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The mitigation potential and cost efficiency of abatement-based payments for the production of short-rotation coppices in Germany

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Abstract.

In Northern and Central Europe, short-rotation coppices (SRC) have become a profitable agricultural production alternative, particularly for marginal fields with suitable groundwater levels. The replacement of fossil fuels by the wood chips produced in SRC contributes to the mitigation of greenhouse gases (GHGs). Due to heterogeneous regional production conditions, the impacts on economy, production and GHG mitigation vary.

Previous studies investigate specific agronomic, environmental and economic aspects of SRC. This study complements the existing literature by estimating the economic mitigation potential from SRC in Germany. It presents an integrated modeling approach that considers agronomic and economic aspects and investigates the mitigation potential and the abatement cost efficiency arising from abatement-based payments.

The simulation of different payment scenarios indicates that SRC could mitigate up to 15 % of the German agricultural sector's GHG emissions. The integrated model approach links a site model and the agro-economic model RAUMIS and can be regarded as a fruitful development for addressing SRC-related research questions.

Keywords: Short-rotation coppice; Site model; Agro-economic model; Agricultural production; Greenhouse gas mitigation

JEL codes: Q11, Q18, Q54, Q58

1 Introduction

In Germany, short-rotation coppices (SRC) have become a new alternative product for marginal land requiring low levels of inputs (Stolarski et al. 2012). Recent technological progress (e.g., in breeding, harvesting, pellet processing), increased demand for renewable energies and new political incentives (e.g., through energy policies) have improved the production conditions for SRC. In addition, compared to arable use, SRC is associated with higher biodiversity (Baum et al. 2012a) and can elevate the structural diversity of landscapes (Baum et al. 2012b). Other advantages of SRC compared to annual arable crops are the reduced use of pesticides and fertilizer as well as the reduced risk of soil compaction and erosion (EEA 2006). In addition, the wood-chips produced in SRC can replace fossil fuels and can therefore mitigate climate change.

Although these developments have improved the competitiveness of SRC, producers have converted only a small agricultural area to SRC (e.g., on side strips), amounting to only $6.5*10^3$ ha (out of $16*10^6$ ha total agricultural area) (Strohm et al. 2012). Due to the expected positive impacts for producers and society, researchers attempt to explain the producers' unwillingness to produce SRC and policy makers intend to develop policy instruments to increase their interest.

Due to the high competition for agricultural land between SRC and conventional production (cash crops and fodder production), assessing the potential impacts of a stronger promotion of SRC requires a regionally disaggregated analysis of SRC production in the context of competing land uses rather than investigating SRC as a stand-alone or in the context of partial agricultural programs.

1.1 Background: recent developments in SRC

In general, the cultivation of SRC requires low input costs. However, the conversion to SRC implies high entrance costs, a long-term investment period for capital and initial lag periods without harvest and revenue. Harvest costs represent more than 50% of the total costs and depend strongly on the topography (Spinelli et al. 2008). Whether farmers adopt SRC depends on SRC's competitiveness with normal agricultural production activities. This competitiveness is influenced by the profitability of the SRC and of the conventional agricultural production, i.e., the opportunity cost of giving up this production. The competitiveness of SRC depends strongly on the site conditions, with factors such as climate (temperature, precipitation), soil characteristics (available water capacity and ground water level) and topography (level terrain allowing mechanical harvest) influencing the profitability of SRC (Reeg et al. 2009, Schweier 2012, Schweier and Becker 2012) and more conventional forms of agricultural use.

1.2 State of the art: recent studies in SRC

Most of the existing SRC studies focus on specific agronomic, economic or environmental aspects. Based on the applied methodology and research scope, this literature can be broadly grouped into several primary strands.

Agronomic studies addressing SRC production and site-specific topics represent the first important strand. Many studies are based on empirical or experimental data, and the results are based on a limited number of experimental plots or smaller regions. These studies focus on the availability of production factors such as water (e.g., Lindroth and Bath (1999) in Sweden) or assess production costs including harvesting costs (e.g., Spinelli et al. 2008). Furthermore, regional yield potentials are derived (e.g., Mola-Yudego and Aronsson (2008) for sites in Sweden) with respect to the site-specific selection of species (Facciotto and Nervo (2011) for sites in Sicily) or varieties (Storlarski et al. (2012) for sites in Poland, Sevel et al. (2012) for sites in Denmark). Wickham et al. (2011) provide a more comprehensive overview of these topics.

A second strand of the literature develops yield potential or site models based on the empirical results for regional production conditions. These studies either provide spatial analysis of yield potential and site-suitability maps for entire production regions (e.g., Tallis et al. (2013) for the UK, Aylott et al. (2008) and Evans et al. (2007a, b) for England and Wales) or an impact assessment (e.g., Ali (2007, 2009) for Saxony). Further studies consider SRC in the broader context of agricultural production or other land use forms. Some of these studies are based on production data and provide farming recommendations (e.g., DBU (2010), Unseld et al. (2010)). Other regional studies are based on site models and assess the production potential given land use and societal constraints (e.g., Kollas et al. (2009), Aust (2012), Aust et al. (2013)). However, the distribution and extent of SRC in these site models is derived from agronomic information and legal/societal constraints and is not driven by economic decision-making algorithms. Therefore, these studies derive a technological potential that normally greatly exceeds the economic potential.

The third strand of the literature addresses the economics of SRC. These studies address issues such as production costs and determining factors (e.g., Mitchell et al. (1999)) or analyze the production chain of SRC (e.g., Marron et al. (2012), Schmidt (2011)). The explanation of the farmers' reluctance to convert agricultural land to SRC has gained some importance in recent years (e.g., Wolbert-Haverkamp and Musshoff (2014), Musshoff (2012), Zeller et al. (2009)).

