $^{-}$ with median annuities ranging between 277€ ha^{-1} a^{-1} (SRC class 1) and 113€ ha^{-1} a^{-1} (SRC class 4)





In contrast to the W-B-OR crop rotation, only 70ha are declared as "SRC class 1" fields in the study area. Providing around 6.5GWh a^{-1}, these areas supply just enough primary energy during the first rotation period. Thus, within the core area, suitable fields from other SRC classes must provide the necessary energy supply for the case study buildings.



Core area results

GIS analysis of the scenario results revealed that there are sufficient suitable arable fields within the core area to grow the SRC biomass needed for the energy supply of the three public buildings. However, in contrast to the W-OR-B crop rotation, biomass supply from three SRC classes is needed to safely cover this energy demand. Note, that increasing SRC class numbers are associated with declining criteria scores – lower annuity differences and higher ecotone densities of the selected fields reflect this fact (see Table 3-3). The corresponding average annuity difference of 207€ is around 39% lower than the annuity difference between SRC and the W-B-OR crop rotation.

	SRC total	SRC Class 1	SRC Class 2	SRC Class 3	Selected SRC Pool
Area (ha)	211	10	43	42	**95**
Annuity difference (€ ha^{-1} a^{-1})	177	313	211	177	**207**
Energy supply (GWh a^{-1})	17.3	0.98	3.63	3.53	**8.14**
Soil erosion risk (t ha^{-1} a^{-1})	25	25	25	25	**25**
Ecotone density (m ha^{-1})	26	24	23.5	26	**25**

Table 3-3 Core area results for suitable SRC fields in comparison to a M-W-M-W crop rotation

3.5.3 Finding the most suitable fields in the core area

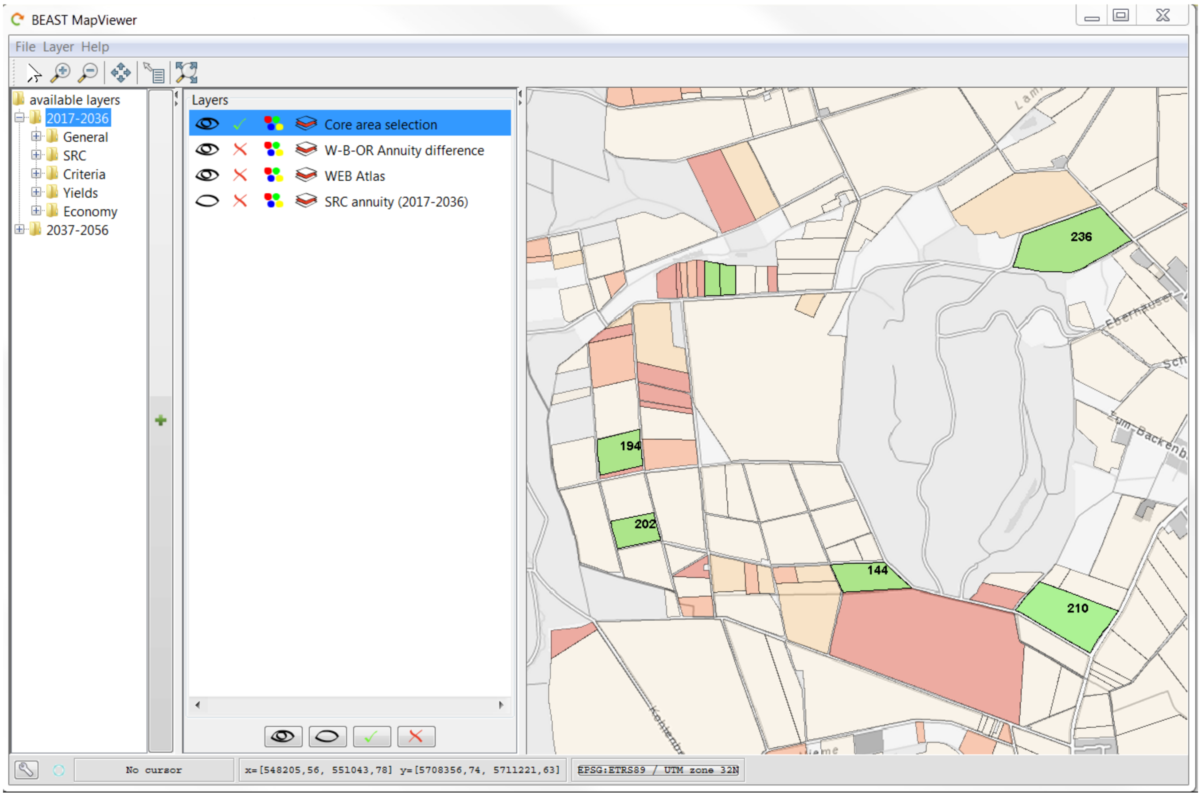
In a next analysis step, the intersection between the suitable fields of the M-W-M-W crop rotation and the W-B-OR crop rotation is investigated. Knowing about the location and the potential of these fields gives farmers the opportunity to grow Poplar SRC as competitive crop to the four main crops oilseed rape, wheat, barley and maize.

GIS analysis revealed that there is a 191ha pool of intersecting suitable arable fields in the core area (see Table 3-4). The energy supply from these potential SRC fields is around 15.9GWh a^{-1} which is more than sufficient to meet the demand of the case study buildings. Following the procedure of the previous sections, 95ha of the most suitable arable fields were selected based on their multi-criteria score ("Selected SRC Pool" – see Table 3-4). These 95ha allow for a safe bioenergy supply even during the first rotation period and provide the highest synergies between economic return, erosion protection and structural enrichment for the core area. An average annuity difference of 275€ (for both crop rotations) is a promising economic result. Every single field selected is subject to Cross Compliance obligations which could be addressed by lignocellulosic cropping. Structural richness of the surrounding agricultural landscape is below district average and could be improved by cropping perennial cultures.

BEAST allows to import shape files to the "MapViewer". This way, the results of the external GIS analysis could be visualized within the tool to support a detailed scenario analysis or to refine the scenario work if deemed necessary. The corresponding figure depicts a part of the Core area showing annuity differences of suitable fields from the selected SRC pool (green colours).

	SRC total	Selected SRC Pool
Area (ha)	191	**95**
Avg. Annuity difference (€ ha^{-1} a^{-1})	227 274 (W-B-OR) 180 (MWMW)	**275** **332 (W-B-OR)** **221 (M-W-M-W)**
Energy supply (GWh a^{-1})	15.9	**8.4**
Pot. Soil Erosion ()	25	**25**
avg. Ecotone density (m ha^{-1})	27	**26**

Table 3-4 Core area results for suitable SRC fields in comparison to both annual crop rotations



3.6 CONCLUSIONS

BEAST-specific:

- With BEAST it is possible to generate rapid appraisals and numerous scenarios in an interactive way – allowing the user to grasp the complexity of land use change and to "play" with scenario consequences during stakeholder meetings.
- Sectoral or multi-disciplinary aspects can be addressed by selecting only 1 criterion for the scenario generation, with up to 6 criteria for multi-criteria assessments.
- Database and geometry export allow for further spreadsheet or GIS analysis.
- GIS-post-processing results can be imported to BEAST and enhance the analysis options considerably. This way, an iterative scenario development can be supported and different kinds of production- or value chains can be analysed.
- Sensitivity analysis (see chapter 4.4.4) of input parameters such as prices, yields and costs could help to define scenario corridors for the economic evaluation.

Example Case study specific results:

- SRC is economically competitive against different crop rotations and creates ecological synergy effects under the given scenario conditions
- The area which is suitable for SRC cropping in comparison to both crop rotations accounts for 191ha in the core area and provides a primary energy supply of 15.9GWh a^{-1}.

- Hence, SRC presents a promising alternative to enlarge the renewable energy mix and brings forth options to link regional planning goals with climate protection and more sustainable land use.
- Farmers can use SRC to broaden their revenue base and spread risks from annual crop production.
- Around 95ha of arable land are needed to supply the case study buildings with biomass. Given the amount of suitable arable fields in the Göttingen district, there is ample opportunity to design local heating networks relying on economically competitive wood chip production. A restriction to a very local production (e.g. the core area of the scenario example) may create benefits – e.g. in terms of transportation costs – but economic return might be higher for "first movers" when using appropriate arable sites all over the district.

4 Background information on methodological issues and reference data input for the scenario generation with BEAST

4.1 ENERGY DEMAND (STEP 1 OF THE CASE STUDY SCENARIO)

The scenario generation starts with the determination of the regional energy demand and the woody biomass contribution to fulfil this demand. The demand can be defined separately for the two 20-year periods (2017-2036; 2037-2056) (Figure 4-1).

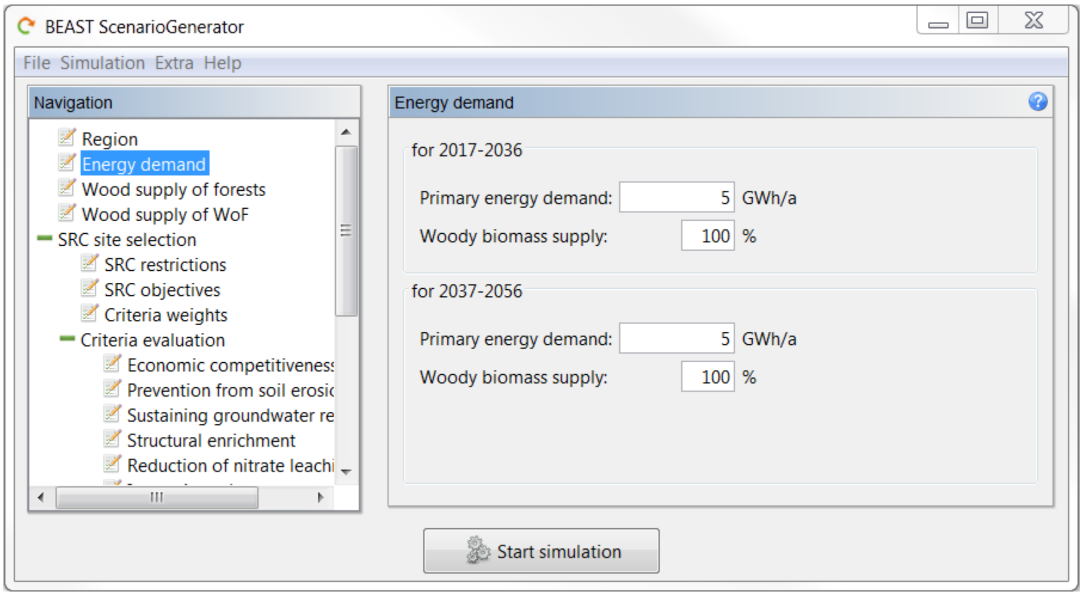


Figure 4-1 Defining the energy demand in BEAST

4.2 SRC SITE SELECTION (STEP 2 OF THE CASE STUDY SCENARIO)

4.2.1 SRC restrictions – Apply spatial filter rules for SRC site selection

A set of 11 filter rules is currently implemented (see Figure 4-2). These filter rules reflect stakeholder preferences in the Göttingen district but can be exchanged and/or modified according to the local/regional specifics of other case study areas. The 12 municipalities of the case study district (see Figure 4-3) serve as administrative units and 34 water catchments were selected as ecological units. "Buffer zones" are represented by 100m buffers around humid-sensitive areas in the district. These humid-sensitive areas are part of the Special Area of Conservation (SAC) designation by the European Union's Habitats Directive (92/43/EEC). The rationale of identifying these zones was twofold: (a) to avoid the input of e.g., nitrate from annual cropping by using SRC fields as "buffer strips", (b) to sustain deep water percolation rates by avoiding cropping with SRC due to its increased water consumption compared to annual crops [49-52].

