

The expansion of short rotation forestry: characterization of determinants with an agent-based land use model

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Abstract

Wood is a limited resource which is exposed to a continuously growing global demand not least because of a politically fostered bioenergy use. One approach to master the challenge to sustainably meet this increasing wood demand is short rotation forestry (SRF). However, SRF is only gradually evolving and it is not fully understood which determinants hamper its expansion. This study provides theoretical insights into economic and environmental determinants of an SRF expansion and their interplay. This assessment requires the incorporation of farmers' decision-making based on an explicit investment appraisal. Therefore, we use an agent-based model to depict the decision-making of profit-maximizing farmers facing the choice between SRF, the cultivation of conventional annual agricultural crops and abstaining from cultivation (fallow land). The land use decisions are influenced by general economic determinants, such as market prices for wood and annual crops, and by site-dependent determinants, such as the environmental site quality. We found that the willingness to pay for SRF-based products and for annual crops most strongly influences the coverage of SRF in the landscape. SRF will in most cases be established on sites with low productivity. However, a decrease in the willingness to pay for annual crops will lead to a reallocation of SRF plantations to sites with higher productivity. Furthermore, our model results indicate that the impact of the distance to processing plants on farmers' decisions strongly depends on general economic determinants and the given spatial structure of the underlying natural landscape. Analysing the relative importance of different determinants of an SRF expansion, this study gives insights into the approach of using SRF to sustainably meet the growing wood demand. Moreover, these insights are taken as a starting point for the design of effective government interventions to promote SRF.

Keywords: agent-based model, bioeconomy, energy crops, farmer, human decision-making, landscape generators, woody biomass

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Introduction

Wood is a limited bio-based resource that serves as a source for material, power and heat. The global wood demand is increasing due to economic growth and demographic change (FAO, 2014). Lamers *et al.* (2012) depicted a more than tenfold increase in EU demand for wood pellets and an exponential increase in global trade of wood pellets from 0.5 to 6.6 Mt between 2000 and 2010. This increase is expected to be further pushed by the growing relevance of the bioeconomy, that is the enclosure of all economic sectors that develop, produce or use bio-based renewable resources. The European

Commission, for instance, has presented a bioeconomy strategy in 2012 that aims at a low-carbon and resource-efficient economy (European Commission, 2012). The Netherlands, Denmark, Sweden, Finland, Germany, Canada and the United States have presented national bioeconomy strategies, and other countries are expected to follow (BMEL, 2014). The associated stronger role of bio-based resources including innovative wood uses may even further increase the wood demand in the future.

As a consequence, the challenge is to meet the increasing wood demand without negative environmental effects. Woodland and natural forests provide multiple regulating ecosystem services such as carbon storage or purification of water and air. Furthermore, forests are a habitat for about 80% of world's terrestrial

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biodiversity (IUCN, 2012). They are cleared at the rapid rate of about 13 million hectares per year leading to severe negative environmental impacts. Therefore, a variety of policy instruments aiming at protecting forests and avoiding such negative impacts are implemented worldwide (e.g. German Federal Forest Act, Código florestal in Brazil or REDD+). These policies set limits to the amount of wood that can be sourced from forests.

An alternative approach to meet the increasing wood demand is short rotation forestry (SRF). SRF plantations consist of fast-growing trees, whose common species include poplar and willow, which are grown as perennial energy crops on agricultural land (Faasch & Patenaude, 2012). SRF plantations can either be managed as stem plantations with rotation cycles of 10–15 years or as coppice systems using stump sprouting with rotation cycles of approximately 4 years. After several of these rotations, the land is re-cultivated. While the first group is used for fibre production, the latter practice is referred to as short rotation coppices (SRCs) and is often used for energy purposes (Mantau *et al.*, 2010). Therewith, SRF plantations may fulfil multiple bioeconomic purposes. At the same time, several environmental advantages over conventional agriculture are being discussed (for overviews of environmental impacts of SRF see BfN 2012, Thrän *et al.* 2011 or Weih & Dimitriou 2012). For example, SRF is expected to have a positive effect on biodiversity (Sage *et al.*, 2006; Rowe *et al.*, 2011; Holland *et al.*, 2015) as well as on soil and water quality (Makeschin, 1994; Schmidt-Walter & Lamersdorf, 2012). Nonetheless, environmental benefits of SRF are strongly dependent on site- and plantation-specific characteristics (e.g. tree species, cultivation design). Negative impacts, for example on the water balance, can also occur (e.g. Dauber *et al.* 2010, Thrän *et al.* 2011 or Strohm *et al.* 2012). Still, positive impacts predominate and SRF expansion is seen as promising approach to sustainably meet the growing wood demand.

However, the expansion of SRF is proceeding slowly. For example, for Germany and the year 2013, Drossart & Mühlenhoff (2013) reported an area of approximately 6500 ha SRF which only represents 0.03% of the total agricultural land (FAOSTAT, 2015). For Sweden and the year 2011, Dimitriou *et al.* (2011) reported an area of 14 000 ha willow SRC cultivations or 0.5% of total agricultural land. Past studies have predicted strong increases in SRF for several European countries. For example, in the 1990s, stakeholders predicted that the SRC area in Sweden would increase to several hundreds of thousands of hectares (Helby *et al.*, 2004). Almost two decades later, in 2006, the European Environment Agency still stated that SRF would substantially increase from 2010 onwards (EEA, 2006). Given the above stated statistics on current cultivation areas, it

becomes evident that these predictions have failed so far. At the same time, EU wood pellet demand increased by 43.5% from 2008 to 2010 (Cocchi *et al.*, 2011).

Various reasons for the slow uptake of SRF in Europe are discussed in the literature. Main barriers include high initial investment costs combined with uncertain returns on investment. The high uncertainty is caused by price volatility (Finger, 2016) as well as by uncertain yields and production costs (Strohm *et al.*, 2012). In such a situation, it is a good strategy to postpone investment in order to wait for the occurrence of learning curve effects (Musshoff, 2012; de Wit *et al.*, 2013). In addition, capital (especially land) is bound for a long time, leading to inflexibility to react to changing market developments (Strohm *et al.*, 2012; Schweier & Becker, 2013). Still, the relative importance of different determinants that hamper SRF expansion in the EU is not fully understood.

Empirical analyses of spatial distributions of SRF are one approach to identify such determinants. For example, Mola-Yudego & Gonzalez-Olabarria (2010) use a geostatistical method to depict determinants of SRC establishment in Sweden. However, low SRF establishment leads to low data availability on commercial plantations, and therefore, only a few studies exist, which focus on specific regions. We believe that this issue can be tackled by considering SRF expansion as a result of land use decisions and by analysing the decision-making and its implication for the regional land use pattern within a modelling framework. Agricultural decisions as on the adoption of SRF are mostly driven by expected profits, that is expected revenues and costs. These can depend on both site conditions (e.g. soil quality or precipitation) and factors that are not site-specific (e.g. market conditions). For our analysis, we will refer to them as *site-dependent determinants* and *general economic determinants*. Mean annual temperature and precipitation, soil quality and transportation costs to the next woody biomass processing plant are important site-dependent determinants for the economic feasibility of SRF (cf. Dunnett *et al.* 2008 and Faasch & Patenaude 2012, respectively). Demands or prices for agricultural products are important general economic determinants. The interplay of general economic and site-dependent determinants and its effect on individual land use decisions have not been systematically analysed so far. This may be owed to the complexity of the underlying decision mechanisms which evolves from the need to compare crops with harvest cycles of different lengths.