To evaluate the relative profitability of SRC, most studies use a representative gross margin computation of selected crops (e.g., Krasuska and Rosenquist (2012), Ericsson et al. (2006), Rosenqvist and Dawson (2005), Zeller et al. (2009)) or representative sites (e.g., Faasch and Patenaude (2012)). However, the studies consider neither the site conditions of complete regions nor the competitiveness of SRC in the context of a region's agricultural structure.

In a last strand of the literature, SRC is evaluated with respect to its impacts on biodiversity, sustainability and greenhouse gas (GHG) emissions. The studies can be based on empirical data (e.g., Baum et al. (2012), impacts on biodiversity), models (e.g., Grote and Haas (2013), isoprene emissions), producers' recommendations (e.g., Simpson et al. (2009)) or conceptual works (e.g., Rösch et al. (2013), Petzold et al. (2014)).

Only a few studies include agronomic, economic and environmental aspects by using empirical and/or model-based approaches and integrating research results for more than one of these aspects for study regions (e.g., Aylott et al. (2010) and Bauen et al. (2010) for the UK, Böhm et al. (2011) for Eastern Germany). Strohm et al. (2012) provide a concise study with a multidimensional assessment of SRC and consider subsidies as political instruments to support SRC production in Germany. Their study is based on case studies and representative farm-type models and thus is not representative of SRC production and does not allow for a regionally differentiated impact assessment.

Many studies cover different aspects of SRC using different approaches. However, assessing the economically feasible mitigation potential and the cost efficiency of abatement-based payments for production concisely and consistently requires a research framework that covers Germany completely with respect to (1) the regional site conditions for SRC production, (2) the regional agricultural production programs and regional competitiveness and (3) the agro-economic production behavior, all while (4) accounting for GHG emissions.

This study complements the existing literature by estimating the mitigation potential from SRC. It presents an integrated modeling approach in which SRC is a component of agricultural production at the regional level. The developed model considers agronomic, agricultural and economic aspects and allows for an evaluation of the GHG mitigation effects of SRC. The study investigates the marginal mitigation costs based on payments for mitigated GHG emissions and the impact of the payments on the competitiveness of SRC.

We describe the integrated model applied in this study in Chapter 2. Chapter 3 presents the scenario assumptions and the simulation results. Chapter 4 discusses the methods, the scenarios and the results in the context of other studies, and it is followed by the conclusions in Chapter 5.

2 Method: The integrated model approach

The integrated model approach used in this study links the agricultural supply model RAUMIS (Regional Agricultural and Environmental Information System) with a newly developed site model for SRC. RAUMIS uses the site model estimations of regional yields and cost data to calibrate regional production functions for SRC. Thus, RAUMIS simulates regional agricultural production, including SRC, in competition with conventional agricultural production and allows for the analysis of simulated markets and policy settings (Table 1).

2.1 Regional agriculture, the environment and the economy according to the agro-economic model

The regional agricultural supply model RAUMIS (e.g., Weingarten 1995; Henrichsmeyer et al. 1996) uses 40 different agricultural crops and animal production activities to represent the agricultural system for 326 regions in Germany. As a regional economic model, RAUMIS maximizes agricultural income by optimizing production programs. It computes indicators for environmental impacts and allows for the simulation of price and policy scenarios.

In RAUMIS, conventional production activities are based on statistical data. Based on these data, non-linear production functions are derived and calibrated using the PMP method according to Howitt (1995). The non-linearity accounts for factors that are not directly observed but influence the past distribution of activities (e.g., risk aversion, site heterogeneity, etc.) (cf. Cypris 1999).

Due to the novelty of SRC production, the empirically observed historical data required to estimate parameters defining the non-linearity are missing. Thus, the SRC production activities were calibrated as linear production functions into the non-linear model. However, the non-linearity of the conventional production function drives the simulation behavior of the SRC functions in a non-linear way. This model behavior can be defended as consistent with behavioral assumptions: on regional farms, the producers’ decision behavior is predominantly driven by (a non-linear) perceived risk aversion and marginal costs for the known production activities. For new production activities such as SRC, the historical information for risk aversion and marginal costs is missing, resulting in the producers' linear perception of the marginal benefit curves.

For each region, 20 site classes with constant economic characteristics for the production of SRC are differentiated. These classes represent the regional site heterogeneity for arable land and grassland. To define the 20 classes, RAUMIS uses the agronomic and economic data from the SRC site model.

2.2 SRC site model and implementation in the RAUMIS model

The developed site model combines a yield model and an economic model to calculate production costs. Based on economic criteria, the model identifies the optimal species for SRC for each 100 m * 100 m grid cell of agricultural land in Germany.

The yield model for SRC is an extended version of Ali's (2009) model for regional biomass production of poplar grown in SRC on the agricultural land of Saxony (Germany). The model extension considers the cultivation of Alder (*Alnus glutinosa*, L.) on wet soils (e.g., fens) and black locust (*Robinia pseudoacacia*, L.) on dry soils (e.g., sandy soils), respectively. Thus, the additional species cultivated on wet and dry soils and regional differentiation in site classes better represents farmers' agronomic/economic decisions for the most favorable species that promise the highest biomass yields.