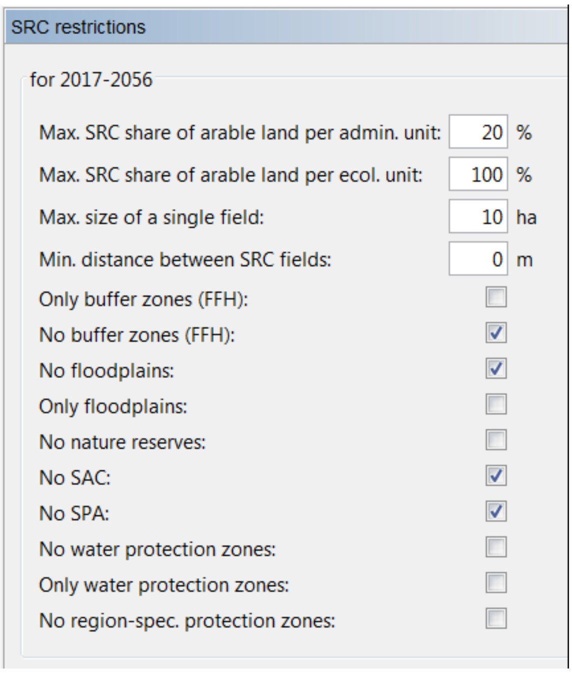


Figure 4-2 SRC restrictions in BEAST

"No/Only floodplains" can be selected when the user wants to (a) avoid hampering water (flood) discharge, or (b) puts emphasis on this lowered discharge rates as a positive downstream effect

The user can exclude various conservation zones in the agricultural landscape from being cropped with SRC. These conservation zones refer to national policies ("Nature reserves", "Water protection zones", other, "region-specific conservation areas") or European legislation (SAC, SPA).

"Special Areas of Conservation" (SPA).

"Special Areas of Conservation" (SAC) are aiming at conserving habitats, fauna and flora, complementing "Special Protection Areas" (SPA) which were designated under the European Union Directive on the Conservation of Wild Birds. Both form the "NATURA-2000" network across the EU.

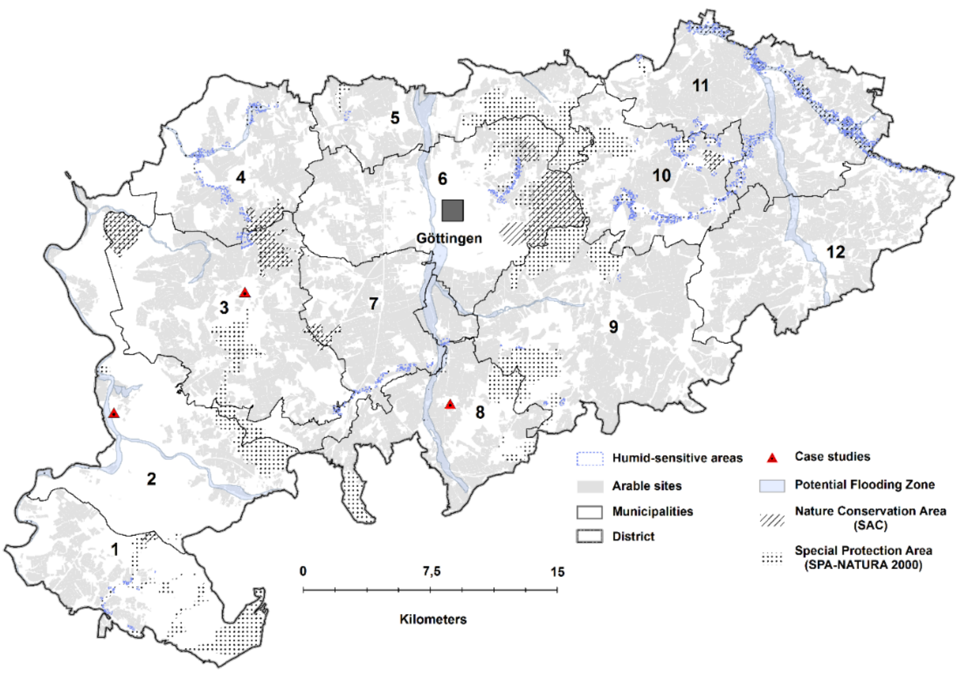


Figure 4-3 Selection of specific spatial filter rules and the visualization of the corresponding areas for the Göttingen district

4.2.2 SRC objectives – setting indicator thresholds as objectives for the SRC site selection

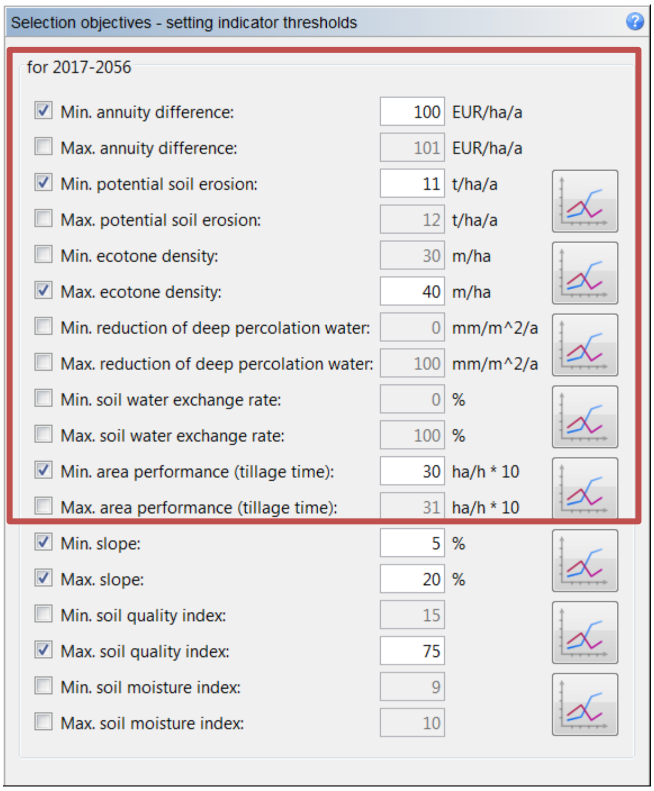


Figure 4-4 Selection objectives in BEAST

The objectives selection menu in BEAST (see Figure 4-4) allows to set min-max thresholds and thus enable the user to define suitable indicator value ranges (a) for the multi-criteria evaluation, and (b) additional spatial filter rules. Threshold setting can follow existing regulations or expert knowledge. Some guidance is provided by the boxplots that are available for each objective. The objectives in the orange frame refer to indicators that are used in the criteria evaluation and are therefore explained in the cores- ponding sections of chapter 4.2.4.

Slope percentages were derived [ARCGIS] from a digital elevation model with a resolution of 12.5m. Soil quality index numbers originate from the German Soil Survey (1:5.000) in 1934 which is still the reference for soil taxation und land rents. The soil moisture index was derived from digital soil maps of Lower Saxony [1:50.000)] according to reference methodologies for soil assessments from the federal state agency of Lower Saxony [45].

4.2.3 Criteria Weighing

In BEAST, criteria weighting can be used to (a) express a specific balance of multiple criteria, and/or (b) to exclude selected criteria from the analysis. The latter is achieved when setting the value to zero, i.e., shifting the slider to the left side (see Figure 4-5). For the example illustrated in Figure 4-5 only three criteria are selected for the calculation with economic competitiveness ranked highest (100) and two ecological criteria having a lower but equal weight.

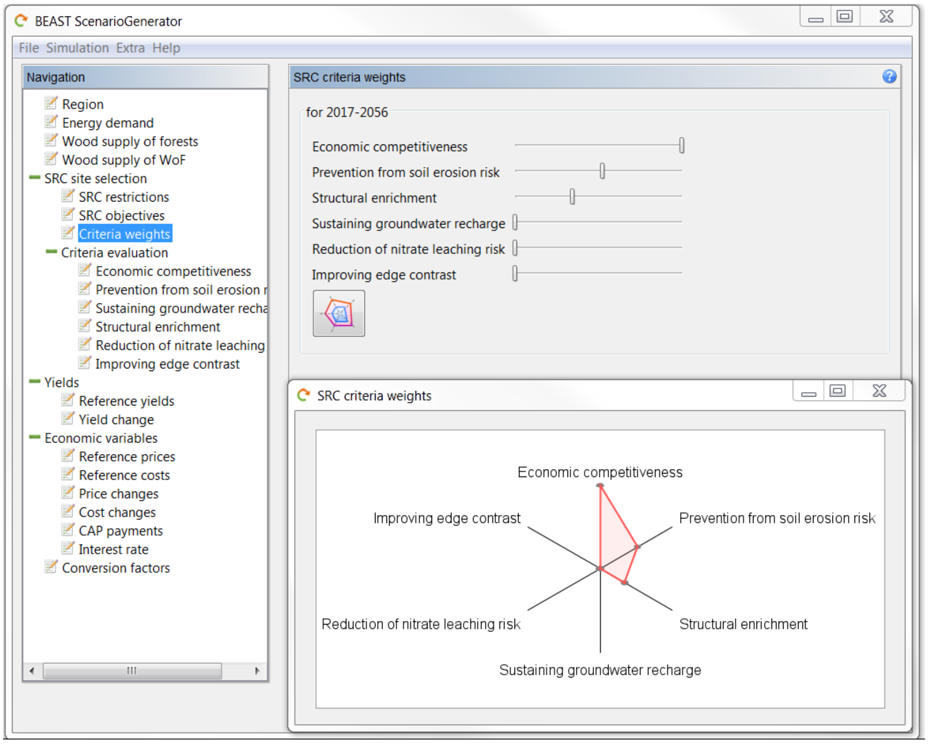


Figure 4-5 Weighting criteria in BEAST

4.2.4 Criteria evaluation (Step 3 of the case study scenario)

Six indicators are available for an evaluation (see Table 4-1). The indicator evaluation provides criteria expressing the effect that SRC could have on a specific subject (e.g., ecosystem services or economic return) in comparison to an annual cropping system. By choosing one, many, or all criteria it is possible to carry out a sectoral analysis or to focus on multiple aspects influencing the site selection of SRC.

No.	Indicator	Unit	Criterion ("The effect of SRC on:")
1	Annuity difference	€ ha^{-1} a^{-1}	Economic competitiveness
2	Potential soil loss	t ha^{-1} a^{-1}	Prevention from soil erosion risk
3	Difference in deep percolation water	mm $m^{-2}a^{-1}$	Sustaining groundwater recharge
4	Ecotone density in agricultural landscapes	m ha^{-1}	Structural enrichment
5	Soil water exchange rate	%	Reduction of nitrate leaching risk
6	Area performance	ha h^{-1}	Improving edge contrast

Table 4-1 Indicators and their associated criteria available in BEAST

For the multi-criteria assessment (MCA), all criteria are scaled to fit in a range from 0 to 100. To do so, an evaluation of the selected indicators needs to take place – i.e. each criterion is characterized by a function that represents the qualitative evaluation of the underlying quantitative indicator. Following existing thresholds of regulations, expert knowledge and/or local perceptions, the user defines 5 supporting points which in turn determine the shape of the evaluation function. An example of this procedure is depicted by Figure 4-6 for the evaluation of potential water-induced soil erosion.

