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Are short rotation coppices an economically interesting form of land use? A real options analysis

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ABSTRACT

Short rotation coppice (SRC) is intensively discussed as being an economical and ecological advantageous alternative to traditional agricultural land use. In various countries, farmers have been encouraged through incentives to cultivate SRC. Nevertheless, they often do not switch from conventional land use to SRC, even if SRC is relatively beneficial according to the net present value (NPV) rule. Therefore, farmers do not follow the classical investment theory. A relatively new theory is the real options approach (ROA). The ROA takes further aspects like irreversibility of the investment costs, flexibility regarding investment timing, and uncertainty of the investment returns into account, which the NPV rule ignores. In the case of SRC, investment (conversion) triggers when a farmer should switch to SRC following the ROA can be higher than those following the NPV rule. As it is often the case in real options applications, decision makers' possibility to disinvest in general and farmers' possibility to reconvert, in particular within the useful lifetime of SRC, is not considered. We build a model to calculate the conversion triggers for switching from annual crop production to SRC following the ROA. We consider the opportunity to reconvert the land and evaluate the respective effects on the conversion triggers according to the ROA. Furthermore, we analyze the effect of a former governmental incentive, in terms of an investment subsidy, on the conversion triggers of both theories. Our calculations show that following the ROA, a farmer should change land use to SRC more slowly than when following the NPV rule. Furthermore, neglecting the reconversion possibility would cause considerable bias amongst the results. The consideration of investment subsidies diminishes the conversion triggers of both theories. We conclude that the ROA can at least partially explain farmers' inertia of converting to SRC.

Introduction

Short rotation coppice (SRC) is more commonly known as the process of planting trees on agricultural land which can be harvested frequently within a few years' time. Currently, the process is being deeply discussed as an alternative form of land use in European countries such as Sweden, Germany and the UK (Mitchell et al., 1999; Larsson and Lindegaard, 2003; SAC, 2008). SRC has also gained interest in Canada and New Zealand (Sims et al., 2001; Rockwood et al., 2004).

Several studies have shown that SRC is ecologically advantageous compared to intensive agricultural land use (Hall and House, 1995; Bryan et al., 2010; Lasch et al., 2010; Langeveld et al., 2012). Moreover, SRC can be more profitable than annual crops (Heaton et al., 1999; Schoenhart, 2008; Wagner et al., 2009). Especially in areas with marginal soil qualities and high levels of groundwater, SRC is from a single farms' point of view competitive because it obtains high and stable yields, despite poor soil quality (Murach et al., 2009; Stolarski et al., 2011).

To support farmers' willingness to convert to SRC, incentives have been established. In Germany, farmers in the federal state of Mecklenburg-Western Pomerania have been allowed to plant SRC on permanent grassland (DGErhVO M-V, 2008) which is not allowed in other federal states of Germany. Farmers in the UK were encouraged to plant SRC with a general planting grant of 400 GBP per hectare for set-aside land and 600 GBP per hectare (equal to approximately 700 €/ha) for non-set-aside land (Mitchell et al., 1999; SAC, 2008).

Despite SRC becoming a more profitable alternative to traditional agricultural land use, few farmers are actually converting to SRC. Although Murach et al. (2009) show that for the Northeast of Germany, the potential area for SRC is up to 200,000 ha, there had only been 5000 ha converted to SRC by 2011 in all of Germany (Marron et al., 2012, p. 116).

If SRC can be competitive with annual crops from a single farms' point of view and farmers do not realize converting to SRC, it is

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necessary to identify farmers' underlying reasons. A part of the inertia can be explained, for example, through the relatively high investment costs in combination with missing financial capital and the technical lack of knowledge (Marron et al., 2012, pp. 114–118). Moreover, traditional behavior in terms of long lasting binding of the land and the investment costs (Marron et al., 2012, pp. 114–118) as well as bounded rationality may cause farmers' inertia.

It is necessary to evaluate SRC as an investment because its useful lifetime amounts to more than 20 years, and the plantation is expensive. When applying the classical investment theory, decision makers in general and farmers in particular choose the land use which promises the highest net present value (NPV). However, if farmers convert to SRC, they first have to take into account that the high costs for the establishment of the plantations are sunk. Second, farmers can postpone the conversion to SRC. Third, SRC are related with uncertain returns because the prices for the harvested wood chips are volatile. The classical investment theory ignores irreversibility and flexibility regarding the timing of investment as well as uncertainty of investment returns (Trigeorgis, 1996, p. 1). However, this can be highly important in causing farmers' inertia to invest in (convert to) SRC because it influences farmers' investment behavior. Because of not considering these aspects, the NPV rule could be perhaps not extensive enough to capture and evaluate farmers' decision situation. A relatively new theory, which takes into account these aspects that the NPV rule ignores, is referred to as the real options approach (ROA) (Dixit and Pindyck, 1994, pp. 3–25). The investment (conversion) triggers which induce the cultivation of SRC calculated by the ROA could be shifted upwards, compared to the conversion triggers of the NPV rule. This effect can be explained because the ROA can consider opportunity costs over time in terms of the value of waiting to invest.

One relevant publication on the conversion to SRC is that of Musshoff (2012), in which he compares the conversion triggers of the NPV rule with those of the ROA relating to an example of a farmer who has set-aside land. Musshoff (2012) calculates that the conversion triggers following the ROA are considerably higher than those of the NPV rule. Therefore, a farmer following the ROA should be slower to convert to SRC compared to the NPV rule. He concludes that the ROA can partially explain farmers' inertia. As it is often done in real options applications, Musshoff (2012) ignores decision makers' disinvestment possibility as well as farmers' flexibility to reconvert the land used for SRC within its useful lifetime. If farmers follow the ROA, they sometimes may not be aware of their reconversion option. If so, their conversion triggers can be overestimated because they have a higher degree of flexibility in practice than farmers would believe and which is, for example, considered in the model of Musshoff (2012).

In this paper, we address the question of whether the ROA still can partially help to explain farmers' inertia if reconversion option is considered. Moreover, we aim to determine the influence of farmers' risk attitude on the conversion recommendation of the NPV rule and the ROA. Additionally, we evaluate the influence of an investment subsidy, which was offered to farmers in the UK, on the conversion recommendation of both approaches.

In our decision situation, we examine farmers' option of switching between traditional agricultural land use and SRC. We assume the land is of marginal soil qualities and a high groundwater level because SRC provides an interesting economic alternative on these soils. Since rye is usually cultivated on marginal soils for which other crops are not suitable (Bushuk, 2000), we compare SRC to rye production. We calculate conversion triggers at which farmers should convert from rye production to SRC following both the NPV rule and to ROA to allow for comparison. In the case of the ROA, we differentiate between conversion triggers with and without a reconversion option to evaluate the effect of a reconversion opportunity. We calculate reconversion triggers at which farmers should switch back from SRC to rye production. In the model applied, we make use of genetic algorithms (GA) and stochastic simulation. With the help of the GA, we can consider a high degree of entrepreneurial flexibility in the model. Using stochastic simulation we can model uncertainty in a very flexible way. This combination seems to be relevant for the determination of the optimal conversion and reconversion triggers. In our calculations we include different degrees of risk aversion to analyze its impact on the conversion and reconversion triggers. Moreover, we consider two stochastic variables for the gross margins (GM) of SRC and rye. Musshoff (2012) considers only one stochastic variable as the price for the harvested wood chips of SRC. If the land is not set-aside and economically interesting for agricultural crop production, it is necessary to include uncertainty concerning the prices and accordingly the GM of this alternative crop. Our model can capture the value of flexibility necessary to change production and farmers' inertia caused by risk aversion.