Climate, soil and agricultural area represent the input data for the agronomic site conditions (Table 1). An adapted version of the KUP-Kalkulator (Schweinle et al. 2012, DLG, 2012) is used to calculate the production costs. Harvesting costs account for more than 50% of the total production costs of SRC. Thus, the costs are heavily influenced by the harvesting technology, which itself depends strongly on the slope. Three harvesting methods represent different cost levels: the combine harvester is the cheapest level, appropriate for a flat terrain until a maximum slope of 10%; the bundler harvester or forestall technique represents a medium cost until a slope of 25%; and the manual harvest is a very expensive method for hilly terrain.

The implementation of SRC activity into the RAUMIS model considers two levels of regional differentiation: (1) the regional competitiveness of SRC with traditional production activities and (2) the regional heterogeneity of costs and yields due to site conditions.

(1) SRC production is assumed to be competitive only on marginal sites. It is assumed that extensively managed arable land represents the production on marginal arable land. Thus, the area of extensive arable cropping is used as a proxy to define the maximum extent of SRC. In other words, on arable land, SRC competes only with marginal cropping activities, i.e., spring wheat, spring barley, rye, oats and fallow. Consequently, the SRC production on grassland is also limited

to extensively managed areas, excluding protected grassland area. Simulating a higher competitiveness for SCR would require extending the maximal SRC by intensively managed arable land or grassland.

(2) Within the regions, the agronomic suitability of the sites is very heterogeneous due to climatic and geographic site conditions. Within the regions, the heterogeneity of costs and yield is represented by 10 site classes on arable land and on grassland. The 20 regional site classes are defined by the ten decentiles of the regional distribution for the expected profitability of SRC production for grassland and arable sites, respectively. The resulting average biomass productivity, processing costs and the maximal extension of the site classes define 20 regional SRC production activities. In RAUMIS, these activities compete with traditional extensive production activities on arable land and grassland and enter the model solution according to their regional specific competitiveness.

Based on this agronomic information from the site model, RAUMIS simulates agricultural production and environmental impacts. This capability allows for the simulation of mitigation policy instruments and the evaluation the mitigation potential of SRC.

3 Scenarios and results

3.1 Scenario assumptions and analysis

We simulate agricultural production, agricultural income and the mitigated quantities in dependence on a payment per ton of CO_{2eq} mitigated by the cultivation of SRC. Only agriculturally used area (UAA) serves as land for SRC production, excluding the production of SRC in environmentally sensitive areas (e.g., protected grassland). We use a counterfactual scenario as the reference situation, assuming that no land-use-related mitigation strategy is in place (Blanco et al. 2010). Agricultural prices are assumed to be lower in the counterfactual scenario than in the normal RAUMIS baseline because in our baseline commodity prices are largely driven by the demand for food and feed. As we interested in the efficiency of SRC as stand-alone mitigation measure, we abstract from the price effect of currently existing bioenergy policies (e.g. biofuel, biomethane). This market situation roughly represents the ones in the early 2000s. We assume that a policy to support SRC would be implemented in Germany only. As the market for most agricultural commodities is global, we argue that small country assumptions are plausible, i.e., no impact from the analyzed scenarios on commodity prices. Due to these assumptions, the results can be interpreted as the impact on agricultural domestic production, which requires compensation for supply by imports. Consequently, we do not account in the GHG balance for the effect due to the domestic substitution of agricultural commodity production (e.g., lower emissions due to a lower domestic cattle stock). In addition, GHG emissions resulting from trade activities and indirect land use change (iLUC) are not analyzed in this study.

In the counterfactual, the low agricultural prices and missing support policies for alternative bioenergy (e.g., energy maize) result in the competitiveness of SCR and in a regional extension and abatement effect without specific support payments in place.

In the policy scenarios, the extent of the production activities provides information on the impact of promoting SRC on agricultural supply. The cost effectiveness of subsidized SRC as a mitigation policy is analyzed using the change in agricultural income and the marginal abatement cost curve (MACC).

3.2 Agronomic results (by the site model)

The site model provides agronomic results for site suitability and biomass growth, which allows for an estimation of the regional distribution of SRC potential.

Most of the agricultural land in Germany (over 90%) is suitable for the cultivation of SRC (Fig. 1). The potential biomass growth is regionally very heterogeneous because it depends strongly on summer temperatures and sufficiently high rainfall or soils with a high available water capacity. Thus, most of the central German low mountain ranges and the German part of the Alps are characterized by low productivity. The regions “Norddeutsches Tiefland,” “Oberrheinische Tiefland,” “Sued-Westdeutsches Schichtstufen Land” and “Alpenvorland” contain a high share of suitable production area (Fig. 2). The highest yields (17 t d. m. per hectare) are found particularly in southern Germany, south of the Danube, and to smaller extent in the “Niederrheinische Bucht.” Both regions are characterized by high summer temperatures. However, in southern Germany, the yields can be attributed to high precipitation during the vegetation period, the yields in the “Niederrheinische Bucht” are strongly driven by the presence of fertile loess soils.

However, the following are relevant for the economic potential of SRC: the competitiveness of conventional agricultural production and production costs due to the terrain and harvest (Fig. 3).

3.3 Scenario simulation results (by the agro-economic model)

In the counterfactual scenario, the extent of SRC is expected to be small in the loess areas due to the high competition with cash crops. In the mountainous regions of the Alps (southern Bavaria), the profitability of SRC production is limited by the steep terrain, which causes high harvesting costs. In eastern Germany, the sandy soils and the low crop yields result in high competitiveness between relatively poorly growing cash crops and SRC, with only low to medium biomass yield growth. Thus, even without any support payments, SRC production is competitive on $283*10^3$ ha (1.7% of UAA), primarily in marginal areas.