This study investigates how the above-mentioned economic and environmental determinants affect SRF expansion in terms of the increase in land cover and spatial distribution of plantations. We focus on the

European context and analyse the relative importance of site-dependent determinants and general economic determinants. More specifically, we investigate the two site-dependent determinants 'environmental site quality' and 'distance to woody biomass processing plants' as well as seven general economic determinants such as 'willingness to pay for agricultural products' or 'investment expenditures'. In addition, we test the transferability of model results between regions by analysing to what extent these findings depend on the spatial structure of the underlying natural landscape. In particular, we assess the relevance of the explicit spatial configuration and the predictive power of aggregated spatial characteristics of the underlying landscape. For this purpose, we develop a spatially explicit agent-based model (ABM) to depict the decision-making of profit-maximizing farmers in a stylized landscape indirectly interacting via a market mechanism. This approach enables us to simulate and analyse land use decisions under different economic framework conditions and in differently structured stylized landscapes. Instead of providing quantitative predictions for a specific case study, we aim to derive a comprehensive general mechanistic understanding on the SRF expansion. We take these insights as a starting point to discuss the design of effective government interventions to promote SRF. Finally, we conclude by reflecting on the potential of the applied modelling approach.

Material and methods

In the following, we present the model INCLUDE (INDividual Cultivators' Land Use DECisions). It is based on an ABM developed by Weise (2014): a stylized model of rational land use decisions that comprises markets and policy instruments to assess land use effects of promoting bioenergy. We expand this model to enable the incorporation of spatial heterogeneity and of an explicit investment appraisal to include crops with harvest cycles of different lengths.

General conception

The model INCLUDE is a simple ABM based on a stylized landscape. These types of models are considered particularly valuable for the purpose of system understanding, hypothesis testing and communication (Schlüter *et al.*, 2013). In this sense, the model purpose of this study is not to provide quantitative predictions for specific case studies but to derive a comprehensive general mechanistic understanding on the SRF expansion.

The model INCLUDE considers regional land use change as result of individual land use decisions. The landscape is described as regular grid of 50 × 50 cells of approximately 45 ha each (based on Fischer *et al.* 2011). In each cell, there is one agent (i.e. farmer) who decides on the crop to be cultivated in the next time step. The agents are assumed to be rational profit maximizers with full knowledge over revenue and costs

of all possible land use options. We believe that profit maximization is an appropriate assumption for decisions in the European industrial agricultural sector.

In the model, agricultural markets are assumed to be endogenous and to mediate interactions among agents. Therefore, equilibrium market prices for both SRF-based products and products based on annual crops are described in the model by the ratio of exogenously given demands and the endogenously resulting supply that is determined by the agents' cultivation decisions. This price formation is in line with standard economic theory (e.g. equilibrium concept; cf. Mankiw & Taylor 2006 or Engelkamp & Sell 2007) and incorporates the critical market feedback of supply decisions that result in prices which influence again supply decisions (as also used by Lawler *et al.* 2014). In the result of the individual decisions of all agents and the interactions mediated by the market mechanism, land use patterns emerge and evolve over time.

We assume that the agents' land use decisions are influenced by *general* economic (i.e. same for all cells) and *site-dependent* determinants (i.e. different between cells). All determinants investigated in this study are shown in Table 1. The site quality of a cell subsumes environmental site characteristics such as mean annual precipitation and soil quality and therefore influences agricultural productivity. In the model, the determinant 'harvest costs' represents the costs for harvesting SRF plantations and no other production factors. Harvest costs of annual crops are included in the production costs of annuals which further include seed and crop protection of these crops. Therefore, and due to the extent of the landscape stated above, harvest and production costs are seen as *general* determinant and transport costs are the only *site-dependent* costs.

To address the site-dependent determinants, we need to incorporate spatial heterogeneity. Moreover, as we aim to gain general mechanistic understanding of SRF expansion, rather than exploring a specific region, we decided to investigate stylized landscapes. The underlying landscape is generated using a randomization algorithm which allows

Table 1 Determinants of land use decisions in the model

Determinants		General	Site-dependent
Economic	Aggregated willingness to pay for SRF products	x	
	Aggregated willingness to pay for annual crops	x	
	Investment expenditures	x	
	Discount rate	x	
	Recovery costs	x	
	Harvest costs	x	
	Transport price	x	
Environmental	Site quality value in cell		x
	Distance to processing plant		x

generating a variety of landscapes that coincide in certain aggregated spatial characteristics but differ in their explicit spatial configuration. This enables to test the transferability of results between landscape types. Each generated landscape consists of a grid of cells with both specific site qualities and locations of woody biomass processing plants (Fig. 1). These site-dependent determinants together with the general economic determinants influence the agents' land use decisions and hence the emerging land use pattern (Fig. 1). The approach of combining the ABM and a landscape generator enables us to systematically investigate the relative importance of the general economic and site-dependent determinants for the SRF cultivation decisions.

In addition to the spatial heterogeneity, the perennial character of SRF requires the incorporation of an explicit investment appraisal. INCLUDE runs on an annual temporal scale as annual crops are also included. To enable the comparison between land use options with different lengths of harvest cycles, the equivalent annual annuity approach from investment theory is chosen (e.g. Brigham & Houston (2006)). This approach calculates a constant annuity from an uneven cash flow for several periods. In a first step, the net present value for the investment is calculated by discounting the annual profits. In a second step, this net present value is multiplied by the annuity factor to receive a constant value per year, the equivalent annual annuity. Discount rates are seen as subjective discount rates which can vary depending on personal risk aversion (Barberis & Thaler, 2003). The equivalent annual annuity approach is appropriate as it is often recommended to farmers interested in SRF practice (for example Schweinle & Franke 2010) and has been used in several studies on the financial analysis of SRF (Kasmioui & Ceulemans, 2012).

Initialization of landscape

At the beginning of each simulation, the underlying landscape is randomly generated: (i) environmental site qualities are assigned to cells, and (ii) woody biomass processing plants are spatially allocated within the landscape.

1. The distribution of site quality for the ABM was generated using a randomization algorithm that returns uniformly distributed, spatially correlated numbers with a fixed arithmetic mean and a certain spatial correlation. For this purpose, the method of Cholesky decomposition, which considers the covariances among all cells, was used (see appendix A in Thober *et al.* 2014 for details). This enables the generation of ensembles of landscapes with varying explicit configuration but the same aggregated spatial characteristics, that is mean and spatial correlation, of the site quality distribution (Fig. 2).
2. A fixed number of woody biomass processing plants are randomly placed within the landscape. At this, the number of processing plants can be adapted to represent regions with different areal densities (see Table S1 for standard parameter values).