In the following section, we describe the decision problem and the methodological approaches. Thereafter, we mention the model assumptions and the data used. Afterwards, the results of our model are illustrated. Finally, the results are discussed and some conclusions are drawn.

Decision problem and methodological approach

In the first subsection, we describe the decision situation. We continue in the second subsection with the explanation of the calculation of the conversion triggers following the classical investment theory. In the third subsection, the ROA is generally explained, and the structure of the model to determine the conversion and reconversion triggers following the ROA is declared.

Description of the decision situation

We consider a farmer who has land with marginal soil qualities and no irrigation possibilities. The land has a higher groundwater level, which in contrast to annual crops can be used by SRC plants. These soils are particularly interesting for SRC (Murach et al., 2009) and is typical in some areas in the northeast of Germany. On these soils farmers usually cultivate rye. Therefore, the farmer in our model has the annual possibility to convert from rye production to SRC or to postpone conversion while further cultivating rye. We assume that through farmers' conversion decision there is no change in machinery equipment or labor.

If the farmer converts to SRC, investment costs occur at the beginning of each useful lifetime. In accordance with the governmental incentive that was offered in the UK, the investment costs are reduced by the amount of subsidy paid if the investment subsidy is considered. SRC generally has a useful lifetime, which often exceeds twenty years. Nevertheless, the farmer can reconvert the land within its useful lifetime and return to rye production. If he cultivates SRC until the end of each useful lifetime, the farmer has the opportunity to continue to convert to SRC further or use the land for rye production. At the end of each useful lifetime as well as in the case of a reconversion within the useful lifetime, recultivation costs occur. Due to farmers' possibility to cultivate SRC multiple times, we have to take into account an infinite period under consideration.

If the farmer converts to SRC, we assume that he cultivates poplar because it is a very promising wood fuel that achieves high yields and low input requirements (Nassi o di Nasso et al., 2010). In the case of SRC in general, and poplar in particular, the frequency between the harvests is dependent on the rotation period. In practice, if there is a rotation period of three years, the farmer receives conversion returns every third year. Moreover, the first harvest is lower than the following ones. As usual in forestry economics, we assume a "normal forest." In forestry literature, a "normal forest" is described as a set of forests with different age classes (Bettinger et al., 2009, pp. 199–203). In general, the upper end of the age class is defined as the expected useful lifetime of the cultures. The advantage of a "normal forest" is that there are constant growths of biomass each year which can be harvested annually (Bettinger et al., 2009, pp. 199–203). We suppose that the farmer who cultivates SRC has several cultures with different years of plantation which allow him to harvest an average yield each year.

To compare the two cultivation alternatives, we make use of gross margins (GM). The GM generally equals the revenues minus the variable costs. Due to the fact that the land, which is converted to SRC keeps the status of agricultural land, the farmer is authorized to get annual CAP support for SRC (European Commission, 2009). Therefore, we have not considered annual subsidies for both alternatives because they do not deviate if the farmer produces rye or cultivates SRC. Concerning SRC, the revenues are calculated by multiplying the average volume of the harvest (wood chips) by the price for the harvested wood chips. In order to calculate the GM, the revenues are subtracted by the variable costs of harvesting, drying, and transporting. In the case of poplar, fertilizer is generally not needed, and pest management is only done in the year of conversion (Dallemand et al., 2007; Marron et al., 2012, pp. 14–41). With regard to rye production, the harvest of rye is multiplied by the price and subtracted by the sum of the variable costs for harvesting, drying, and transporting.

Risk aversion of the decision maker could have an important impact with the adoption of new production techniques in agriculture (cf. Anderson, 1974; Isik and Khanna, 2003; Hugonnier and Morellec, 2005). Therefore, we have to include farmers' risk attitude in our calculations. To do so, risk-adjusted discount rates are frequently used. For this reason, we distinguish between the interest rate for discounting the GM, the investment costs, and the recultivation costs of SRC and the interest rate for discounting the GM of rye.

Conversion decision following the classical investment theory

The classical investment theory analyzes a 'now or never' decision. Referring to our decision situation, a farmer regarding the NPV rule can only convert to SRC now or never at all. Following the theory, the value of the investment at a time t is expressed as the difference between the present value of the returns and the present value of the expenditures. In general, the investment decision following the classical investment theory should be made if the NPV is positive (Hull, 2009, p. 737).

If the farmer converts to SRC, investment costs IC accumulate at the very beginning of each useful lifetime. Within the useful lifetime he earns the average GM of SRC $\mathrm{GM}_t^{\mathrm{SRC}}$. While earning the GM of SRC it is no longer possible to receive the GM of rye $\mathrm{GM}_t^{\mathrm{rye}}$. At the end of each particular useful lifetime, recultivation costs RC must also be considered. Therefore, the NPV equals:

$$\mathrm{NPV}_t = V(\mathrm{GM}_t^{\mathrm{SRC}}) - V(\mathrm{IC}) - V(\mathrm{RC}) - V(\mathrm{GM}_t^{\mathrm{rye}}) \quad (1)$$

$V()$ indicates the present value. Assuming an infinite period under consideration, the present value of the GM of SRC equals the expected GM of SRC multiplied with 1 divided by the risk-adjusted discount rate of SRC. The calculation of the present value of the GM of rye is done analogously. The NPV rule evaluates an investment possibility in which the farmer cultivates SRC for an infinite amount of useful lifetimes if he has converted to SRC. On the basis of the Eq. (1), the critical value of the GM $\mathrm{GM}_t^{\mathrm{SRC}*M}$ (conversion trigger) at which the NPV equals zero and from which a farmer should convert from rye production to SRC in the year t can be calculated as follows:

$$\mathrm{GM}_t^{\mathrm{SRC}*M} = [V(\mathrm{IC}) + V(\mathrm{RC}) + V(\mathrm{GM}_t^{\mathrm{rye}})] \cdot i^{\mathrm{SRC}} \quad (2)$$

i^{SRC} equals the risk-adjusted discount rate of SRC. The index $^*M$ belongs to the investment thresholds that are in the context of the NPV rule often referred to as Marshallian-triggers. For purposes of presentation, the conversion trigger is subtracted by the expected GM of rye in order to calculate the additional value of the conversion trigger $\Delta\mathrm{GM}_t^{\mathrm{SRC}*M}$ a farmer would need to switch from rye production to SRC:

$$\Delta\mathrm{GM}_t^{\mathrm{SRC}*M} = \mathrm{GM}_t^{\mathrm{SRC}*M} - \mathrm{GM}_t^{\mathrm{rye}} \quad (3)$$

With regard to the NPV rule, a reconversion trigger is not relevant because the classical investment theory does not consider the entrepreneurial flexibility of a disinvestment possibility.