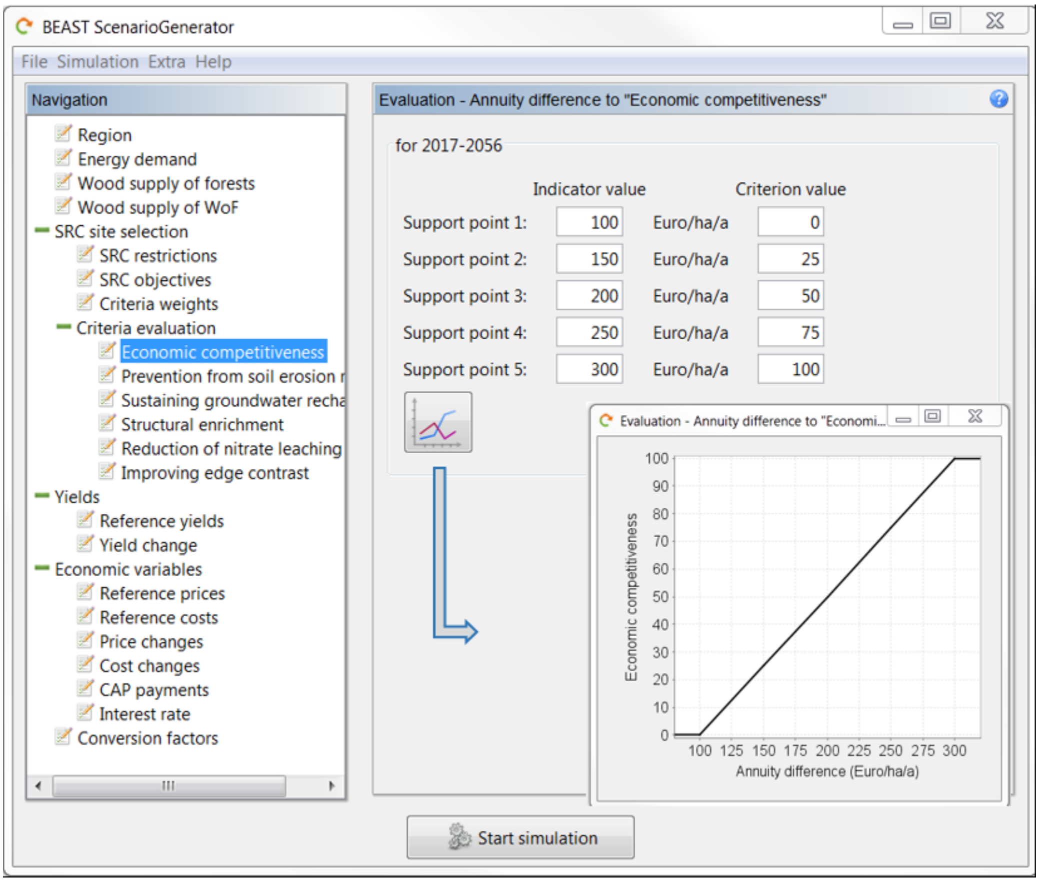


Figure 4-6 Indicator evaluation in BEAST: "Annuity difference" as example to assess "Economic competitiveness"

Economic indicator

Annuity difference – describes the difference in annual economic return (€ ha^{-1} a^{-1}) between the selected crop rotation of annual arable crops and Poplar SRC. A description of the calculation procedure and the underlying economic variables can be found in chapter 4.4.1.

Ecological indicators

Depending on the existing landscape mosaic, its land use intensity and the type of ecosystem services being provided, SRC could be both, beneficial or detrimental to various ecosystem services (e.g., [11, 12, 14, 35, 53, 54]). In BEAST, the user can address this issue in two ways: (1) by defining spatial rules to express preferences for selecting potential SRC sites, (2) by addressing ecological indicators and evaluating the effect a SRC can have on the associated ecosystem services.

Potential soil erosion

Potential water-induced soil erosion was calculated for each agricultural field geometry by applying reference methodologies for soil assessments from the federal state agency of Lower Saxony [45]. These methodologies in turn are based on the German adaptation of the Universal Soil Loss Equation (USLE) and refer to soil information of the German Soil Survey (1:5.000) and a digital elevation model with a resolution of 12.5m. Details can be derived from Schäfer et al. [46]. The risk classification in the subsequent table can be used to evaluate the quantitative indicator in BEAST (see chapter 4.5).

Evaluation	Potential soil loss in t ha^{-1} a^{-1}	Erosion risk according to Cross Compliance regulation [45]
Very low erosion risk	<2.5	CC0
Low erosion risk	<5	CC0
Medium erosion risk	<7.5	CC0
High erosion risk	<15	CC0
Very high	<25	CC1
Extremely high	>25	CC2

Table 4-2 Adapted and modified risk classification of water-induced potential soil loss according to the federal state agency of Lower Saxony, LBEG [45]

Reduction of deep percolation water

Average annual deep percolation water rates for the annual reference crops and for the poplar SRC in 5-year rotation were calculated according to the procedure described by Busch [28]. This approach in turn builds on an empirical function in the form of:

$$Deep\ percolation\ water = a(P_y - K)^b$$

With "a " describing the soil-texture-specific factor, "P_Y" the annual precipitation, "K" the soil-texture-specific constant, and "b" the land use-specific exponent (e.g., for annual crops = 0.98). A broad range of sand, silt and clay textures is covered by 5 reference soil types which were taken into account to carry out a multiple linear regression-based fitting procedure (a, K, b) to derive annual deep percolation water with respect to soil texture and annual precipitation (see Busch [55] for more details). In a second step, the model was validated with data from the Göttingen district [56, 19]. These data, provided by Richter, represent simulation results of the WASIM [57] model for the 1981-2010 period with annual data on deep percolation rates of a silty and a sandy site in the "Dramme" catchment, Göttingen (see Figure 4-7). To calculate the difference of deep percolation water between annual crops and poplar SRC DWD [58] average annual long-term precipitation values for the 1981-2010 period served as input information on a $1km^2$ grid.

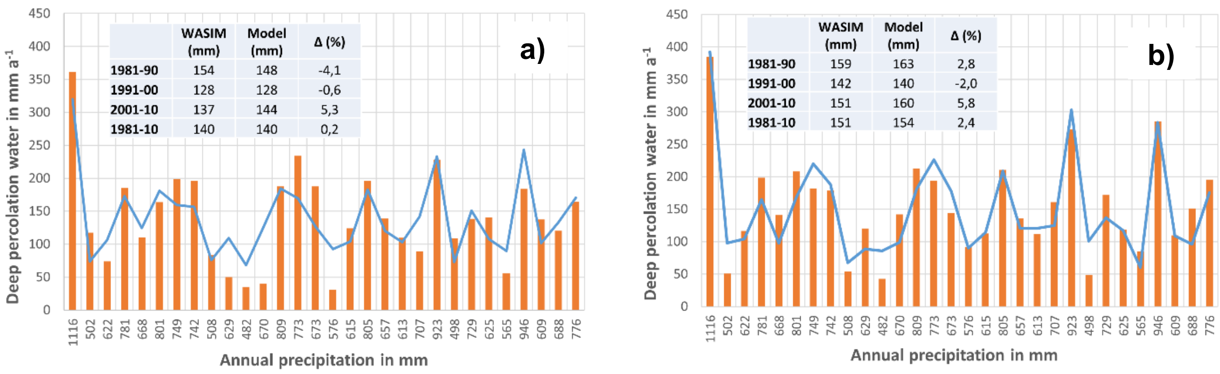


Figure 4-7 Annual deep percolation water fluxes for the 1981-2010 time period on a sandy loam. Comparison of WASIM results (orange bars) with statistical modelling results (blue line) for poplar in 5-year rotation (a) and wheat as annual reference annual crop (b)

Soil water exchange rate

According to the reference methodologies for soil assessments from the federal state agency of Lower Saxony [45] the risk of nitrate leaching can be evaluated by determining the soil water exchange rate. The soil water exchange rate (ER) in turn is determined by dividing the amount of deep percolation (DPW) water by the available soil capacity in the rooting zone ($ASWC_{rt}$).

$$ER[\%\ a^{-1}] = \frac{DPW[mm\ a^{-1}]}{ASWC_{rt}} * 100$$

Again, the existing risk classification according to the LBEG (see Table 4-3) could be used to evaluate the criterion "Reduction of nitrate leaching risk" in BEAST.

	Very low	Low	Medium	High	Very high
Exchange rate (% a^{-1})	<70	70-100	100-<150	150-<250	>=250

Table 4-3 Classification of the local nitrate leaching risk based on soil water exchange rate

Ecotone density

Ecotone density was calculated for agricultural landscapes surrounding each arable field geometry in a 250m radius with agriculture as the dominating land cover (>50% of the area covered). Within this radius all woody edges were summarized and divided by the area total to get a density measure. In a last step, the density values of the agricultural landscapes were associated to the corresponding arable field geometry. Thus, an agricultural landscape with low ecotone density will profit from the enrichment with woody structures provided by an arable field converted from arable cropping to SRC. German ATKIS [59] data (1:25.000) and its land cover classification was used in combination with the district mapping of woody structures outside forests [60] to identify the agricultural landscapes.

Field shape complexity

The classification of arable fields by their shape [61] (e.g. irregular or square contours) served as an entry point to derive a type-specific function expressing the time required for tillage per hectare ("area performance function"). Building on methods used by the Kuratorium für Technik und Bauwesen in der Landwirtschaft (KTBL, https://www.ktbl.de/inhalte/ unregelmaessige-schlaege/), the labour input and basic time required to work each of the six arable field geometry types was calculated for varying field sizes, ranging from 0.5ha up to 20ha. As a result, a type-specific logarithmic function of tillage time per hectare was derived (see Figure 4-8). With the change in tillage time per hectare adopted as a proxy for change in labour costs, this provided a type- and area-specific area performance value for each arable plot in the Göttingen district. For further details refer to Busch & Meixner [61].

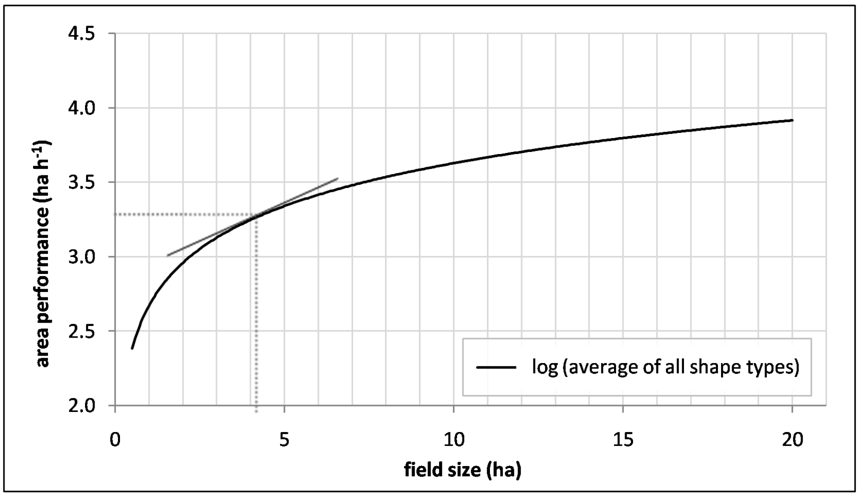


Figure 4-8 Averaged area performance function for the six types of arable field geometries

4.3 YIELDS (STEP 4 OF THE CASE STUDY SCENARIO)

4.3.1 Crop yields

Crop yield data for the annual reference crops (i.e. wheat, oilseed rape, barley, maize) were calculated with statistical yield models and reflect the average decadal yield for each reference crop. The yield models are based on the correlation between climate and soil parameters and yield numbers from 52 sites all over Lower Saxony, Germany [62]. The yield models were calibrated and validated for the Göttingen district [18]. In BEAST, the corresponding yield information is available as reference value for each arable field geometry (see Figure 4-9)and can be adapted by the user by increasing or reducing the reference yield levels (see chapter 4.3.2).

As can be depicted from Figure 4-11, there has been a considerably stable annual yield increase over decades which translates to an average annual yield incline of about 1.6% for wheat, barley and oilseed rape and even 2.4% for sugar beet between 1978 and 2017. The yield increase of maize, however, almost stagnated over the last four decades. The user can address yield increases of annual crops in BEAST (see Figure 4-12). Except for sugar beet, yield increases of annual crops dropped considerably during the 2008-2017 decade (see Table 4-4 Reference yield level input for BEAST). For wheat, yields even declined. If this is due to unfavourable weather conditions or indicating a new trend is unclear. Hence, the reference value of yield increases for arable crops in BEAST was set to 1.1% a^{-1}.