The simulation of payments for mitigated GHG from SRC do not show any or only a marginal impact on intensive cash crops and livestock production at the sector level (i.e., intensive cereals, root crops, oil seeds, fodder crops, pigs and poultry) (Table 2). This result is primarily driven by the assumptions of competitiveness (cf. Section 2.2). The intensive production alternatives are too competitive and decrease only slightly when payment levels exceed 25 EUR g^{-6} CO_{2eq}. The impacts on extensive crop and grassland based animal production (e.g., extensive cereals, fallow, extensive grassland, dairy cows and other cattle) are more relevant. The SRC extension on arable land and grassland is primarily crowding out extensive cereals (i.e., rye, oat, winter barley, spring barley, meslin) and extensive grassland area, which is not protected. The increased area of fodder crops on arable land does not fully compensate for the reduction of fodder cereals (rye, oat, barley) and grassland. Thus, the stock of dairy and other cattle declines slightly.

For payment levels below 100 EUR g^{-6} CO_{2eq}, the development of the area converted to SRC shows a comparable pattern for arable land and grassland (Fig. 4). The primary difference is that the conversion of arable land starts from a higher reference. Marginal arable land equivalent to $210*10^3$ ha (1.3% of the UAA) would be converted to SRC, whereas the respective figure for grassland is $73*10^3$ ha (0.3% of the UAA).

Mitigation payments of 50 EUR g^{-6} CO_{2eq} induce a conversion of $1125*10^3$ ha (7% of the UAA) to SRC (Fig. 4) and an abatement of GHG equivalent to $8.8*10^{12}$ g CO_{2eq} (11% of the counterfactual scenario) (Fig. 5). These payments imply a relatively small agricultural income loss (before mitigation payments) of $317*10^6$ EUR (2% of the counterfactual scenario). For mitigation payments of 100 EUR g^{-6} CO_{2eq}, the land demand rises to $1685*10^3$ ha (10% of the UAA), resulting in an abatement of GHG equivalent to $12.0*10^{12}$ g CO_{2eq} (15% of the counterfactual scenario) and a loss of agricultural income of $843*10^3$ EUR (6% of the counterfactual scenario).

If the simulated payment levels are considered public costs, then the marginal abatement cost curve (MACC) is the inversion of Fig. 5. If the abatement exceeds $12.0*10^{12}$ g CO_{2eq} (15% of the counterfactual), the curvature becomes increasingly asymptotic to the y-axis, indicating strongly increasing marginal abatement costs for relatively small abatement effects. The development of the income related to the abatement effect illustrates the significantly increasing losses for abatement quantities larger than this benchmark.

An economically/politically important threshold is situated at payment levels in the magnitude of 100 EUR g^{-6} CO_{2eq} (implying an abatement of ~15%). According to Schwermer et al. (2012), 100 EUR g^{-6} CO_{2eq} is a conservative central estimate for the potential damage costs.

Fig. 7 analyzes the regional development of the conversion of agricultural land to SRC for payments below 100 EUR g^{-6} CO_{2eq}. The adoption of SRC cultivation in response to higher support levels has two starting points. One lies in the Northeast and the other in the South. Despite the low SRC yield potential of the sites, in the Northeast, SRC increasingly replaces the low-yielding cereal production on sandy dry soils. In the South and Southwest, SRC is an alternative use of grassland. Here, the high summer temperatures from the continental climate combined with high precipitation during the vegetation period permit high yields. Currently, there is frequently fairly low stocking with grazing livestock in these regions. As a consequence, the high yield potential for grassland is not exploited, resulting in "excess" grassland.

Although the loess regions in northwestern and central Germany allow high yields (cf. Section 3.2.), SRC is adopted in this area only at payments exceeding 50 EUR g^{-6} CO_{2eq} due to the strong competition with highly profitable cash crops. To summarize the findings, the adoption of SRC will primarily occur in regions where SRC presents an economic advantage due to its low management costs, particularly in terms of labor demand per ha. These regions do not coincide with the regions where SRC is the most profitable due to high yields.

4 Discussion

4.1 Overall impacts on agriculture, the environment and the economy

The scenario results indicate the strong dependency of income losses and marginal abatement costs on the intended level of abatement. An abatement of approximately $6*10^{12}$ g CO_{2eq} could be achieved with a payment of 25 EUR g^{-6} CO_{2eq}. This abatement would require the conversion of $710*10^3$ ha (4% of the UAA). Consequently, SRC has only a small impact on agricultural production but achieves a significant positive environmental impact (in terms of the abated GHG quantities). Thus, subsidizing SRC can be considered to be a cost-efficient abatement strategy. This finding is in line with, e.g., WBA (2007) and van Bussel (2006). However, doubling the intended abatement to $12.0*10^{12}$ g CO_{2eq} would imply a fourfold increase in the required payments. At this payment level, the economic potential of SRC is widely exploited. Even an increase of the payments from 100 to 500 EUR g^{-6} CO_{2eq} would result only in an additional abatement of $2.8*10^{12}$ g CO_{2eq}.

This study assumes a self-subsistent domestic supply. Assumptions of higher agricultural prices (as actually observed in 2015) might result in a different evaluation of the cost efficiency (tending to be lower). The consideration of leakage effects and iLUC lowers the net abatement effect and decreases cost efficiency. Estimations using a preliminary GHG accounting in the model framework indicate an abatement effect that is 2 to 3% smaller for support payments of 100 EUR g^{-6} CO_{2eq}. However, the estimations of iLUC and leakage effects depend strongly on the assumed emission factors and require further development to improve the model.