Conversion decision following the real options approach

In contrast to the NPV rule, the ROA also considers sunk costs, entrepreneurial flexibility with regard to the investment's implementation, and uncertainty of investment returns in a comprehensive dynamic-stochastic context (Dixit and Pindyck, 1994, pp. 3–25). This means that the ROA takes into account that a farmer can convert to SRC now, or he can wait while continuing to produce rye. Moreover, it considers sunk costs in terms of investment costs and uncertainty concerning the future GM of SRC. The ROA is based on the analogy between financial options and real investment projects. The option to invest now or to postpone the investment is similar to American call options. The owner of an American call option as well as the investor (e.g. the farmer) has the right—but is not obligated—to choose to buy an asset (e.g. the conversion to SRC) with stochastic returns (e.g. present value of conversion returns) within a certain time period (e.g. lifetime of the option).

As mentioned in the previous subsection, following the classical investment theory, a positive NPV would suggest investing immediately. Regarding the financial options theory, it can be said that the classical NPV, also referred to as intrinsic value, is only a part of the options value of the investment project (Trigeorgis, 1996, p. 124). Moreover, the investment option has a continuation value, which is defined as the discounted expected value of the investment at the next possible time of investment. If a decision maker invests now, he is earning the intrinsic value but cannot earn the continuation value. A rational investor will only invest immediately if the intrinsic value is greater than the continuation value. The Bellmann equation for this binary decision-making problem is defined as follows (Dixit and Pindyck, 1994, pp. 93–134):

$$F_t = \max(\mathrm{NPV}_t; E(\mathrm{NPV}_{t+1}) \cdot (1+i)^{-1}) \quad (4)$$

F is the value of the investment at time t, i stands for the interest rate, $E()$ is the expectation operator, and max() implies the maximum operator. The classical NPV is the lower limit for the options value F. Referring to Eq. (4), there is a stopping region, where the intrinsic value exceeds the continuation value, and a continuation region, where the continuation value exceeds the intrinsic value. Under specified regulatory conditions (Dixit and Pindyck, 1994, p. 128), the two regions are separated from each other by a critical value of the stochastic variable. The critical value is generally referred to as the investment trigger. In our decision situation, we calculate the critical value as the additional value $\Delta\mathrm{GM}^{\mathrm{SRC}^*}$ of the conversion trigger a farmer needs to switch from rye production to SRC (cf. Eq. (3)).

The solution of Eq. (4) is not trivial. Analytical solutions only exist for simple valuation problems or special cases (cf. McDonald and Siegel, 1986). They require a variety of restrictions which are not fulfilled in our case. For example, the analytical solution requires that the development of the stochastic variable strictly follows a geometric Brownian motion (GBM) (cf. McDonald and Siegel, 1986; Gjolberg and Guttormsen, 2002). In relation to the GBM, stochastic variables cannot become negative and, therefore, cannot be applied to cash flows or GM. Since we use the GM of SRC and rye as stochastic variables, we may not make use of the GBM in our decision situation. Therefore, we have to use numerical-approximative approaches. Hull (2009, pp. 399–442) provides an overview of different numerical options valuation methods.

One numerical-approximative approach is the combination of stochastic simulation and GAs. Using stochastic simulation we can accommodate any stochastic process referring to the stochastic variables (Hull, 2009, pp. 418–421). Moreover, it allows us to calculate the options value of investment possibilities for a given investment strategy (i.e. conversion trigger). To include an optimization algorithm, it is possible to combine the stochastic simulation with the GA. GAs are oriented on the natural evolution (Holland, 1975; Goldberg, 1989; Mitchell, 1996). We can adopt the GA for a decision problem such as the conversion decision from rye to SRC and vice versa. The GA selects a number of randomly chosen conversion strategies and tests them with regard to their options value. Through different operators of the GA, the conversion strategies are modified from one generation to the next generation in order to increase the options value. The purpose of this computation is to find the conversion strategy with the highest options value.

The GA considers a high degree of flexibility that, for example, includes reconversion options in the model. The consideration of the reconversion possibility is needed in order to determine conversion and reconversion triggers simultaneously. For example, Feil et al. (2013) developed a real options market model to evaluate the influence of different political schemes on firms' willingness to invest with the help of the combination of stochastic simulation and the GA. Graubner et al. (2011) used GA in order to analyze a general spatial competition model and to study firms' choices of spatial pricing policy.

As done in the case of the determination of the conversion triggers of the NPV rule, the critical value in terms of the additional value of the conversion trigger ΔGM^{SRC^*} concerning the switch from rye to SRC has to be determined. Since we consider farmers' possibility to reconvert the land to rye production within the useful lifetime of SRC, the additional value of the reconversion trigger $\Delta GM^{rye*} = (GM_t^{rye*} - GM_t^{SRC})$ has to be calculated. The additional value of the reconversion trigger is an average value over the useful lifetime of SRC.

In our model, the farmer switches to SRC if he has cultivated rye in the exhausted period and the GM of SRC in time t is equal to or higher than the GM of rye of the same time and the additional value of the conversion trigger ($GM_t^{SRC} \geq GM_t^{rye} + \Delta GM_t^{SRC*}$). Reconversions happen if SRC is cultivated in the exhausted period and the GM of rye of the relevant year is greater than or equal to the GM of SRC of the same year plus the additional value of the reconversion trigger ($GM_t^{rye} \geq GM_t^{SRC} + \Delta GM_t^{rye*}$). The determination of the optimal additional values for the conversion and reconversion triggers is explained in detail in Appendix A1.

Data and model assumptions

In the first subsection, we describe cultivating SRC and determine the production costs of SRC and rye. Moreover, we show how we calculate the historical GM of SRC and rye. In addition, we describe the used stochastic process for the uncertain GM. With regard to the second subsection, we explain the determination of the risk-adjusted discount rates. At the end of the subsection, we give an overview of our model parameters.

Planning assumptions for SRC and rye

We conduct literature research on SRC and interview experts to gather the data needed to determine the costs of investment, production, and recultivation. Because the data varies in the literature (Dallemand et al., 2007; Kroeber et al., 2010; Marron et al., 2012, pp. 53-54), the following costs are average values of the collected data.

Investment costs including preparation of the land, planting, poplar plants, and possible necessary care in the first year amount to approximately 2736 € per hectare (€/ha). If an investment subsidy is considered, the investment cost decreases by approximately 700 €/ha. We assume a planting density of 10,000 trees per hectare, which is often used in practice (Simpson et al., 2009).

For our plantation we anticipate a physical possible useful lifetime of 21 years. Given that Nassi o di Nasso et al. (2010) have shown that a 3-year harvest frequency guarantees high net energy yields, we assume a rotation period of about 3 years. Consequently, the number of rotations is up to seven. In practice, the first harvest is lower than the following harvests upon establishment of the plantations. Assuming a "normal forest", we suppose the farmer receives an average harvest in each year after cultivation. Considering the mentioned soil and groundwater conditions in the northeast of Germany, we anticipate an average annual yield of around 10 tons of dry material per hectare (t_{DM}/ha) (Murach et al., 2009; Simpson et al., 2009). In accordance with Musshoff (2012), we assume that the yield of SRC can be well forecasted and is constant over time. This assumption is affirmed by, for example, Calfapietra et al. (2010) who note that "SRC would guarantee good yields over several growing seasons." Moreover, Caslin et al. (2010, pp. 31–32) argue that in the case of willow, yields will reach a stable plateau, which is only influenced by weather conditions. Due to the fact that we assume that SRC has access to groundwater and has a perennial harvest, the plants are not confronted by stress caused through droughts.