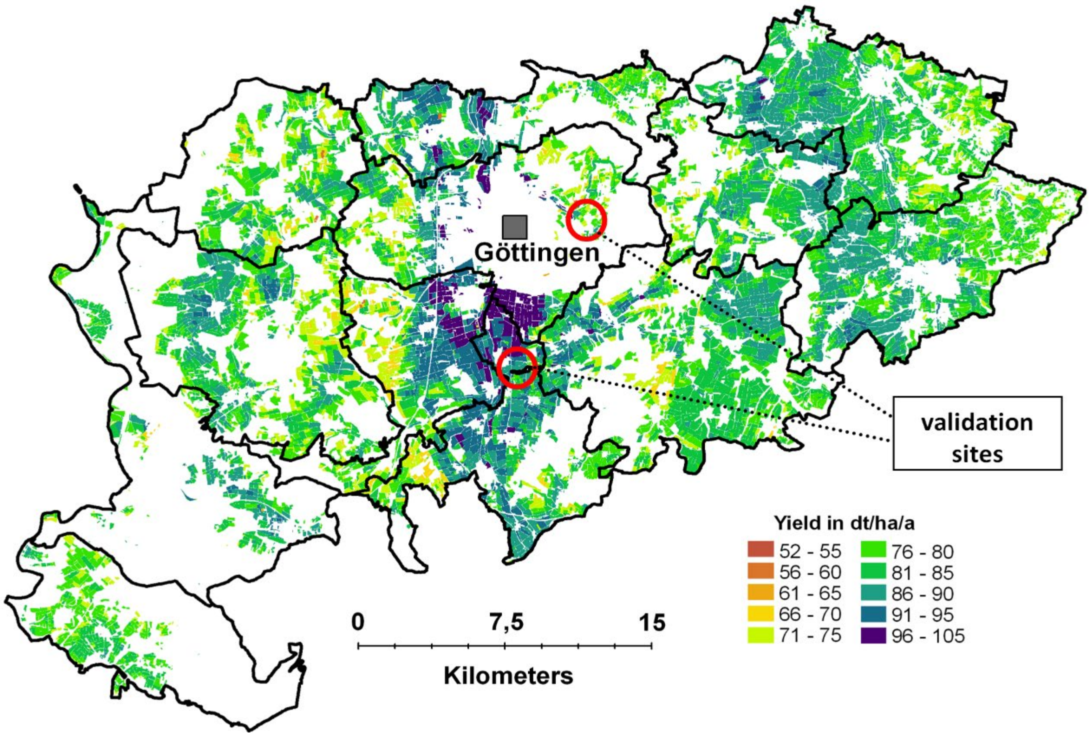


Figure 4-9 Average annual wheat yield for the decade of 2008-17 as reference yield level in BEAST

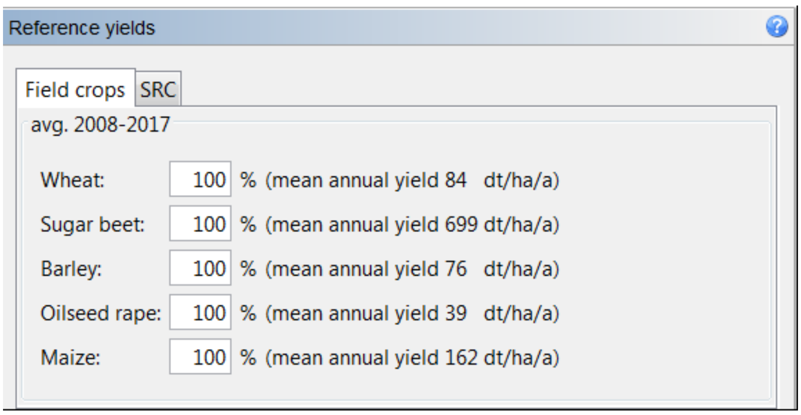


Figure 4-10 Reference yield levels of annual crops in BEAST and graphical user interface to adjust yield levels

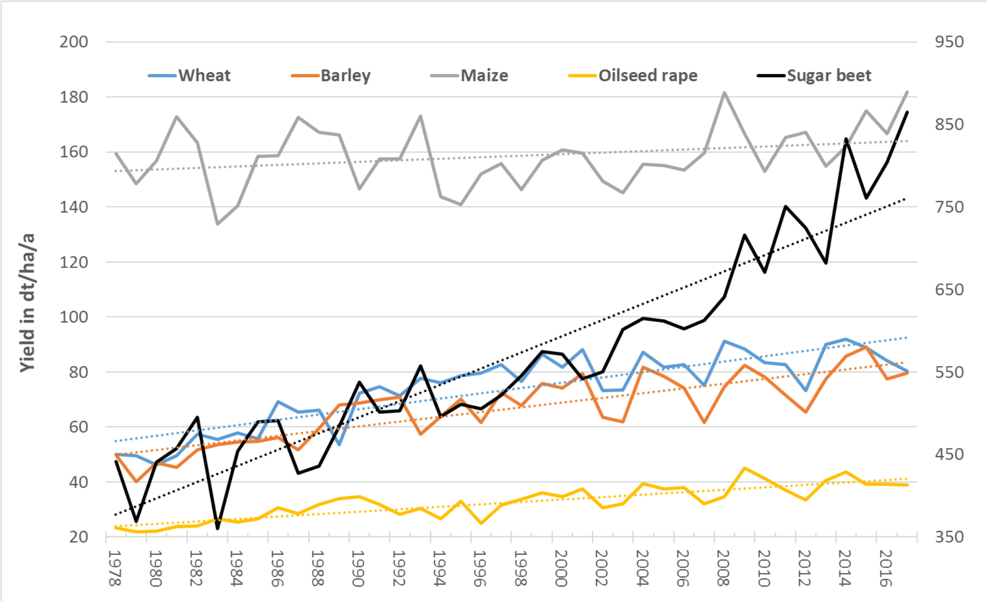


Figure 4-11 Yield development of the reference crops wheat, barley, oilseed rape (left axis) and maize (right axis) in the Göttingen district (adapted and modified from NMELV [63]) Right y-axis values refer to sugar beet yields

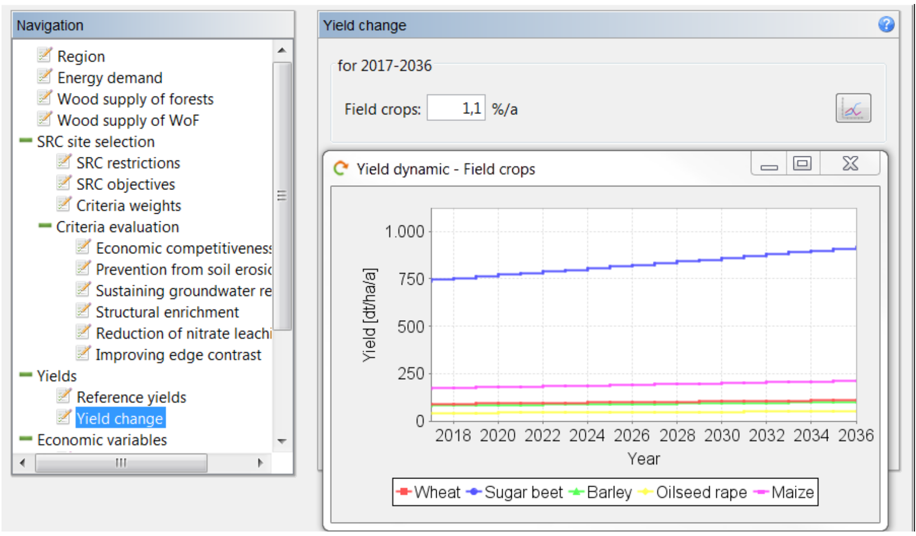


Figure 4-12 Reference yield levels of annual crops in BEAST and graphical user interfaces to adjust yield levels and yield increase

Note, that the number of yield increase applies to all annual crops and has a substantial impact on both future yield levels and the annual economic return.

Item	Description	Average
Yield level of reference crops	avg. yield level (2008-17) for reference crops in decitons (dt) in the study area	84 dt ha^{-1}(Wheat) 76 dt ha^{-1} (Barley) 39 dt ha^{-1} (Oilseed rape) 162 dt ha^{-1} (Maize) 699dt ha^{-1} (Sugar beet)
Yield increase of reference crops 1978-2017	Trend analysis (1978-2017) of annual yield increase for reference crops in the study area	1.5 % Wheat) 1.5 % (Barley) 1.8 % (Oilseed rape) 0.4 % (Maize) 2.4 % (Sugar beet)
Yield increase of reference crops 2008-2017		-1.2 % Wheat) 0.6 % (Barley) 1.3 % (Oilseed rape) 0.01 % (Maize) 3.5 % (Sugar beet)

Table 4-4 Reference yield level input for BEAST [63]

4.3.2 SRC yields

Mean annual increment of the MAX-I poplar SRC was simulated according to a modified approach published by Petzold et al. [64]. The approach is based on the relation between mean annual increment of biomass, available water capacity (soil- and precipitation water) and temperature sum of the vegetation period providing a function of potential annual biomass production for the specific plantation age of 9 years.

Long-term data of SRC field experiments under various rotation periods with a design that is transferrable to practical applications are scarce. Busch and Thiele [18] applied this approach to three long-term data sets of yield levels (Max-I poplar) from Thuringian sites [65-67] and introduced an age-specific modifier to the yield function that allows to model yields for various ages of SRC in a 5-year rotation period. The simulation results proved to be robust [18] so that the approach was used to calculate SRC yields of poplar plantations in 5-year rotation (7000 cuttings) in the Göttingen district (see Figure 4-13).

In contrast to annual crops, SRC species are at the very beginning of specific cultivation progress and few data are available yet to support assumptions on future yield level increases.

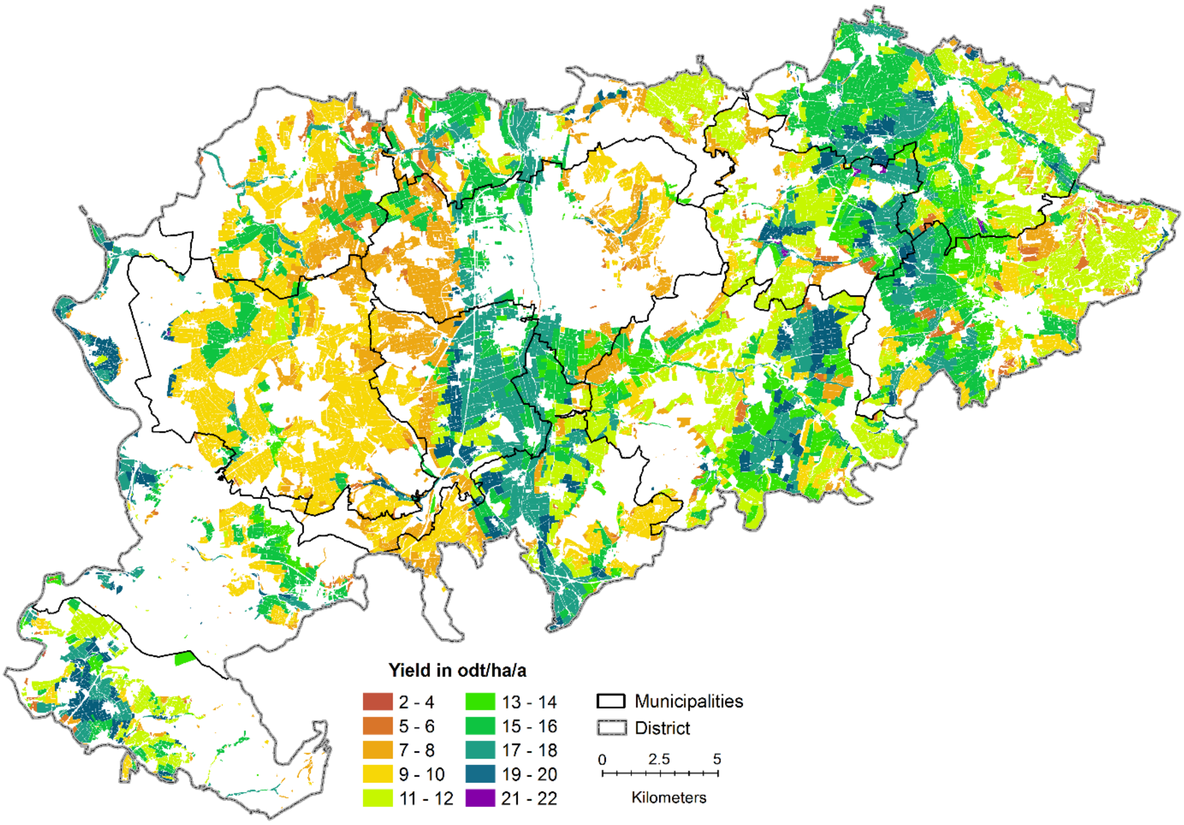


Figure 4-13 Average annual SRC yield (Poplar-SRC with 7000 cuttings per hectare) in oven dry tons over a 20year management period as reference yield level in BEAST