This study highlights that the increase in the share of SRC would not be comparable across Germany. With a market-based support mechanism, the SRC would primarily be planted in certain areas, inducing relevant changes in the regional landscapes. Whereas at a payment of 25 EUR g^{-6} CO_{2eq}, only 4% of the national UAA would be dedicated to SRC, this share can easily exceed 20% of the regional UAA (9 regions located either in southwestern Bavaria or in Brandenburg).

4.2 SRC agronomy by the site model: area suitability and yield potentials

The regional distribution of the suitable production area and the estimated yield potential are roughly in line with Kollas et al. (2009) and Aust et al. (2013) (cf. Section 3.2).

We estimate an average yield potential of $9*10^6$ g dry matter (d. m.) ha^{-1} a^{-1}. This potential is larger than the average $6*10^6$ g (d. m.) ha^{-1} a^{-1} published by Kollas et al. (2009). This difference results from different assumptions for the SRC activities. Kollas et al. (2009) simulate Germany-wide SRC production only for aspen. Aspen is a representative SRC species that can be grown on both high- and low-quality soils. The universal assumption of aspen production allows production on all sites but might result in an underestimation of yield potential on favorable sites. For example, the yield for aspen in Baden-Wuerttemberg is estimated at 8 to $10*10^6$ g (d. m.) ha^{-1} a^{-1}, but poplar allows significantly higher yields of 10 to $15*10^6$ g (d. m.) ha^{-1} a^{-1}.

The presented site model avoids an underestimation of yields by assuming three different SRC species: poplar, black locust (*Robinia pseudoacacia* L.) and alder (*Alnus glutinosa*, L.). Furthermore, the developed site model assumes the production of the most favorable species on the sites with the corresponding soil suitability (e.g., on dry or wet soils). Thus, the chosen site model considers the relative competitiveness of different species and represents the farmer's economic decision behavior to ensure profit maximization (cf. Section 2.1).

4.3 SRC area restriction

The simulated SRC area varies between $0.28*10^6$ ha (i.e., 1.7% of UAA) for no subsidization in the counterfactual scenario to $2.24*10^6$ ha (i.e., 14.9% of UAA) for extremely high mitigation payments of 500 EUR g^{-6} CO_{2eq}. The $2.24*10^6$ ha represents the maximal available area assumed in the integrated model approach and is in line with Aust et al. (2013), who estimated $2.12*10^6$ ha.

However, the estimated technological potential in these two studies results from different model assumptions. Aust et al. (2013) simulated with their site model the maximum available area in a scenario assuming technical, ethical and ecological constraints (e.g., no production in environmentally protected areas and UAA for food production). In the present study, both linked models define the constraints for the maximal SRC area. From an agronomic and environmental perspective, the site model defines the technical assumptions (e.g., given by climate, topography and harvest cost) and excludes environmentally protected areas for SRC production. Thus, it corresponds to the environmental and ethical constraints in Aust et al. (2013). From the agricultural and economic perspective, the RAUMIS model considers additional constraints, representing the relative competitiveness between SRC and other agricultural production.

4.4 Advances in SRC modeling

The developed integrated model approach considers agronomic, agricultural and economic aspects and allows for the assessment of the abatement effect caused by SRC. Thus, the present study complements previous studies in Germany by combining regional site modeling with regional agro-economic modeling.

Kollas et al. (2009) developed a site model that allows for the simulation of climate scenarios, being based on a process analytical model (C4) and a regional climate model to estimate regional biomass/yield potential. Aust et al. (2013) took a GIS-based approach; consider three different site classes for slopes, soil quality and grassland protected area; and use spatial restrictions to estimate the regional land availability for SRC.

Strohm et al. (2012) used crop farm-type models based on standard production costs to simulate prices and policy scenarios and provide an analysis of economic and ecological impacts on cash crop farms. Faasch and Patenaude (2012) developed net present value models based on data from 7 pilot sites to simulate scenarios on yield levels, wood chip market prices, required payment levels, cost levels and opportunity costs for conventional agricultural crops.

Although Kollas et al. (2009) and Aust et al. (2013) consider the regional sites for SRC production, they neither explicitly model other agricultural activities nor provide an economic simulation of policy scenarios. In contrast, Strohm et al. (2012) and Faasch and Patenaude (2012) provide economic simulation analysis based on farm-type production programs, although neither considers the regionality of sites nor the complete agricultural production programs.

The present study aims at a concise evaluation of SRC as a mitigation strategy. This evaluation requires consideration of the previous studies' aspects, which is achieved by an integrated model approach based on two suitable linked models. Within the site model, 20 site classes for each of the 326 model regions are discriminated. This detail allows for a much more differentiated representation of the regional yield potential compared to Kollas et al. (2009) and Aust et al. (2013), with 3 and 15 site classes, respectively. Furthermore, the presented model extends these studies by including aspects of economic decision making in the assessment of SRC potential. The derived figures therefore depict the economic potential and not only the technological potential. The economic decision-making process enters the model at two points. First, the most favorable SRC species for the corresponding sites is autonomously selected, and second, the competition with ordinary agricultural production on the respective sites is taken into account. The linked agro-economic model RAUMIS provides the analysis of economic and policy scenarios (as in Strohm et al. (2012) and Faasch and Patenaude (2012)) but considers regional SRC sites and full regional agricultural production programs.

4.5 Outlook

The integrated model approach consisting of a linked site-model and the agro-economic model RAUMIS can be regarded as a fruitful development for addressing SRC-related research questions that require economic or policy simulation. However, several aspects are not considered in this study that should be considered in future work.