If the plantation is harvested, costs for harvesting, drying, and transporting roughly amount to € 32 per ton of dry material (€/t_{DM}). Due to the very complex recultivation process, the corresponding costs amount to approximately 1121 €/ha.

To calculate the GM, the costs of harvesting, drying, and transporting are subtracted from the revenues. The revenues of SRC are calculated by multiplying the metric tons of dry material by the price for the harvested material of SRC (wood chips). Since a long time series of wood chip prices does not exist,[1] the prices are derived from the heating oil prices. Therefore, the inflation-adjusted price of oil per liter from 1970 to 2011 is divided by the heating value of oil and multiplied by the average heating value of wood chips (Hawliczek, 2001; IWO, 2012). In relation to the heating value, the observed oil prices are higher than the prices of wood chips between 2003 and 2011. Therefore, the mean of the wood chip prices deducted from the heating oil prices from 2003 to 2011 is compared with the mean price of the real wood chip prices from the same period published by C.A.R.M.E.N. e.V. (2012). Here, it becomes clear that the wood chip prices we deducted from the heating oil prices is on average 2.47 times higher than the real prices of wood chips. Hence, the calculated wood chip prices are divided by 2.47. The wood chip prices from 2003 to 2011 which we derived from the heating oil prices are correlated with the real observed

[1] A long time series is needed in order to estimate the parameters of the stochastic process as exact as possible (Campbell et al., 1997, p. 363; Chevalier-Roignant and Trigeorgis, 2012, p. 438).

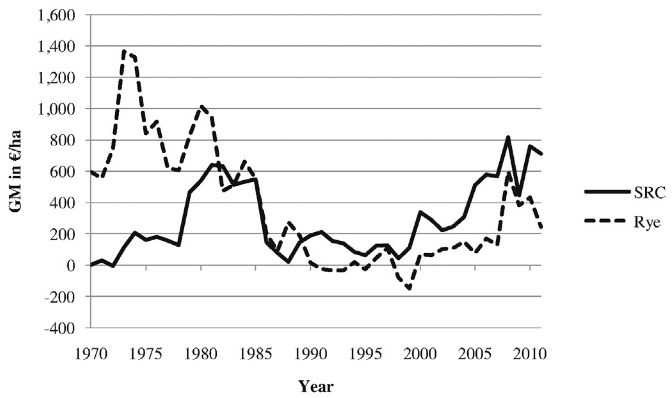

Fig. 1. Historical GM of SRC and rye between 1970 and 2011.

wood chip prices of the same period published by 92%. Therefore, our wood chip prices can be used as a substitute to calculate the historical revenues and the GM of SRC.

With regard to the annual rye production, neither investment costs nor recultivation costs have to be considered. To calculate the revenues, we utilize the rye prices in Ontario and the average yields of rye from 1970 to 2011 in Germany. The inflation-adjusted time series of rye prices in Ontario is used because the rye prices in the European Union (EU) in general, and Germany in particular, were influenced by changes in political framework (e.g. the abolishment of the intervention price of rye) (Von Ledebur and Schmitz, 2012). Changes in political framework lead to structural breaks which could result in suboptimal investment decisions (Khajuria et al., 2009). In comparison to the German rye prices the Canadian show a higher variance because of the intervention in the German rye market. Since the intervention has been stopped the variance of the German rye prices is comparable to the variance of the rye prices in Ontario.

We utilize the trend-adjusted time series of the average yields in Germany from 1970 to 2011 concerning rye production to determine the yield of land with marginal soil. To appoint the variable production costs of rye, we use the standard values of the variable costs for rye from the year 2011 (LWK, 2011).

Fig. 1 depicts the time series for the GM of SRC and rye from 1970 to 2011. The detailed calculations of the historical GM of SRC and rye are shown in the appendix (Tables A2 and A3).

The future development of the GM of SRC and rye are modeled using stochastic processes. These processes describe the evolution of the value of stochastic variables through time (Hull, 2009, p. 271). Using a time series analysis, we gather distribution information of the time series and aim to identify the best fitting stochastic process for the given data. To analyze stationarity, both time series are tested using an augmented Dickey–Fuller test (Dickey and Fuller, 1981; Enders, 2003, pp. 76–80) and a KPSS-Test (Kwiatkowski et al., 1992). The historical GM shown in Fig. 1 are taken as input data for these tests. The results of the tests show that both time series are non-stationary (tested at the 5% level of significance).

For modeling the time series of the stochastic GM of SRC and rye, we apply an arithmetic Brownian motion (ABM). The ABM is frequently used for developments of non-stationary cash flows and GM because it allows a change of sign of the stochastic variable (Dixit and Pindyck, 1994, pp. 65–74). The time discrete and state-continues version of the ABM can be expressed as follows:

$$\mathrm{GM}_t^m = \mathrm{GM}_{t-1}^m + \alpha^m + \sigma^m \cdot \varepsilon_t^m, \quad \text{with } m = \text{SRC, rye} \tag{5}$$

The parameter GM_t^m indicates the GM at time t for production activity m. The parameter α^m is the drift. σ^m is the standard deviation of the absolute changes of the values. The standard deviation is multiplied by a standard normally distributed random number ε_t^m. In the case of SRC and rye, a two-tailed t-test reveals that the drift parameters of the ABM are not different from zero at a significance level of 5% (SRC: p-value = 0.79; rye: p-value = 0.43). Following this, the expected value of the future GM of SRC and rye is equal to its value observed in period 0. The standard deviation of SRC is 139.75 €/ha. The standard deviation of rye is 208.20 €/ha. Thus rye is the riskier production activity. The correlation between the GM of SRC and the GM of rye is up to 0.18 and is taken into account in our model.[2]

Risk-adjusted discount rate

In order to determine the risk-free interest rate which would be adequate for a risk-neutral decision maker, the mean of the nominal returns of the German federal bonds with a residual lifetime of 15–30 years from 1988 to 2011 of 5.70% per year (Deutsche Bundesbank, 2012) is used. The average inflation rate of the same period is approximately 1.94% per year (IHK, 2012). Consequently, the corresponding real interest rate, which we employ as the risk-free interest rate, is about 3.69% per year.

Since Maart-Noelck and Musshoff (2013) have shown that more than 50% of German farmers are risk-averse following Holt and Laury (2002), we analyze the influence of risk aversion. Therefore, we determine the optimal conversion and reconversion triggers of farmers with different degrees of risk aversion. The risk attitude can be reflected via the use of risk-adjusted discount rates. The risk-adjusted discount rate i^m for the production activity m, for a risk-averse farmer can be expressed as the following:

$$i^m = rf + \rho^m, \quad \text{with } m = \text{SRC, rye} \tag{6}$$

rf is defined as the risk-free interest rate. ρ^m is the additional value for the risk-free interest rate. Due to the difficulties in determining the risk premium of decision makers in general, the additional value for the risk-free interest rate is often parameterized (Gebremedhin and Gebrelul, 1992; Berg, 2003; Hudson et al., 2005). Corresponding to Musshoff et al. (2012), we determine the additional value based on the following equation:

$$\rho^m = (1 + rf) \cdot \left[\left(\frac{E(\mathrm{GM}_N^m)}{E(\mathrm{GM}_N^m) - \mathrm{RP}_N^m} \right)^{1/N} - 1 \right], \quad \text{with } m = \text{SRC, rye} \tag{7}$$

