- MASTER THESIS -

Title:

Straw for renewable energy production: impact of market dynamics

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Summary

In order for the EU to reach its renewable energy and GHG emission reduction targets, member states need to find alternative source for energy supply to fossil fuels. One potential energy source that could help in this endeavour whose potential has been overlooked so far comes in the form of cereal straw. While large potentials are theoretically available, straw however still has other uses in the agricultural sector most notably for animal husbandry and for humus supply. Targeting straw for renewable energy production could therefore impact these existing uses. Furthermore, how much of the theoretically estimated straw potential could actually be mobilized from the backdrop of competing uses, different farming practices and market interactions and what the consequences of an increase from the energy sector would be is not entirely clear. The objective of this research was therefore to investigate how the different elements influence each other and explore the dynamic impacts if straw is used for renewable energy production.

To investigate the dynamic impacts of increase in straw demand from the energy sector an agent-based model was developed that assumes the operation of a straw based bioethanol plant in a specific region in Germany, which has been identified with potentially large surplus straw potentials. The model results show that market dynamics and farmer straw use behaviour can greatly influence the yearly straw availability for energetic purposes and could impact the overall feasibility and sustainability of mobilising straw for renewable energy production especially in cases where straw demand exceeds regional supply.

Introduction

To mitigate global warming and reduce the severe risks from climate change, we need to substitute fossil fuels with renewable energy sources that do not add to net greenhouse gas (GHG) concentrations in our atmosphere (IPCC, 2014). The EU has set out several targets and policies to accelerate the transition to a low carbon economy. The long-term target is to have its GHG emissions reduced by 80-95% by 2050 (as compared to 1990 levels) (European Commission, 2011). To achieve this goal, member states have to look into all available options of carbon emission reduction. One potentially sustainable option that has been overlooked so far, but which could contribute to meet national energy demands, is the use of biomass from agricultural and forestry residues and by-products (Scarlat et al., 2015). Looking at Europe, a considerable portion of potential bioenergy feedstock could be derived from cereal straw. This energy potential has been estimated at 50 000 ktoe, with countries such as France, Germany, Poland, Hungary, Italy or Romania showing the largest potentials (Elbersen et al., 2012).

So far, only Denmark – facilitated through national support programs that started 30-40 years ago – is making full use of its straw potential to serve as feedstock for energy supply (Gawor et al., 2014). Straw could be used as feedstock for heat and power production, as well as for the production of biofuels. The prospect of biofuel production is of especially high interest. Biofuels produced from lignocellulosic material (especially from domestic residues) have the potential to increase the GHG emissions saving potential per litre as compared to crop-based 'first generation' biofuels and are able to avoid the negative impacts from land use change mechanisms (cf. Balan et al., 2013; Eisentraut, 2010; Fargione et al., 2008).

Nevertheless, increasing the utilization of straw for bioenergy or biofuel production does not come without its challenges. While being a residue product, straw still fulfils important functions in the agricultural sector most notably for humus supply and for animal bedding. It also has its uses in vegetable and mushroom production and some other minor applications (Kretschmer et al., 2012). The new demand for straw for bioenergy production could thus impact these existing applications by diverting straw to energetic uses on the expense of existing applications or by affecting straw prices as a result of the new competition (Gawor et al., 2014). Furthermore, the actual yearly availability of straw is subject to many different factors. These range from natural variations in yearly cereal yields to yearly variations in farmers straw use decisions in response to changing market conditions. Straw supply and its variation, as well as the resulting price variations are however important aspects for the economic viability of biorefineries (cf. Hess et al., 2007, Glithero et al., 2012, Gawor et al., 2014). From an environmental perspective, the overharvesting of straw has been emphasized as of particular concern, as it can lead to the depletion of soil organic carbon (SOC) (Blanco-Canqui & Lal, 2009) thereby reducing the GHG saving potential of straw-based energy production. Further, overharvesting can deteriorate soil functions, which would lead to further environmental and economic consequences (e.g. lower resilience of agro-ecosystems, additional fertiliser requirements) (Monforti et al., 2015).

Research objective

Research so far has shown that considerable straw potentials for bioenergy production is theoretically available, but that competing uses and farmer attitudes as well as natural and regional variations can have quite an impact on yearly straw availability.

Weiser et al. (2014) investigated the available straw potential for Germany and the feasibility and GHG abatement potential of different energetic pathways. They concluded that theoretically all potentially available energetic utilization pathways are possible to implement given the surplus straw potential in Germany without negatively impacting soil humus balances. However, differences exist in regional availability of straw and in GHG abatement potential of the different energetic utilization pathways. The authors did not investigate the impacts of farmer behaviour or market interactions on straw supply or the influence the increase in demand for energy production itself would have on market.

Glithero et al. (2013) conducted a study investigating available straw potentials for bioethanol production in the UK based on farmers' straw use practices and concluded that farmers' attitudes towards straw use can play a significant role both for feedstock availability and soil properties.

The difference in attitudes towards straw use and its relevance for straw availability within regions has also been mentioned in Kretschmer et al. (2012) who analysed the possibilities for mobilising straw for bioethanol production. Furthermore, the authors conclude that competing uses for straw and variability of straw supply pose key challenges for the operation of straw-based biorefineries.

So far, straw potentials and critical factors for the promotion of straw for bioenergy production have been assessed separately. To date no study has looked at the joint interaction between the separate elements and how differences in farmer attitudes influence straw market development and impact the region in terms of straw use and straw availability.

This research therefore aims at investigating the dynamic impact an increase in straw demand for renewable energy production has for a region with potential surplus straw.

Research questions

The central research question this investigation attempts to find answers to is:

What are the dynamic impacts of increased use of straw for renewable energy production?

The following sub-research questions have been formulated:

1. *What is the impact of increased demand of straw from the energy sector on the dynamic behaviour of the straw market and the straw production sector with regards to straw price developments, straw use and straw supply?*

2. *How does the increased demand and market developments affect farmers in their farming practices and management of straw?*

3. *What are elements/mechanisms or systemic traits to be aware of that could lead to unintended/unsustainable developments/consequences and under what conditions do they occur?*

Outline

In the subsequent section of this paper, the method will be introduced, which has been chosen to find answers to the formulated research questions. The following section gives a short description of the real-world system under study. Section four describes the model development process. The description of the final model is presented in section five. Section six describes the experiments and their individual setup that were conducted with the final model. The experiment results are presented in section seven, followed by a conclusion and discussion of the research results.

Method

To find answers to the formulated research questions and analyse the dynamic impacts of using straw for large-scale bioenergy production a modelling approach has been chosen. The modelling approach allows simulating market developments for different market scenarios and to explore, ex-ante, the influence of different elements on change in system behaviour over time.

The construction of the model is based on the generative science approach (Epstein, 2006) using systems theory and a computational environment to conceptualise and simulate the real world system under study.

Agent-based modelling

Different modelling approaches exist to perform ex-ante impact analyses. They can be divided into 'top-down' or computable general equilibrium (CGE) models – most commonly classified as macro-econometric and system dynamic models– and 'bottom-up' or agent-based models (ABMs), which include behavioural or algorithmic models, agent-based computational economics (ACE) and simulations (Bale, 2015). CGE or partial equilibrium (PE) models are the dominant method for analysing and simulating macro-economic behaviour (Wicke et al., 2015). Prominent examples include the CAPRI (Common Agricultural Policy Regionalized Impact) model (Heckelei & Britz, 2000) to analyse impacts of policies on the agricultural sector or the GLOBIOM model (Havlík et al., 2011), a dynamic partial equilibrium model that integrates agricultural, bioenergy and forestry sectors to assess land use competition.

CGE models are highly aggregated and neglect the heterogeneity of economic actors and the impact of interactions between them. They are based on neoclassical theory, which necessitates actors to be homogenous in their behaviour, act fully rationally and have full access to market information (cf. Tesfatsion, 2006).

However, with regards to our problem context, which is concerned with regional impacts and the promotion of new innovative practices, the influence of individual actor behaviour (e.g. individual straw-use behaviour), the heterogeneity of economic actors and the reality of bounded rationality (e.g. decisions under uncertainty, limited information, limited processing capacity, limited time, social influence (Simon, 1982)) could play an important role for an adequate assessment of how an increase in straw demand for renewable energy production will impact a specific region. Hence, these characteristics should be incorporated into the model in order to make meaningful insights about potential emerging market dynamics.

The agent-based modelling paradigm is able to provide for these including these facors (cf. Axelrod, 1997). Through the individual modelling of agents, different from classical economic models, ABMs are able to depict the inherent diversity of market actors with regards to their individual attributes and behaviours (Macal & North, 2010). Furthermore, through the bottom-up modelling approach, ABMs give the opportunity to explicitly track and explain why and how certain macroeconomic developments have emerged, a feature missing in the classical general equilibrium (GE) models (Arthur, 2006), but important to gain more insights into transition dynamics.

ABMs have been successfully used in many applications to assess the effects of technological changes or policy interventions on agricultural or energy systems (e.g. Shastri et al., 2011; Matthews et al., 2007; Ding et al., 2015; Brady et al., 2012; Chappin & Dijkema, 2010, Moncada et al.), study economic behaviour (cf. Tesfatsion, 2006) and have been proven a suitable tool explicitly for the modelling of systems that are of a distributed character (i), where actors are to some extent autonomous (ii), where the environment is highly dynamic (iii) and where a wide variety of interactions among actors and sub-systems exist (iv) (van Dam, 2009). With regards to our problem context these conditions are met:

i. Distributed supply of straw suppliers and straw consumers;
ii. Multiple farmers and straw users that have their individual agendas;
iii. A highly dynamic environment is given by, amongst others, the varying availability of straw, local competition, yearly land use and investment decisions by farmers, price fluctuations;
iv. Farmers react on economic incentives for land use and straw harvesting, farmers exchange information with other farmers; bioethanol plants are approaching farmers to negotiate contracts.

Structure of an ABM

ABMs model systems from the bottom up with agents being its core modelling entity. All agents can be assigned with individual attributes and behavioural rules/ methods of interaction, which allows incorporating the full effect of heterogeneity among actors and actors' behaviours into the model.

All agents act autonomously making independent decisions based on their assigned behaviours and interactions with their environment and other agents. Agents furthermore can be assigned rules that modify their behaviour or method of interaction with other agents or the environment (agents are able to adapt to changing environments). Thus, ABMs are capable of depicting evolution of complex adaptive systems over time emerging from the defined agent behaviours, attributes, relationships, and interactions of agents with each other and their environment (Macal & North, 2010).

Figure 1 gives an illustration of the basic functioning of an ABM.

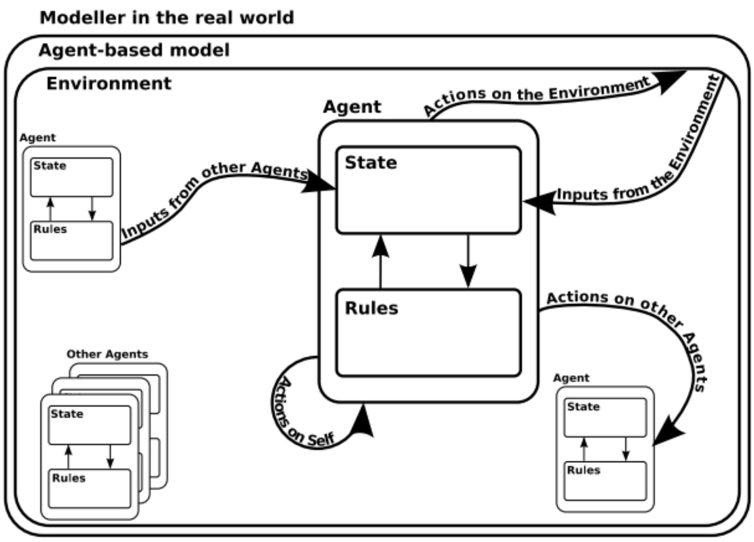

Figure 1: Basic structure of an agent-based model (Source: van Dam et al. (2013, p.58))

Through the bottom-up modelling approach, ABMs give the opportunity to explicitly track and explain why and how certain macroscopic behaviours have emerged - a feature that for instance cannot be offered by classical general equilibrium (GE) models (Arthur, 2006), but which is important to gain more insights into transition dynamics (van Dam et al., 2013).

Theoretical Framework

Generative science

Generative science starts from the premise that phenomena (macroscopic regularity) can be generated or explained through the interactions of individual units and their ways of interaction among each other (Epstein, 2006).

It tries to find explanations for macroscopic regularities by finding the different elements (heterogeneous autonomous agents) and individual behaviours and interactions (decentralized local interactions) that are able to grow or are responsible for the emergence of the macroscopic regularity of interest (Epstein, 2006). The macroscopic regularity becomes an emergent property of the interactions of the systems elements. And by growing the particular macroscopic regularity of interest out of the individual elements' interactions in an agent-based computational environment, it allows the investigation of how and to what extent the different elements, behaviours and existing relationships influence the macroscopic regularity of interest.

In our problem context, the macroscopic regularity of interest refers to the use of straw, total straw supply, the potential available to the market and straw prices.

System theory and complex adaptive systems

System science explores any kind of phenomenon as a web of relationships among individual entities. It looks at causal networks, interdependencies and interrelationships to explain a certain phenomena. A system can be defined as "a whole of some sort made up of interacting or interdependent elements or components integrally related among them in a way that differs from the relationships they may have with other elements" (Mobus & Kalton, 2015, p.73).

Systems are idealisations of observations made from the real world. They consist of multiple components, which directly or indirectly stand in relation to each other (interdependence) and interact. Systems usually have some sort of internal organisation and structure that tells what elements are linked to what other elements and in what type of interaction (van Dam et al., 2013). The greater the heterogeneity in the system composition (number of different components/sub-systems and elements) and the higher the hierarchical organization (number of sub-system levels), the more complex a system usually becomes, creating a more complex internal structure with more different components and more kinds of interaction possibilities and links that increase possible system outcomes/pathways (Source).

Complex (adaptive) systems

Complex adaptive systems (CAS) refer to dynamic networks in which components of the system are active agents that act, interact and react (adapt) to their (changing) environment and the actions of other agents in the system (Holland, 1995). They are characterised by "self-organisation" – meaning that there is no central controlling element that determines alone over the systems' behaviour and development. Rather, the overall system behaviour and direction of development emerges from the entirety of the individual decisions made by the individual agents over time and the resulting activities and interactions (Holland, 1995).

Main properties of complex adaptive systems:

- Self-organisation
- Connectivity
- Co-evolution
- Sensitive dependence on initial conditions
- Emergence

Socio-technical systems

Socio-technical systems refer to systems that include actors, technical elements and social elements as system component. The motivation for the distinction comes from the difference in rules and laws that the different groups of elements are subject to, but which all influence system behaviour. On the one hand, there are laws of nature to which physical entities like actors and technical elements obey. On the other hand, there are social elements and social rules, which have an influence on actors behaviour and their intentions. The result is a network of elements that stand in physical, functional, intentional or normative relation to each other (Ottens et al., 2006).

Straw use for energy production as a complex adaptive system

Straw use for bioenergy/biofuel production resembles a socio-technical system in that:

- it includes a network of multiple actors (farmers, bioethanol producers, other potential straw-based energy producers, other straw-consuming producers, contractors/brokers);
- who are dependent, use or manage different kinds of technology or infrastructure and;
- are influenced by social institutions of formal and informal kinds like existing farming traditions, norms and routines or governmental regulations and existing promotion policies.

It furthermore also displays the features of a complex adaptive system. The actors very in their traits and properties and interact in different ways or stand in different kind of relationship with one another. They repeatedly engage with one another to reach their individual objectives and in their interactions influence for instance how much straw is sold in the market and to what prices. Actors furthermore react to the decisions and activities of the other actors involved in the market, as well as to other global developments (i.e. changing market prices, changing policies) or changes in their environment and adapt their straw-related business activities (e.g. farmers react on market developments like growth in straw demand or average market prices and incorporate these information in their business decisions for the next growing season). Thus, straw use and total straw availability, as well as straw market prices emerge from the individual interactions of the different actors and elements in the system.

Figure 2 gives an illustration of the regional straw market conceptualised as a socio-technical system, consisting of a social network of actors (i.e. farmers, straw demand side actors), a physical network of technical artefacts (i.e. straw, soil, distribution network, technical infrastructure) and influencing social elements (e.g. policies, habits).