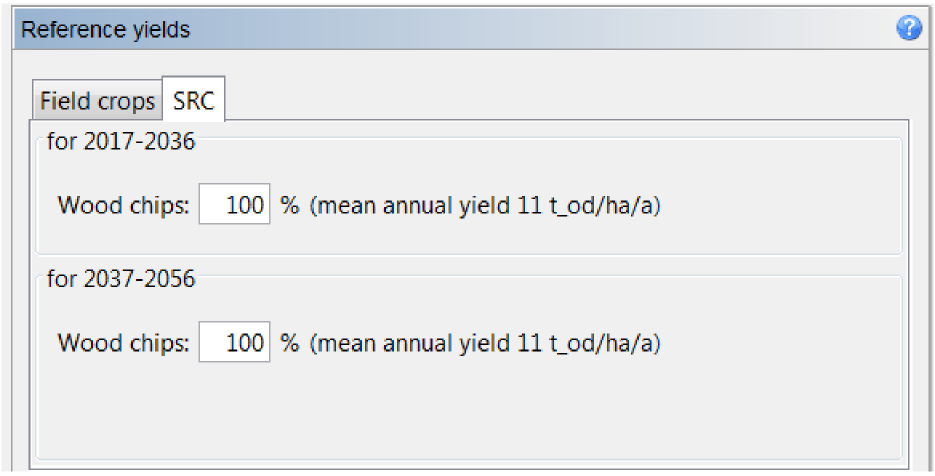


Figure 4-14 Graphical user interface to adjust SRC yield levels

Thus, no yield increment option was implemented in BEAST. Yield levels can be modified in the same way as described for the annual crops. The reference SRC yield level of $11t_{od}$ ha^{-1} a^{-1} reflects the area-weighted average yield level over a 20year management period on arable sites in the study area (Figure 4-14).

The simulated yield development for the four rotation periods within this management period and its relation to the field experiment results from Thuringian sites can be depicted from Figure 4-15. Results show that the yield levels of the Thuringian field experiments are within the range of yield levels simulated for the Göttingen district.

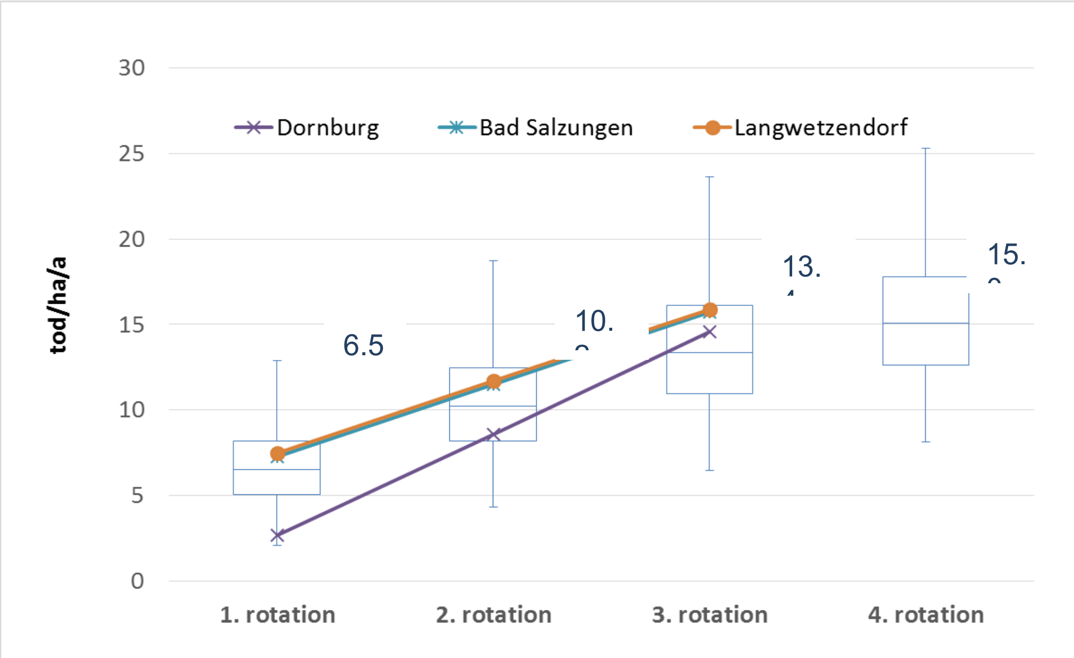


Figure 4-15 Boxplots showing quartile yield levels in t_{od} ha^{-1} a^{-1} for various rotation periods of Poplar-SRC on arable sites in the Göttingen district compared to results from Thuringian field experiments ([65-67]) with long-term Poplar-SRC cultivation

4.4 ECONOMIC CALCULATION OF WOOD SUPPLY FROM SRC IN COMPARISON TO ANNUAL REFERENCE CROPS (STEP 5 OF THE CASE STUDY SCENARIO)

4.4.1 Commodity prices and price changes of annual reference crops and SRC woody biomass

Commodity prices were gathered from regional and national statistics [47, 48, 68-70]. Prices were calculated as net prices without VAT (see Figure 4-16). Two price levels were calculated as reference input for BEAST - the 2017 price and the average of the last decade (2008-17). The decadal averages as well as the calculation of the price changes were adjusted for inflation with 2017 as base year (Table 4-5). As can be depicted from Figure 4-16 and from Table 4-5, inflation adjusted commodity prices show high price fluctuations over the last decade(s). During the last decade prices for wheat, barley and sugar beet dropped while prices for oilseed rape and maize increased. Wood chip prices dropped as well over the last decade but at a smaller rate and with lower price fluctuations compared to the annual reference crops. This fact should be kept in mind when weighing up the risks of SRC against annual cropping.

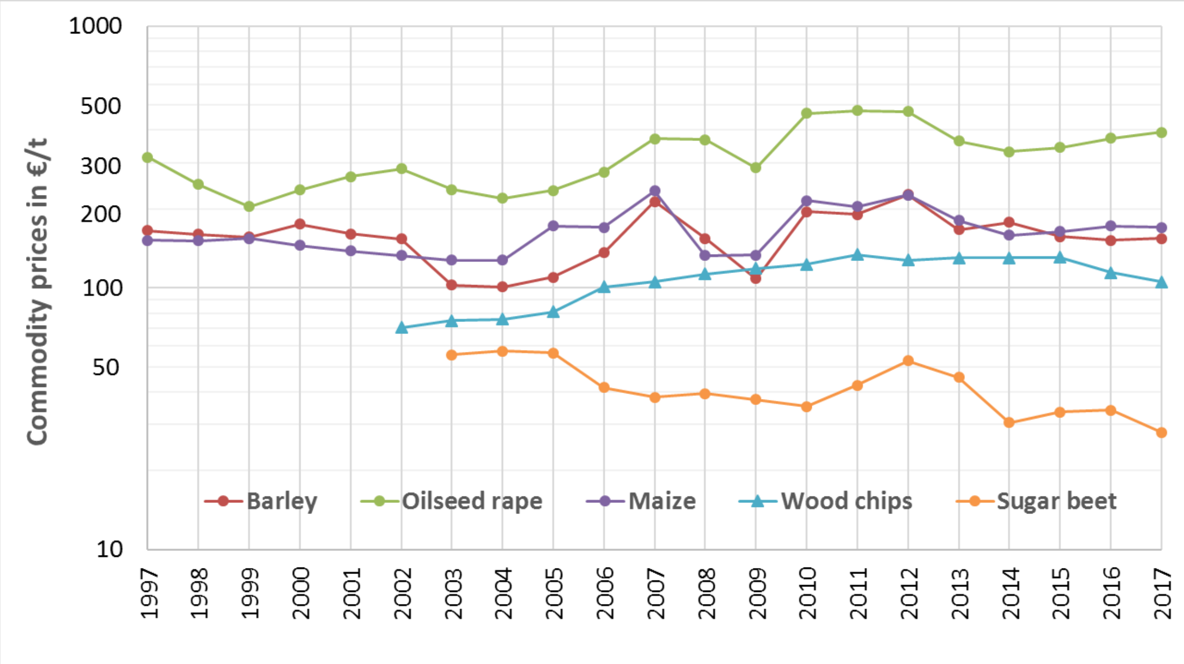


Figure 4-16 Inflation-adjusted commodity prices per ton, respectively oven-dry ton (wood chips). Note that the y-axis is in logarithmic scale which allows a better inter-commodity-comparison of price fluctuation. Data compiled from [47, 48, 70].

Prices [€ t_{od}^{-1}; € dt^{-1}]	Wood chips	Wheat	Barley	Oilseed rape	Maize*	Sugar beet
Avg. 2008-2017	116,0	18,6	17,3	38,8	3.3	3,8
2017	106,0	14,8	15.4	39,3	2.9	2.8
Avg. annual price development (%)						
2008-2017	-0.6	-1.8	-1.2	0.6	2.9	-3.2
1998-2017	-	0.2	-0.1	2.3	0.6	-

*Table 4-5 Input price levels (net) in € per t_{od} for wood chips, respectively dt for annual crops and average annual percentage change of commodity prices (inflation-adjusted) for different time periods - * maize with 33% dry matter weight*

Despite the recent decrease of fossil fuel prices, there is still a notable gap between the energy-related prices of oil and gas and wood chips for the end consumer (Figure 4-17) indicating that using wood chips for energy supply could be an attractive alternative – for farmers as well as for other end-users.

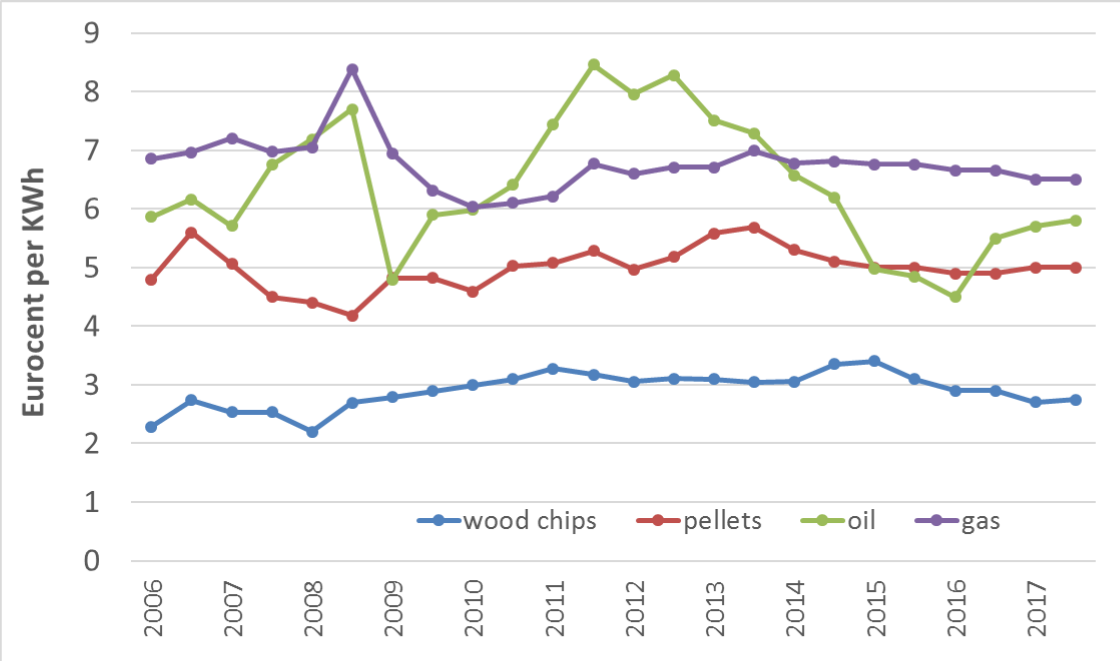


Figure 4-17 Energy related (heating) prices of fossil fuels and woody biomass sources in Eurocent per KWh. Prices are inflation-adjusted and taken from C.A.R.M.E.N [69] and Statistisches Bundesamt [71].