$E(\mathrm{GM}_N^m)$ equals the expected GM and RP_N^m is the risk premium of production activity m; N is the length of the discount period. We can estimate the risk premiums with a combination of the power risk utility function and the coefficients of constant relative risk aversion θ as well as the consideration of the standard deviations and the expected values of the GM of SRC and rye. The higher the standard deviation in relation to the expected GM, the higher is the risk premium. The calculation of the risk premiums is shown in details in Appendix A2. In order to calculate the risk-adjusted discount rate, we parameterize the coefficient of constant relative risk aversion and calculate the corresponding risk-adjusted discount rates for a θ = 0.2, 0.4, 0.6, 0.8, and 1.[3] If the θ equals 0, the farmer is risk neutral. The higher the θ the more the farmer is risk averse. If θ equals 1, the farmer is strongly risk averse. While the standard

[2] The GM of rye and SRC are correlated because of the strong correlation of the prices for rye and wood chips. The inflation-adjusted prices of rye and wood chips from 2003–2011 are correlated by 73%. This can be justified due to the fact that they are partially substitutable.

[3] Due to the fact that referring to Eq. (A3) we cannot calculate the risk-adjusted discount rate with θ = 1, we calculate the risk-adjusted discount rate for θ = 0.99.

Table 1
Overview of the interest rates used[a].

Risk attitude	Risk neutral	Risk averse				
	$\theta = 0.0$	$\theta = 0.2$	$\theta = 0.4$	$\theta = 0.6$	$\theta = 0.8$	$\theta = 1.0$
SRC	3.69%	4.46%	5.25%	6.06%	6.89%	7.68%
Rye		5.49%	7.44%	9.51%	11.68%	13.83%

[a] Given $N = 1$, $E(\mathrm{GM}_N^m) = 373$ €/ha (θ is defined as the coefficient of constant relative risk aversion).

Table 2
Overview of the model parameters.

Investment costs for SRC IC	2736 €/ha
Investment subsidy for SRC	700 €/ha
Useful lifetime of a SRC	21 years
Rotation period	3 years
Number of rotation periods	7
Average annual output of the SRC	10 t_{DM}/ha
The total cost of harvesting, drying and transport	32 €/t_{DM}
Recultivation costs for a SRC RC	1121 €/ha
Potential time of conversion/reconversion	∞ (annual conversion and reconversion opportunity)
Stochastic process for the GM	arithmetic Brownian motion (ABM)
Process parameters	
Standard deviation of rye σ^{rye}	208.20 €/year
Standard deviation of SRC σ^{SRC}	139.75 €/year
Correlation between GM of SRC and rye	0.18

deviations of SRC and rye are known, we have to make assumptions concerning the expected GM of SRC and rye and the length of the discount period. For simplicity reasons, we chose 1 for the length of the discount period. In relation to the expected GM of SRC and rye, we start with a value of 373.32 €/ha (equals the mean of the time series of the GM of rye). The resulting interest rates are shown in Table 1.

One can see that the risk-adjusted discount rates of rye are higher than those of SRC. This is justified by the fact that the GM of rye is riskier because it has a higher standard deviation compared with SRC.

Table 2 summarizes all assumptions of the model.

Results

In this section, we first present the results in terms of the additional values of the conversion and reconversion triggers of both the NPV rule and the ROA. Thereafter, we analyze the influence of the investment subsidy offered by governments on the conversion and reconversion triggers.

Using a numerical approach to evaluate the options, it is common to approximate an infinite period under consideration through a finite one. In the model, a time period of 500 years is considered. The resulting approximation error is not significant and can, therefore, be neglected. For example, the present value of 100,000 € with an interest rate of 3.69% received in 500 years is less than 1 cent.

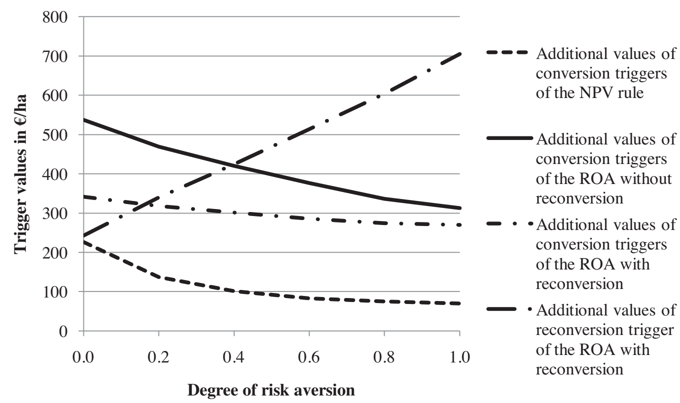

Fig. 2. Additional values depending on the risk attitude.

We decide to reach 50,000 simulation runs for the stochastic simulation. Haug (1998, p. 140) suggests to carry out at least 10,000 simulation runs.

Table 3 and Fig. 2 illustrate the results of our model.

Our results show the additional value of the conversion trigger which a farmer should need to change from rye production to SRC as well as the additional value of the reconversion trigger at which a farmer should switch back from SRC to rye production. In the case of the NPV rule, the additional value of the conversion trigger, which covers the investment and recultivation costs for a risk-neutral farmer, is 226 €/ha. Consequently, the conversion trigger is 599 €/ha if the expected GM of rye is 373 €/ha (Eq. (3)). Following the classical investment theory, the conversion to SRC is profitable for a risk-neutral farmer at a GM of SRC higher than 599 €/ha.

In comparison to the NPV rule, the conversion from rye to SRC according to the ROA is not profitable if the investment and recultivation costs are just covered. For a risk-neutral farmer the ROA without reconversion option suggests converting if the additional value of the conversion trigger is higher than 537 €/ha. Therefore, the GM of SRC has to be higher than 910 €/ha. Hence, farmers following the ROA should be more reluctant concerning SRC cultivation than following the NPV rule. For the risk-neutral farmer, the calculated additional values of the conversion triggers according to both the NPV rule and the ROA are independent of the expected GM level of SRC and rye. This is reasonable due to the fact that the risk-free interest rate for discounting the payments is equal for both alternatives.

Table 3
Additional values of conversion and reconversion triggers without investment subsidy according to different risk-attitudes in €/ha.

Theory	Reconversion option		Risk neutral	Risk averse				
			$\theta = 0.0$	$\theta = 0.2$	$\theta = 0.4$	$\theta = 0.6$	$\theta = 0.8$	$\theta = 1.0$
NPV		Conversion $\Delta\mathrm{GM}_t^{SRC*M}$	226	137	101	83	75	70
ROA	Without	Conversion $\Delta\mathrm{GM}^{SRC^*}$	537	469	420	377	336	313
	With	Conversion $\Delta\mathrm{GM}^{SRC^*}$	342	318	301	286	274	270
		Reconversion $\Delta\mathrm{GM}^{rye^*}$	243	340	425	514	604	705

θ is defined as the coefficient of constant relative risk aversion; $\Delta\mathrm{GM}_t^{SRC*M}$ indicates the additional value of the conversion trigger following the NPV rule; $\Delta\mathrm{GM}^{SRC^*}$ is the additional value of the conversion trigger of the ROA; $\Delta\mathrm{GM}^{rye^*}$ equals the additional value of the reconversion trigger of the ROA with disinvestment possibility.