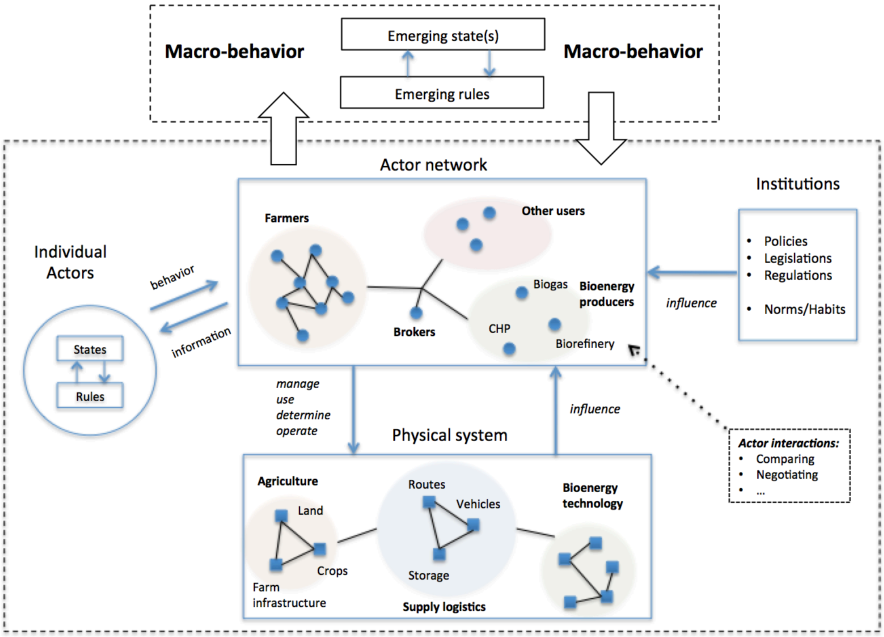

Figure 2: Conceptualisation of the real-world system as a socio-technical system.

Data collection

To build the model, a series of information is required. Information is needed on the relevant actors and their ways of interaction/behaviour, the factors and elements that drive agents' behaviours and existing mechanisms or relationships among the different elements.

In detail:

- Information is needed on the different types of actors in the system and their individual properties that determine their behaviour and interactions
- Information is needed on the existing practices with regards to straw procurement, farming practices and straw use
- Information is needed on the elements and factors that influence straw utilization including information on farmer decision-behaviour
- Data is needed on the model region to determine the theoretical straw supply
- Information and data is needed on cost factors and costs for straw supply, as well as for bioethanol production

Most of the data was obtained by reviewing academic literature and publicly available documents. The data to describe the model region and define theoretical straw supply has been obtained from statistical data available from governmental databases (www.regionalstatistik.de). Furthermore, an online forum was used to engage directly with farmers to find out especially more about the farmers' perspective with regards to straw use and their individual attitudes (www.landtreff.de).

Building the model

To develop the agent-based model, the methodology as proposed by van Dam et al. (2013) for developing agent-based models of socio-technical systems has been used to guide the modelling process consisting of the following elements:

1. Problem formulation and actor identification
2. System identification and decomposition
3. Concept formalization
4. Model formalization
5. Software implementation
6. Model verification

Problem formulation and actor identification

First, the problem is formulated by identifying and describing the macroscopic regularity of interest and by identifying the problem owner and other actors involved in the system (system analysis section).

System identification and decomposition

The second step includes the collection of information and data to first, identify what constitutes the system and decide on system boundaries, and second, make an inventory of all relevant elements that have an influence on straw availability or the use of straw. After data collection, the system is decomposed and structured regarding agent types, agent interactions, agent properties, agent behaviours and the elements constituting the environment with an influence on straw availability and straw use.

Concept formalization

After deciding on the system definition and identifying the relevant agents, interactions, agent behaviours and relationships, the third step includes the translation of identified concepts into software data structures to make the concepts computer-understandable. The results of the concept formalization can be reviewed in the section where the final model is described.

Model formalization

The fourth step includes developing the model narrative that specifies exactly which agent is doing what with whom and at what point in time during the model simulation. The results of the model formalization can be reviewed in the section where the final model is described.

Software implementation

The modelling environment that has been used to create the final computational agent-based model is NetLogo[1].

Model verification

The correctness of the model (model verification) has been tested is assured by conducting a set of standard verification tests (van Dam et al., 2013, p.100ff), where in iterative steps the logic and consistency of individual and aggregated behaviour of individual agents, system modules and the system as a whole is tested.

[1] https://ccl.northwestern.edu/netlogo/

Experiments & Data analysis

To explore the system behaviour and investigate what kinds of patterns or regularities might emerge, different experiments have been designed that test the influence of different combinations of parameter settings. Every experiment is run with multiple repetitions to prevent unrepresentative outliers. To conduct the experiments the BehaviourSpace tool in NetLogo has been used.

For the data analysis, the tool "R" has been used to analyse and visualise the produced data outputs. First each experiment is analysed independently by combining and statistically describing the results of the repeated runs per experiment. In a second step, the different individual experiment outputs are compared with each other to identify patterns/regularities that give answers to the formulated research questions.

System analysis: Using straw for biofuel production

System description

Straw supply and use in Germany

Straw is an agricultural by-product in the cultivation of cereal crops. The usual farming practice with regards to straw use at cereal harvest is to either reincorporate it back into the soils or to harvest it, press it into bails and utilize it for animal husbandry (Weiser et al., 2014). The harvestable potential depends on cereal yield and the corn-straw ratio of the crop (the amount of straw per crop) and is restricted by technical factors such as cutting height and dry matter content (Weiser et al., 2014). The average theoretical straw potential in Germany has been estimated to be around 30 million tons per year of which about 16.6 % are used as litter for animal husbandry (Henneberg et al., 2012, p.7).

The purpose of reincorporating straw back into the soils is twofold. First, it enables the farmer to quickly prepare the land for the seeding of the next crop. Second, and more importantly, straw serves as a valuable supply of organic carbon and organic material to maintain soil humus balances. If the share of soil organic matter is too low it will affect humus production and endanger soil fertility (Henneberg et al., 2012).

Different attitudes exist among farmers concerning the value of straw for humus supply. While some farmers strictly advocate its use as a humus supplier and are not willing to sell any of their available straw potentials, other more market-oriented farmers are willing to sell straw potentials as long as it increases their overall profit (Kretschmer et al., 2012).

Due to the limited time window in which straw must be harvested, special equipment is required that enable a high productivity (Henneberg et al., 2012). As farmers do not always own the appropriate equipment, often the harvesting of straw is commissioned to contractors that have specialised in these activities and have the appropriate equipment to their disposal.

The main existing buyers of straw include other businesses of animal husbandry that are in need of straw for animal bedding and businesses in horticulture, vegetable and mushroom production (Kretschmer et al., 2012).

The EU tries to promote sustainable agriculture by making their direct payments to farmers conditional on farmers complying with different standards and policies that aim to protect the environment, maintain soils and promote food safety and animal health (EU 1307/2013).

The EU Cross Compliance policy demands farmers to prove that they take sufficient care of maintaining soil organic matter levels/ humus balances. Farmers can prove their compliance either by displaying their land uses, reporting soil humus samples or by calculating the soil humus balance for his land based on land use and fertilizing practices (EU 1307/2013).

Straw market characteristics

As straw is low in energy density, transport and storage costs are rather high which result in regionally constrained markets (FNR, 2015). As a result, market prices for straw can vary quite a bit nationally depending on regional differences in supply and demand (FNR, 2015).

The regional supply is the result of a combination of factors. It depends on farmers land use decisions (i.e. using land for cereal production), farmers use of straw for animal husbandry, soil humus balances, farmers decisions in soil humus supply, variations in wheat yield (i.e. seasonal variations due to weather/climate), farmer convictions as well as the actual demand.

The straw potential in Germany that could be available for renewable energy production without negatively affecting soil humus balances has been quantified between 8 and 13 million tonnes (Weiser et a., 2014). The surplus potentials are however distributed unevenly in different parts of the country. The regions in Germany that have been identified to have the highest potential surplus straw available are Schleswig-Holstein, Mecklenburg-West Pomerania, North-Rhine-Westphalia and Lower Saxony.

Straw use for energy production

Straw potentials are regionally distributed. Together with its low energy density (14,05 MJ/kg) large straw-based energy plants need to consider rather large transport distances to be able to meet their required feedstock demands (Thrän et al., 2012). As straw-based conversion facilities require a continuous feedstock supply throughout the year, straw-based energy production further requires the possibility for storage, as straw can only be harvested once per year during cereal harvest.

Straw can be used as an energy carrier for heat supply, power supply or biofuel production using different conversion technologies. Heat supply from straw can be realized by combusting straw as pellets in boilers or by direct combustion in small and large-scale heating plants. Straw can also be used as energy carrier for combined heat and power plants for the combined generation of heat and electricity. Another way to make use of the energetic potential of straw is by anaerobic digestion together with other substrates for the production of biogas. Biofuel production can be realized by using straw as feedstock in biorefineries. Through pre-treatment and a combination of biochemical or thermochemical processing steps ethanol, biodiesel or jet fuels can be produced (cf. Yue et al., 2014). The production of biofuel from straw is still in its development phase, but it is expected that first plants of commercial scale will be feasible soon (cf. Balan et al., 2013).

Bioethanol production from straw

The conversion pathway that this study focuses on is the production of ethanol (EtOH) from straw. As mentioned earlier, large-scale straw-based bioenergy facilities require a large and continuous supply in feedstock. This is usually realized by making supply contracts with farmers or straw merchants of one or more years previous to the harvesting period. For the energetic utilization, especially in large-scale facilities, straw is pressed in squared bales (as opposed to traditional round bales), as the squared format provides better pre-conditions for further processing and automatisation of processing steps. The volumes in feedstock requirement depend on the technological readiness and size of the facility. Estimates for straw demands for commercial sized plants range from 180 000 to up to 500 000 t per year producing 50 to 100 million litres of ethanol (Kretschmer et al., 2012).

In order for straw-based bioethanol plants to become successful enterprises, three elements are essential (Slade et al., 2009; Hess et al., 2007): feedstock costs, the value obtained from bioethanol sales (i.e. bioethanol market prices and production costs) and feedstock availability.

Model development

Problem formulation and actor identification

While theoretically surplus straw potentials are available for renewable energy production, it is unclear what consequences the promotion of large-scale mobilisation of straw for renewable energy production might yield when considering market dynamics. Straw is traditionally either reincorporated into soils or used for animal bedding. It also has its use in horticulture and vegetable production. Increasing demand for renewable energy production will create new options for straw use for farmers and new demand in the market.

Depending on the farmers straw use decisions, which are affected by factors such as straw market prices, on-farm straw needs and farming attitudes, this will have subsequent consequences for existing uses and users as well as on actual straw supply. This in turn could affect the viability of larger-scale straw-based energy production sites, or impact its overall sustainability (i.e. neglecting soil humus balances, negatively affecting other sectors through increasing straw prices and limiting straw availability.)

The problem owner in this context is the national government that needs to find ways to replace fossil fuels with renewable "clean" energy in sustainable ways.

Other actors involved in the system "straw use for biofuel production" include the farmers as straw producers, sub-contractors for harvesting straw, straw merchants/intermediaries, existing parties that use straw for their individual purposes and the biorefinery operator.

Central modelling question:

What are the elements that influence straw availability for biofuel production?

Patterns of interest:

- Straw supply
- Straw use
- Soil humus balances
- Straw market prices

Problem owner:

- Government

Other actors involved:

- Farmers
- Intermediaries
    - Sub-contractors
    - Straw merchants
- Existing straw users
- EtOH plant operator

System identification and decomposition

Naturally, not all of the elements that have an influence on straw availability, straw use, straw prices or soil humus balances can be included in the model and boundaries have to be set in what depth and width the different processes and mechanisms will be modelled.

In the following section, the decisions are presented with regards to system boundaries, what elements have been included or excluded in the model simulation and what further assumptions have been made. The description in detail of the model setup is given in the following chapter.

Model region

A specific region in Germany has been selected for input data on the straw supply side with regards to number, size and type of farms and land use for wheat production. The region selected includes four districts – Lippe, Hoexter, Paderborn and Guetersloh – which are located in North-East North Rhine Westfalia. According to Weiser et al. (2014), this region theoretically has significant surplus straw potentials available that could be used without harming soil fertility. The four neighbouring districts was combined to form the model environment. The total area corresponds to approximately 4700 km2. The data for the individual districts, which has been obtained from governmental statistics (www.regionalstatistik.de), was aggregated.

Competing energetic utilization pathways

Theoretically there are different energetic utilization pathways for straw, which would potentially compete for the same feedstock. In this model however, competition between different energetic utilization pathways is not included and the only energetic utilization pathway is in the way of ethanol production from straw.

Farmers land use decisions and factors influencing humus content of soils

The amount of straw farmers can supply to the market is partly determined by the farm's soil humus balance. The soil humus balance is affected by factors such as soil type, water supply, temperature/climate and farmers' decisions on land use, crop rotation and choice/use of organic fertilisers (LWK NRW, 2012). Incorporating these elements into the model simulation would require extensive additional research and programming which however surpassed the scope of this research project. Hence, a uniform yearly net humus deficit was assumed per farmer symbolising the reduction of humus content that results from crop cultivation.

Further model assumptions

- The demand for straw from existing users and the EtOH plant is assumed to be constant.
- Sub-contractors and straw merchants are not included as individual agents in the model
- All straw trade takes place pre-season in which commitments are made to the quantity that will be delivered after harvest and the price the farmer will receive. The possibility of selling straw from stock is not modelled explicitly.
- EtOH plant will make price offer for straw directly off field, as it is assumed that they have their own specialised equipment to take care of harvest, pressing and transport or have special contractors with own specialised machinery.
- Requests for straw from existing users is assumed to be for already pressed bales (round bales) and to include the transport by the farmer to the potential buyer
- Farm systems

- To account for the different attitudes with regards to farming practices and straw use, farmers are divided into three type of groups or "farm systems": conventional farm systems, integrated farm systems and biodynamic farm systems.
    - Conventional farm refer to farms where farming decisions are motivated entirely on maximizing profits. They use straw wherever they receive the highest profit. It is assumed that most farms are still operated conventionally.
    - Integrated farm systems on the other hand are characterised by trying to integrate business opportunities with sustainable agriculture. Their first priority is to maintain positive soil humus balances. They give a higher value to straw in comparison to conventional farmers due to its humus supply function, which results in higher straw asking prices.
    - Biodynamic farm systems refer to farmers who are not willing to give up any straw as according to them straw should be only used for the reincorporation into soils.

- Straw for livestock
  - It is assumed that mixed farms use a particular share of their straw for animal husbandry. It is assumed that conventional mixed farms use 15% of their straw potential for livestock (assuming that most animals are held in stables with slotted floors), integrated mixed farms use 30% of their straw for animal husbandry, and biodynamic farms use 50% of their straw for livestock.

Inventory

Inventory of relevant concepts, actors, actor behaviours, interactions, flow, states and properties that are included in the model:

- Relevant concepts
  - Competition for straw between existing straw buyers and the new EtOH plant
  - Bounded rationality of farmers in terms of limited information on future wheat yields/straw potential or straw demand, as well as considering the long-term effects of neglecting soil humus balances
  - Importance of straw to maintain soil quality (humus supply function)
  - Farmers have different attitudes towards straw use
  - Farmers are profit oriented

- Actors
  - Farmers
  - Existing straw buyers
  - EtOH pant
- Relevant behaviours
  - Estimating straw potential
  - Deciding on straw use
  - Straw trade
- Interactions and flows
  - Exchanging information on straw needs, straw availability, asking prices and willingness to pay
  - Buying and selling straw
- States or properties
  - Farmers
    - Size of farms / land use for cereal production

        - Number of animals
        - Farm type/ farmer attitude
        - Land humus balance
    - Existing straw buyers:
        - Feedstock demand
        - Willingness to pay for straw
    - EtOH plant
        - Feedstock demand
        - Willingness to pay for straw

Structuring

Structuring of elements into agents, agent properties, type of actions and interactions:

- Farmer agents
    - Properties
        - have farm specifications
            - land size for cereal production
            - mixed or arable farms
            - straw production costs
        - differ in their farming practices, which influence their use of straw
        - follow different criteria with respect to straw reincorporation into soils
        - are generally profit oriented
        - have limited information about future wheat yield and straw demand
    - Actions
        - Estimate their soil humus balance
        - Estimate soil humus needs
        - Estimate straw potential
        - Estimate straw needs
        - Calculate profit from different straw uses
        - Decide on straw use
        - Compare straw requests to maximise profits
        - Sell straw
        - Determine straw asking prices
        - Adapt straw asking prices
    - Interactions
        - Respond to requests of buyers that are interested in buying straw with offers (exchanging information)

- Existing straw buyers agents
    - Properties
        - have a certain feedstock demand
        - source straw locally
        - are price takers in the market
        - try to minimise straw procurement costs
        - have an upper boundary on price willing to pay
    - Actions and interaction
        - Make requests to farmers for straw
        - Choose offers that yield minimum straw procurement costs
        - Increases sourcing radius if no straw is available in original sourcing radius

- EtOH plant agents
    - Properties
        - has plant specifications
            - Capacity
            - Operating hours
            - Efficiency
            - Yield
            - Production costs
            - Markup
        - has feedstock demand based on his plant specifications
        - knows costs for straw pressing, handling and transport
        - requires straw in squared bales
        - makes offers for straw directly off field and organises pressing, handling and transport himself
        - has maximum price willing to pay for straw
        - actively makes price offers for straw to farmers
        - has no information on straw supply in the market
        - acts for own profit maximization
    - Actions
        - Calculates feedstock demand
        - Calculates reserve price/ maximum willingness to pay for straw
        - Adapts price offer for straw off field
        - Increases sourcing radius if no straw is available in original sourcing radius
    - Interactions
        - Makes requests for straw to farmers
        - Accepts/selects offers from farmers that yield minimum straw procurement costs

- Request agents
    - Properties
        - Have request specifications
            - Straw volume
            - Demand type (pressed bales or off field)
            - Price offer (if request form EtOH agent)
- Offer agents
    - Properties
        - Have offer specifications
            - Price per ton of straw
            - Quantity
            - Demand type (pressed bales or straw off field)
- Contract agents
    - Properties
        - Have contract specifications
            - Price per ton of straw
            - Quantity
            - Demand type (pressed bales or straw off field)
        - created between straw buyer and straw seller after buyer chooses minimum price offer

- Environment

- Randomly distributes farmer agents and buyer agents
- Determines bioethanol price and price development
- Determines nutrient price of straw
- Determines yearly wheat yield

Model description

The model description follows the ODD (Overview, Design concepts, and Details) protocol that has been developed to improve the communication of model design of individual-based and agent-based models (Grimm et al., 2010).