Model processes

At the beginning of each decision step, the current market prices $p_j(t)$ in year t for the different products j , that is annual crops (ANN) and SRF crops, are calculated based on the regional supplies $H_j(t)$ and the following pricing rule:

$$p_j(t) = \frac{D_j}{H_j(t)} \text{ with } H_j(t) = \sum_{i=1}^n h_j^i(t), \quad (1)$$

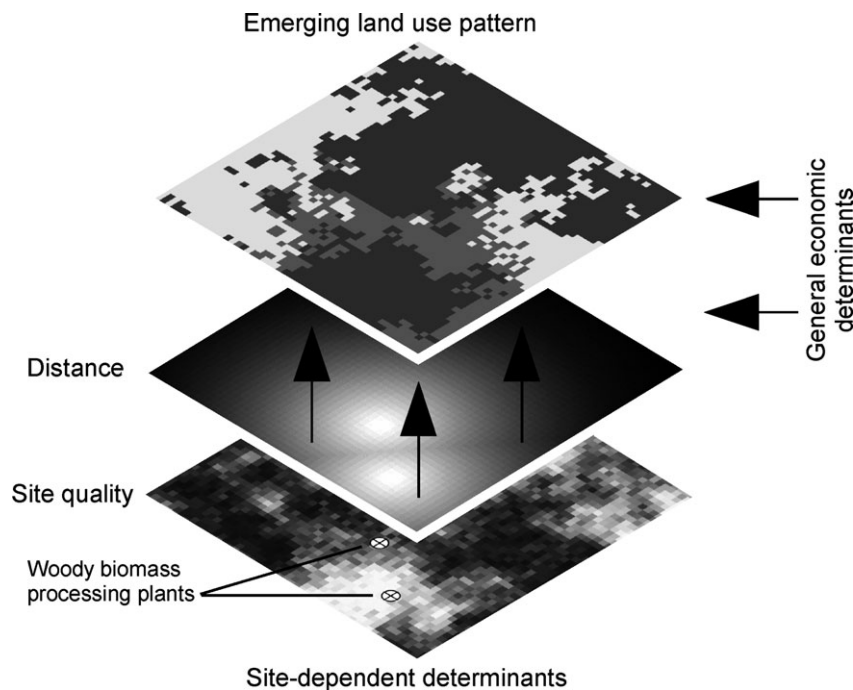


Fig. 1 Interplay of general economic and site-dependent determinants in the course of the short rotation forestry expansion.

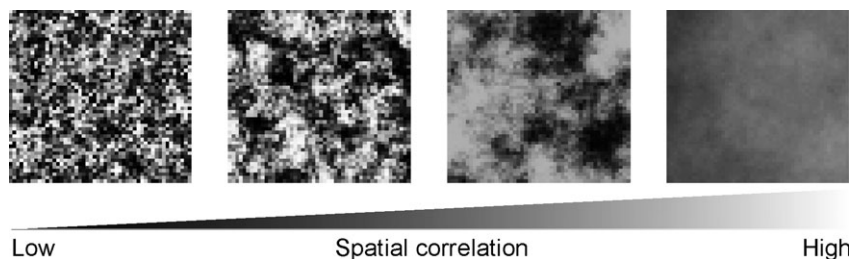


Fig. 2 Examples of generated landscapes with increasing spatial correlation from left to right.

where D_j is the aggregated willingness to pay for product $j \in \{\text{ANN}, \text{SRF}\}$, n the number of agents and $h_j^i(t)$ the harvest amount of product j in cell i given by:

$$h_{\text{ANN}}^i(t) = \begin{cases} q^i, & \text{if land use is ANN} \\ 0, & \text{if land use is not ANN} \end{cases} \quad (2)$$

$$h_{\text{SRF}}^i(t) = \begin{cases} q^i \cdot 0.2 + h_{\text{min}}, & \text{if land use is SRF} \\ 0, & \text{if land use is not SRF} \end{cases}, \quad (3)$$

where q^i is the site quality of the cell of agent i . Site quality subsumes factors such as mean annual precipitation and soil quality known to strongly impact the agricultural output and. Therefore, we assume that the yield of the annual crops and the site quality are linearly correlated with both factors being normalized between 0 and 1. The yield of SRF plantations is also assumed to decrease on poor sites. At this, the dependence on the site quality is less pronounced than for annual crop production because SRF is more resistant against poor site conditions than annual crops.

The land use in the cells is determined by the agents' decisions based on profit calculation. This calculation differs between the three land use options: no cultivation (NoC), ANN and SRF. If agent i abstains from cultivation, neither costs nor revenue arise and the related profit Π for agent i is therefore:

$$\Pi_{\text{NoC}}^i = 0. \quad (4)$$

For annual agricultural crop production, the following profit function applies:

$$\Pi_{\text{ANN}}^i(t) = p_{\text{ANN}}(t) \cdot h_{\text{ANN}}^i - c_{\text{ANN}}, \quad (5)$$

where $p_{\text{ANN}}(t)$ is the current market price (calculated by the pricing rule shown in Eqn 1), h_{ANN}^i the harvest of annual crops in the cell of agent i and c_{ANN} the production costs of annuals. For the profit calculation of the SRF option, the profit of agent i in year t , $\Pi_{\text{SRF}}^i(t)$, over the whole lifetime T of the SRF is calculated by Eqn (6). This stream of profits will be the basis for calculating the equivalent annual annuity (Eqn 11). In the first year, only costs accrue, followed by both profit and costs accruing after each rotation cycle:

$$\Pi_{\text{SRF}}^i(t) = \begin{cases} -c_{\text{SRF}}^i(t), & \text{if } t = 0 \\ p_{\text{SRF}}(t) \cdot h_{\text{SRF}}^i - c_{\text{SRF}}^i(t), & \text{if } t \bmod a = 0, \\ 0, & \text{else} \end{cases} \quad (6)$$

where $p_{\text{SRF}}(t)$ is the current market price in year t for SRF products produced in one rotation cycle on optimal site conditions calculated by the pricing rule shown in Eqn (1), h_{SRF}^i the harvest of SRF in the cell of agent i , $c_{\text{SRF}}^i(t)$ are all incurring costs

in year t calculated by Eqn (7) and a is the number of years after which harvest takes place, that is the rotation cycle (therefore $t \bmod a = 0$ indicates the end of a rotation cycle).

Finally, all occurring costs are calculated by Eqn (7). As perennial crops are associated with higher risks than annual crops (e.g. damages from drought or pests), farmers require a compensation for accepting the higher risk (Sherrington & Moran, 2010; Rosenquist *et al.*, 2013). To reflect this, we include yearly risk costs in the decision model as have been empirically quantified by Rosenquist *et al.* (2013). These risk costs are assumed to decrease with the increase in SRF coverage in the landscape due to learning effects.