Although RAUMIS considers regional heterogeneity, the modeling of conventional crops is not site specific within the model region, as it is for the SRC. A site-specific modeling of conventional crops could represent more exactly the competitiveness between the activities and could be of particular interest for commodities with substantial transport costs (e.g., silage) or crops linked to specific environmental conditions or restrictive crop rotation constraints (e.g., sugar beets).

In this study, we analyzed neither the potential impact of an increasing plantation of SRC on agricultural commodity prices nor the impact of different agricultural commodity price levels on the mitigation costs and mitigated quantities. Especially with regard to the first question, the definition of price changes, including SRC prices, requires plausible price assumptions for the agricultural and energy markets. Because agricultural commodity markets are global, at least for bulk commodities as cereals, a relevant impact of a policy on the market prices will only manifest itself if non-negligible quantities are affected. In the case of SRC, it is very likely that such a promotion policy must at least be implemented on an EU scale to induce a price reaction. Analyzing the interaction of SRC cultivation and agricultural commodity prices should be addressed in additional studies (e.g., Strohm et al. (2012) or Faasch and Patenaude (2012)).

This study does not consider the indirect land use changes (iLUC) and/or leakage effects. These aspects are important for a more global evaluation of mitigation impacts. With additional GHG accounting, both effects could be addressed.

Though quite concise, the developed model approach is not suitable for addressing important aspects of scientific interest in SRC that take place at the farm level. The underlying normative model approach assumes regional competitiveness and the extension of SRC on marginal arable land and grassland, resulting in an SRC area of $280*10^3$ ha in the counterfactual scenario. Currently, SRC is practiced on only $6.5*10^3$ ha. How can this difference be explained? First, we were interested in the mitigation effect of SRC if no other land use-based mitigation strategies were in place. Therefore, we abstracted from the fact that policies are in place that strongly support certain agricultural land uses, i.e., the renewable energy law for promoting the use of maize to produce biomethane and the blending mandates for biofuels. The additional demand caused by these policies leads to higher agricultural commodity prices compared to the counterfactual scenario. Second, in reality, farmers are reluctant to invest and change from traditional production to SRC. However, to explain farmers' decision and investment behavior, other model approaches have been developed (e.g., Musshoff 2012, Wolbert-Haverkamp and Musshoff 2014).

5 Conclusions

This study complements the existing literature by estimating the economic mitigation potential from short-rotation coppice throughout Germany.

The developed integrated model approach considers agronomic, agricultural, environmental and economic aspects and complements previous studies in Germany by combining regional site modeling with regional agro-economic modeling.

The scenario results indicate the strong dependency of income losses and marginal abatement costs on the intended level of mitigation. At an economically reasonable cost of 100 EUR, one could mitigate GHG in the magnitude of $12.0*10^{12}$ g CO_{2eq} (15% of the counterfactual scenario). These costs sharply rise if higher quantities are intended.

The results show that the increase in the share of SRC would not be evenly distributed across Germany. At higher payment levels would lead to a pronounced change of the landscape in a couple of regions. Experience with the recent development of energy maize production shows that changes of such a magnitude are very likely to induce resistance from the local population. If SRC is to be more evenly distributed, market instruments must be accompanied by other policy instruments (e.g., land use planning and zoning).

Thus, the integrated model approach consisting of the linked site-model and the agro-economic model RAUMIS can be regarded as a fruitful development in addressing SRC-related research questions, and they provide a promising base for further work.

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TABLE 1: OVERVIEW OF THE MODEL LINKAGE BETWEEN THE REGIONAL SITE MODEL AND THE AGRO-ECONOMIC MODEL

Regional model	**Parameter**	**Input data**	**Data source**	**Model approach**
Site model	SRC agronomy: regional yields	mean rainfall (May to June) mean temperature (April to July) soil quality available water storage capacity slope production area protected area	DWD BKG BfN BGR	Ali (2009) extended for sandy and organic soils
	SRC economy: regional costs	topography: slope yields	BKG SRC Agronomy	Schweinle et al. (2012)
Agro-economic model (RAUMIS)	agriculture: regional acreage & biomass harvest	regional yields regional costs production area	SRC site model Regional Federal Statistics	Henrichsmeyer et al. (1996)
	economy: income	prices support payments	Offermann et al. (2012), Kretschmer et al. (2012), OECD (2008)	Offermann et al. (2012)
	GHG mitigation	emissions factor	MODE, GAS-EM	Henseler and Dechow (2014), Haenel et al. (2012)