Model Purpose

The purpose of the model is to investigate the dynamic impact of increased straw demand for renewable energy production on straw availability, straw use and straw prices.

Entities, state variables, and scales

Table 1: Entities, state variables and scales in the model.

Type of agents/entities	Properties	Values/Units
Farmers	Farm system	Conventional Integrated Biodynamic
	Farm type	Arable Mixed
	Acreage wheat production	[ha]
	Soil humus balance	[t humusC/ha]
	Estimated wheat yield	[t]
	Actual wheat yield	[t]
	Estimated straw potential	[t]
	Actual straw potential	[t]
	Estimated straw use for soils	[t]
	Straw use for soils	[t]
	Estimated straw use for livestock	[t]
	Straw use for livestock	[t]
	Estimated straw potential for sale	[t]
	Straw sold	[t]
	Asking price straw off field	[€/t]
	Asking price round bales	[€/t]
	Straw humus value	[€/t]
	Markup	[€/t]
Existing straw users	Feedstock demand	[t]
	Stored feedstock	[t]
	Required feedstock	[t]
	Sourcing radius	[km]
	Reserve price	[€/t]
EtOH plant	Feedstock demand	[t]
	Stored feedstock	[t]
	Required feedstock	[t]
	Sourcing radius	[km]
	Price offer	[€/t]
	Price offer bidding	[€/t]
	Reserve price	[€/t]
	Production capacity	[MW]
	Production costs	[€/t of EtOH]
	Markup	[€/t]
Environment	Global wheat yield	[t]
	Bioethanol market price	[€/t of EtOH]
	Bioethanol market price development	Constant Increasing Decreasing
	Straw nutrient value	[€/t]
	Straw bedding substitution price	[€/t]

Scales

- Temporal
  - One simulation step represents one year
  - 30 years (steps) make one simulation run
- Spatial
  - One grid cell equals 25 km2 (5x5 km)
  - The total area equates to an area of 4900 km2 (70x70km)

Process overview and scheduling

Sequence of one simulation run:

1. Reset of straw use and straw trade variables
2. Update bioethanol market price
3. Update soil humus balances of farmers
4. EtOH plant updates straw demand
5. EtOH plant updates bidding variables
6. Farmers estimate straw yield
7. Farmers estimate soil humus needs
8. Farmers determine humus supply
9. Farmers determine straw uses and straw potential for sale
10. Straw procurement (requests, offers, making contracts)
11. Harvest
    i. Determination of individual wheat and straw yield per farmer
    ii. Determination actual straw potential
    iii. Straw accounting
    iv. Humus supply to soils
12. Update soil quality
13. Agent reactions to straw procurement results
14. Farmer reaction to harvest

Design concepts

Basic principles

- Bounded rationality of farmers
  - Farmers have limited access to information (e.g. future straw demand, future straw yield) requiring them to make decisions under uncertainty
  - Farmers make decision based on their convictions
- Straw is an important source for humus supply to soils. Neglecting soil humus balances negatively affects the quality and productivity of soils and thereby crop yields.
- Delays in feedback loops (i.e. negative impact of negative soil humus balances on soil quality/yields) might significantly influence system behaviour
- Farmers vary in their farming practices or convictions which leads to different straw use behaviours in response to increased demand for straw for renewable energy production
- Straw use and straw availability for renewable energy production is dependent on the farmers decision-making, which in turn is influenced by his personal convictions, yields, humus balances, on-farm needs, and the market situation with regards to existing demand and expecting sales prices. The decision context varies every year with consequences for overall straw use and straw supply.

- Market dynamics and feedback loops influence straw availability, straw use and straw prices

Emergence

Model outputs that emerge from the adaptive traits, or behaviours, of individuals:

- Straw use
- Straw prices
- Soil humus balances
- Straw availability

Adaptation

Table 2: Adaptive traits of agents in the model.

Agent	Element	Rule/mechanism	Objective
Farmers	Asking prices for straw	Farmers increase asking prices if demand exceeds straw availability Farmers decrease asking prices if straw sales are lower than potential for sale	Increase profit from straw sale
	Straw use for soils	Farmers adapt their straw use for soils based on their soil humus balance and farm system	Complying with EU Cross compliance policy Maintaining soil quality
	Straw potential for sale	If straw price surpasses alternative bedding material price, farmers allocate straw originally used for animal bedding for potential straw sale If profit from straw sale outweighs substitution costs with alternative humus supply option, farmers allocate straw originally used for humus supply for straw sale	Profit maximization
EtOH plant	Price offered to farmers	During straw procurement: EtOH plant agent increases price offered for straw if he does not receive any offers for straw procurement in response to his requests	Securing sufficient feedstock supply
		After straw procurement: If feedstock demand could be met, the EtOH plant agent decreases price offered to farmers in next season If feedstock demand could not be met, the EtOH plant agent increases starting price offered to farmers in next season	Maximizing profits
	Sourcing radius	EtOH plant increases sourcing radius if he doesn't receive any offers for straw procurement in response to his requests	Securing feedstock supply
	Reserve price	EtOH plant agent adapts reserve price according to bioethanol market price and production costs	Assuring economically viable plant operation

Objectives

Table 3: Individual objectives of agents in the model.

Agent	Objective	Measurement
Farmers	Profit maximization	Farmers select potential buyers to make offers to that promise highest profit
		Farmers increase asking prices, if demand exceeds straw availability
		Farmers react to decreases in wheat yield, by increasing humus supply
Farmers (conventional farm system)	Complying to EU Cross Compliance regulation	Farmers compare estimated soil humus balance with minimum soil humus balance requirements to comply with EU Cross compliance policy (-75 kg humusC / ha)
Farmers (integrated farm system)	Maintaining soil humus balances	Farmers estimate soil humus balance and determine straw required to supply the necessary amount of humus to meet minimum soil humus balances
Existing straw users	Securing straw supply	Agents make contracts with farmers until feedstock demand is met (and straw price lies below maximum willingness to pay)
	Minimizing procurement costs	Buyers choose offers with minimal price per ton
EtOH plant	Securing straw supply for own straw demands	EtOH plant agent makes contracts with farmers until feedstock demand is met (and straw price lies below maximum willingness to pay)
	Minimizing procurement costs	EtOH plant agent chooses offers with minimal procurement costs (straw price per ton + transport costs)
		Decreasing starting price offer for straw, if feedstock demand has been met

Learning

No elements of learning / changing adaptive behaviours have been implemented in this model.

Prediction

Farmers:

- Straw potential estimation
  - Farmers estimate future wheat yield based on historic average values for wheat yields typical for the region
  - Farmers estimate the technically available straw potential by assuming a straw/crop ratio of 0.8 and by assuming that one third of the straw will not be able to harvest due to technical limitations
- Straw demand expectation
  - If farmers sold all their available straw they allocated for straw sale, farmers assume the same demand or increasing demand for next season and increase their asking prices
- Soil humus needs
  - Farmers take count of their soil humus levels (prescribed in the model) and derive their humus needs to reach their desired soil humus levels per ha based on their straw yield estimations and humus supply from the estimated non-harvestable straw

EtOH plant:

- Starting price offer
  - If the EtOH plant agent did not manage to secure his feedstock demand, he raises his starting price offer (as long as it stays below his maximum price he is able to afford) to outcompete other buyers in the market in the next season
  - IF the EtOH plant agent managed to meet his feedstock demand, he lowers

Sensing

Farmers:

Internal state variables farmers can sense:
- Wheat yield
- Humus soil balance
- Straw production costs

Environmental state variables farmers can sense:
- Reproduction coefficient straw
- Straw nutrient value
- Bedding substitution price

State variables of other individuals and entities farmers can sense:
- Straw demand of buyers that make requests for straw
- Price offered by EtOH plant for ton of straw off field (through requests)

Local users:

Internal state variables local user can sense:
- Feedstock demand
- Stored feedstock during straw procurement procedure
- Required feedstock during straw procurement procedure
- Maximum price able to pay (reserve price)

External state variables local user can sense:
- (Not applicable)

State variables of other individuals and entities local users can sense:
- Asking prices of farmers that respond with offers to straw requests

EtOH plant:

Internal state variables etoh plant operator can sense:
- Feedstock demand
- Stored feedstock during straw procurement procedure
- Required feedstock during straw procurement procedure
- Maximum price able to pay (reserve price)
- Production costs EtOH
- Production and transport costs for straw

External state variables etoh plant operator can sense:
- Straw nutrient value
- Bioethanol market price

State variables of other individuals and entities the EtOH plant agent can sense:
- Asking prices of farmers that respond with offers to straw requests

Interaction

Direct agent interactions:

- Buyers make requests to farmers for straw (by creating links)
- Farmers decline offers or make offers to buyers in response to straw requests (by erasing and creating links)
- Buyers accept /decline offers (by creating or erasing links)
- Buyers make contracts with farmers whose offer they accepted (by creating links)

Indirect agent interactions:

- Buyers compete for straw
- Farmers compete with other farmers in straw sale

Stochasticity

Random:

- Agent locations

Partly random:

- Uniform distribution of wheat yield (7 – 9 t/ha): to recreate variations in wheat yields per season
- EtOH production costs (450 – 550 €/t etoh): to represent uncertainty in EtOH production costs
- Mark-up farmers (mark-up + 0 – 10 €/t) : to represent variations in farmers profit expectations

Collectives

(Not applicable for this model)

Observation

Collected data:

- Average straw market prices
    - Straw off field
        - Round bales
- Straw use for soils
    - Total average
    - Aggregate per farm system
- Total straw use for livestock
- Straw sold
- Straw supplied to traditional users
- Straw supplied to EtOH plant
- Soil humus balances per ha
    - Total average
    - Aggregate average per farm system

Point of observation:

- Collection of data at the end of every year (tick)

Initialization

The initial model state includes farmers (straw producers) and straw buyers. The total land use for wheat production is based on governmental statistics, as well as the share of arable farms and mixed farms. Straw demand from existing buyers is conceptualised by a number of representative agents. The EtOH plant enters the market after year five to investigate the impact of change in straw demand (point of market entry after five years is arbitrarily chosen). To reduce the model simulation time, farmers were aggregated by a factor of 10, meaning that 10 farmers were summarised into one farmer agent. All agents are distributed randomly in the model.

Global variables:

- Land use wheat production: 50 000 ha
- Farm type distribution
  - Share arable farmers: 57%
  - Share mixed farmers: 43%
- Farm system distribution
  - Conventional: 75%
  - Integrated: 20%
  - Biodynamic: 5%
- Number of farmers: 5400
- Aggregation factor: 10
- Simulation period: 30 years
- Total straw demand existing users: 30 000 t
- Number of existing user agents: 150
- Scale (conversion of pixel length into km): 5 km/pixel-length
- Number EtOH plants: 1
- Capacity EtOH plant: 50 – 150 MW depending on scenario
- Soil impact factor: 0.95
- Soil recovery factor: 1.05
- Yearly humus deficit from crop rotation: -0.5 t humusC/ha

In the following table, the setup of the agents in the model is described in detail:

Table 4: Initialisation of agents in the model setup.

Type of agent	Property/Variable	Value	Sources
Farmer agents	Acreage wheat production	10 – 1200 ha	www.regionalstatistik.de
	Wheat yield expectation	8 t/ha	www.regionalstatistik.de
	Farm type	Arable Mixed	www.regionalstatistik.de
	Farm system	Conventional Integrated Biodynamic	Own assumption based on Kretschmer et al. (2012) and communications with farmers
	Pressing round bales	17,7 €/t	Harms (2015)
	Handling round bales	12.3 €/t	Harms (2015)
	Fixed transport costs	12.4 €/t	Harms (2015)
	Variable transport costs	0.48 €/t	Harms (2015)
	Straw humus value	Conventional: 4 €/t Integrated: 8 €/t Biodynamic: 20 €/t	Own assumptions
	Asking price round bales	Costs straw production + straw nutrient value + straw humus value + markup	
	Asking price off field	Straw nutrient value + straw humus value + markup	

	Reserve price round bales	Costs straw production + straw nutrient value + straw humus value +	
	Reserve price off field	Straw nutrient value + straw humus value	
Existing straw users	Feedstock demand	Even distribution of total straw demand among existing user agents	
	Reserve price	150 €/t	Own assumption based on literature study
	Sourcing radius	15 km	
EtOH plant	Capacity	50 – 150 MW (depending on scenario)	
	Feedstock demand	50% of maximum feedstock demand at maximum capacity	
	Sourcing radius	50 km	Weiser et al. (2014)
	Operating hours (full capacity)	7500 h	Weiser et al. (2014)
	Conversion efficiency	0.24	Zech et al. (2016)
	Yield	0.25 t EtOH/ t straw	Zech et al. (2016)
	Production costs	450 – 550 €/t EtOH	Zech et al. (2016)
	Markup	30% of production costs	
	Pressing bales	22,1 €/t	Harms (2015)
	Handling bales	12,3 €/t	Harms (2015)
	Fixed transport costs	10,0 €/t	Harms (2015)
	Variable transport costs	0,38 €/t	Harms (2015)
	Price offer	20 €/t or 40 €/t (depending on experiment setup)	Own assumption
	Reserve price	Bioethanol market price – production costs	
Environment	Straw nutrient value	11,40 €/t	Harms (2015)
	Bioethanol price	820 €/t	Zech et al. (2016)
	Bedding substitution price	105 €/t	Harms (2015)

Input data

(No data from external models or input files were used in this model)

Submodels

Reset of straw use and straw trade variables of farmers

Certain farmer variables are reset to zero as these parameters are supposed to report annual values.

Farmer variables that are reset to “0”:

- turnover
- profit
- liquidManureUse
- estimatedStrawForSoil
- strawSold
- strawForSoil
- strawForLivestock
- strawAccount

Update bioethanol market price

The model involves three scenarios for bioethanol market price development that can be selected (“constant”, “increasing”, “decreasing”).

If the scenario setting is set to be “constant”, the bioethanol market price remains the same for all years. If it is set on “decreasing” or “increasing”, the bioethanol price is decreased or increased by 2% per year, respectively.

The adaptation of the bioethanol market price starts when the EtOH plant enters the market.

Update soil humus balances

Farmers’ soil humus balances are updated based on the assumed yearly deficit from land use for crop production.

In the current model setup all farmers are assigned with the same yearly humus deficit per ha.

Algorithm:

$$humusSoilBalance = humusSoilBalance - humusBalanceFomCropRotation$$

Parameters	Dimensions	Values
soilHumusBalance	[t humusC/ha]	
humusBalanceFromCropRotation	[t humusC/ha]	-0.5 t humusC/ha

EtOH plant updates straw demand

In the setup of the EtOH plant, it is assumed that it will start running at only 50 % of its maximum capacity to illustrate the ramp-up time to optimize process technology and logistics. After the plant has been setup, the EtOH plant’s feedstock demand is increased annually by 20% until it meets its feedstock demand to run at full capacity.

Algorithm:

$$FeedstockDemand = feedstockDemand * 1.2$$

$$Maximum\ Feedstock\ Demand = \frac{capacityEtOHPlant * operatingHours * efficiency}{heatValueEtOH} * \frac{1}{yieldEtOH}$$

$$If\ feedstockDemand > Maximum\ Feedstock\ Demand, set\ feedstockDemand = Maximum\ Feedstock\ Demand$$

EtOH plant updates bidding variables

The EtOH plant adjusts his reserve price based on the expected bioethanol market price. The reserve price is the maximum price; the EtOH plant is willing to pay for straw during the straw procurement procedure.