In the first year, only investment expenditures v accrue. At the end of each rotation cycle (i.e. $t \bmod a = 0$), harvest costs h , transport costs to the processing plant Γ^i and risk costs k occur. Finally, at the end of the lifetime T , in addition to harvest, transport and risk costs, recovery costs of the land r have to be paid. In all other years, no treatments are needed, and therefore, only risk costs occur:

$$c_{\text{SRF}}^i(t) = \begin{cases} v, & \text{if } t = 0 \\ h + \Gamma^i \cdot h_{\text{SRF}}^i + k(\Phi_{\text{SRF}}), & \text{if } t \bmod a = 0 \text{ and } t < T \\ h + \Gamma^i \cdot h_{\text{SRF}}^i + r + k(\Phi_{\text{SRF}}), & \text{if } t = T \\ k(\Phi_{\text{SRF}}), & \text{else} \end{cases}, \quad (7)$$

where t is the current year, v are the investment expenditures, k are the risk costs calculated by Eqn (8), Φ_{SRF} is the SRF coverage, h the harvest costs, Γ^i the transportation costs of wood produced under optimal site quality conditions calculated by Eqn (9), h_{SRF}^i the actual harvest of SRF in the cell of agent i , a the rotation cycle and r the recovery costs. The risk costs k are assumed to be linearly dependent on the current SRF coverage Φ_{SRF} (given in percentage of the whole landscape). The function has been parameterized following results of Rosenquist *et al.* (2013):

$$k(\Phi_{\text{SRF}}) = \max(0, k_{\text{max}} - k_{\text{slope}} \cdot \Phi_{\text{SRF}}). \quad (8)$$

The transportation costs are calculated based on Bauen *et al.* (2010), including a tortuosity factor of 1.6 to model the road network. The transportation costs are assumed to be linearly dependent on the distance to woody biomass processing plants:

$$\Gamma^i = \tau + \gamma \cdot d^i, \quad (9)$$

where d^i is the distance of agent i to the processing plant, τ are fixed costs for transportation and γ the transport price per distance. We assume a homogeneous cell size f to calculate the distance d using Euclidean distance (Deza & Deza, 2013).

From the sequence of profits $\Pi_{\text{SRF}}^i(t)$, the net present value is calculated as the sum of the discounted profits:

$$N^i = \sum_{t=0}^T (1+s)^{-t} \cdot \Pi_{\text{SRF}}^i(t), \tag{10}$$

where T is the lifetime of the plantation, s the discount rate and $\Pi_{\text{SRF}}^i(t)$ the profit in year t calculated by Eqn (6). Subsequently, the equivalent annual annuity E is calculated from the net present value N to enable the comparison of land use options with unequal lifespans:

$$E^i = \frac{1}{1 - (1+s)^{-T}} \cdot N^i, \tag{11}$$

where s is the discount rate, T the lifetime of a SRF plantation and N^i the net present value calculated by Eqn (10).

Finally, the agent compares the equivalent annual value E^i with the possible profit from annual agricultural crop production $\Pi_{\text{ANN}}^i(t)$ and chooses the option with the higher profit. If both, the equivalent annual value E^i of SRF and the profit of annual agricultural crop production $\Pi_{\text{ANN}}^i(t)$, would yield negative profits, the agent decides to abstain from cultivation.

All model parameters, their values and the references for parameterization can be found in the Table S1.

Evaluation criteria and simulation experiments

In this study, we investigate how different determinants affect a possible SRF expansion after entering the market in terms of the increase in SRF coverage and their spatial distribution across the stylized landscape. We assess the relative importance of different general economic and site-dependent determinants in differently structured stylized landscapes.

For this purpose, we apply an ensemble approach and perform a spatial sensitivity analysis as follows. All landscapes

belonging to the same ensemble coincide in the aggregated spatial characteristics but differ in their explicit spatial configuration. Accordingly, the variance in the outcomes for all landscapes of the ensemble indicates the sensitivity of the evaluation criteria to changes in the explicit spatial configuration. Additionally, the randomization algorithm enables us to generate ensembles with different aggregated spatial characteristics. In this study, we compare two scenarios with ensembles of different spatial correlations of site quality (Fig. 2). Therefore, we vary the spatial correlation and hold the mean site quality constant. As a consequence, the frequency of site qualities also changes with the spatial correlation because of the changing spatial variability. A low spatial correlation leads to a uniform frequency distribution because site qualities of all levels are occurring. A high spatial correlation implies a clustering of site qualities around their mean while extreme values are not occurring.

Based on this ensemble approach, we perform a systematic model analysis in two steps, which are summarized in Table 2.

In the first step, we analyse the impact of general economic determinants (see Tables 1 and 2 for the specific determinants and the respective model parameters) on the land use pattern in general and the SRF coverage in particular. At this, we vary each general economic determinant individually, while all other parameters are kept constant. To quantify how sensitive the SRF expansion reacts to these determinants, we use the sensitivity index SI (see for example Bauer & Hamby 1991) which is given by the percentage difference in model output when varying one parameter over its entire range:

$$SI = \frac{O_{\max} - O_{\min}}{O_{\max}}, \tag{12}$$

where O represents the model output. As we are interested in SRF expansion, we chose the SRF coverage Φ_{SRF} in year 50, that is the number of cells with SRF divided by total number of

Table 2 Overview of analysis steps: evaluation measures and model parameters investigated under different scenarios for which the single analysis steps are repeated

Subject of analysis	Evaluation measure	Investigated model parameters	Scenarios for transferability test	Section
Step 1: General economic determinants	Sensitivity index of short rotation forestry (SRF) coverage in landscape	Aggregated willingness to pay for SRF-based products D_{SRF} ; Aggregated willingness to pay for annual crops D_{ANN} ; Investment expenditures v ; Recovery costs r ; Harvest costs h ; Transport price γ	a) Standard b) High discount rate c) High spatial correlation of site quality	Influence of general economic determinants
Step 2: Site-dependent determinants and interplay with general economic determinants	Probability of SRF occurrence	Aggregated willingness to pay for SRF products D_{SRF} ; Aggregated willingness to pay for annual crops D_{ANN}	a) Standard b) High spatial correlation of site quality	Influence of site-dependent determinants

cells in the landscape, as investigated model output. As a result, a ranking of the relative importance of general economic determinants can be derived. As stated above, the standard deviation of the SRF coverage Φ_{SRF} and of the sensitivity index over the ensemble gives insights into the importance of the explicit spatial configuration. In addition, we test the transferability of the sensitivity results between landscapes with different aggregated spatial characteristics (high and low spatial correlation of site quality) and between landscapes populated by farmers with different risk attitudes. Therefore, we repeat the gradual variation in general economic determinants for two more scenarios: a high discount rate of the agents and a high spatial correlation of site quality.

In a second step, we analyse the impact of the two site-dependent determinants 'site quality' and 'distance to processing plant'. Therefore, we determine the probability that an agent in year 50 cultivates SRFs given a certain site quality and distance to processing plant. The probability calculation is based on the ensemble of underlying landscapes. In addition, we analyse the interplay of the site-dependent determinants with general economic determinants by repeating the analysis for an increasing aggregated willingness to pay for the two agricultural products. Finally, we again test the transferability of this interplay between landscapes with different aggregated spatial characteristics of the underlying natural landscape (high and low spatial correlation of site quality).

Results

When SRF enters the market

For a better understanding of model dynamics, we first show land use patterns that emerge under the standard parameter set (see Table S1). Here, we compare the case

with and without SRF as land use option available (Fig. 3a, b respectively).