TABLE 2: DEVELOPMENT IN AGRICULTURAL PRODUCTION AT THE SECTOR SCALE UNDER DIFFERENT PAYMENT ASSUMPTIONS

		Abatement payments in EUR g^{-6} CO_{2eq}										
		CF	**5**	**10**	**25**	**50**	**75**	**100**	**125**	**150**	**175**	**200**
Intensive cereals [a]	**[10^6 ha]**	5.78	5.78	5.78	5.78	5.78	5.78	5.77	5.77	5.77	5.77	5.77
	[% of AL]	52	52	52	52	52	52	51	51	51	51	51
Extensive cereals [b]	**[10^6 ha]**	1.04	1.00	0.97	0.87	0.70	0.56	0.47	0.39	0.34	0.31	0.29
	[% of AL]	9	9	9	8	6	5	4	4	3	3	3
Others [c]	**[10^6 ha]**	4.00	4.00	4.00	4.00	4.00	4.01	4.01	4.01	4.01	4.02	4.02
	[% of AL]	36	36	36	36	36	36	36	36	36	36	36
Fallow	**[10^6 ha]**	0.18	0.17	0.15	0.09	0.04	0.02	0.01	0.00	0.00	0.00	0.00
	[% of AL]	2	1	1	1	0	0	0	0	0	0	0
Intensive grassland	**[10^6 ha]**	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
	[% of GL]	62	62	62	62	62	62	62	62	62	62	62
Extensive grassland	**[10^6 ha]**	1.88	1.85	1.82	1.71	1.52	1.35	1.22	1.12	1.03	0.96	0.90
	[% of GL]	37	2	2	2	2	1	1	1	1	1	1
SRC on arable land	**[10^6 ha]**	0.21	0.26	0.31	0.47	0.69	0.85	0.95	1.03	1.08	1.12	1.14
	[% of AL]	2	2	3	4	6	8	9	9	10	10	10
SRC on grassland	**[10^6 ha]**	0.07	0.10	0.13	0.24	0.44	0.60	0.73	0.83	0.92	0.99	1.06
	[% of GL]	1	2	3	5	9	12	14	16	18	19	21
Dairy cows	**[10^6 LU]**	3.84	3.84	3.83	3.81	3.77	3.74	3.72	3.71	3.70	3.69	3.68
Other cattle	**[10^6 LU]**	4.28	4.33	4.32	4.30	4.28	4.27	4.25	4.24	4.22	4.21	4.21
Pigs	**[10^6 LU]**	3.18	3.18	3.18	3.18	3.18	3.18	3.18	3.18	3.17	3.17	3.17
Poultry	**[10^6 LU]**	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59
Income	**[10^9 EUR]**	13.5	13.5	13.5	13.4	13.2	12.9	12.6	12.4	12.1	11.9	11.6
Abatement effect by SRC	**[10^{12} g CO_{2eq}]**	2.3	3.0	3.7	5.9	8.8	10.8	12.0	12.8	13.4	13.8	14.1

Notes: CF = Counterfactual scenario assuming no subsidies for mitigated quantities

a) including winter cereals and grain maize; b) including oat, rye, spring meslin; c) including oilseeds, legumes, fodder crops, and special crops