Algorithm:

$$expectingSalesPriceEtOH = bioethanolMarketPrice$$

$$reservePrice = expectingSalesPriceEtOH - production\ costsEtOH - markup - averageTransportCostAssumption$$

$$averageTransportCostAssumption = costsTransportFixedSquaredBales + \left(\frac{sourcingRadius}{scale}\right) * costsTransportVariableSquaredBales$$

$$if\ priceOffer > reservePrice, set\ priceOffe\square = reservePrice$$

Parameters	Dimensions
expectingSalesPriceEtOH	[€/t]
bioethanolMarketPrice	[€/t]
reservePrice	[€/t]
priceOffer	[€/t]
averageTransportCostAssumption	[€/t]

Farmers estimate straw yield

Farmers estimate straw yield based on their expected wheat yield and the amount of straw expected to be produced from one crop (straw/grain ratio). Wheat yield expectations are for all farmers the same and are a conservative estimate based on wheat yield typical for the region. The straw/grain ratio that is typically used for wheat is 0.8, meaning that 1 t of wheat yield, 0.8 t of wheat straw. Farmers furthermore make an estimate on the share of straw that will probably not be possible to harvest due to technical factors (e.g. cutting height or dry matter content). Most studies use recovery rates between 60 and 80%. Following the approach by Weiser et al. (2014) a recovery rate of 66% is assumed for the model. The actual technically available potential is the product of estimated harvestable straw potential times the acreage used by the farmer for wheat production.

Algorithm:

$$estimatedStrawYield = wheatYieldExpectation * grainStrawRatio$$

$$estiamtedNonHarvestableStraw = estimatedStrawYield * (1 - strawHarvestFactor)$$

$$es\square imatedStrawPotential = (estimatedStrawYield - estimatedNonHarvestableStraw) * acreageWheat$$

Parameters	Dimensions	Reference values	Sources
WheatYieldExpectation	[t/ha]	8	
grainStrawRatio		0.8	(Weiser et al., 2014)
estimatedStrawYield	[t/ha]		
estimatedNonHarvestableStraw	[t/ha]		
strawHarvestFactor		0.66	(Weiser et al., 2014)
estimatedStrawPotential	[t]		
acreageWheat	[ha]		

Farmers estimate soil humus needs

- Farmers estimate humus supply from estimated non-harvestable straw
- If the farm system is conventional and the “yield alert” variable is not activated, the humus requirement is the difference between -0.075 t humusC/ha and the estimated soil humus balance after considering humus supply from non-harvestable straw (Complaince with EUCC requirements to receive direct payments. There are a few options for farmers to comply with the EUCC policy on maintaining soil humus balances. One of the options, which has been chosen to represent the compliance mechanism, is to present a minimum soil humus balance per ha of -0.075 t humusC/ha)
- If the “yield alert” variable is activated – meaning that farmers have registered a significant difference between their wheat own yields and the regional average – then the farmer makes sure that sufficient humus supply is guaranteed by setting the humus requirement so that it will yield a soil humus balance of +0.1 t humusC/ha.
- If the farm system is integrated, the humus requirement is the difference between 0 and the estimated soil humus balance after considering humus supply from non-harvestable straw
- Humus supply from straw is calculated by using humus reproduction coefficients, which give average values of humus supply from substrates of organic material
- In the scenario setting that farmers do not comply with EUCC requirements, conventional farmers only consider humus supply if their “yield alert” is activated (yieldAlert = TRUE)
- In the scenario setting that conventional farmers ignore their soil quality completely, conventional farmers do not consider the need for any additional humus supply

Algorithm/formulas:

$$HumusSupplyFromNonHarvestableStraw = nonHarvestableStraw * reproductionCoefficient$$

Parameters	Dimensions	Reference values	Sources
ReproductionCoefficientStraw	[t humusC/t straw]	0.1	Weiser et al. (2014)
YieldAlert	TRUE / FALSE		
FarmersComplyToEUCC	TRUE / FALSE		
FarmersIgnoreSoilQuality	TRUE / FALSE		

Farmers determine humus supply

In this procedure, farmers determine what option they use to meet their specified humus demand.

In this model, options for humus supply are either straw or liquid manure from pigs. Farms with livestock (i.e. mixed farms) are assumed to maximize their use of liquid manure for humus supply. The use of liquid manure is however limited by the maximum quantity of nitrogen that is allowed to be supplied per ha per year (DüngV, 170 kg N/ha). If not all of the humus demand can be met with liquid manure, the rest of the humus needs is supplied from using straw, which makes up the estimated amount of straw for soil by the farmer.

Farms with no livestock (i.e. arable farms) choose between either using liquid manure, using straw for humus supply, or both, if nitrogen levels are surpassed with only using liquid manure. They make their decision based on a cost-benefit analysis comparing expected profits and expected losses from using the respective options.

One peculiarity that has been found out in the system analysis is that due to the model region being the main area for pig production in Germany, in many cases farmers have an excess of nutrients and to reduce their excess of nutrients they actually pay other farmers to take liquid manure from them. Hence, in this model the price of liquid manure is negative, implying that farmers actually gain from using liquid manure from other farms. The price of liquid manure varies however from region to region, depending on the agricultural structure and supply and demand.

Parameters	Dimensions	Reference values	Sources
Maximum nitrogen level per ha	kg N/ha	170	LWK NRW (2012)
Nitrogen supply per m^3 of liquid pig manure	kg	4.3	LWK NRW (2012)

Farmers determine straw uses and straw potential for sale

- If farms have livestock, it is assumed that they use a certain share of their straw potentials for animal husbandry. Mixed farms with conventional farm systems are assumed to use only a small share for animal husbandry (15%) as most animals in conventional farm systems are held in stables with slotted floors. Integrated mixed farms are assumed to use 30% of their straw for animal husbandry, and biodynamic farms use 50% of their straw for livestock.
- If the selling price of straw surpasses the price that makes it beneficial for the farmer to substitute straw as a bedding material, mixed farms also consider to sell straw originally used for animal bedding
- The amount the farmer is willing to sell is the potential left after considering straw use for livestock, estimated straw needs for humus supply and the estimated non-harvestable straw.
- If the straw price is above the bedding substitution prices, mixed farmers are also willing to sell 80% of their straw that was originally allocated for animal husbandry
- To prevent over calculation, farmers only calculate with 90% of the originally estimated technically available straw potential
- Farmers that run a biodynamic farm system are not willing to sell any of their straw, due to their farming convictions

Algorithm/formulas:

$$potentialStrawForSale = estimatedStrawPotenital * 0.9 - estimatedS\square rawForSoil - estimatedStrawForLivestock$$

Straw procurement (requests, offers, making contracts)

In this submodel, all buyers with demand for straw engage with potential sellers – the farmers with allocated straw for sale – to meet their individual demand for straw. In the traditional straw trade between existing users and farmers, existing users are assumed to be price takers, in the sense that they only indicate their demand and the farmers reply with a price offer. The

EtOH plant on the other hand as a new actor in the market makes concrete offers with a price they are willing to pay for straw.

The procedure follows the following schedule:

1. Existing straw user agents make requests for straw by creating links to farmers within their sourcing radius that indicate the total demand of the agent and the type of demand (“round bales”) as link-attributes.
2. The EtOH plant makes requests for straw by creating requests to farmers within their sourcing radius that indicate the price they are willing to offer, the total demand of the EtOH plant and the type of demand (“off field”) as link attributes.
3. Farmers check if they have any requests for straw, and depending on the higher expected profit from either selling their straw to the existing traditional users or selling to the EtOH plant respond with offers (links) to either existing users or the EtOH plant.
    a. Profit calculation
        i. From requests from traditional users:

           (askingPriceRoundBales – reservePriceRoundBales) * quantity of requests *(or total straw available of the farmer for sale if requests surpass farmer’s straw availability)*

        ii. From request from EtOH plant:

           (askingPriceOffField – reservePriceOffField) * quantity of EtOH request *(or total straw available of the farmer for sale if requests surpass farmer’s straw availability)*

    b. Offers to traditional users
        i. Farmers create links to traditional buyers that send requests for straw indicating the farmer’s asking price and the quantity they are able to supply. If the quantity specified in the potential buyers request surpasses the farmers straw availability, the quantity in the offer corresponds to the farmers straw availability. Otherwise, it corresponds with the quantity specified in the potential buyers request. After the farmer replied to all requests, all link-requests are erased by the farmer
    c. Offers to EtOH plant
        i. Farmers create links to the EtOH plant adopting the EtOH plants price offer and indicating the quantity they are able to supply. If the quantity specified in the EtOH plant’s request surpasses the farmers straw availability, the quantity in the offer corresponds to the farmers straw availability. Otherwise, it corresponds with the quantity specified in the potential buyers request. After the farmer made his offer, all link-requests are erased.
4. After the farmers reacted to straw requests and made their offers, traditional agents and the EtOH plant review the offers they received and make a contract – by creating a link – with the farmer from whom they received the offer that yields the minimal costs for the buyer (price per ton of straw in the case of traditional user agents; price per ton and costs for transport/transport distance in the case of the EtOH plant) provided that the price offered is below his reserve price. All other offers are erased, as well as the buyers outgoing requests, as the existing requests and offers are based on the old feedstock demand of the buyer.
    a. In the contract-link the following attributes are specified: demand type (“round bales” or “off field”), price per ton, straw quantity and if it’s a

contract with the EtOH plant agent the transport costs per ton and the total costs for the buyer per ton (price per ton + transport costs per ton).

b. After the contract is made,
    i. The buyer updates his feedstock demand (requiredFeedstockBidding – quantity of straw determined in contract)
    ii. The buyer updates his money balance by subtracting the total costs created by the straw contract from his money balance
    iii. The straw availability of the seller is updated by subtracting the quantity of the contract from his straw availability account
    iv. The money balance of the seller is increased by the revenue from the contract (priceTon * quantity)
    v. The profit made from the contract is added to the sellers profit account taking into consideration the type of demand ("round bales" or "off field"), its production costs, the transport costs and the revenue made from straw sale.
    vi. If the feedstock demand of the buyer is met with the quantity of straw specified in the contract, he exits the procurement procedure (bidding status = "feedstock demand met", requiredFeedstockBidding = 0)
    vii. If the straw availability of the farmer is zero after making the contract, the farmer exits the procurement procedure (biddingStatus = "out of stock"

c. If the price in the offers is higher than the buyers reserve price, he rejects all offers and exits the market/straw procurement procedure

d. If the buyer did not receive any offers in response to his requests,
    i. He erases all his requests
    ii. Increases his sourcing radius by 5 km
    iii. The EtOH plant agent increases his price offer in the procurement procedure ("priceOfferBidding") by 10% but not more than his reserve price

Steps one to four will continue until there is either no more straw available for sale or no more demand from buyers. The stop in demand thereby includes that buyers met their demands or that they exited the market because the asking prices surpassed their willingness to pay (reserve prices).

Harvest

Wheat yield

Simulating a random value each year using a normal distribution function simulates the wheat yield per year. The average mean has been set to 8.5 and the standard deviation of 0.5, which corresponds to the wheat yields recorded for the region (www.regionalstatistik.de).

The individual wheat yield per farmer is determined on the basis of the farmer's individual soil quality (0 – 1).

Straw potential

Based on the individual wheat yield, the farmers' actual straw yield per ha, his theoretical straw potential, actual non-harvestable straw and actual available technical straw potential are determined.

Straw accounting

- Farmers determine the overall amount of straw sold based on the quantity agreed in the contracts made in the procurement procedure
- Farmers subtract the quantity sold from their actual technical straw potential
- Farmers evaluate straw potential left for animal husbandry based on sold straw

Humus supply

- Non-harvestable straw, any surplus straw and straw that has been dedicated for soil use for humus supply is reincorporated into soils
- Humus soil balance is adjusted by humus supply from reincorporated straw and by predetermined liquid manure use

Update soil quality

To account for the negative impact of negative soil humus balances on soil properties, a soil quality parameter is introduced with a range from 0 to 1. At the end of each year/simulation step, this parameter is increased or reduced by a predefined factor ("soil impact factor"), depending if the farmer's soil humus balance is negative or positive.

If soil humus balance of farmer > 0: soil quality * 1.05
If soil humus balance of farmer < 0: soil quality * 0.95

The soil quality parameter has direct impact on the farmer's individual yearly wheat yield by multiplying the simulated regional wheat yield with the soil quality parameter. The type of relationship is not based on scientific findings, but has been introduced as a simple exemplification of the existing relationship between soil humus balances and soil quality/productivity.

Agent reactions to outcome straw procurement

Farmers and the EtOH plant adjust their asking prices and price offers for straw by evaluating the outcome of the straw procurement procedure.

The EtOH plant adjusts its starting price offer for the next season based on its success in meeting its feedstock demand. If it could not meet its feedstock demand it raises its price offer by 20%, but not higher than its reserve price, to convince more farmers to sell theirs straw and outcompete other potential buyers. If it did meet its feedstock demand, it reduces its price offer by 10% with the attempt to reduce feedstock costs.

Farmers adjust their asking prices based on the amount of straw he was able to sell taking his originally estimated straw potential for sale as reference. If he sold all of his straw potential, he raises his straw asking price for round bales and for straw off field by 15%. If the farmer remains with more than 50% of his straw potential he reduces his asking prices by 30%, but not lower than his reserve price. If he remains with a straw potential between 50% and 30%, he reduces his straw price by 20%, but not lower than his reserve price. If he sold more than 70% of his straw potential allocated for straw sale, his asking price stays the same.

Furthermore, buyer agents store their average straw buying price in the year and farmers store their average selling prices and quantities, as well as the average transport distance.

Farmer reactions to harvest

- If farmers register a deviation in individual wheat yield compared to the regional wheat yield of more than 15%, farmers are alerted and concerned about their yields/profits (yield alert = TRUE)
- The "yield alert" is set back to *false* if individual wheat yield deviation is lower than 5 % from the regional wheat yield and soil quality equals 1

Experiments

Different experiments have been designed to explore the behaviour of the system in the presence of additional demand for straw for renewable energy (i.e. biofuel) production.
The experiments test different scenarios and combinations of parameter settings to simulate possible future conditions or test hypothetical cases and see how it influences straw use, straw prices, straw supply and soil humus balances.

Experiment 1: Impact straw demand for biofuel production

Objective

In the first experiment the effect of differences in scale of new straw demand for bioethanol production (i.e. EtOH plant size) is investigated for different bioethanol market price scenarios (constant/increasing/decreasing bioethanol market price). The goal is to explore how different supply-demand conditions affect the system behaviour with regards to soil humus balances, straw market prices, straw availability and straw use.

Patterns of interest

- Average straw market prices
- Straw availability
- Straw use
- Soil humus balances of farmers

Variables that have been varied:

- EtOH plant operation: Yes / No
- EtOH plant capacity: 50 MW / 100 MW / 150 MW
- Bioethanol market price development: Constant / decreasing / increasing

Experiment setup

Table 5: Parameter settings experiment 1 (impact straw demand for biofuel production).

Experiment Setup			
Time scale	30 years		
Parameters		Values/Settings	
		Reference scenario	Experiment 1
Policy compliance	Farmers comply with Cross Compliance humus policy	TRUE	TRUE
Farmer behaviour	Farmers take count of soil quality	TRUE	TRUE
Straw demand	Existing market	30 000 t	30 000 t
EtOH plant operation	EtOH plant operation	FALSE	TRUE
	Capacity EtOH plant	-	50 MW 100 MW 150 MW
	EtOH starting price offer	-	20€
Straw supply	Land use wheat	50000 ha	50000 ha
	Share conventional farmers	75 %	75 %
	Share mulch farmers	5%	5%
	Share integrating farmers	20%	20%
Market prices	Straw nutrient value	11,40 €/t	11,40 €/t
	Price liquid manure	- 5 €/t	- 5 €/t

	Bedding substitution price	100 €/t	100 €/t
	EtoH market price	820 €/t	820 €/t
	EtOH market price scenario	Constant	Constant Decreasing Increasing
Humus values to farmers	Humus value conventional farmers	4 €/t	4 €/t
	Humus value Integrated farmers	8 €/t	8 €/t
	Humus value mulch farmers	20 €/t	20 €/t

Experiment 2: Impact buying power of EtOH plant

Objective

The second experiment has been designed to test the influence of different EtOH plant buying power on system behaviour.

Patterns of interest

- Average straw market prices
- Straw availability
- Straw use
- Soil humus balances of farmers

Variables that have been varied

- Price offer EtOH plant: 20€ / 40€
- Bioethanol market price development: constant/ decreasing/ increasing

Experiment setup

Table 6: Parameter settings experiment 2 (impact EtOH plant buying power).

Experiment Setup			
Time scale	30 years		
Parameters		Values/Settings	
		Reference scenario	Experiment 2
Policy compliance	Farmers comply with Cross Compliance humus policy	TRUE	TRUE
Farmer behaviour	Farmers take count of soil quality	TRUE	TRUE
Straw demand	Existing market	30 000 t	30 000 t
EtOH plant operation	EtOH plant operation	FALSE	TRUE
	Capacity EtOH plant	100 MW	100 MW
	EtOH starting price offer	20 €/t	20 €/t 40€/t
Straw supply	Land use wheat	50000 ha	50000 ha
	Share conventional farmers	75 %	75 %
	Share mulch farmers	5%	5%
	Share integrating farmers	20%	20%
Market prices	Straw nutrient value	11,40 €/t	11,40 €/t
	Price liquid manure	- 5 €/t	- 5 €/t
	Bedding substitution price	100 €/t	100 €/t
	EtoH market price	820 €/t	820 €/t
	EtOH market price scenario	Constant	Constant Decreasing

			Increasing
Humus values to farmers	Humus value conventional farmers	4 €/t	4 €/t
	Humus value Integrated farmers	8 €/t	8 €/t
	Humus value mulch farmers	20 €/t	20 €/t

Experiment 3: Impact EU Cross Compliance

Objective / rationale

This experiment aims to investigate the impact of the EU Cross Compliance policy from the backdrop of increased demand for straw for renewable energy use, as farmers might be tempted to neglect their soil humus balances in return for the (short term) profit.
The hypothesis is that without the EUCC policy in place there will be more overharvesting of straw as farmers see the opportunity of increasing their income by selling straw.