Table 4
Additional values of conversion and reconversion triggers with investment subsidy of 700 €/ha according to different risk-attitudes in €/ha.

Theory	Reconversion option		Risk neutral	Risk averse				
			$\theta = 0.0$	$\theta = 0.2$	$\theta = 0.4$	$\theta = 0.6$	$\theta = 0.8$	$\theta = 1.0$
NPV		Conversion ΔGM_t^{SRC*M}	177	93	60	44	36	32
ROA	Without	Conversion ΔGM^{SRC^*}	514	439	390	346	302	278
	With	Conversion ΔGM^{SRC^*}	296	274	253	239	226	217
		Reconversion ΔGM^{rye^*}	227	320	411	492	580	670

θ is defined as the coefficient of constant relative risk aversion; ΔGM_t^{SRC*M} indicates the additional value of the conversion trigger following the NPV rule; ΔGM^{SRC^*} is the additional value of the conversion trigger of the ROA; ΔGM^{rye^*} equals the additional value of the reconversion trigger of the ROA with disinvestment possibility.

To find out how much the ROA without the recultivation option overestimates the conversion triggers, we calculate conversion triggers with a reconversion possibility. The results show that the additional value of the conversion trigger for a risk-neutral farmer following the ROA with reconversion option is much lower than the one of the ROA without this opportunity. Hence, the possibility to reconvert the land has a pronounced influence on the conversion triggers. In terms of the ROA, not considering reconversion options, which exist in farmers' real decision situation, lead to wrong results. Nevertheless, the calculated conversion trigger is still considerably higher than the value of the NPV rule. Relating to the ROA with reconversion option, the corresponding additional value of the reconversion trigger is 243 €/ha. Thus, the farmer should switch back from SRC to rye production if the GM of SRC is lower than 130 €/ha at a given expected GM of rye which is 373 €/ha. The additional value of the reconversion trigger for a risk-neutral farmer also is independent of the expected GM level of SRC and rye.

With respect to risk aversion, the additional values of the conversion triggers of the NPV rule for the supposed risk attitudes are lower than that of the risk-neutral farmer. This is justified by the risk-adjusted discount rate. If the degree of risk aversion increases, the risk-adjusted discount rates rise as well because the risk premium rises (Eq. (7)). The amount of the increase of the risk premium and consequently of the risk-adjusted discount rates depends on the standard deviation of the GM and the expected GM of the alternatives. Since rye has a higher standard deviation (Table 2), the risk-adjusted discount rates, which affect payments of rye are higher than the corresponding risk-adjusted discount rates of SRC (Table 1).

In reference to the ROA, the additional values of the conversion triggers of the model with and without reconversion possibility decline with higher degrees of risk aversion. Therefore, following the ROA, as in case of the NPV rule, a risk-averse farmer should be more likely to convert to SRC than a risk-neutral farmer because the GM of SRC are more stable than the GM of rye. The additional values of the conversion triggers following the model without the option to reconvert the land within the useful lifetime converge to those of the model, which considers reconversion with a rising degree of risk aversion. This is justified by the fact that an increasing degree of farmers' risk aversion should lead farmers to cultivate SRC. Thus, the bias, which is caused by neglecting the reconversion possibility in the model, decreases with increasing degree of risk aversion. In relation to the fact that the higher the degree of risk aversion the more the farmers should favor cultivating SRC, the additional values of the reconversion triggers increase by raising the degree of risk aversion. Both the decreasing additional values of the conversion triggers and the rising additional values of the reconversion triggers are induced by the risk-adjusted discount rates. The risk-adjusted discount rates affect payments of rye more than payments of SRC.

Governmental investment subsidies that have been offered in order to increase farmers' willingness to convert to SRC are observed to determine their influence on the conversion recommendation of both the NPV rule and the ROA. Table 4 illustrates the additional values of the conversion and reconversion triggers with an investment subsidy of 700 €/ha, which was offered to farmers in the UK. Our results show that the investment subsidy decreases the additional values of the conversion triggers of the NPV rule by 49 €/ha. Following the ROA without reconversion option, the investment subsidy decreases the additional value of the conversion triggers of the risk-neutral farmer by 23 €/ha. One can see that the conversion trigger of ROA without consideration of the reconversion possibility does not decrease by the same value that the additional value of the conversion trigger of the NPV rule decreases. This can be justified because the ROA can quantify the influence of irreversibility, temporal flexibility, and uncertainty. Nevertheless, it could be reasonable because reconversion possibility within the useful lifetime is not considered. Referring to the ROA with consideration of the reconversion possibility, the investment subsidy decreases the conversion triggers of the risk-neutral farmers by 46 €/ha. Therefore, the consideration of the reconversion option following the ROA in terms of the risk-neutral farmer leads to an approximation of the decrease of the conversion triggers of the ROA to those of the NPV rule (49 €/ha). Moreover, the additional value of the reconversion trigger is 16 €/ha lower when an investment subsidy is offered. If risk aversion is considered, the decrease of the conversion triggers of the NPV rule and the ROA as well as the reconversion trigger of the ROA remain relatively similar.

Discussion and conclusions

Former Studies have shown that, from a single farms' point of view, SRC can be an interesting alternative to annual crop production, especially on sandy soils. Moreover, governments have offered incentives to increase farmers' willingness to convert to SRC. Nevertheless, the share of SRC on the total agricultural land use remains relatively low as farmers are reluctant to convert to SRC. Therefore, the classical investment theory, which is widely used for evaluating investment alternatives, is in contrast with the real behavior of farmers regarding the conversion to SRC. Some studies adopt the ROA in order to explain decision makers' inertia in general, and farmers' inertia in particular, concerning investments. Many researchers conclude that the ROA can at least partially explain the investment inertia as investment triggers, which induce investments, can be higher than those of the NPV rule. Often these studies neglect the possibility of disinvestment. Hence, decision makers and farmers actually often have a higher degree of flexibility than indicated by the models used. Consequently, there is the risk of bias in the results. In our model, we calculate conversion triggers concerning the switch from rye production to SRC following the NPV rule and the ROA. We differentiate in the case of the ROA between conversion triggers with and without reconversion possibility and determine reconversion triggers for switching back from SRC to rye production within its useful lifetime. As decision makers and especially farmers generally are not risk neutral, we take into account different levels of risk aversion in our calculations. In addition, we evaluate the effect of an investment subsidy on the conversion recommendation of the NPV rule and the ROA.

In accordance with Musshoff (2012), our results show that the conversion triggers from traditional agricultural land use to SRC of the NPV rule are considerably lower than those of the ROA. Therefore, the ROA suggests that farmers should have a lower tendency to convert to SRC than indicated by the NPV rule. However, the possibility to reconvert the land within the useful lifetime of SRC has a high influence on farmers' conversion recommendation because it lowers the conversion triggers and farmers should have a higher tendency to convert. Nevertheless, the conversion triggers of the ROA with including the reconversion opportunity are still higher than those of the NPV rule. Therefore, it can be concluded that the ROA can have the potential to explain at least a portion of farmers' inertia concerning the cultivation of SRC. In accordance with Ridier (2012), our results show that risk-averse farmers should be more likely to convert from traditional crops to SRC than risk-neutral farmers. This confirms to the decreasing bias in the results caused by neglecting the reconversion possibility with a higher degree of risk aversion. Moreover, if an investment subsidy is offered, the conversion triggers following the NPV rule and the ROA with and without reconversion possibility as well as the reconversion triggers decrease.