Without SRF (Fig. 3a) as agricultural option, annual crops represent the dominant land use option with coverage of approximately 94% in this example and occupation of cells with high environmental site quality. The remaining 6%, characterized by low site quality, are covered with fallow land. The parameterization of this baseline scenario was chosen based on the situation in European countries where on average, 6% of agricultural land is fallow land (Allen *et al.*, 2014). In the model, the fallow sites are not chosen for agricultural production because here the yield of annual crops is low and agricultural practice hence not profitable, given the assumed willingness to pay for annual agricultural crops D_{ANN} . With SRF as land use option available (Fig. 3b), 17% of the landscape is covered by SRF plantations, largely at the expense of fallow land. The sites where SRF is cultivated are characterized by inferior sites. The reason for SRF cultivation on inferior sites is the low profit that annual crop cultivation yields on these sites. In the following section, we will investigate how different general economic determinants affect the expansion of SRF.

Influence of general economic determinants

To investigate the relative role of different general economic determinants, we analyse their impact on the mean SRF coverage Φ_{SRF} over the ensemble of landscapes with low spatial correlation of site qualities.

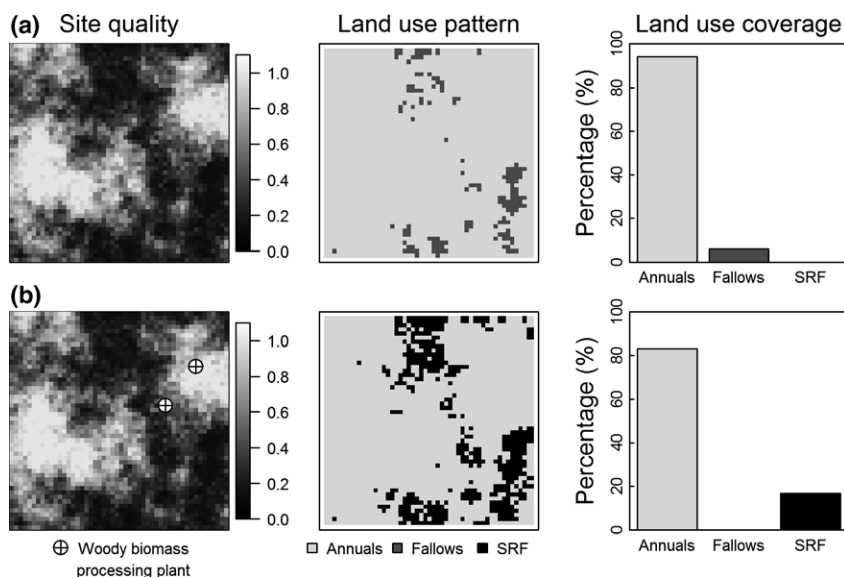


Fig. 3 Underlying landscape of site qualities and processing plants, resulting land use patterns and coverage of land use options after 50 years (a) without and (b) with short rotation forestry available as option.

Increasing aggregated willingness to pay for SRF products D_{SRF} as well as decreasing investment expenditures v positively affect the mean coverage of SRF plantations (Fig. 4a, b respectively). Triggered by a higher willingness to pay, the market price increases and positively influences the profit (see Eqns 1 and 6). The other way around, high investment expenditures represent a hurdle, which hinders the SRF cultivation decision. Note the very low standard deviation (indicated by the grey shading in Fig. 4) for the entire regarded parameter range. The landscapes within the ensemble only differ in their explicit spatial configuration. Therefore, the low standard deviation indicates that the explicit spatial configuration is not important for SRF coverage (possible reasons will be discussed in section General economic determinants). Instead, the general economic determinants strongly affect the coverage of SRF plantations in the landscape and dominate the importance of the explicit spatial configuration.

In a second step, we quantified the impact of various general economic determinants on the SRF coverage by performing a local sensitivity analysis and calculating sensitivity indices (see Eqn 12). To test the relative importance of these general economic determinants and the aggregated spatial characteristics of the underlying

landscape, we performed the analysis for (i) the standard scenario, (ii) a higher discount rate and (iii) higher spatial correlation of site qualities. Therefore, we derive an indication whether general economic determinants would equally affect SRF expansion in different scenarios.

High-sensitivity indices indicate a high impact of the corresponding determinant. Under the standard scenario, the main drivers of the SRF expansion are the aggregated willingness to pay for SRF products and annual crops, the investment expenditures and the harvest costs (see Fig. 5a). The relative importance of these major determinants is influenced by the spatial correlation of site quality (Fig. 5c) and the higher discount rate (Fig. 5b). In the scenario with a higher discount rate, the impact of investment expenditures strongly increases (see Fig. 5b). With a higher discount rate, agents value profit accruing at the end of each rotation cycle less, and therefore, the initial hurdle of investment expenditures more strongly influences the SRF cultivation decision. Regarding landscapes with a different spatial structure, namely a higher spatial correlation of site qualities, the relative importance of the different economic variables is also changing. For instance, the impact of the aggregated willingness to pay for annual

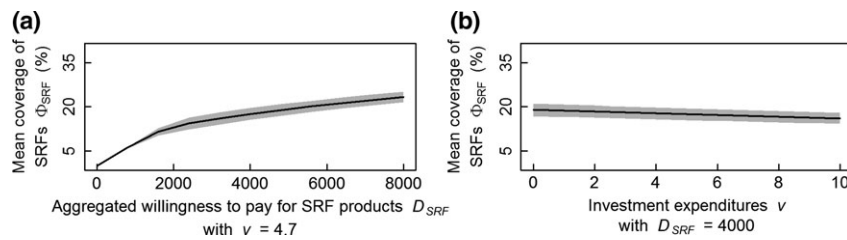


Fig. 4 Mean short rotation forestry (SRF) coverage Φ_{SRF} for increasing (a) aggregated willingness to pay for SRF products D_{SRF} and (b) investment expenditures vs. Grey shading indicates the standard deviation over the ensemble of the low spatial correlation of site qualities.

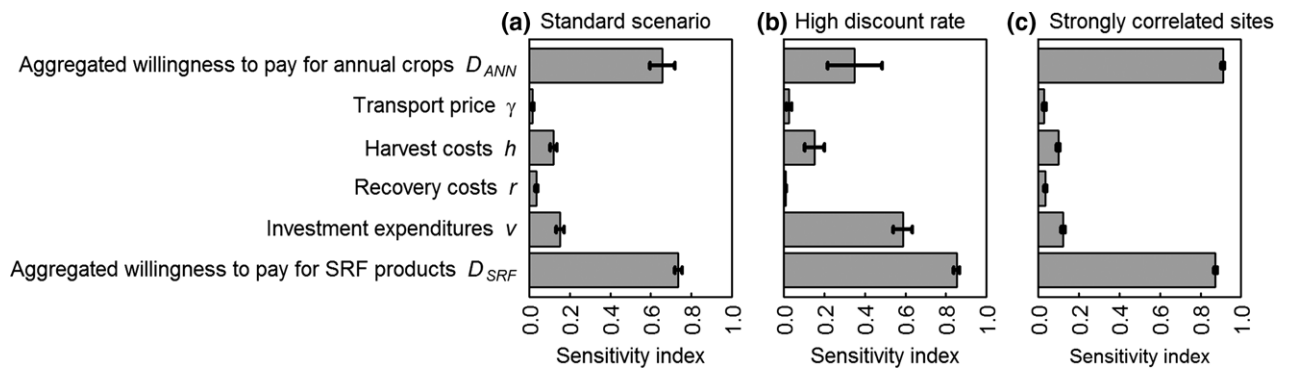


Fig. 5 Sensitivity indices of short rotation forestry coverage to general economic determinants in the three scenarios: (a) standard, (b) higher discount rate and (c) higher spatial correlation of site qualities. Error bars indicate the standard deviation over the respective ensemble.