Patterns of interest

- Straw availability
- Straw use
- Straw prices
- Soil humus balances of farmers

Variables that have been varied:

- EtOH plant capacity: 50 MW / 100 MW
- Policy compliance: Yes / No

Experiment Setup

Table 7: Parameter settings experiment 3 (impact EU Cross Compliance).

Experiment Setup			
Time scale	30 years		
Parameters		Values/Settings	
		Reference scenario	Experiment 3
Policy compliance	Farmers comply with Cross Compliance humus policy	TRUE	TRUE FALSE
Farmer behaviour	Farmers take count of soil quality	TRUE	TRUE
Straw demand	Existing market	30 000 t	30 000 t
EtOH plant operation	EtOH plant operation	TRUE	TRUE
	Capacity EtOH plant	100 MW	50 MW 100 MW
	EtOH starting price offer	20 €/t	20€
Straw supply	Land use wheat	50000 ha	50000 ha
	Share conventional farmers	75 %	75 %
	Share mulch farmers	5%	5%
	Share integrating farmers	20%	20%
Market prices	Straw nutrient value	11,40 €/t	11,40 €/t
	Price liquid manure	- 5 €/t	- 5 €/t
	Bedding substitution price	100 €/t	100 €/t
	EtoH market price	820 €/t	820 €/t
	EtOH market price scenario	Constant	Constant
Humus values to	Humus value conventional	4 €/t	4 €/t

farmers	farmers		
	Humus value Integrated farmers	8 €/t	8 €/t
	Humus value mulch farmers	20 €/t	20 €/t

Experiment 4: Impact ignoring soil humus balances

This experiment investigates the impact it has if farmers only act to maximize profit, but ignore the feedback loops of overharvesting ignoring their soil humus balances.

Variables that have been varied:

- EtOH capacity: 0 MW, 50MW, 100MW
- Farmers consider soil quality: TRUE / FALSE

Observed patterns:

- Straw availability
- Straw use
- Straw price
- Humus balances

Experiment setup

Table 8: Parameter settings experiment 4 (impact ignoring soil humus balances).

Experiment setup			
Time scale	30 years		
Parameters		Values/Settings	
		Reference scenario	Experiment 4
Policy compliance	Farmers comply with Cross Compliance humus policy	TRUE	TRUE FALSE
Farmer behaviour	Farmers take count of soil quality	TRUE	TRUE
Straw demand	Existing market	30 000 t	30 000 t
EtOH plant operation	EtOH plant operation	TRUE	TRUE
	Capacity EtOH plant	100 MW	50 MW 100 MW
	EtOH starting price offer	20 €/t	20€
Straw supply	Land use wheat	50000 ha	50000 ha
	Share conventional farmers	75 %	75 %
	Share mulch farmers	5%	5%
	Share integrating farmers	20%	20%
Market prices	Straw nutrient value	11,40 €/t	11,40 €/t
	Price liquid manure	- 5 €/t	- 5 €/t
	Bedding substitution price	100 €/t	100 €/t
	EtoH market price	820 €/t	820 €/t
	EtOH market price scenario	Constant	Constant
Humus values to farmers	Humus value conventional farmers	4 €/t	4 €/t
	Humus value Integrated farmers	8 €/t	8 €/t
	Humus value mulch farmers	20 €/t	20 €/t

Results

This section presents the model results for the experiments that have been described in the previous section. For each experiment the dynamic behaviour of straw supply, straw use, straw prices and soil humus levels is analysed. The experiments are run with multiple repetitions (10 repetition per experiment). The solid lines in the presented graphs refer to the average value across the set of repetitions. The shadowed area around the solid lines indicates the standard deviation or uncertainty in the individual value output.

Impact straw demand for biofuel production

Scenario space (model parameters that have been varied):

- EtOH plant capacity: 0 MW / 50 MW / 100 MW / 150 MW
- Bioethanol market price development: Constant / decreasing / increasing

Straw supply

Figure 3 shows the experiment results for total straw yield (theoretical potential), the technically harvestable straw potential (technical potential) and the straw potential available for sale (potential for sale) for the different assumptions on EtOH plant size (columns) and bioethanol market price development (rows). It also indicates the total demand for straw in the market (red line).

One can see that straw supply remains relatively constant in all bioethanol market price scenarios in the case of a small EtOH plant capacity (50 MW). Only a slight decrease in the straw potential available for sale can be noticed for the stable and increasing bioethanol market price scenario. The total market supply exceeds total straw demand in the region.

However, different system behaviour can be seen if straw demand for biofuel is at higher levels. In the case of a 100 MW capacity plant, in all bioethanol market price scenarios a drop in straw supply to the market can be registered, while the technical straw potential remains stable. After a time period of about ten years, the straw market supply returns to more or less its previous level.

If straw demand for biofuel production increases even further (150 MW EtOH plant), the drop in straw availability to the market is even larger reducing the straw potential to about half of the original volume. Furthermore, instead of returning to its original level and maintaining this level, straw market supply starts oscillating in a regular pattern between the original straw supply level (before EtOH plant market entry) and about half of its original supply level. This pattern however does not apply for the case of the decreasing bioethanol market price scenario. The reason for this is that the EtOH plant is not participating anymore in the market, as it cannot meet the asking prices for straw anymore while maintaining an economically viable plant operation. The impact of a decreasing bioethanol market price for the EtOH plant can also be well observed in Figure 5, where after a sharp increase in straw supply to the EtOH plant, this value sharply drops to zero after five to ten years.

One other outcome of the model simulation is that at an EtOH capacity of 150 MW, different to the other demand scenarios, also considerable variations in theoretical and technical straw potential can be detected which mirror the oscillating pattern in straw market supply.

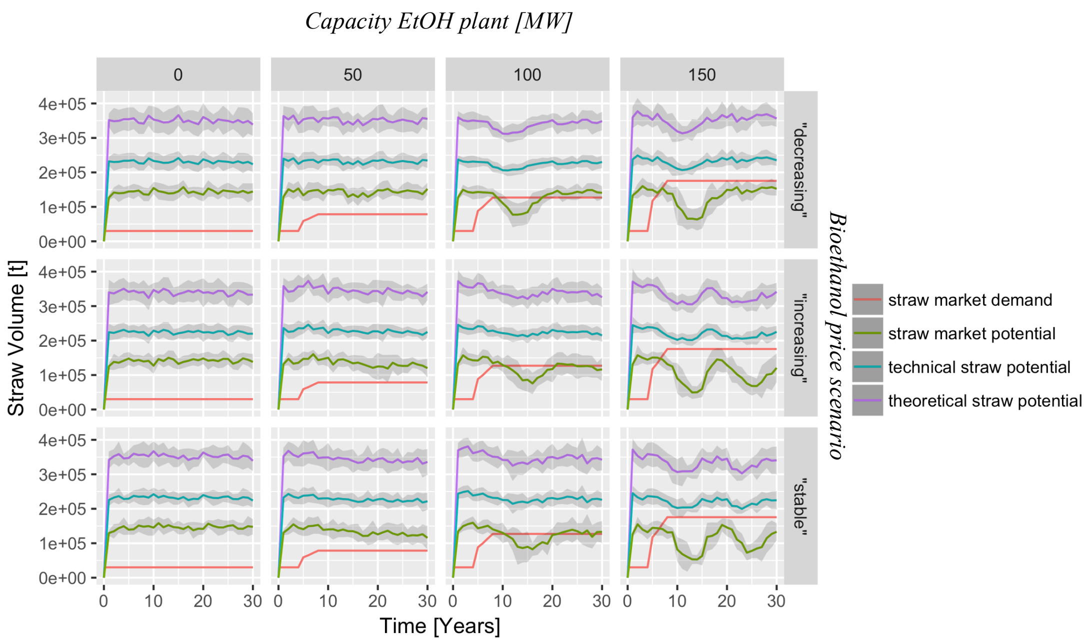

Figure 3: Impact of straw demand for biofuel production on straw supply.

Straw use

The model results on how the increase in straw demand for biofuel production influenced straw uses can be seen in Figure 4. It displays the aggregated values for the total region on straw used for humus supply (straw for soil), straw used for livestock and straw that has been sold.

Decreasing bioethanol market price

In the case of a decreasing bioethanol market price we see that the EtOH plant can influence straw use not only during the EtOH plants operation, but also after the EtOH plant left the market in case of large feedstock demands (100 MW and 150 MW plant size scenario) (see straw use for soils). One can also observe that straw use for livestock is also reduced in case of a EtOH plant of large size.

Stable and increasing bioethanol market price

In the case of a 50 MW EtOH plant, straw use for sale immediately jumps to meet the new straw demand in the market. Straw use for soils remains the same over the first 10 years and then gradually starts to increase. Straw use for livestock remains unchanged for most of the time but starts to decrease slightly towards the end.

At higher straw EtOH plant sizes and resulting straw demands, a clear pattern can be observed with regards to straw used for selling and straw used for the reincorporation into soils. Every increase in straw sales is followed by an increase in straw use for soils in the following years and a respective decrease in straw sales. Especially in the highest straw demand scenario this alternating straw use behaviour becomes evident and also explains the oscillating straw market supply in Figure 3. The alternating straw use between straw sales and straw used for soils is less extreme for the case of the 100 MW EtOH plant scenario. While it also shows a large increase in straw sales followed by an almost equal increase in straw use for soils, the average levels in straw use for soils and straw sales seem to level off and approach the same level. Straw use for livestock decreases in all of the high demand scenarios, as a result of the high straw market price (see Figure 6) that makes it beneficial for farmers to choose alternative bedding options and free up straw for selling.

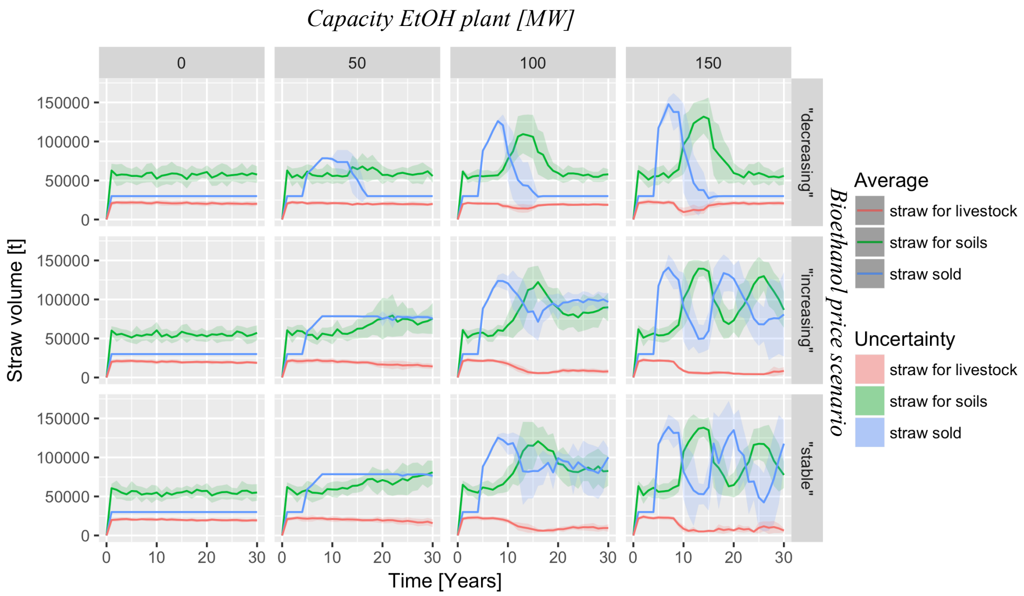

Figure 4: Impact of straw demand for biofuel production on straw use.

Straw flows

Concerning the impact of the new straw demand for existing straw users in the market, the model results show that at an EtOH plant size of 50 MW all buyers in the market are able to secure their straw needs. At larger EtOH plant sizes, however, straw flows increasingly shift to supply the EtOH plant and existing straw users increasingly fail to secure their straw needs (see “straw to existing users” in Figure 5).

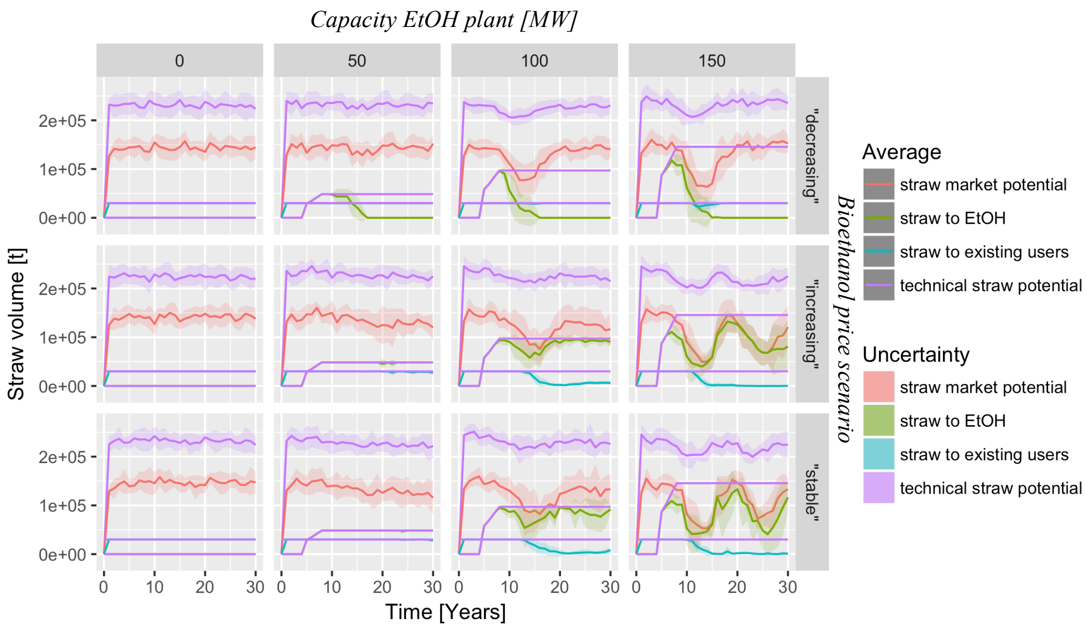

Figure 5: Impact of straw demand for biofuel production on straw flows.

Straw price development

Figure 6 shows the average straw market price development per ton. The price per "round bale" and the price "off field" are indicated separately. In the 50 MW plant scenario with stable or increasing bioethanol market price, straw prices experience a steady increase at about the same constant rate. At greater EtOH plant feedstock demands the picture however changes.

Increasing bioethanol market price

In the case of an increasing bioethanol price, straw prices rise more quickly. Average straw prices for straw "off field" describe an exponential curve that gets steeper at higher straw demand scenarios (i.e. 150 MW EtOH plant scenario). Straw prices for "round bales" however reach a peak at about 150 €/t (the maximum price that has been assumed for existing straw buyers to be willing to pay for straw) about 10 years after the EtOH plant started its operation. In the 100 MW EtOH plant scenario the average "round bale" price experiences a drop for a period of about 10 years before it increases again and remains constant at about 100 €/t for the following years. In the 150 MW EtOH plant scenario average "round bale" prices experience a larger decrease and ultimately sink to zero – meaning that no straw trade for "round bales" has occurred at all in these particular years.