As SRC (poplar) provides some ecological advantages compared to the traditional agriculture, it can be of general interest to increase the area used for SRC. Some advantages of SRC are that it does not require fertilizer and pesticides only need to be deployed until plants are established (Dallemand et al., 2007; Marron et al., 2012, pp. 14–41). Moreover, there is a lower danger of soil consolidation because machinery runs over the land only for planting, harvesting, and recultivating. Baum et al. (2009) and Rockwood et al. (2004) describe that SRC is advantageous regarding soil and biological diversity. Rockwood et al. (2004) note that it is possible to use contaminated soil and groundwater for SRC and that SRC allows a better control on soil erosion. In addition, they state that SRC can be grown on soils with agricultural and industrial wastes and that it is advantageous for wildlife habitats.

If the area used for SRC should be increased, policymakers generally have to understand that decision makers, particularly farmers, may often not follow the classical investment theory as it ignores flexibility regarding the time of investment and uncertainty concerning investment returns. This is important because farmers only convert to SRC if the efficiency of SRC is considerably higher than that of traditional agricultural land use. If farmers follow the ROA and consider temporal flexibility and uncertainty but are not aware of considering their reconversion option within the useful lifetime of SRC, policymakers could inform farmers about their reconversion possibility. Consequently, farmers can understand that their calculated conversion triggers (without considering the reconversion opportunity) are much higher than the real conversion triggers (with consideration of the reconversion option) because farmers were not aware of the amount of flexibility they really have in practice. Therefore, governmental guidance is a possible policy measure as farmers' conversion triggers may decrease by a higher level of knowledge/education regarding the aforementioned facts. Moreover, it could be another way to increase the economical competitiveness of SRC in order to generally raise farmers' willingness to convert to SRC. One possibility may be to offer governmental incentives as done, for example, in terms of investment subsidies in the UK (Mitchell et al., 1999; SAC, 2008). Ridier (2012) shows that investment subsidies motivate farmers to convert to SRC. This is in line with our results. Although, the conversion triggers of the ROA decrease if investment subsidy is included, they stay constant over time if the investment subsidy is temporarily unlimited. However, if the investment subsidy is temporarily limited, the conversion triggers following the ROA decrease with a declining remaining lifetime. This is justified by the reason that if the last period of possible engaging investment subsidy is reached, farmers' conversion decision approximates to a 'now or never' decision. With regard to the investment subsidy, the decrease of the conversion triggers of the risk-averse farmers is similar to the decline of the conversion triggers of the risk-neutral farmers. Therefore, investment subsidies do not particularly motivate risk-averse farmers. Due to the fact that farmers are by trend risk-averse, their willingness to convert to SRC could be increased by, for example, minimal wood chip prices through supply contracts (Ridier, 2012). Consequently, the volatility of the GM of SRC decreases, and risk-averse farmers would have a higher tendency to convert to SRC.

The results of our study show that the ROA can help to explain a portion of farmers' inertia to convert at least a part of the farmland to SRC. To determine the exact degree of explanation of the ROA in reality, experiments may be useful to focus on impacts, which lead to farmers' inertia. Impacts could be farmers' traditional behavior of refusing to plant trees on agricultural land because of, for example, esthetic reasons. Another reason could be that if the land is converted to SRC, the farmer is less flexible because land and capital is bound for a longer time compared to traditional crop production.

Furthermore, future research should address the yield forecast of SRC. To do so, experiments with SRC on different soil types over several useful lifetimes may be performed. Moreover, further research is needed in order to determine which governmental incentives may help to increase the land used for SRC because of its ecological advantages. Following our results, SRC should be especially interesting for risk-averse farmers. Therefore, it might be interesting to point out how their willingness to convert at least a part of their land to SRC can be increased.

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Appendix A.

A.1. Description of the determination of the optimal additional values for the conversion and reconversion triggers

The determination of the optimal additional values of the conversion and the reconversion trigger with the help of the stochastic simulation and the GA occurs as follows:

1. An additional value of the conversion trigger and an additional value of the reconversion trigger build a genome. In the initial test run respectively in the first generation, a number of genomes with additional values are randomly selected.
2. Using stochastic simulation we calculate the present value of farms' returns for each observed period under consideration for each genome. The present value of farms' returns of the particular year S_t can be determined as follows:
   - S_t equals the present value of the GM of rye minus the present value of the GM of SRC, if the land has been used for rye production in an exhausted period and a conversion to SRC does not happen. The land will be used for rye production in the next period.
   - S_t equals the negative present value of the investment costs if the land has been used for rye production or has reached the last period of harvesting (SRC) in the previous year and the conversion to SRC takes place.
   - S_t corresponds to the present value of the GM of SRC minus the present value of the GM of rye if the land is used for SRC within its useful lifetime and no reconversion occurs.

Table A1
Parameters of GA and stochastic simulation.

Number of simulation runs	50,000
Number of genomes	50
Operators of the GA	
Selection rule	Quadruplicate the five fittest genomes, triplicate the next five, duplicate the next five, reproduce the next five, delete the remaining 30
Recombination rule	Starting with the eight fittest genomes from Selection, the arithmetic mean of a genome with its foregoing neighbor is calculated with 5% recombination rate
Mutation rule	Starting with the eight fittest genomes of Recombination, a random number from the range between −2% and 2% is added to a genome with 20% mutation rate

- S_t corresponds to the present value of the GM of SRC minus the present value of the GM of rye and the present value of the recultivation costs if the land has been used for SRC in the exhausted period and one of the two following conditions is met: First, the useful lifetime of SRC has ended. SRC will be converted another time in the next period. The second possibility is that a reconversion happens within the useful lifetime of SRC. Accordingly, the land will be used for rye production in the next period.

The present value of farms' returns of each simulation run is calculated by adding up the present value of farms' returns of each particular year S_t obtained when using the pair of an additional value of the conversion trigger ΔGM^{SRC^*} and an additional value of the reconversion trigger ΔGM^{rye^*} during the period under consideration ($t = 0,1,\ldots,\infty$). Through various simulation runs we determine the average present value of farms' returns over all simulation runs for each genome.

3. The genomes are ordered by their fitness. The fitness generally determines the probability of survival of each genome for the next generation and is dependent on the average present value of farms' returns. The higher the value, the better is the fitness of the respective genome. A number of genomes with the highest fitness are adopted for the following generation. The relatively less fit genomes are replaced with better ones which are doubled (selection and replication). Also, it is necessary to create new genomes with pairs of additional values, because the more fit ones of the previous generation are often not the optimal genomes (recombination and mutation). The operators of the GA (selection, replication, recombination, and mutation) are used to determine the genomes for the next generation.
4. Steps 2 and 3 are repeated until the pairs with additional values are homogenous and stable.
5. Due to the fact that GA is a heuristic search method, it is not guaranteed that the global optimum is found in each particular search run. Therefore, we start various search runs with different genomes in order to determine optimal and stable additional values of the conversion and the reconversion triggers. Details on the parameters of GA and stochastic simulation are shown in Table A1.