crops increases (see Fig. 5c). The reason for this lies in the distribution of site qualities in the underlying landscape. While the spatial correlation of the distribution of site quality is higher than that under the standard scenario, the mean site quality is kept constant. As a consequence, the range of available site qualities for the landscape with high spatial correlation of site quality is narrower. The landscape contains fewer sites with low site qualities. We assume that the productivity of annual crops is more affected by low site quality than that of SRF. Therefore, fewer sites of low site quality also imply fewer sites on which the yield of annual crops is very low and the cultivation of SRF is therefore competitive. Therefore, the coverage of SRF is more strongly dependent on the economic situation of the competitive land use option. Again, the explicit spatial configuration is not influential as standard deviations are low for all parameters and scenarios. Hence, the results are transferable to regions with the same aggregated spatial characteristics but different explicit spatial configuration.

Influence of site-dependent determinants

In the second step of the analysis (cf. Table 2), the attention is shifted to the spatial pattern of SRF occurrence, its determinants and the explanatory power of certain site-dependent determinants. The focus is on the relative importance of environmental site quality and the distance to woody biomass processing plants for SRF allocation, that is two attributes which are both site-dependent, heterogeneously distributed and known to influence yield and/or costs of the various options of crop cultivation under consideration. Additionally, we

investigate the extent to which general economic determinants influence this relationship.

In all cases with the standard value for the willingness to pay for annual crops D_{ANN} , SRF occurrence is restricted to sites with low environmental site qualities (Fig. 6). On sites with high site qualities, the cultivation of SRF is economically not competitive with the high yields of annual crops.

In the scenario with standard spatial correlation of site qualities (Fig. 6a) and for a low to medium willingness to pay for SRF crops, the probability of SRF occurrence is positively correlated to the site quality, however, only up to a certain threshold of site quality above which the probability decreases abruptly. Higher site qualities increase the yield of SRF and therefore the probability of cultivating SRF. Here, higher distances to the processing plants d and therewith higher transport costs lead to a decreasing probability of SRF occurrence. Additionally, higher site qualities compensate for higher distances and, vice versa, lower distances for lower site qualities (indicated by the triangle shape of high probabilities in Fig. 6a). Yield of SRF, and therewith revenue, is higher on good sites. This compensates for higher transport costs of longer distances. Contrary, lower transport costs compensate for the lower revenue of SRF on sites with lower site quality.

The distance of the chosen SRF sites to their next processing plants d varies with the aggregated willingness to pay for SRF products D_{SRF} . For an increasing D_{SRF} (left to right column in Fig. 6a), sites with higher distances d become economically attractive and are therefore chosen for SRF cultivation. The higher willingness to pay leads to higher revenues from SRF which compensates for higher costs of longer distances.

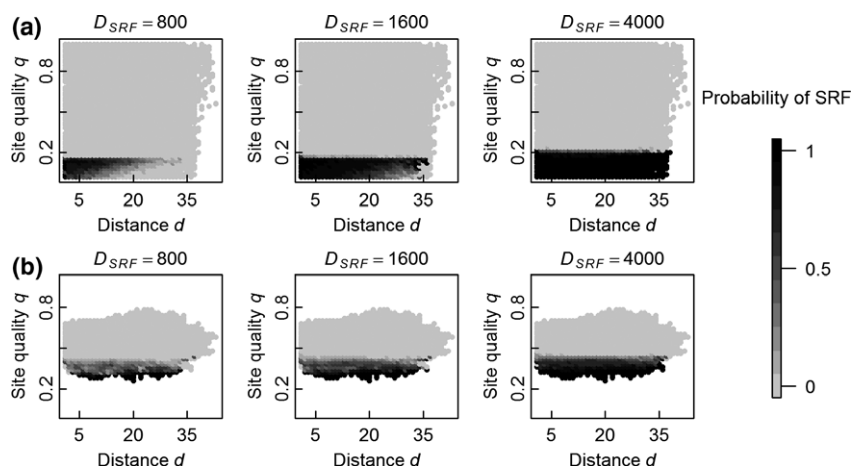


Fig. 6 Probability of short rotation forestry (SRF) occurrence for combinations of site quality q and distance d present in the underlying landscapes for an increasing aggregated willingness to pay for SRF-based products D_{SRF} and scenarios (a) standard and (b) high spatial correlations of site qualities. The willingness to pay for annual crops is set to the standard value of $D_{ANN} = 20500$.

In contrast, the importance of site quality as site-dependent determinant for SRF cultivation decision does not change with D_{SRF} . SRF plantations are cultivated on lower quality sites, independent of D_{SRF} . This is not a gradual interrelation. Instead, a threshold of site quality can be identified above which the cultivation of SRF is economically not competitive anymore. .

Finally, we investigate how the aggregated spatial characteristic of the underlying landscape affects the results (i.e. the spatial correlation of site quality; compare Fig. 6a, b). Recalling, a higher spatial correlation leads to a narrower range of available site qualities in the landscape; that is, site quality varies closely around the mean. While the site quality and SRF occurrence probability are positively correlated up to certain threshold for the standard scenario (Fig. 6a), they are negatively correlated up to a certain threshold for the high spatial correlation of site qualities (Fig. 6b). In the latter case, very low-quality sites are not available and farmers need to evade to higher site qualities to cultivate SRF. Here, the competition with annuals increases with the increase in site quality, resulting in a decrease in SRF probability. The importance of distance also changes between the two scenarios. Under the scenario with highly correlated site qualities, distance is not relevant under all of the investigated D_{SRF} (Fig. 6b). As described above, for higher correlated site qualities, fewer sites with low site qualities are available. This reduces the number of potential sites where SRF cultivation is competitive with annual crops. Therefore, farmers accept longer distances to processing plants. In other words, the comparison of the two scenarios indicates that the general economic determinant D_{SRF} alters the

importance of the site-dependent determinant ‘distance’ for the SRF decision. While the distance is still influential for a low and medium aggregated willingness to pay for SRF-based products D_{SRF} in the standard scenario, it is not in the landscape with high spatial correlation of site qualities. Hence, the results are not fully transferable between landscapes with different aggregated spatial characteristics.

In addition to the impact of the aggregated willingness to pay for SRF-based products D_{SRF} , we assessed the influence of the aggregated willingness to pay for annual crops D_{ANN} (Fig. 7). Again, higher distances to the processing plants d negatively influence the SRF occurrence probability. Moreover, site qualities and distances can compensate for each other (see explanation of Fig. 6). Here, these relationships are even more sensitive to the willingness to pay for annual crops D_{ANN} than they were to D_{SRF} .