Stable bioethanol market price

In the case of a stable bioethanol market price, straw prices start increasing in the same manner as for the increasing bioethanol, market price scenario. This time, however, the straw price "off field" reaches a plateau at a certain point instead of continuing to increase. The straw price for "round bales" follows the same pattern as in the scenario with an increasing bioethanol market price for the case of a 100 MW EtOH plant, but behaves differently in the 150 MW plant scenario. In the latter, while prices also first start to grow and reach a peak at around 150€/t, the average price does not fall to zero but starts to fluctuate in a regular pattern with average prices between 50 and 100 €/t

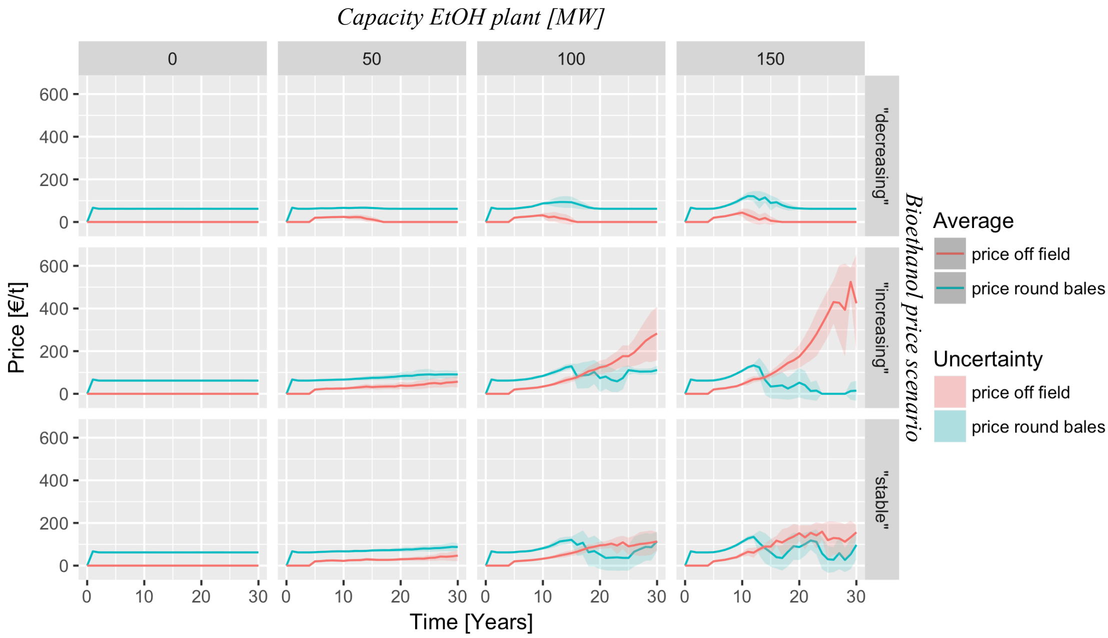

Figure 6: Impact straw demand for biofuel production on straw price development.

Soil humus balance

The model results for soil humus balances are presented in Figure 7. It shows the total average value for all straw-producing farmers (aggregate humus balance), as well as the aggregated values per farm system (humus balance integrated farmers/ humus balance conventional farmers). The first row in which the EtOH plant is only present in the market for a few years due to the decreasing bioethanol market price clearly shows the impact of the presence of the EtOH plant on soil humus levels. The average soil humus levels drop significantly and are especially drastic for the higher plant scenarios (100 MW and 150 MW). In the latter scenarios, one can observe that also the humus levels of farmers of integrated farm system type considerably decrease in contrast to the 50 MW plant scenario.

When the EtOH plant remains as a buyer in the market (bioethanol price scenario "stable" and "increasing") one can observe the following dynamics. In the case of a 50 MW plant size the aggregate humus balance steadily decreases in the following years until it stabilizes at a new lower level at around 0.1 t humusC/ha. The humus balance of integrated farmers also decreases but stabilizes at a higher humus level at around 0.2 t humusC/ha. At higher EtOH plant size scenarios soil humus levels follow a different pattern. In the case of the 100 MW EtOH plant scenario aggregate soil humus levels experience a steep fall after the entry of the EtOH plant into the market until the reach a bottom minimum level and then slightly increase again to a slightly higher level, which is however still way below the average humus level that existed before the EtOH plant entered the market.

In the case of the 150 MW scenario, one can again observe an oscillating pattern, which also explains the pattern in straw use that can be observed in Figure 4. First, the aggregate humus level experiences a drastic drop, which in its magnitude is even larger than in the 100 MW plant scenario. After staying at a bottom level for a few years, the aggregate humus level sharply rises again and falls into an oscillating pattern. The humus balance of farmers with an integrated farm system does not, however, follow an oscillating pattern. While it also quite significantly decreases it starts to stabilize at new lower level as compared to the level previous to the EtOH plant's market entry.

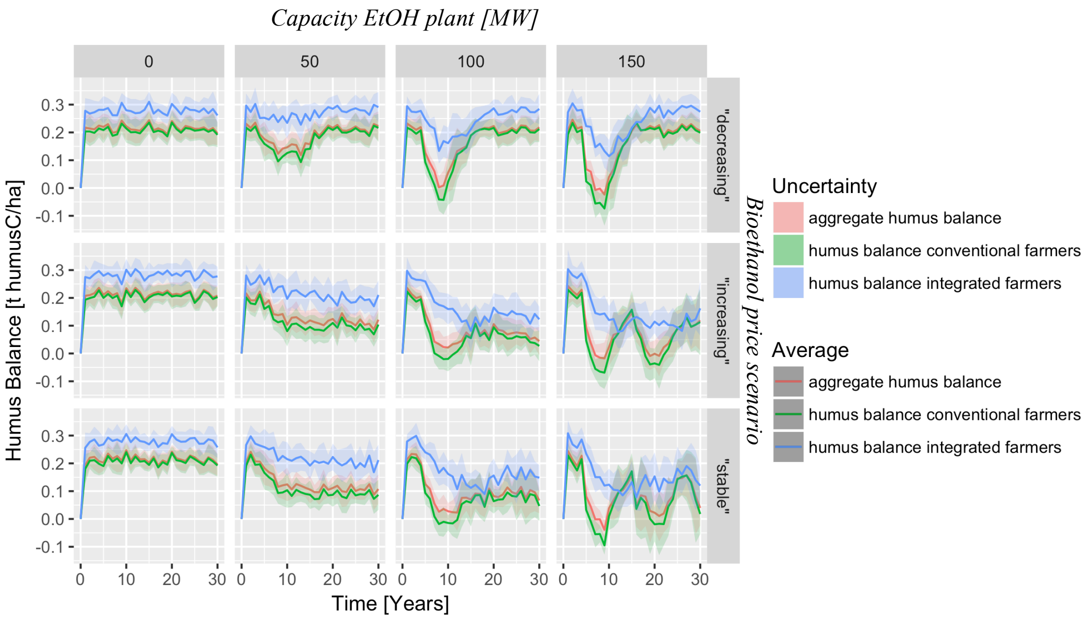

Figure 7: Impact straw demand for biofuel production on humus balances.

Impact EtOH plant buying power

Variables that have been varied

- Price offer EtOH plant: 20€ / 40€
- Bioethanol market price development: constant/ decreasing/ increasing

Straw supply

Figure 8 presents the model results for straw supply for different EtOH plant buying power assumptions and the different bioethanol market price scenarios. No large differences in straw supplies can be detected. However, when looking at the scenarios with stable and increasing bioethanol market price, one can detect that after a first decrease in straw market supply between year 10 and year 20, the straw available to the market in the scenario with lower buying power is slightly higher than in the scenario where the EtOH plant has a higher buying power.

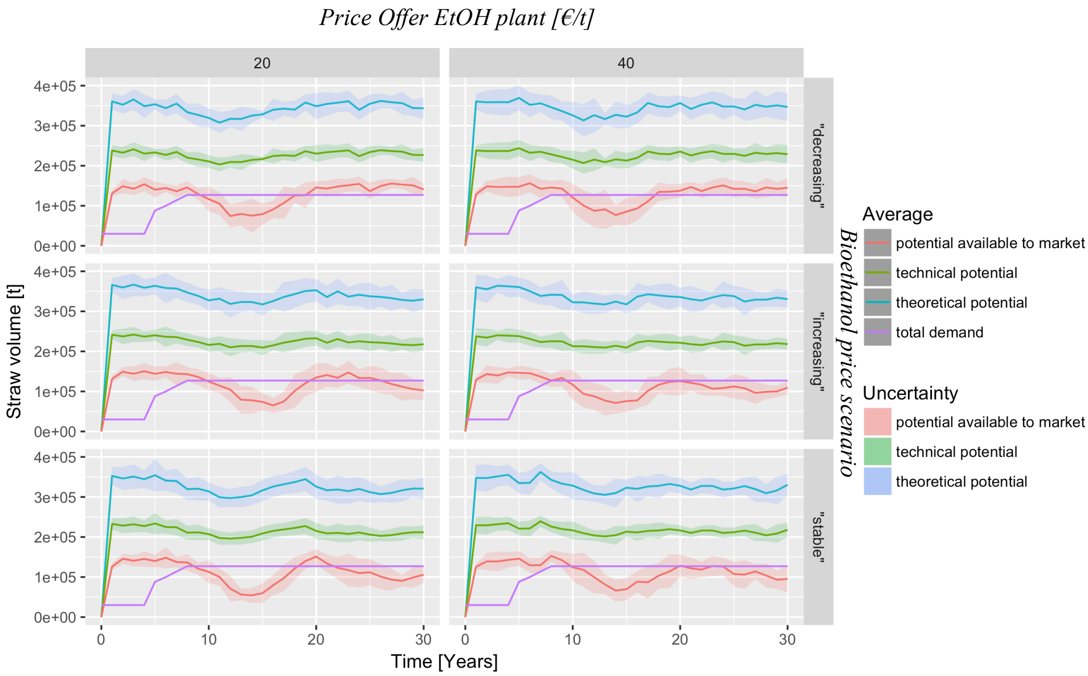

Figure 8: Impact of EtOH plant buying power on straw supply.

Straw use

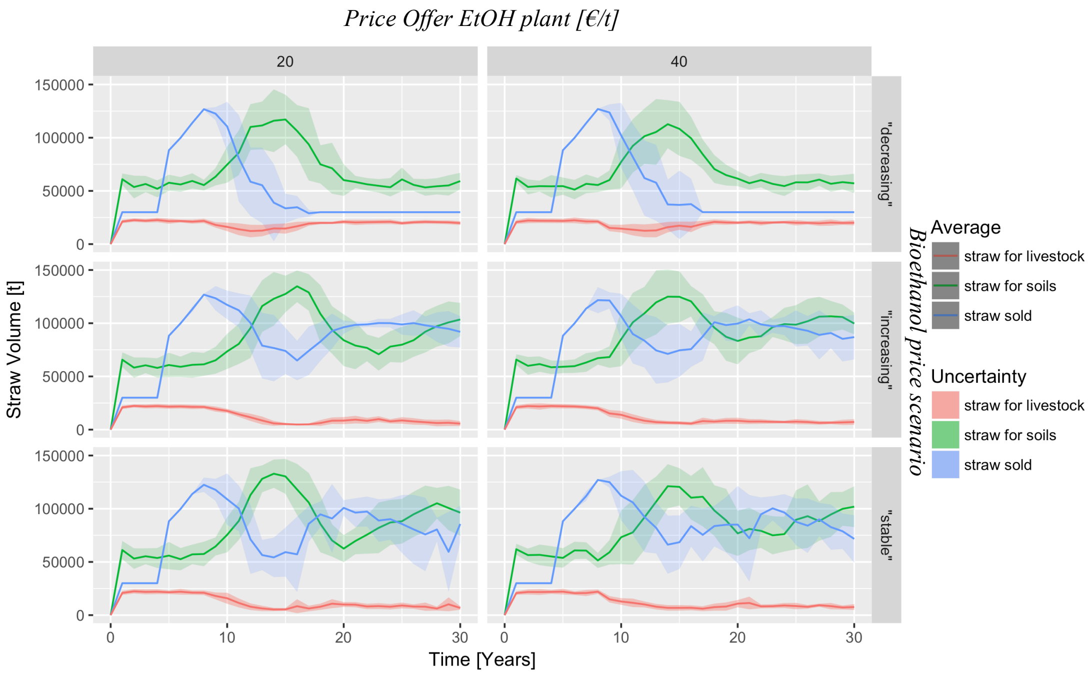

Figure 9: Impact of EtOH plant buying power on straw use.

Figure 10 shows the sales flows of straw in the region for the different EtOH plant buying power scenarios and for different bioethanol market price scenarios. The difference in buying power has no impact on straw flows in the case of decreasing bioethanol market price. The sales flows also follow the same pattern in the other scenarios in the first years. While in the case of an increasing bioethanol market price straw trade flows follow more or less the same pattern, a slight variation can be detected when the bioethanol market price remains constant. In that scenario, the average volume of straw that is supplied to the EtOH plant drops lower in the case of lower buying power between year 10 and 18 but on the other hand is higher on average after the initial drop as compared the higher buying power scenario.

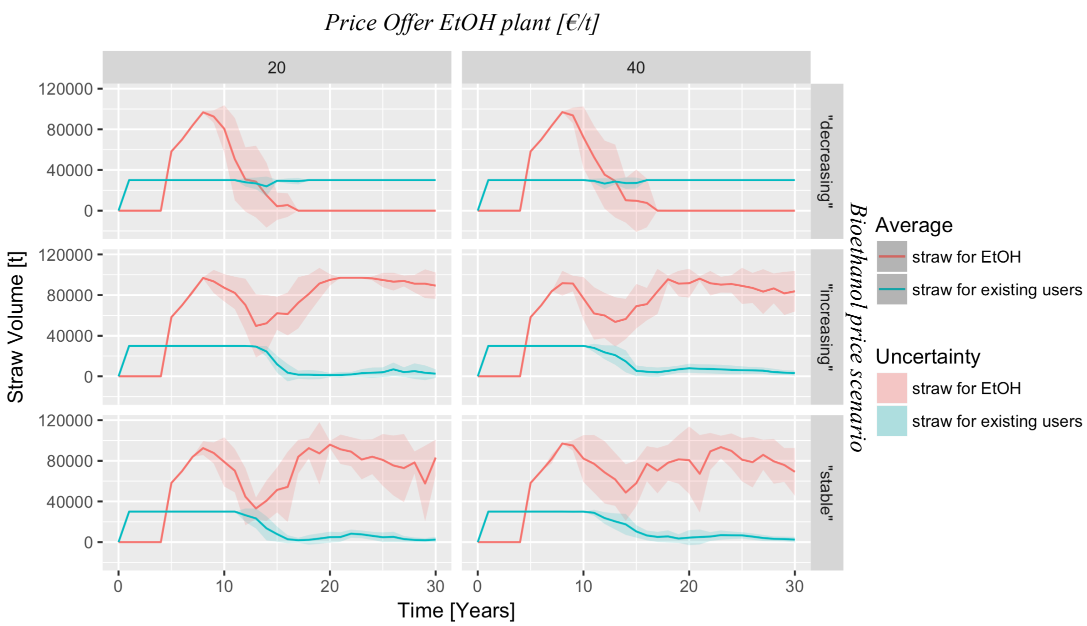

Figure 10: Impact EtOH plant buying power on straw flows.

Straw price development

With regards to the impact on straw price development (Figure 11) the model results showed a large difference in impact in the case of an increasing bioethanol market price scenario, where straw prices on average increased twice as much for straw off field in the case of higher buying power as compared to the case of lower EtOH plant buying power. However, this rise in straw prices has to be seen in perspective as the model assumes a constant increase in bioethanol market price, which in reality would probably not be the case.

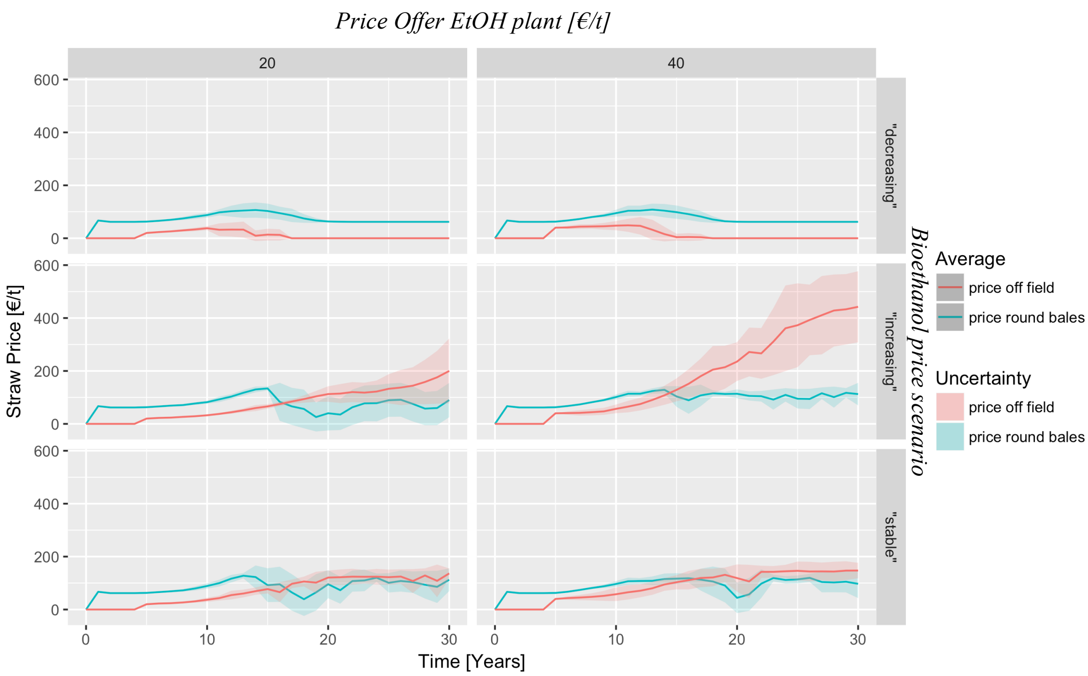

Figure 11: Impact of EtOH plant buying power on straw price development.

Soil humus balances

Figure 12 shows the impact on soil humus balances in the region. The only particular difference that can be observed from the model results is that in the case of a stable bioethanol market price and a lower EtOH plant buying power the average aggregate soil humus balance returns to a higher level as compared to the case of a higher EtOH plant buying power in the period between year 10 and year 20.