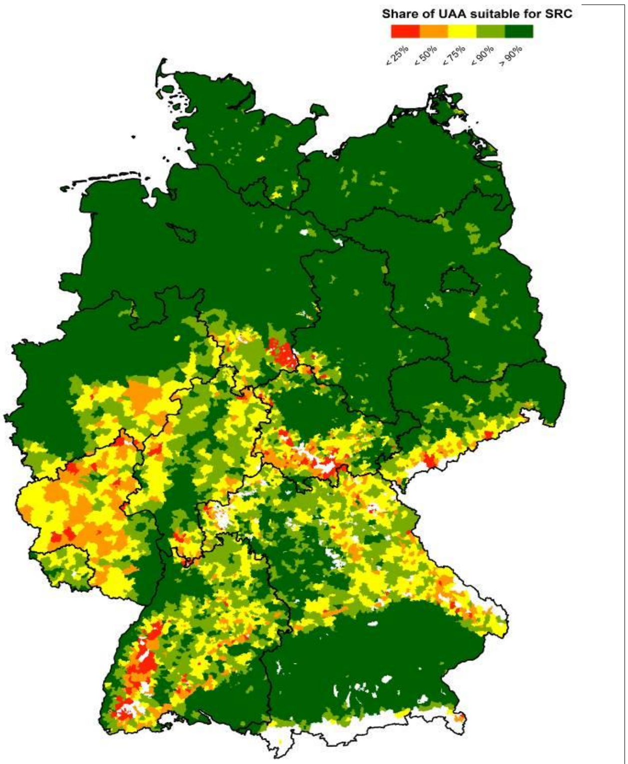

FIG. 1. SHARE OF UAA SUITABLE FOR THE CULTIVATION OF SRC

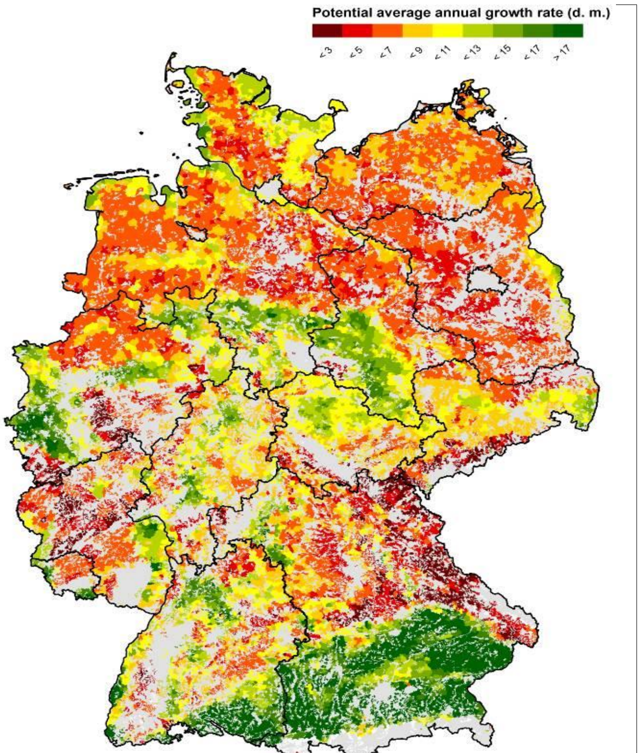

FIG. 2. POTENTIAL AVERAGE ANNUAL GROWTH RATE OF SRC OVER THE HARVESTING CYCLE

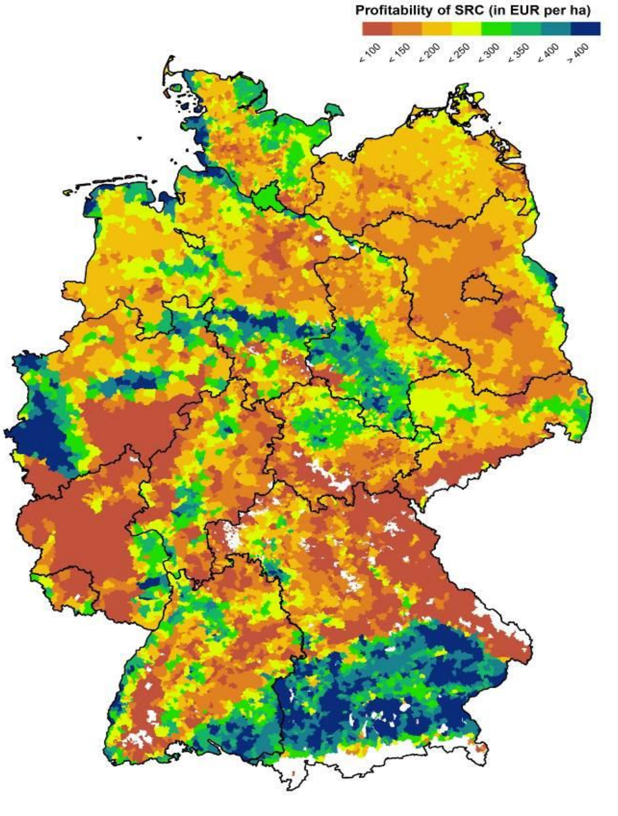

FIG. 3. ESTIMATED ANNUAL PROFIT OF SRC IN THE COUNTERFACTUAL SCENARIO (AVERAGE OF THE SITES WITH A POSITIVE PROFIT FOR EACH MUNICIPALITY) (IN EUR PER HA)

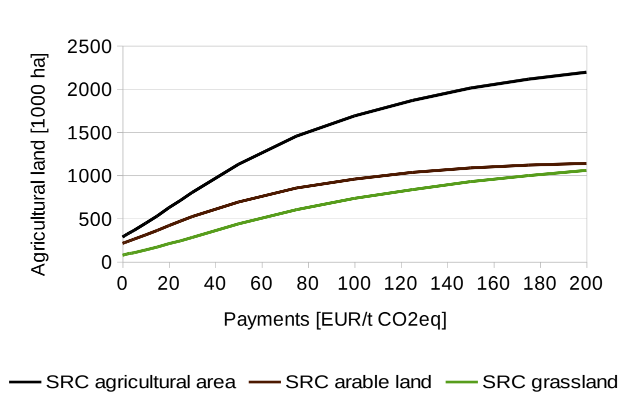

FIG. 4. AREA DEMAND IN RELATION TO THE ABATEMENT PAYMENT

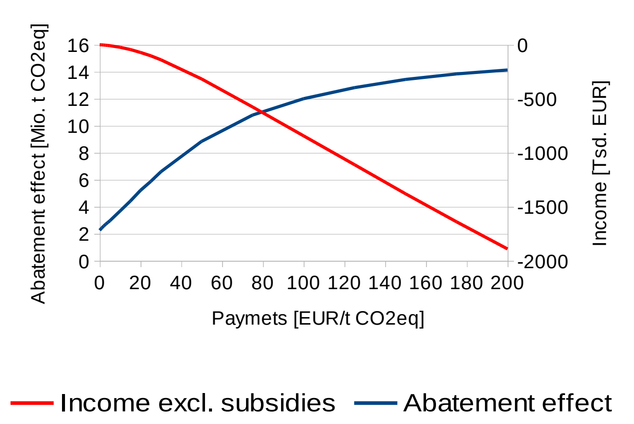

FIG. 5. AGRICULTURAL INCOME AND ABATEMENT COSTS IN RELATION TO THE ABATEMENT PAYMENT

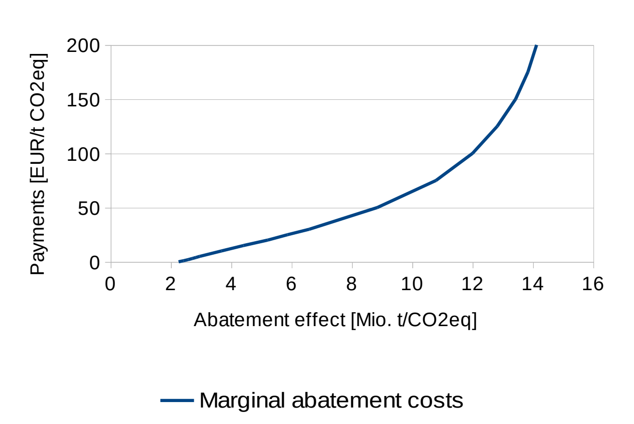

FIG. 6. MARGINAL ABATEMENT COST CURVE (MACC)

FIG. 7: REGIONAL DISTRIBUTION OF SRC AREA AT DIFFERENT LEVELS OF PAYMENTS PER MITIGATED TON OF CO_{2EQ}

Payments	EUR g^{-6} CO_{2eq}	10	25	50	75	100
Emissions without abatement by SRC	10^{12} g CO_{2eq}	80.1	79.7	79.1	78.6	78.2
Abatement by SRC absolute	10^{12} g CO_{2eq}	3.7	5.9	8.8	10.8	12.0
Abatement by SRC relative to CF	%	4.7	7.5	11.3	13.8	15.4
SCR on UAA						
SCR on arable land						
SCR on grassland