For a lowered willingness to pay for annual crops D_{ANN} , sites with high site qualities are more likely to be chosen for SRF cultivation, independent of the spatial correlation of site qualities (left column of Fig. 7). Here, no competition with annuals takes place and SRF plantations are most profitable on good sites due to higher yields. As demand for annuals D_{ANN} increases, sites with low to medium site qualities are chosen for SRF cultivation.

A high willingness to pay D_{ANN} also leads to an increase in the realized distance of the chosen SCF sites to the processing plants. Due to the advantageous situation of the competitive annual crops, only sites with lower site qualities are chosen for SRF cultivation where yield of annual crops is low. These sites, however, can also be located far away from processing plants, and

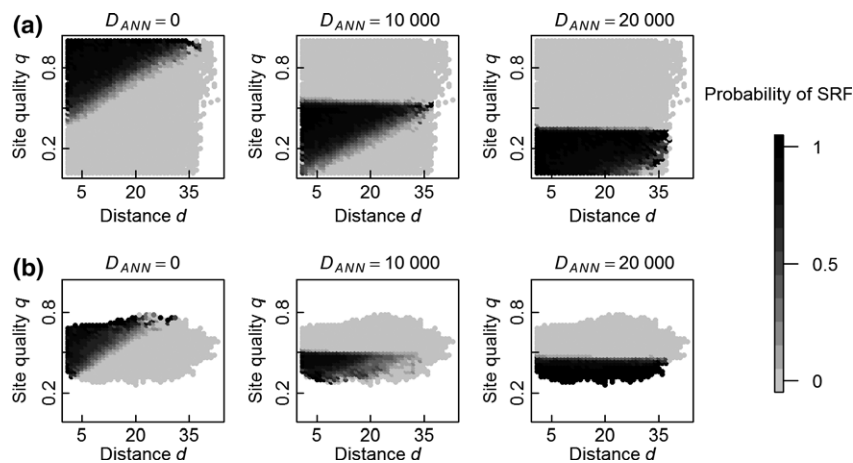


Fig. 7 Probability of short rotation forestry (SRF) occurrence for combinations of site quality q and distance d present in the underlying landscapes for an increasing aggregated willingness to pay for annual crops D_{ANN} and scenarios (a) standard and (b) high spatial correlations of site qualities. The willingness to pay for SRF-based products is set to the standard value of $D_{\text{SRF}} = 4000$.

therefore, also these sites with long distances to processing plants are chosen for SRF cultivation.

The spatial structure of the underlying landscapes again influences the impact of distance: while distance is still slightly influential for a high willingness to pay D_{ANN} in the standard scenario, it is not in the landscape with high spatial correlation of site qualities. The impact of site quality is again stable across the different spatial structures.

Discussion

In this work, we assessed the relative importance of different economic and environmental determinants for agricultural crop cultivation choice and showed how these influencing factors might affect a possible SRF expansion in terms of the SRF coverage and their spatial distribution. In the following paragraphs, we will draw conclusions from our model results, discuss advantages of the applied method and finish with an outlook on future research.

Determinants of SRF expansion

General economic determinants. Our model results indicate that general economic determinants have a strong impact on the uptake of SRF practice. This effect is relatively stable across the investigated scenarios with differently structured landscapes and different risk attitudes of farmers:

1. Independent of the investigated scenarios (i.e. spatial correlation of site quality and discount rate of farmers), the willingness to pay for SRF products showed to be one influential economic determinant of SRF expansion in the model. The reason is that the willingness to pay strongly affects the revenue of SRF.
2. Furthermore, given our model assumptions, the willingness to pay for the competitive land use option 'annual crops' and the investment expenditures represent strong determinants of SRF expansion. Therefore, the strength of their impact depends on the investigated scenario.
3. Transport price, harvest costs and recovery costs have a relatively low impact under all investigated scenarios.

These results are in accordance with empirical and model-based studies which showed the importance of electricity prices (analogue to the importance of the willingness to pay for SRF-based products in our model), establishment grants and demand for the spread of SRF cultivation (Mola-Yudego & Gonzalez-Olabarria, 2010; Alexander *et al.*, 2014; Mola-Yudego *et al.*, 2014). The low impact of the transport price is contrary to previous

studies (e.g. Dunnett *et al.* 2008) and might increase when investigating a larger landscape than the one in this study.

In addition, we assessed to what extent these findings depend on the spatial structure of the underlying natural landscape. Therefore, we assessed the relevance of (i) explicit spatial configurations and (ii) aggregated spatial characteristics (i.e. the spatial correlation influencing the range of environmental site qualities present):

1. We showed that while general economic determinants have a strong impact on the SRF coverage, the importance of the explicit spatial configuration as we depicted it in the underlying landscape is negligible.
2. In contrast, the range of site qualities present in the landscape influenced the impact of the general economic determinants more strongly.

The results are therefore fully transferable between regions with different explicit spatial configurations but are not between regions with different aggregated spatial characteristics. However, further model experiments showed that with a substantial increase in transport price, the variation over the ensemble increases. This indicates that the transport price governs the relevance of the explicit spatial configuration of site quality distribution. Furthermore, in this study, we did not model the spatial allocation of the processing plants in dependence on the current feedstock supply. Modelling the two-way interaction between the establishment of processing plants and feedstock suppliers (as done by Alexander *et al.* 2013) may increase the importance of spatial configuration in our model results. In this study, the focus was on the supply side because the allocation of processing plants may be influenced by external factors such as political incentives or the proximity to consumer centres (esp. when the wood from SRF is used for heat supply).

Relevance of site-dependent determinants. Another focus of our analysis was on the impact of site-dependent determinants of SRF cultivation decisions. SRF plantations in the model will be located on sites with low productivity in most cases as annual crops are economically more competitive on sites with higher environmental site quality. This is confirmed by a survey among SRC operators in Bavaria in which SRC sites show below-average land rents (Hauk *et al.*, 2014). Skevas *et al.* (2015) showed a reduced difference in revenue between corn and bioenergy perennials on poor soils. Similarly, Helby *et al.* (2004) revealed a slight economic disadvantage for SRCs over food production on good soils. However, we showed that an intense decrease in the willingness to pay for annual crops will lead to a reallocation of SRF

plantations in the model to sites with higher site quality.

In our model, sites chosen for SRF cultivation are characterized mostly by low environmental site qualities. Therefore, direct conflicts with food production are negligible because yields of annual crops would be low on these sites. This is in line with Aust *et al.* (2014): the authors argued that SRC on marginal agricultural land will only slightly affect food and feed production due to low yields on these sites. Similarly, various studies promote the use of marginal land as option to reduce competition with food production (Fitzherbert *et al.*, 2008; van Dam *et al.*, 2009; Hartman *et al.*, 2011). On the other hand, areas with low site quality may possess high ecological value (e.g. in the case of grasslands (cf. BfN 2012)). We do not model the ecological value of sites, but land which has been left fallow before the SRF expansion might have potentially built up ecological value.

The influence of the site-dependent determinant 'distance to the processing plants' was found to be more sensitive to general economic determinants such as the aggregated willingness to pay for SRF products and for annual crops, respectively.

Policy implications for promoting SRF. In this section, we take the model results as a starting point to discuss the design of effective government interventions to promote SRF. Therefore, we go beyond the model results to position them within the real-world context and focus on the political situation in Germany. Derived insights may also propose ways for other European countries, in particular as the model is not specific to the German case.