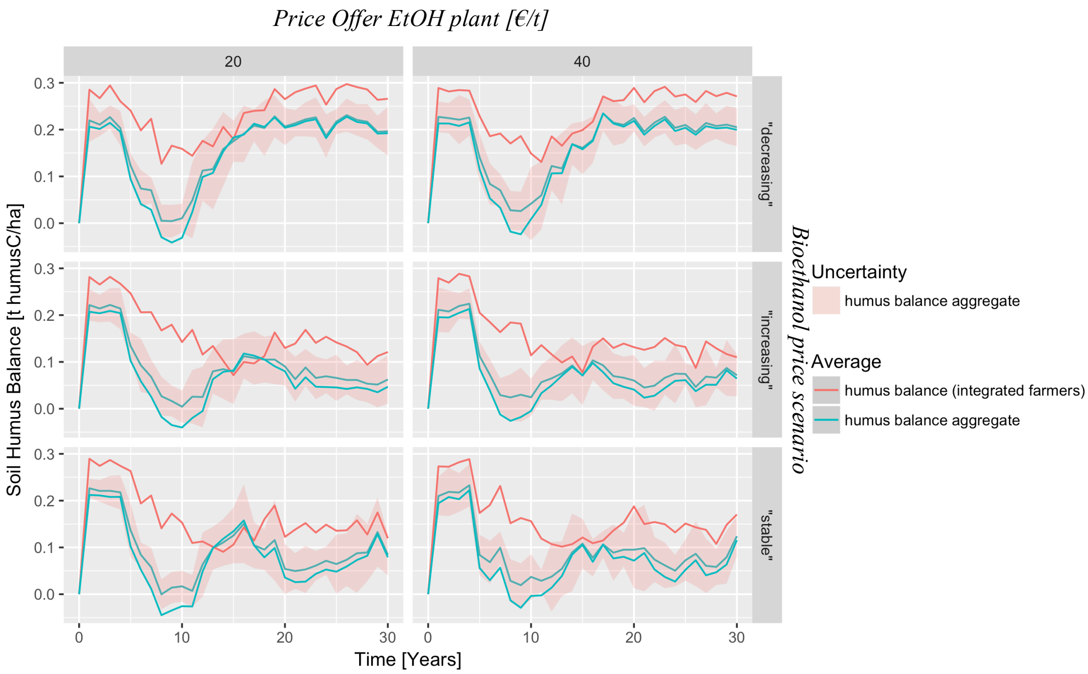

Figure 12: Impact EtOH buying power on humus balances.

Impact EU Cross Compliance Policy

Variables varied

- EtOH plant capacity: 50MW / 100MW
- Policy compliance: TRUE / FALSE

Straw supply

Figure 13 shows the impact of the EU Cross Compliance policy on straw supply over time for the two EtOH plant size scenarios.

In the case of a 50 MW EtOH plant the model results show that once demand for straw increases, without the EUCC policy in place the straw market supply significantly decreases in the following years. It reaches a low at about year 15 (10 years after market entry of the EtOH plant), while on average still remaining above total market demand, and then starts to increase gradually again over the next 10 years. With the EUCC policy in place, the decrease in straw potential is much more gradual and the average potential available to the market remains at a constant margin of more than 20 000t above total market demand.

In the case of a 100 MW plant without the EUCC policy in place, a clear dip in theoretical and technical straw potential can be detected after about 5 years after the EtOH plant entered the market. The reason for this is the overexploitation of straw on the expense of using straw for soil humus supply and its repercussions on soil productivity. In case of having the EUCC policy in place, the theoretical and technical potential decrease more gradually. In both cases, however, technical and theoretical straw potential recovers and continues to be more or less on the same level, although on a slightly lower level than before the EtOH plant entered the market.

Concerning the potential available to the market, the model results show that in the case of no EUCC policy straw market supply steeply decreases after the EtOH plant enters the market until it reaches a low after about 5 years at less than half of the original potential. Straw market supply then increases again to come back to its original level in about 5 years before it begins to decrease again. This time, however, it decreases at a lower rate than previously. With the EUCC policy in place, the average straw market supply follows the same pattern, but fluctuates with lower amplitudes. What is striking, however, is that the uncertainty in straw supply with a EUCC policy is larger.

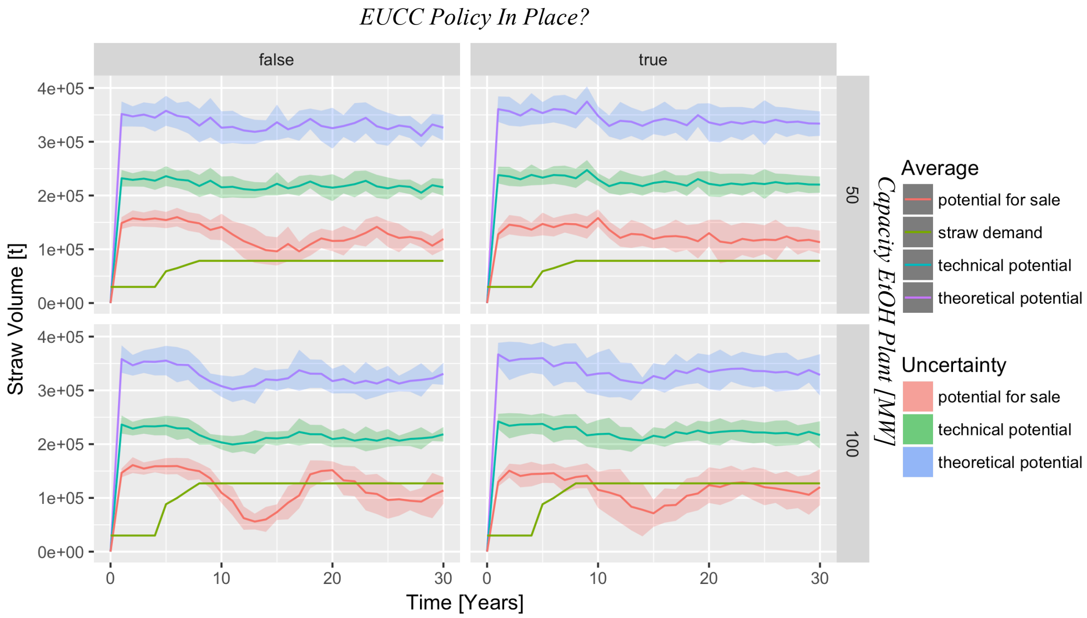

Figure 13: Impact EU Cross Compliance policy on straw supply.

Straw use

Figure 14 displays the experiment results on the aggregated straw use in the region for the two different straw demand scenarios (50 MW EtOH plant and 100 MW EtOH plant).

50 MW EtOH plant scenario

In the 50 MW plant scenario straw use for livestock and straw use for selling is the same with and without the EUCC policy in place. What changes is the aggregated straw use for soils in the region. With the EUCC policy in place, average straw use for soils in the region is generally higher before the EtOH plant enters the market. After a time period of about ten years average straw use for soils then starts to constantly increase every year for the rest of the observation period and surpasses the amount of straw sold in the region. Without the EUCC policy in place, straw use for soils is logically lower in the beginning (farmers are not obliged to conform with minimum soil humus balances). Once the EtOH plant enters the market, straw use however starts to steadily increase year by year until it reaches a peak within a time period of about ten years surpassing total straw sales and doubling the total straw use for soils. Total straw use for soils then decreases again slightly to the same level of straw sales.

100 MW EtOH plant scenario

At greater straw demand for biofuel production (100 MW plant scenario), straw use patterns are slightly different. In the case of no EUCC policy straw use for soils and straw sales are negatively correlated and are subject to constant periodic fluctuations with decreasing amplitude. With the EUCC policy in place, the average straw use for soils and straw use for selling follow the same periodic pattern, but with lower negative and positive variations over time. The uncertainty in how straw will be used in the region is however significantly higher once straw demand increases as compared to no EUCC policy being in place.

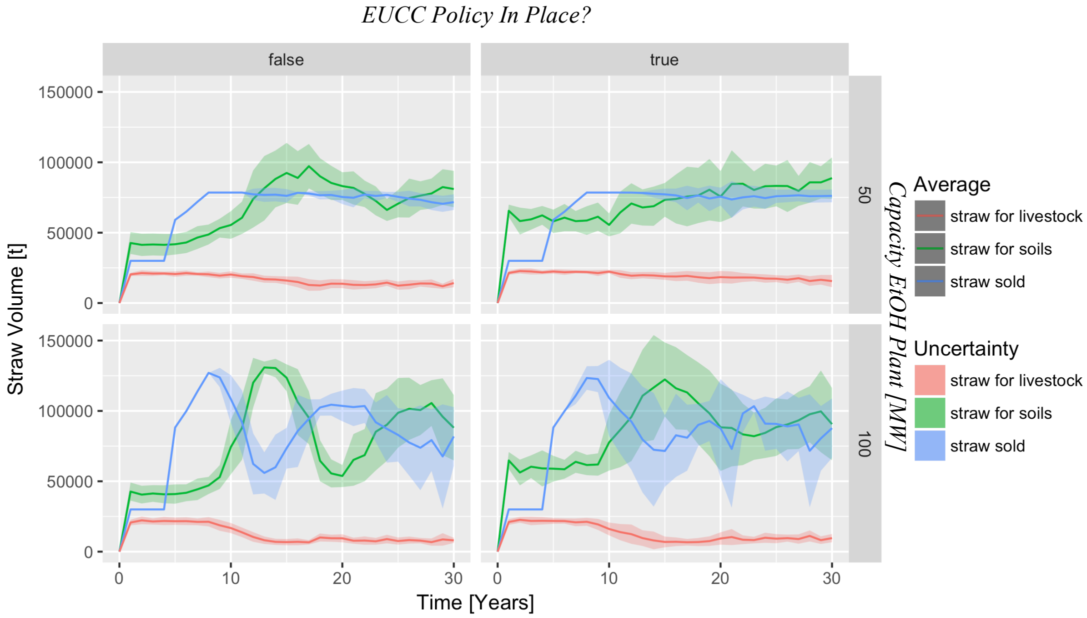

Figure 14: Impact EU Cross Compliance policy on straw use.

With regards to the impacts on existing straw users, model results show that in the case of the high straw market demand scenario (100 MW plant capacity), existing straw users have a slightly larger chance to secure their straw needs in the market with the EUCC policy in place (Figure 15) before they are ultimately driven out of the market.

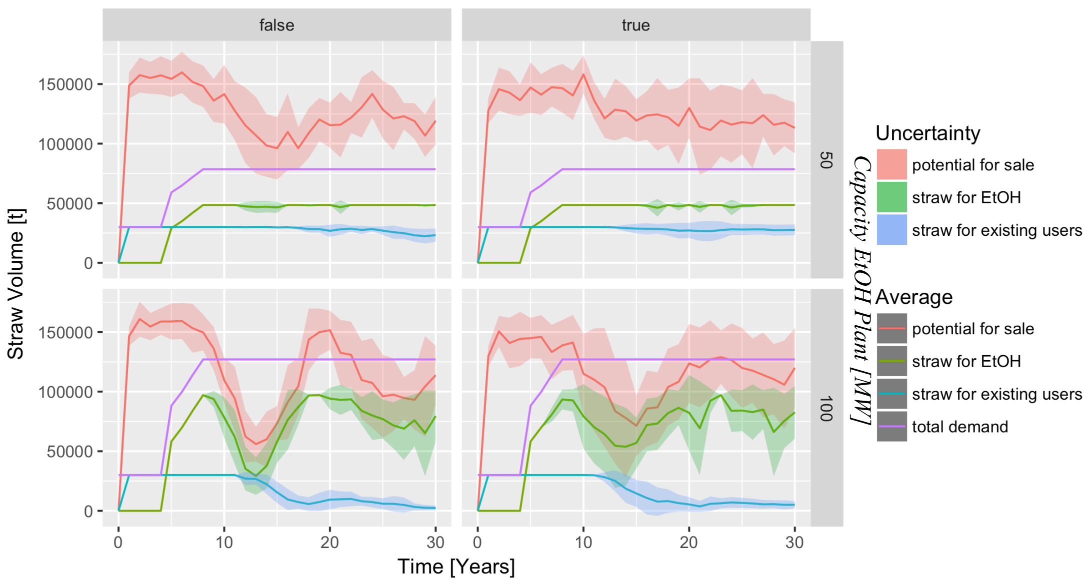

Figure 15: Impact EU Cross Compliance policy on straw flows.

Straw price development

Figure 16 shows the experiment results with regards to the influence of the EUCC policy on straw price development. The upper two graphs show the scenario of a 50 MW EtOH plant entering the market. If the EUCC policy is in place, average straw prices increase at an equal constant rate for the whole observation period. Larger uncertainty exists however in straw price development for the case of straw prices off field. If no EUCC policy is in place, straw prices rise more quickly and reach to higher levels as compared to having the EUCC policy implemented. The average price for round bales reaches its peak value about 15 years after the EtOH plants entry into the market. It stays on that level for a couple of years but then slightly decreases. The average price off field first follows the same pattern, but instead of decreasing after reaching a plateau after 15 to 20 years continues to increase again to almost levelling up with the average straw price for round bales.

In the lower two graphs that represent the higher straw demand scenario, the model results show a far greater uncertainty in straw price development for straw off field if the EUCC policy is in place. The average value is however a little lower than for the case without the EUCC policy implemented. The prices for straw off field follow the same pattern in both EUCC policy scenarios. However in the case of the EUCC policy being in place the average straw price off field reaches to slightly higher levels towards the end.

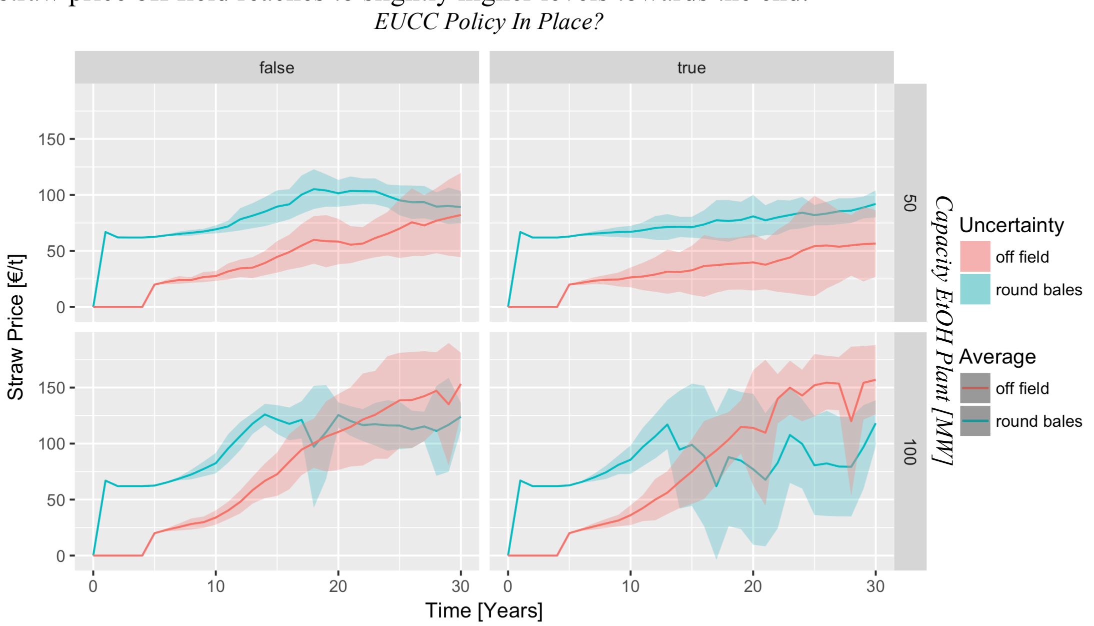

Figure 16: Impact EU Cross Compliance policy on straw price development.

Soil humus balance

Figure 17 shows the model results for soil humus balances. In the case of a 50 MW EtOH plant, with no EUCC policy in place, the average aggregated soil humus balance (blue) oscillates around zero, but on average still remains above. Soil humus values for conventional farmers do however lean into the negative area with its maximum drop before year ten with values around -0.1 t humusC/ha. With the EUCC policy in place, soil humus levels do decrease, but clearly stay above zero. In the case of a 100 MW EtOH plant with no EUCC policy in place, the drop in average soil humus balance after the EtOH plant enters the market is more severe than for the 50 MW plant scenario. Average soil humus levels sink to -0.1 t humusC/ha within 5 years and soil humus levels of conventional farmers can even fall to below -0.2 t humusC/ha. The soil humus levels do recover again to their previous level but only to drop again, even though not as deep as in the first incident. With the EUCC policy in place, the model results do show a steep decrease in aggregate soil humus levels humus levels of conventional farmers. The average aggregate reaches its lowest point at around zero; the average value for conventional farmers reaches its lowest value at about -0.05 t humusC/ha. After this initial downfall, the average soil humus levels rise again and continue to remain within the range of 0 and +0.2 t humusC/ha.