In BEAST, the user can vary the commodity prices as well the annual price change (see Figure 4-18). Decadal averages as stated in in Table 4-5 are used as reference price input. Due to the high price fluctuations no reference values for price change were set. Note, that the input for price changes in BEAST applies to commodity groups, i.e. to all annual reference crops.

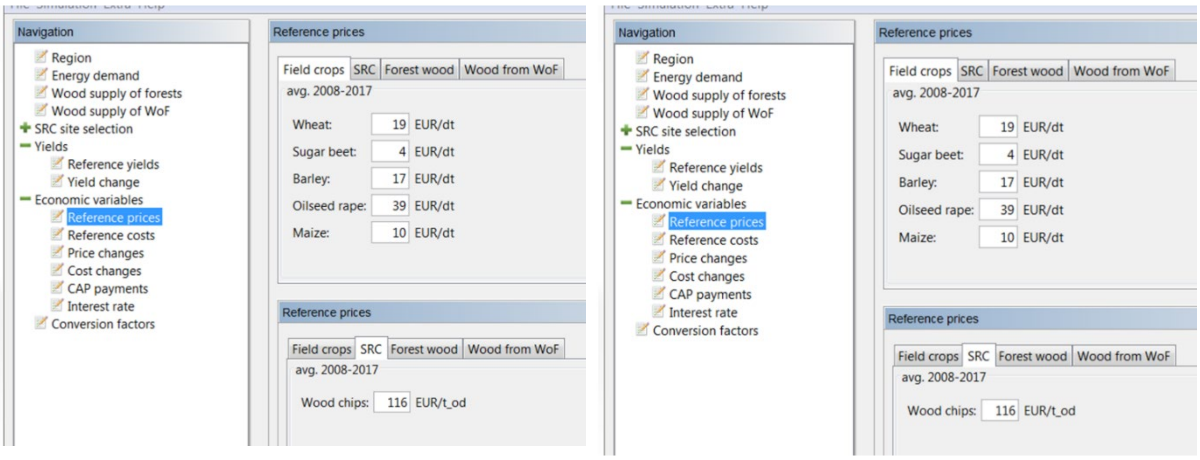


Figure 4-18 Reference prices and price changes of annual crop commodities and SRC wood chips in BEAST

4.4.2 Production costs of annual crop commodities and SRC wood chips

Cost calculation for annual reference crops

Linear yield-related cost functions were derived for the aggregate of cost positions a-f (see Table 4-6) and each reference crop (Table 4-7) based on the annual reports on yield-related costs and revenues from the Niedersachsen Chamber of Agriculture [47]. Since the cost position "Labour and machinery costs for field cultivation and cropping" (see Table 4-6) is not only yield-related but also slope- and field-size-dependent, two functions [18] were additionally applied to the linear yield-related functions to address this issue:

$$area\ size - related\ increase\ of\ costs(\%) = (\frac{field\ size\ (ha)}{5})^{-0.095} - 1) \times 100 \qquad (1)$$

$$slope - related\ increase\ of\ costs(\%) = 0.02288e^{0.1123 * slope(\%)} \qquad (2)$$

The area function (1) causes increasing costs with diminishing field size and the slope function (2) addresses the impact of increasing slope on costs.

n	Cost position	Aggregated variables in BEAST – calculated as	
20	Seed, fertilizer, plant protection (a)	Yield-related function	
20	Depreciation on machinery (b)		
20	Transportation (c)		
20	Storage (d)		
20	Drying (e)		
20	Labour and machinery costs for field cultivation and cropping (f)	Yield-related function	Slope-function Area-function

Table 4-6 Cost calculation of annual crops in BEAST –Input categories and underlying cost positions

Consequently, two cost categories were implemented in BEAST: (a) yield-related costs, and (b) yield-, slope- and field-size-related costs Numbers from Table 4-7 serve as reference values.

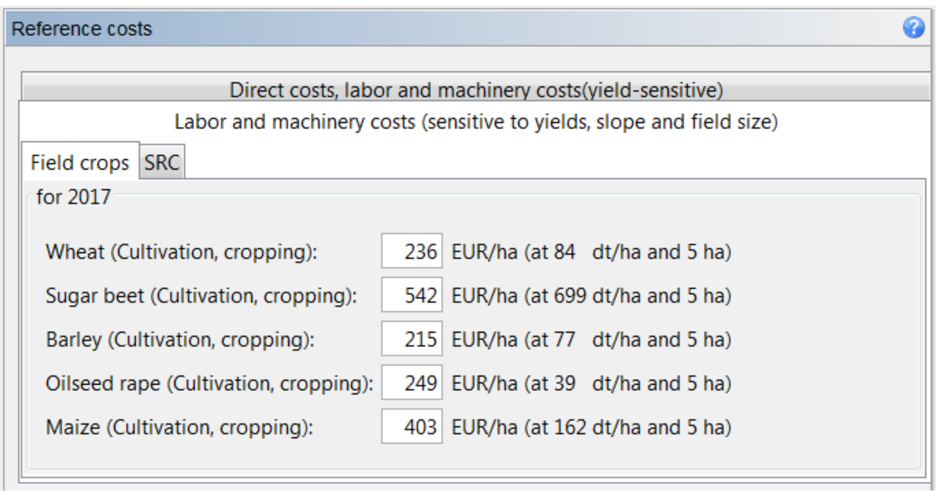


Figure 4-19 Cost categories and reference costs for annual crops in BEAST

Cost position	Function	Reference costs in €/ha	Cost changes (2008-17) in %
Crop		**(x= reference yield) in dt/ha/a**	
Wheat		**(84)**	
Direct costs, labour and machinery costs for transportation, storage, drying, including depreciation on machinery	4,5768x + 497,58	882	2.58
Labour and machinery costs for field cultivation and cropping	0,4314x + 199,66	236	-0.04
Sum		**1118**	
Barley		**(76)**	
Direct costs, labour and machinery costs for transportation, storage, drying, including depreciation on machinery	3,1177x + 527,21	764	1.14
Labour and machinery costs for field cultivation and cropping	0,3118x + 191,78	215	-0.25
Sum		**979**	
Oilseed rape		**(39)**	
Direct costs, labour and machinery costs for transportation, storage, drying, including depreciation on machinery	3,8979x + 726,72	879	2.90
Labour and machinery costs for field cultivation and cropping	0,188x + 241,57	249	-0.48
Sum		**1128**	
Maize (33% dm)		**(162)**	
Direct costs, labour and machinery costs for transportation, storage, drying, including depreciation on machinery	2,3091x + 399,96	774	1.09
Labour and machinery costs for field cultivation and cropping	0,5599x + 312,58	403	0.55
Sum		**1177**	
Sugar beet		**(699)**	

Direct costs, labour and machinery costs for transportation, storage, drying, including depreciation on machinery	0,5527x + 832,88	1219	2.81
Labour and machinery costs for field cultivation and cropping	0,1153x + 461,1	542	-1.72
Sum		**1761**	

Table 4-7 Functions of cost calculation in BEAST. Base costs result from the cost calculation with the crop-related functions and the crop-specific reference yield-level (x). Maize yield levels refer to the dry matter weight (33%).

Cost changes, as provided by Table 4-7, can be used in BEAST as reference values. Note, however, that BEAST takes values for the two cost categories but only as aggregates for all annual crops.

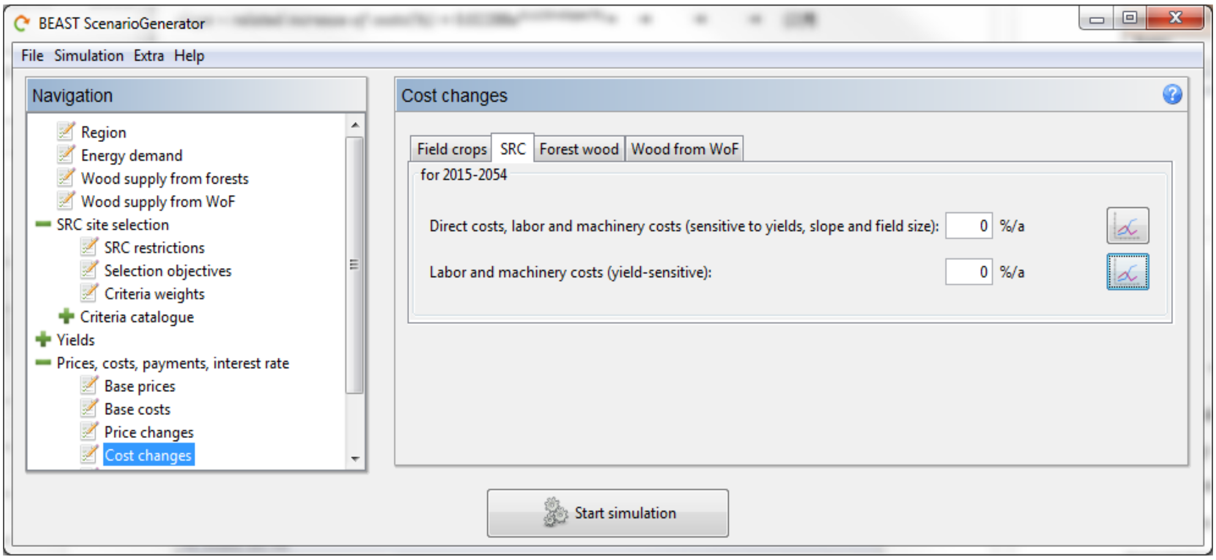


Figure 4-20 Graphical user interface to address cost changes of annual crops in BEAST

SRC cost calculation

SRC cost calculation was carried out for 5 cost positions (a) Cultivation & planting, (b) Harvesting operation, (c) Transportation, (d) Storage and drying, (e) Re-conversion (see Table 4-8). A poplar plantation with 7000 cuttings in a 5-year rotation serves as reference system. The information on SRC-related costs was gathered from 30 literature sources on German SRC production [72-102].

SRC			
n	**Cost position**	**Aggregated variables in BEAST – calculated as**	
1	Cultivation & planting	Fixed costs (user-defined)	
4	Harvesting & chipping	Yield-related function	Slope-function Area-function
4	Transportation	Yield-related function	
4	Storage & drying		
1	Re-conversion	Fixed costs (user-defined)	

Table 4-8 Cost calculation of SRC in BEAST –Input categories and underlying cost positions

Figure 4-21 illustrates the results for the cost positions a-d, and f. The findings for all cost positions are summarized in Table 4-9. "Cultivation & planting" costs were adjusted since most of the reviewed studies refer to plantations with 10.000 cuttings. To reflect the reduced amount of 7000 cuttings in the reference system of BEAST the median value of 2607€ was reduced by 500€ to 2107€, accordingly. For "Harvesting & chipping", literature findings were used as reference do derive a yield-based cost function (see Table 4-9). The function reflects the median value of 16€ t_{od}^{-1} (Figure 4-21) for a base yield of 11t_{od} a^{-1} in the study area. For transportation, median values of the literature review were taken as reference values (see Table 4-9).