Currently, two main policy instruments to promote SRF expansion are applied in Germany. First, investment subsidies exist in some federal states and differ with respect to design (Strohm *et al.*, 2012; Peschel & Weitz, 2013). They are important to overcome the barrier of high initial investment costs and to reduce the risk of investment (e.g. Faasch & Patenaude 2012, Strohm *et al.* 2012 or Wolbert-Haverkamp & Musshoff 2014). This is also supported by one of our model results: the high impact of investment expenditures. Therefore, it would be valuable to improve the subsidy design and provide coordination and harmonization of investment subsidies: requirements regarding minimal investment amount and minimal number of trees should be adjusted to allow for participation of small plantations and lower participation barriers (Strohm *et al.*, 2012). Secondly, as of late, SRC can be accounted for as an ecological focus area under the greening component of the European Common Agricultural Policy (CAP) (Finger, 2016).

Further proposed instruments include the support of networks between SRF suppliers and demand side

actors, support for research and development and information instruments (Strohm *et al.*, 2012). Additionally, in some studies, setting minimum wood chip prices through supply contracts is named as a measure to reduce investment uncertainty (Ridier *et al.*, 2012; Wolbert-Haverkamp & Musshoff, 2014). This is also supported by our model results: the high impact of the willingness to pay for SRF products which substantially influences wood chip prices.

However, guaranteeing minimum wood chip prices or wood-specific quotas by public support instruments might cause market actors to choose cheapest wood or biomass resources available, not necessarily SRF. Therefore, a very technology- and feedstock-specific design of support instruments would be required to incentivize SRF (e.g. a higher substrate tariff class for SRF as implemented in the German Renewable Energies Act (EEG) 2012). However, attempting to incentivize SRF specifically through demand-sided, sectoral deployment support has high risks for steering errors. Large-scale SRF plantations may be incentivized if demand resulting from policy instruments is high enough, but it may end up not to be a competitive feedstock compared to other biomass resources nor a competitive climate change mitigation option. This would result in high public costs of errors as it was for example seen for the 'NaWaRo bonus' (renewable raw material bonus) in earlier versions of the EEG (cf. Britz & Delzeit 2013). In addition, decisions about the sectoral use of SRF wood would be distorted in favour of energetic applications as long as comprehensive bioeconomy policies are absent.

When assessing the appropriateness of policy instruments, it is important to consider that environmental benefits of SRF strongly depend on site- and plantation-specific characteristics (e.g. tree species, cultivation design) and that negative impacts are also possible (e.g. Dauber *et al.* 2010, Thrän *et al.* 2011 or Strohm *et al.* 2012). If SRF were supported through a demand-sided deployment support instrument, this would need to be complemented by specific spatial explicit environmental requirements or SRF-specific sustainability certification standards. This would ensure a positive environmental balance, but also increase complexity and transaction costs of demand-sided interventions.

From our model results and the discussion of current policy options, we conclude that investment subsidies in combination with information, networking, and research and development support seem to be the most promising approach to reduce barriers posed by high initial investment requirements, but should be combined with environmental minimum requirements (cf., Thrän *et al.* 2011 or Strohm *et al.* 2012). These subsidies would be only viable for the market entry phase to

generate learning effects and should be phased out eventually.

Income stream risks would already be reduced by providing consistent and reliable political framework conditions, which increase planning security about future demand for woody biomass. Reliable framework conditions encompass general reliability of signals from sectoral bioenergy policies (e.g. in Germany the EEG in the electricity sector or the Renewable Heat Act (EEWärmeG) and the Market Incentive Programme in the heating sector), but also from biofuel policies (for innovative applications, e.g. wood gasification) and bioeconomy policies.

In general, the effectiveness increases with increasing specificity of intervention (ranging from instruments directed at renewable energy in general over wood in general to SRF-specific instruments), but so does the risk of inefficiency and market distortions. Whether SRF emerges as a competitive resource option should therefore be left to market actors, to reduce distortions of land, energy and material biomass markets.

Advantages of the applied methodology

The cultivation of perennial energy crops, such as SRF, resembles a long-term investments decision (Skevas *et al.*, 2015). Modelling SRF cultivation decisions therefore requires incorporating different timescales and risk attitudes. We use approaches from investment theory which allow the comparison between land use options with different lengths of harvest cycles. Furthermore, perennial crops are associated with higher risks than annual crops (e.g. damages from drought or pests). Therefore, farmers require a compensation for accepting the higher risk (Sherrington & Moran, 2010; Rosenquist *et al.*, 2013). To reflect this, we included risk costs in the decision model as have been empirically quantified by Rosenquist *et al.* (2013).

While financial barriers showed to be the most influential determinant of SRF cultivation decisions (e.g. Aylott & McDermott 2012), behavioural and nonfinancial determinants of SRF expansion were also identified significant by modelling (e.g. Sherrington & Moran 2010) as well as by empirical studies (e.g. Sherrington *et al.* 2008). In this context, diffusion processes driven by farmers' imitation or communication are of particular importance (Mola-Yudego & Gonzalez-Olabarria, 2010; Alexander *et al.*, 2013). ABMs represent a strong tool to model diffusion of innovation processes compared to aggregated approaches (such as Bass' differential equation model) because they enable to depict heterogeneous agents and their interaction (Kiesling *et al.*, 2012). Multiple application examples exist (Kiesling *et al.*, 2012) which differ in the way decision rules

are modelled (e.g. simple rules such as threshold behaviour or utilitarian approaches) and the depiction of social networks (e.g. full networks, random networks). In the INCLUDE model, we follow a simple diffusion model of risk costs which decrease with the increase in SRF coverage due to learning effects (Rosenquist *et al.*, 2013). In general, INCLUDE provides a reference model that could be enhanced in future research by including also noneconomic influence factors of decisions.

The chosen method of using stylized landscapes enables us to derive a general understanding beyond a specific region. Furthermore, the use of a landscape generator for the underlying landscape enables us to test the transferability of results between landscapes. We generate an ensemble of initial landscapes with fixed aggregated statistical characteristics (termed geostatistical model by Jager *et al.* 2005). Model evaluation was then performed using statistics over the entire ensemble. Besides statistically significant results (Dibble, 2006), this also enables the investigation into the relevance of explicit spatial configuration by quantifying the variation in model predictions due to variation in spatial structure (as proposed as spatial uncertainty analysis by Jager *et al.* 2005). Furthermore, the approach enables to test the transferability of results between landscapes with different aggregated spatial characteristics.

To conclude, by assessing different general economic and site-dependent determinants of SRF cultivation decisions, this study gave insights into barriers of a possible SRF expansion. The identification of determinants with strong impacts, such as investment expenditures or the willingness to pay for SRF products, can be taken as starting point for the future design of effective government interventions to promote SRF. This might contribute to sustainably meet an increasing demand for wood, especially in the context of a worldwide politically fostered bioeconomy. The analysis suggests that investment subsidies might be a promising approach to promote SRF, but should be combined with environmental minimum requirements.

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Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article:

Table S1. Table of model parameters, their values and, if available, the references for parameterization.