A.2. Determination of the risk premium

The calculation of the risk premium involves the following steps: first of all, a risk utility function must be determined to define the farmers' risk attitude. In our model, a power risk utility function is adopted which has a declining absolute risk aversion and a constant relative risk aversion (Holt and Laury, 2002):

$$U(GM^m) = (GM^m)^{1-\theta}, \quad \text{with } m = \text{SRC, rye} \tag{A1}$$

U indicates the utility, and θ stands for the coefficient of constant relative risk aversion. For simplicity reasons, we assume the state-discrete version of the ABM (Dixit and Pindyck, 1994, pp. 65–74) in order to calculate the risk-adjusted discount rates. Accordingly, we estimate the expected utility of the alternative m as follows:

$$E[U(GM^m)] = 0.5 \cdot U(GM^{m-}) + 0.5 \cdot U(GM^{m+}), \quad \text{with } m = \text{SRC, rye} \tag{A2}$$

Due to the fact that the drift equals 0, the probability of occurrence is equal to 0.5. GM^{m-} is the expected value of the GM of alternative m minus the standard deviation σ^m. GM^{m+} is defined as the expected value of the GM of alternative m plus the standard deviation.

Since for a risk-averse farmer, the certainty equivalent has the same utility as the expected value of an uncertain alternative, we can calculate the certainty equivalent with the help of the coefficients of constant relative risk aversion. The certainty equivalent CE^m of the alternative m is calculated as follows:

$$E[U(GM^m)]^{1/1-\theta} = CE^m, \quad \text{with } m = \text{SRC, rye} \tag{A3}$$

The determination of the certainty equivalent is required in order to calculate the risk premium RP^m. The risk premium is defined as the difference between the expected value of the GM of SRC or rye and the certainty equivalent of the particular alternative (cf. Eq. (A4)).

$$RP^m = E(GM^m) - CE^m, \quad \text{with } m = \text{SRC, rye} \tag{A4}$$

The risk premium is needed in order to calculate the additional value for the risk-free interest rate ρ^m (Eq. (7)) (Tables A2 and A3).

Table A2
Calculation of the historical GM of SRC.[a]

Year	Inflation-adjusted heating oil prices (€/l)	Inflation-adjusted wood chip prices derived from heating oil prices (€/t_{DM})	Revenues (€/ha)	GM (€/ha)
1970	0.23	32.17	321.75	1.75
1971	0.25	34.93	349.34	29.34
1972	0.23	31.61	316.07	-3.93
1973	0.31	43.31	433.07	113.07
1974	0.38	52.62	526.21	206.21
1975	0.35	48.09	480.94	160.94
1976	0.36	50.18	501.84	181.84
1977	0.34	47.75	477.47	157.47
1978	0.32	44.90	449.04	129.04

Table A2 (*Continued*)

Year	Inflation-adjusted heating oil prices (€/l)	Inflation-adjusted wood chip prices derived from heating oil prices (€/t_{DM})	Revenues (€/ha)	GM (€/ha)
1979	0.57	78.51	785.15	465.15
1980	0.62	85.97	859.68	539.68
1981	0.69	95.95	959.54	639.54
1982	0.69	95.31	953.07	633.07
1983	0.60	83.32	833.16	513.16
1984	0.62	85.36	853.63	533.63
1985	0.63	86.83	868.33	548.33
1986	0.34	46.58	465.75	145.75
1987	0.29	39.80	398.03	78.03
1988	0.25	34.22	342.23	22.23
1989	0.34	46.62	466.22	146.22
1990	0.37	50.96	509.63	189.63
1991	0.38	53.09	530.94	210.94
1992	0.34	47.40	473.96	153.96
1993	0.33	45.98	459.83	139.83
1994	0.29	40.57	405.73	85.73
1995	0.28	38.22	382.20	62.20
1996	0.32	44.31	443.10	123.10
1997	0.32	44.61	446.10	126.10
1998	0.26	36.33	363.35	43.35
1999	0.31	43.11	431.15	111.15
2000	0.48	65.83	658.34	338.34
2001	0.44	60.91	609.08	289.08
2002	0.39	54.30	543.04	223.04
2003	0.41	56.61	566.10	246.10
2004	0.45	62.86	628.59	308.59
2005	0.60	82.99	829.86	509.86
2006	0.65	89.96	899.61	579.61
2007	0.64	88.81	888.07	568.07
2008	0.82	113.78	1137.80	817.80
2009	0.55	76.45	764.55	444.55
2010	0.78	108.04	1080.43	760.43
2011	0.74	103.13	1031.27	711.27

[a] Mean of the heating oil prices per kilowatt hour (kWh) from 2003 to 2011 was 2.47 times higher than the mean of the prices for wood chips of the same period. Heating value of heating oil: 11.86 kWh/liter. Heating value of wood chips (poplar): 4057 kWh/t_{DM}. Variable Costs: 320 €/ha.

Table A3
Calculation of the historical GM of rye.[a]

Year	Inflation-adjusted rye prices (€/t)	Trend-adjusted average yields of rye (*t*)	Revenues (€/ha)	GM (€/ha)
1970	200.00	5.13	1025.37	595.23
1971	184.80	5.50	1017.00	555.29
1972	221.90	5.41	1199.76	746.12
1973	337.58	5.38	1816.94	1365.36
1974	327.04	5.46	1785.63	1327.54
1975	245.38	5.20	1276.21	839.85
1976	270.58	4.91	1329.05	916.95
1977	200.41	5.32	1065.49	619.44
1978	196.04	5.42	1062.97	608.06
1979	238.21	5.34	1272.61	824.38
1980	272.52	5.39	1468.96	1016.72
1981	269.97	5.07	1367.94	942.81
1982	170.63	5.47	933.78	474.64
1983	186.63	4.99	931.73	512.88
1984	199.13	5.74	1143.17	661.50
1985	183.16	5.58	1021.11	553.36
1986	120.23	5.52	663.90	200.63
1987	101.78	5.08	516.88	90.80
1988	135.43	5.32	720.83	274.28
1989	116.74	5.80	676.79	190.38
1990	86.89	4.83	419.41	14.44
1991	79.58	5.68	451.66	-24.52
1992	77.17	4.89	377.33	-32.90
1993	77.56	5.41	419.33	-34.26
1994	87.19	5.62	490.37	18.51
1995	79.38	6.05	480.05	-27.32
1996	91.39	5.96	544.42	44.64
1997	101.80	6.13	623.95	109.73
1998	70.33	5.75	404.22	-78.02
1999	60.42	6.38	385.73	-149.93
2000	96.43	5.48	528.28	68.63

Table A3 (*Continued*)

Year	Inflation-adjusted rye prices (€/t)	Trend-adjusted average yields of rye (*t*)	Revenues (€/ha)	GM (€/ha)
2001	93.27	6.63	618.46	62.12
2002	102.43	5.48	561.52	101.57
2003	107.01	4.69	501.47	108.29
2004	107.25	6.48	694.72	151.23
2005	98.00	5.39	527.90	75.94
2006	116.71	5.16	601.68	169.16
2007	114.15	4.22	481.86	127.70
2008	198.30	5.23	1037.04	598.27
2009	149.72	5.80	868.32	381.72
2010	176.39	4.68	825.48	432.83
2011	143.58	4.11	590.13	245.30

[a] Variable costs: 83.88 €/ha.

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