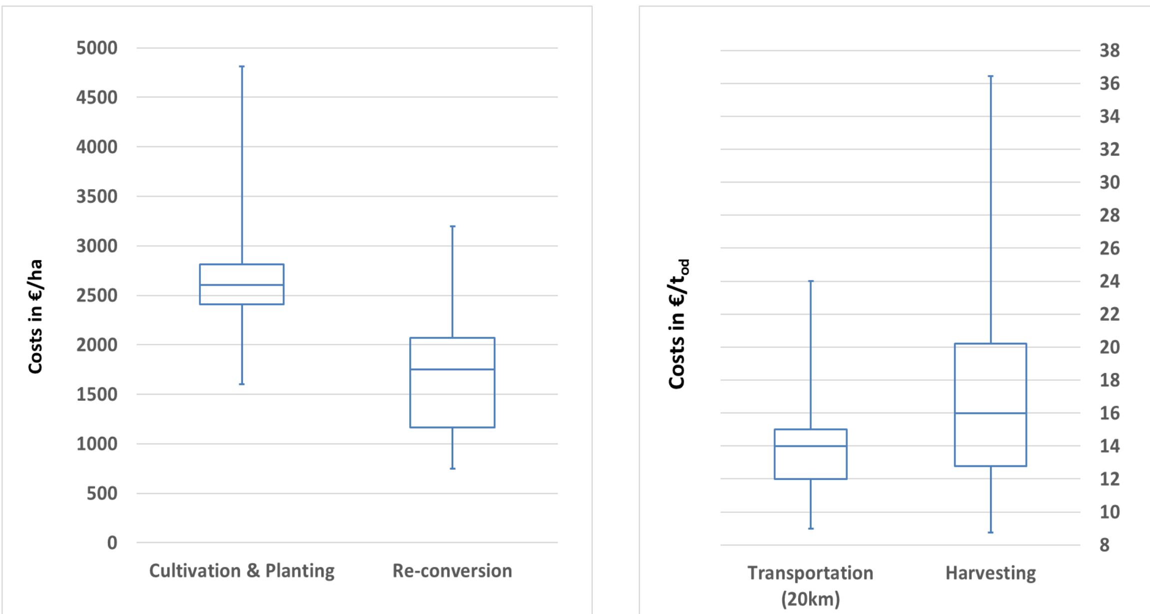


Figure 4-21 Cost variation of SRC cost positions based on a literature review of 30 sources on German SRC plantations [72-102]

Only a few sources dealt with drying costs [79, 87, 91, 93, 97, 100]. Based on their findings and the technology referred to, costs were assumed between 6.5€ $t_{od}^{-1}$and 25€ t_{od}^{-1} (see Table 4-9). Costs of 7€ $t_{od}^{-1}$for drying with waste heat from biogas plants originates from averaging the data provided by Schweier [93] and C.A.R.M.E.N [100]. Wood chips drying by storage under a roof top was calculated with 6.5€ t_{od}^{-1} by Bärwolff and Hering [79]. The same authors introduced a newly developed ventilation system for wood chips drying without external energy that was calculated with costs of 17.5€ t_{od}^{-1}. Drying with the supply of external energy was calculated with costs between 20€ t_{od}^{-1} [87], and 30€ t_{od}^{-1} [97]. Again, the average was used as reference value in BEAST.

The various drying techniques are associated with specific biomass losses during the drying process. For the drying variants (a) and (d) Wagner et al. [87] reported losses of 10% while storage under a roof top (b) accounts for losses of 14% [79] to 22% [102]. Storage with ventilation (c) produces biomass losses of 15% according to Bärwolff and Hering [79].

For "Re-conversion" as the last cost position, again, the median value of the literature review was taken as reference (see Table 4-9).

Cost position	**Reference value/ yield-dependent function**	**Base costs in € ha^{-1} (base yield 11t_{od} ha^{-1} a^{-1} or 55t_{od} ha^{-1} rot^{-1})**
Cultivation & planting	2107	2107
Harvesting & chipping	8,1818x + 430	880
Transportation (20km)	14x	770
Storage & drying (a)	7x	385
Storage & drying (b)	6.5x	358
Storage & drying (c)	17.5x	963
Storage & drying (d)	25x	1375
Re-conversion (incl. fertilizer application)	1900	1900 (1600+300)

x = t_{od} per rotation period (a) waste heat from biogas plants, (b) storage under roof top, (c) ventilation, (d) drying with external energy

Table 4-9 Reference values for various cost positions of a poplar SRC plantation in 5-year rotation and 7000 cuttings. Reddish colour indicates that this function is not only yield-sensitive but field size- and slope-sensitive (see Table 4-7). Yellowish colours determine the yield-sensitive cost positions.

The "Harvesting and chipping" variant was used as reference input for the BEAST cost calculation interface (see Figure 4-22). Since short rotation coppice has not been an established agricultural system for the last years, there are no data on cost changes available. It is however reasonable to calculate with the numbers given for annual crops in the previous paragraphs.

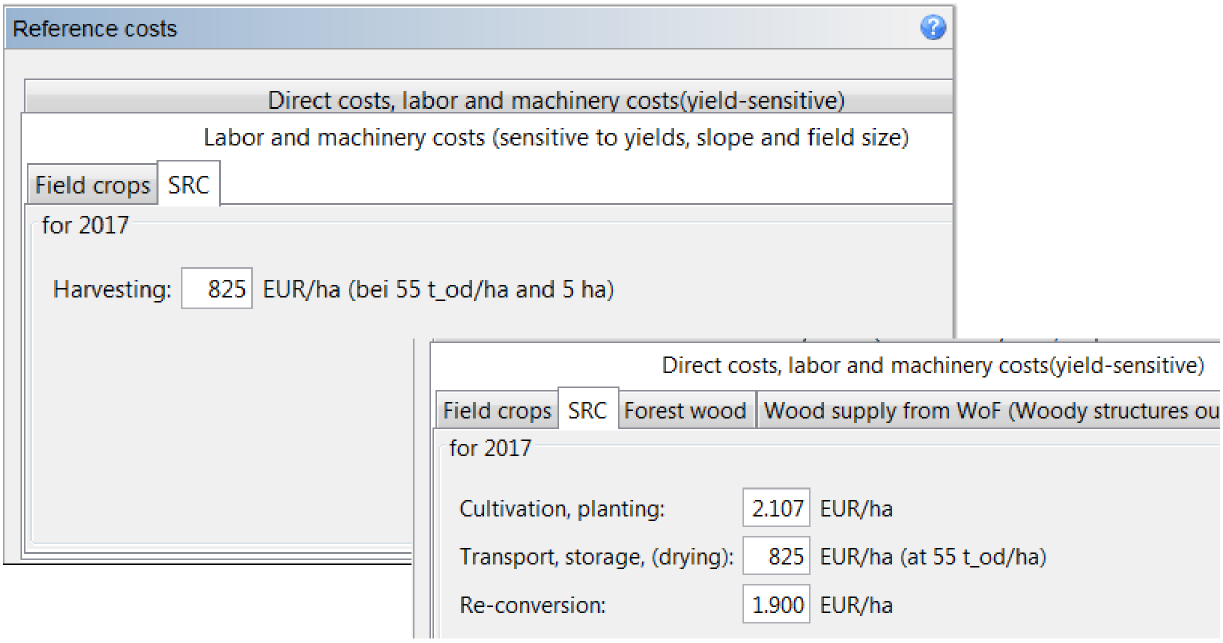


Figure 4-22 Cost categories and reference costs for SRC in BEAST

4.4.3 Calculating annuity differences

Establishing an SRC plantation is a long-term investment with initial as well as final investments and a "delayed" financial return, beginning with the wood chip sale from the first harvesting operation. This is a major difference to annual cropping systems and needs a suitable economic calculation approach. The contribution margin calculation, farmers are used to, is not suitable to cover the different timing of payments and revenues in a perennial system like SRC. Therefore, the dynamic capital budgeting approach has to be applied to compare the profit margins of an annual cropping system with a SRC plantation. Annuities (see equation (1) as the result of this calculation approach represent the average annual profitability and can thus be used for an economic comparison. Annuities reflect the sum of all cash flows (in and out) over time including their interest rate – the net present value (NPV) – which are discounted back to the beginning of the investment t_0.

In a second step, annuities were calculated for both systems (a reference crop rotation and poplar SRC) to determine "annuity differences" by subtracting the annuities of annual crops from SRC annuities (see equation 3). For further details see [18, 19, 29].

(1) $Annuity = NPV * \frac{(1+i)^n * i}{(1+i)^n - 1}$

with

(2) $NPV = \sum_{t=0}^{n} (\frac{E_{(t)} - A_{(t)}}{(1+i)^t})$

where

(3) $Annuity\ difference = Annuity_{SRC} - Annuity_{crop\ rotation}$

NPV = Net present value
n = utilization in years (20)
$E_{(t)}$ = Payments in
$A_{(t)}$ = Payments out
I = Interest rate

Annuity calculation in BEAST is carried out for agricultural field geometries. Based on the analysis of aerial photographs around 28.000 agricultural field geometries were identified and mapped as pasture, respectively arable land. The current implementation addresses only arable fields (around 20.000 geometries) for the allocation of potential SRC sites (see Figure 2-1 in chapter 2).

Table 4-10 summarizes the procedure applied to generate the necessary input information on production-specific costs, commodity prices, and yield levels of both, SRC and annual reference crops to calculate annuity differences in a spatially explicit way.

<table>
<tr><th colspan="8">Productivity (yield simulation)</th></tr>
<tr><td colspan="4">SRC</td><td colspan="4">Annual crops</td></tr>
<tr><td colspan="4">Yield levels for 4 rotation periods (5,10,15,20)</td><td colspan="4">Yield levels for a base year or a reference time horizon</td></tr>
<tr><th colspan="8">Commodity prices</th></tr>
<tr><td colspan="4">SRC</td><td colspan="4">Annual crops</td></tr>
<tr><td colspan="4">Net prices from national statistics</td><td colspan="4">Net prices from national and federal state statistics</td></tr>
<tr><th colspan="8">Cost calculation</th></tr>
<tr><td colspan="4">SRC</td><td colspan="4">Annual crops</td></tr>
<tr><td>n</td><td>Cost position</td><td colspan="2">Aggregated variables in BEAST – calculated as</td><td>n</td><td>Cost position</td><td colspan="2">Aggregated variables in BEAST – calculated as</td></tr>
<tr><td>1</td><td>Cultivation & planting</td><td colspan="2">Fixed costs (user-defined)</td><td>20</td><td>Seed, fertilizer, plant protection</td><td colspan="2" rowspan="4">Yield-related function</td></tr>
<tr><td>4</td><td>Harvesting & chipping</td><td>Yield-related function</td><td>Slope-function
Area-function</td><td>20</td><td>Depreciation on machinery</td></tr>
<tr><td>4</td><td>Transportation</td><td colspan="2" rowspan="2">Yield-related function</td><td>20</td><td>Transportation</td></tr>
<tr><td>4</td><td>Storage & drying</td><td>20</td><td>Storage</td></tr>
<tr><td>1</td><td>Re-conversion</td><td colspan="2">Fixed costs (user-defined)</td><td>20</td><td>Labour and machinery costs for field cultivation and cropping</td><td>Yield-related function</td><td>Slope-function
Area-function</td></tr>
<tr><th colspan="8">Interest rate</th></tr>
<tr><td colspan="8">User-defined – applies to all commodities</td></tr>
</table>

Table 4-10 Annuity calculation (for 20 years) in BEAST –Input categories and cost positions

4.4.4 Sensitivity analysis of economic input variables

To illustrate the impact of specific cost positions on the annual economic return (annuities) a set of 8 variables for SRC (Table 4-11) and a set of 7 variables for annual crops (Table 4-12) were varied.

For SRC, “Cultivation and planting”, “Harvesting and chipping”, “Re-conversion”, “Transportation”, “Yield-level”, and “Price-level” were varied by 10% in relation to the 2017 reference values (see Table 4-9). The cost-impact of diminishing “field size” was calculated for a 1ha field while the reference annuities were calculated for a 5ha field. The impact of “slope” on costs was derived by increasing the field slope from 0% (reference) to 10%. Further, SRC annuities were calculated for 5 variants – ranging from SRC production without transportation (a) to different drying techniques (b-e). Note that different biomass losses are associated with the various drying techniques, having, apart from the specific costs, an additional impact on the annuity calculation (see Table 4-11). The 2008-2017 average price level of 116€ t_{od}^{-1} was used for the annuity calculation of SRC production variants b-d. Alternative “a” was calculated with 93€ t_{od}^{-1}, reflecting the lower price paid for fresh material delivery [72].

		Annuities in €/ha of SRC production variants				
		406	466	369	260	287
Cost position	**Reference value**	only transportation (14€ t_{od}^{-1}) [a]*	Storage and drying (+7€ t_{od}^{-1}) [b]	Storage and drying (+6.5€ t_{od}^{-1}) [c]	Storage and drying (+17.5€ t_{od}^{-1}) [d]	Storage and drying (+25€t_{od}^{-1}) [e]
Cultivation & planting	2107€	+/-15	+/-15	+/-15	+/-15	+/-15
Harvesting & chipping	825€ (16€ t_{od}^{-1})	+/-15	+/-15	+/-15	+/-15	+/-15
Re-conversion (incl. fertilizer application)	1900€ (1600+300)	+/-7	+/-7	+/-7	+/-7	+/-7
Transportation (20km)	725€ (14€ t_{od}^{-1})	+/-14	+/-13	+/-12	+/-12	+/-13
Yield-level	55t_{od} rot^{-1}	+/-70	+/-75	+/-70	+/-61	+/-59
Price-level (2008-17 average)	116 (93*)€	+/-91	+/-103	+/-97	+/-97	+/-103
Field size (1ha)	5ha	-25	-25	-25	-25	-25
Slope (10%)	0%	-11	-11	-11	-11	-11

Table 4-11 Impact of cost variations on SRC annuities from SRC production with (a) no drying but reduced commodity prices of 93€t_{od} (80%), (b) drying with waste-energy from biogas plants – 10% biomass loss, (c) drying by storage under a roof top – 20% biomass loss, (d) drying with ventilation – 15% biomass loss, (e) drying with external energy input – 10% biomass loss

Table 4-11 shows that drying techniques and yield- as well as price-changes have the greatest impact on the annual economic return. The effects of the other cost positions turned out to be much smaller. These findings are in line with Kröber et al. [94] who carried out a sensitivity analysis for SRC sites in Saxony, Germany.

The economically most attractive option is to aim for synergies between biogas and SRC production and to provide capabilities to use waste-heat from biogas plants to dry wood chips.

Sensitivity analysis for annual crops was carried out in the same way as described for SRC. Additionally, yield incline due to breeding progress was included with an annual increase that reflects the long-term trend of each crop (see Table 4-4). Results are presented in Table 4-12 and indicate the dominating effect of yield increase followed by price- and yield-changes. Note in this context, that the yield increase for wheat and oilseed rape was, considerably lower than the long-term-trend in the last decade.

As stated for SRC, the changes in prices and yields have a substantial impact on economic return of annual crops. The relative impact is even more pronounced for annual crops, ranging from an annuity change of +/- 25% to +/-54%. Thus, the risk of substantial fluctuations in income is higher for annual crops compared to SRC.

	Annuity in € ha^{-1} and commodity prices (2008-17 average) in € dt^{-1}				
	Wheat	**Oilseed rape**	**Barley**	**Sugar beet**	**Maize**
Cost position	**494** **(18.8)**	**371** **(37.8)**	**326** **(16.9)**	**1078** **(3.96)**	**488** **(10.08)**
Seed, fertilizer, plant protection	+/-53	+/-78	+/-57	+/-89	+/-43
Depreciation on machinery					
Transportation					
Storage					
Drying					
Weed control, seedbed cultivation, cropping	+/-21	+/-26	+/-21	+/-49	+/-33
Field size (1ha)	-42	-44	-38	-96	-76
Slope (10%)	-18	-19	-16	-41	-32
Yield level (+/-10%)	+/-124	+/-141	+/-110	+/-246	+/-124
Price-level (+/-10%)	+/-169	+/-158	+/-137	+/-296	+/-173
Yield increase (+1.5%)	+/-178	+/-202	+/-157	+/-354	+/-178

Table 4-12 Impact of cost variations on annuities from annual crop production with reference yield levels for wheat: 84dt ha^{-1} a^{-1}, oilseed rape: 39dt ha^{-1} a^{-1}, barley: 76dt ha^{-1} a^{-1}, sugar beet 699dt ha^{-1} a^{-1}, maize 162dt (33%dm) ha^{-1} a^{-1}

4.5 FURTHER INFORMATION ON SCENARIO WORK WITH BEAST

4.5.1 Calculating the multi-criteria score

The final score reflecting the suitability of a field geometry according to the given scenario setting is a simple weighted average of the input criteria values. Since all values including the criteria weights were scaled in a range from 0-100 no normalization of the input numbers is necessary.

$$Criteria\ sum = \sum_{k=1}^{no\ of\ criteria} scaled\ criterion\ value_k * criterion\ weight_k \qquad (1)$$

$$Criteria\ sum_{max} = \sum_{k=1}^{No.of\ criteria} 100 * criterion\ weight_k \qquad (2)$$

$$Final\ Score = \frac{Criteria\ sum}{Criteria\ sum_{max}} * 100 \quad (3)$$

4.5.2 Loading and saving scenarios

Scenario data are stored and compressed into a file with the extension ".best". This compressed file contains several sub-files, including scenario parameters and scenario results. Detailed information on process flow overview including data structures and storage are described in Thiele und Busch [29]. Existing scenario settings are loaded into the "ScenarioGenerator" of BEAST by using the menu item "Load" in the "File" menu and select the appropriate ".best" file in the data explorer (see Figure 4-23). To load scenario results, the same procedure is carried out in the "ResultsExplorer".

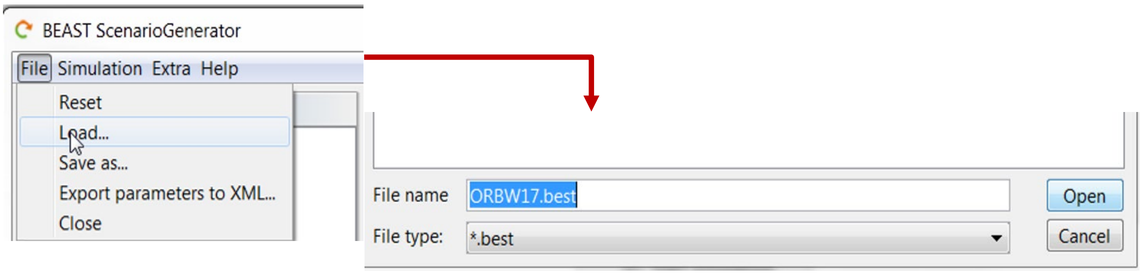


Figure 4-23 Loading scenario data into BEAST

4.5.3 Loading additional data into the "MapViewer"

The "MapViewer" provides the opportunity to visualize additional external vector and raster data. Further, data from webmapping-services (WMS) can be used as "basemaps" (see Figure 4-24). Note that the current reference system (CRS) is UTM zone 32N (with the EPSG code ETRS89). When loading vector or raster data the projection of the input data needs to match the running CRS.

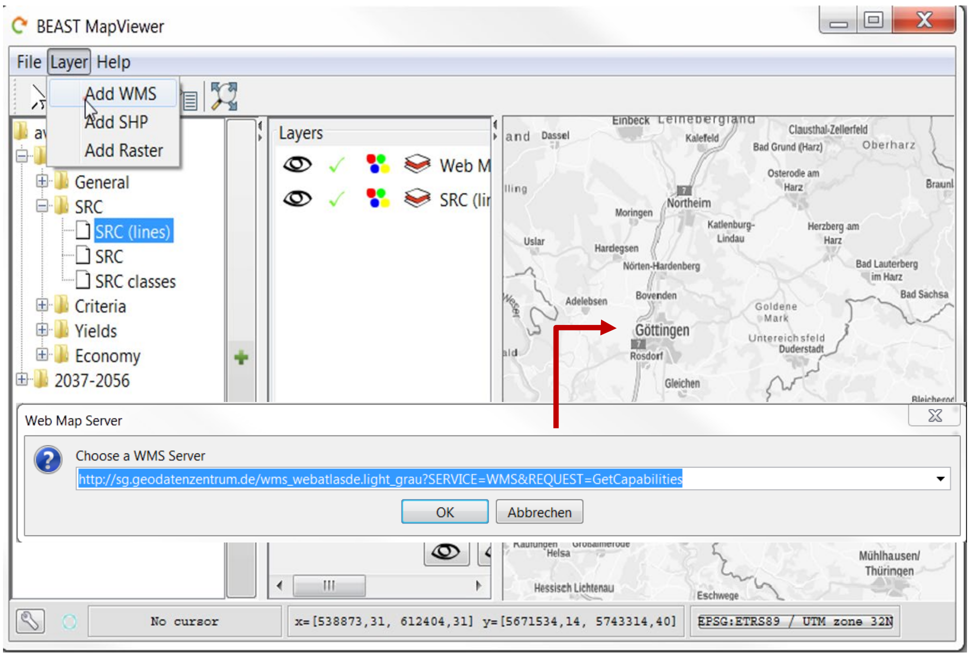


Figure 4-24 Loading external data from the "Layer" menu into BEAST

4.5.4 Exporting Results and post-processing options

The subsequent flowchart depicts how the database and the geometries can be exported from BEAST to a GIS and reloaded to BEAST again after being processed in a GIS, respectively a spreadsheet software.

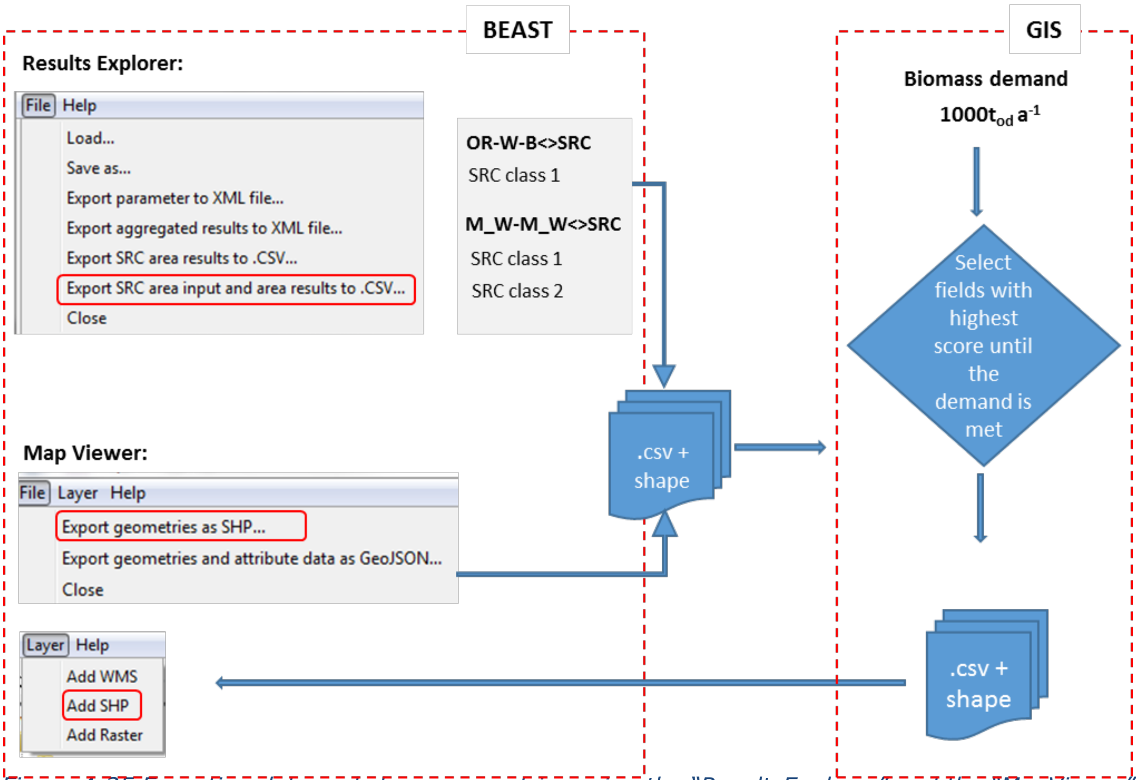


Figure 4-25 Exporting data and shape geometries using the "ResultsExplorer" and the "MapViewer" of BEAST

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