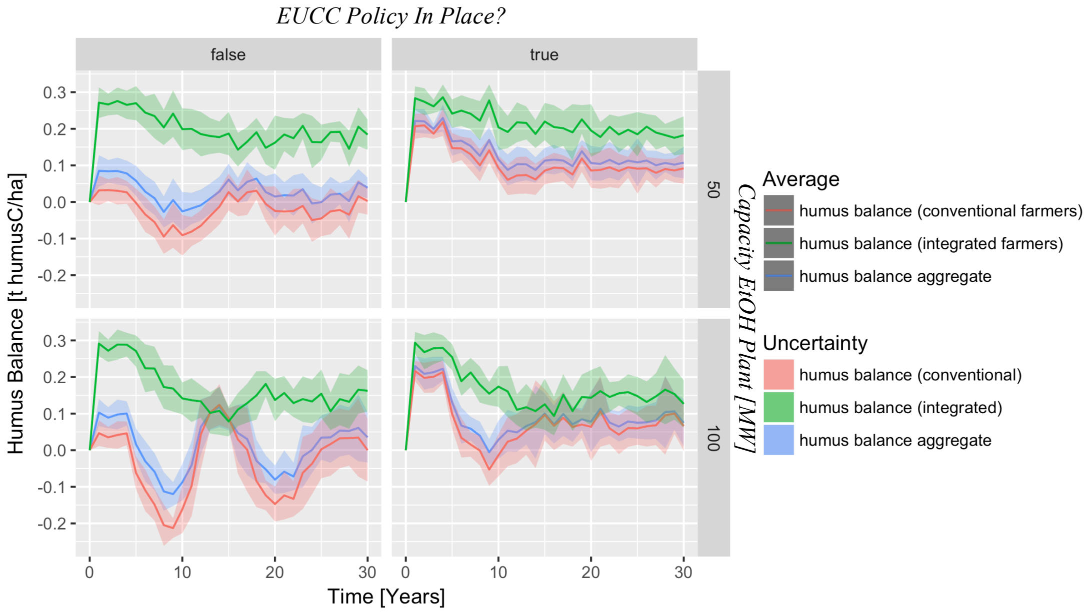

Figure 17: Impact EU Cross Compliance on humus balances.

Impact ignoring feedback of soil humus balances

Variables that have been varied:

- EtOH capacity: [0 MW, 50MW, 100MW]
- Farmers consider soil quality: [TRUE , FALSE]

Other relevant parameter settings:

- Straw demand existing users: 30 000 t

Straw supply

The model results with regards to the impact of ignoring the feedback of soil humus balances on straw supply are presented in Figure 18. As one would expect, in all EtOH plant scenarios the total supply in straw (theoretical potential) is reduced at a constant rate year by year. The technical potential and the potential that is available for sale follows the same pattern. One can also observe that with higher total straw demand in the market, the downwards slope in straw potentials is getting steeper reducing straw potentials at a higher rate per year.

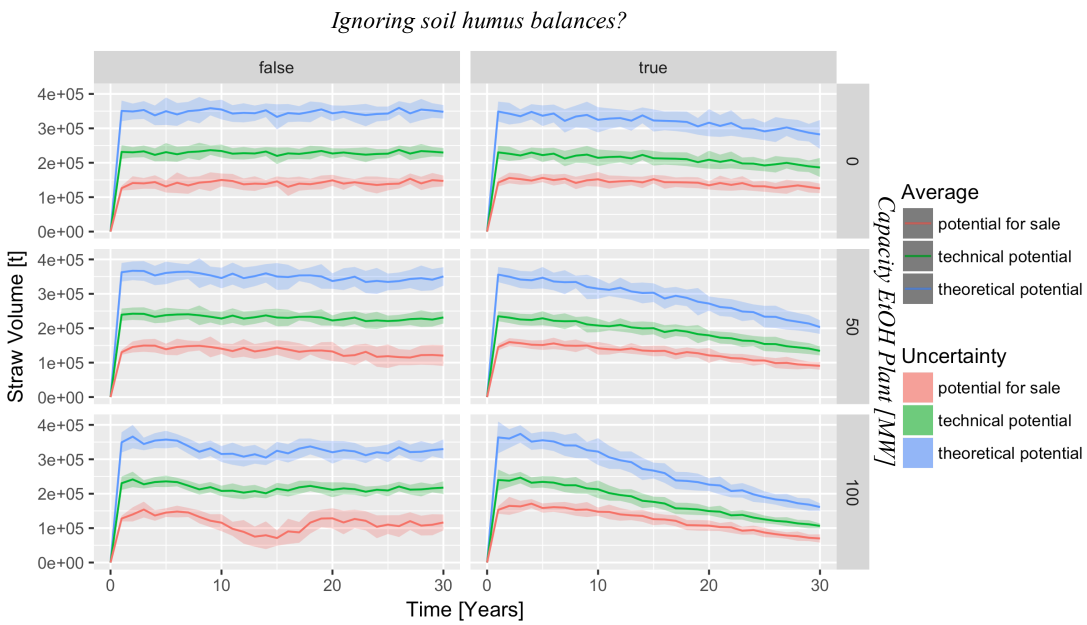

Figure 18: Impact conventional farmers ignoring humus balances on straw supply.

Straw use

Figure 19 shows the model results with regards to the impacts on straw use in the region. With no additional straw demand from an EtOH plant, straw uses remain constant for the whole observation period. In the case of a 50 MW EtOH plant straw sales increase to supply the EtOH plant straw demand. One can detect a constant decrease in straw use for livestock and towards the end of the observation period the EtOH plant has a small uncertainty to not be able to secure its straw feedstock requirements. The effect of neglecting the feedback of negative soil humus balances on yields becomes clearly visible when the additional straw demand is especially high (100 MW EtOH plant). In that scenario, most of the available straw potential is used for selling. After the EtOH plant enters the market, straw sales quickly steeply increase and straw sales continue to remain at a high level for about ten years. The total volume in straw sales then starts to gradually decline, due to the declining yields. By looking at Figure 20 we can observe that this decline in straw sales concerns the existing users first, who are not supplied with straw anymore or - in other words - are not able to secure their straw needs anymore in the market as result of the declining yields and the competition with the EtOH plant. The latter is able to secure its straw requirements for a couple of more years until it also runs into difficulties to meet their feedstock demands.

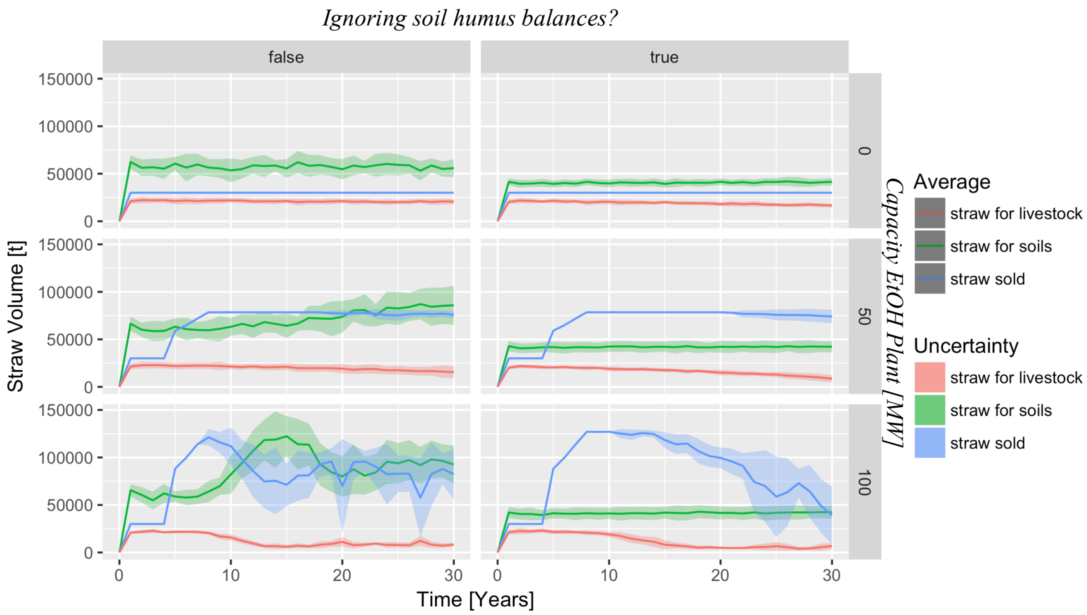

Figure 19: Impact conventional farmers ignoring soil humus balances on straw use.

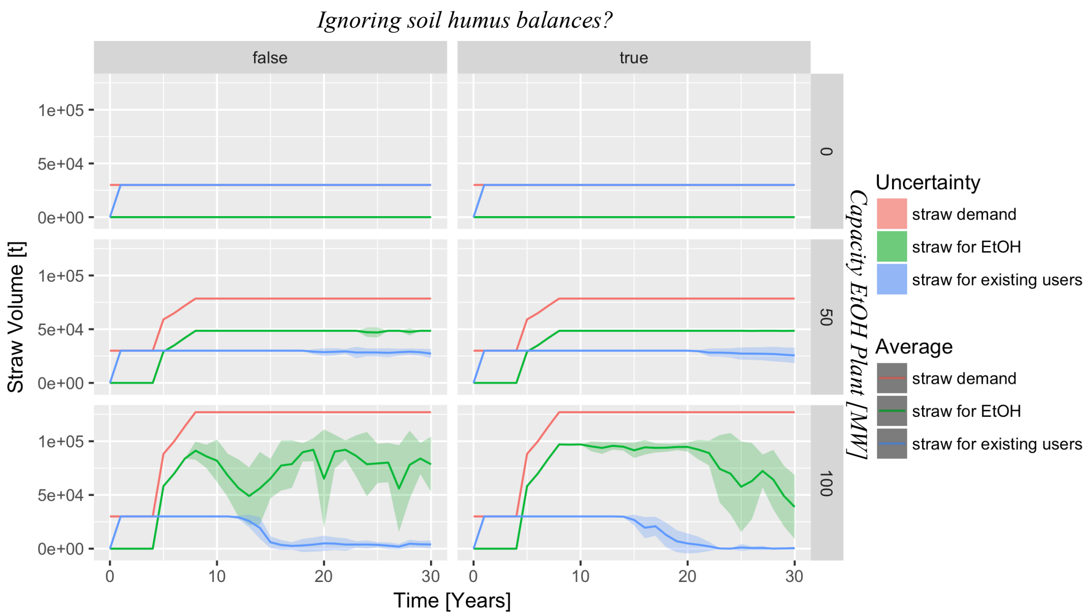

Figure 20: Impact conventional farmers ignoring soil humus balances on straw flows.

Straw price development

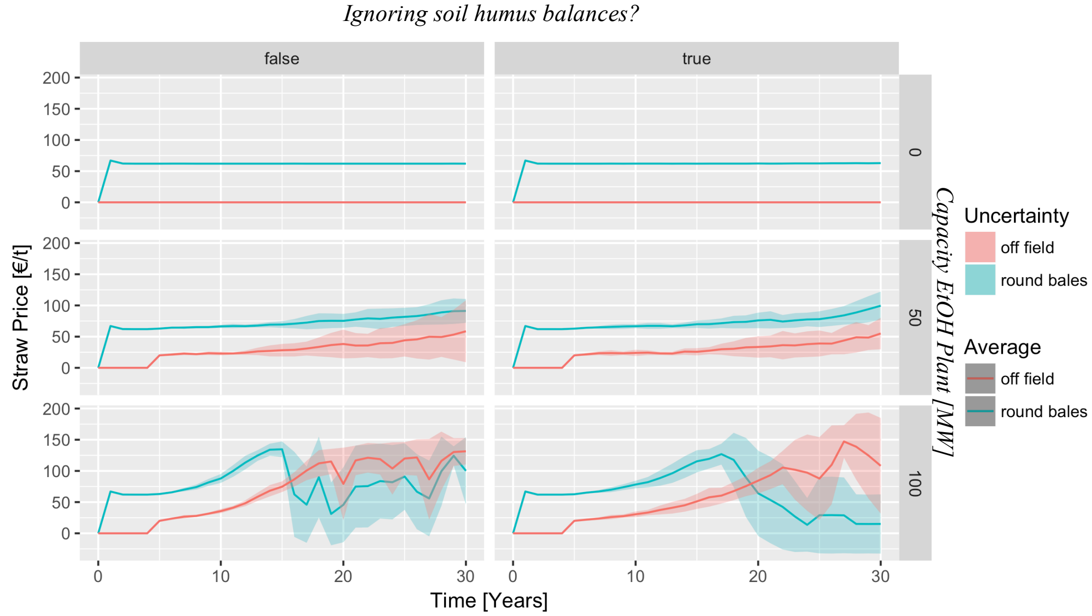

Figure 21: Impact conventional farmers ignoring soil humus balances on straw price development.

Soil humus balance

Figure 22 shows the results of the experiment for the impact on soil humus balances. As expected, the soil humus levels decrease continuously and thereby also explain the reduction in total straw supply (Figure 18) as a result of the impact of negative soil humus balances on soil productivity/crop yields.

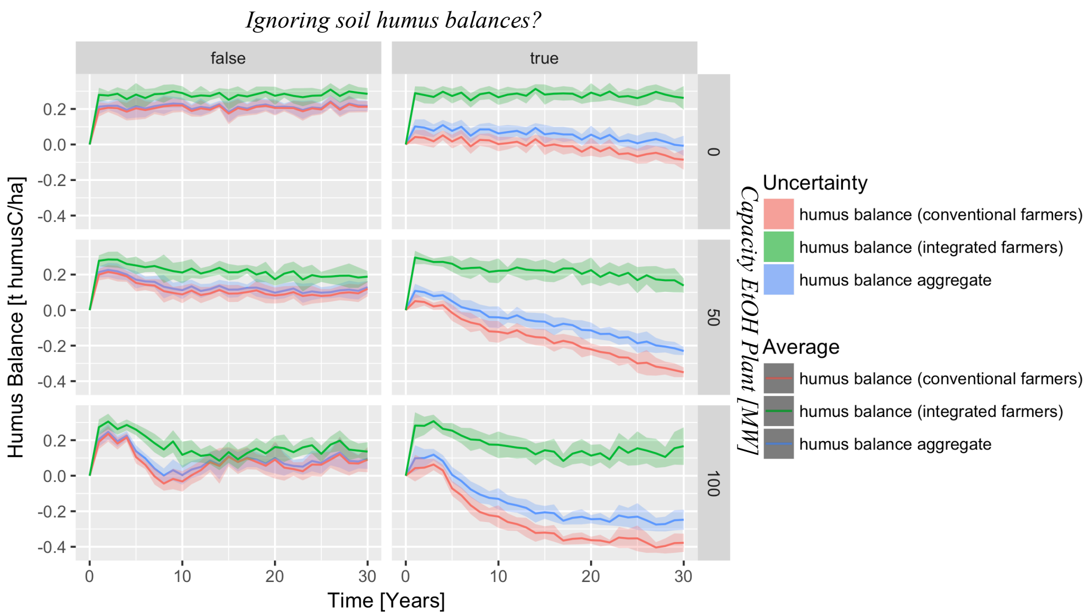

Figure 22: Impact conventional farmers ignoring soil humus balances on humus balances.

Conclusions

Research question:

What are the dynamic impacts of increased use of straw for renewable energy production?

1. *What is the impact of increased demand of straw from the energy sector on the dynamic behaviour of the straw market and the straw production sector with regards to straw price developments, straw use and straw supply?*

2. *How does the increased demand and market developments affect farmers in their farming practices and management of straw?*

3. *What are elements/mechanisms or systemic traits to be aware of that could lead to unintended/unsustainable developments/consequences and under what conditions do they occur?*

Short summary of what has been done:

To find answers to the research questions a model has been developed that includes the different actors and elements that play a role in using straw for biofuel production. By running multiple experiments with different parameter settings, the model has then been used to explore the dynamic behaviour of the system for different scenario settings and record the emerging results in straw supply, straw use, straw market prices and soil humus balances.

From the model results the following conclusions can be drawn:

The model results show that the magnitude in additional straw demand for biofuel/renewable energy production can have a significant impact on the straw availability in the market and straw price development. In cases where the additional demand approaches or exceeds the originally available surplus straw potential significant variations in yearly available straw market potentials can appear as farmers –attracted by the revenues from straw sales – overharvest their straw, but due to the negative impacts of overharvesting on crop yields change their straw use back to supplying it to soils in later years. The variations in straw market supply in turn could have implications for straw-based energy production facilities by reducing feedstock availability or respectively increasing feedstock procurement costs by needing to pay higher prices or find alternative sources for feedstock supply.

The magnitude in additional straw demand also has an effect on straw price developments. In the case of additional straw demands for biofuel/renewable energy production considerably lower than the actual surplus potential in the region straw prices are more likely to experience only a gradual increase according to the model results. At higher straw demands that exceed regional surplus straw potential, straw prices could however rise significantly with consequences for existing straw users in the future and future straw uses of farmers. The model results show that if straw demand remains high and straw prices rise above specific levels, farmers shift their straw use to selling it to the energy producer at the expense of original straw uses on farm. As a consequence, large-scale mobilisation of straw for renewable energy production could result in changes in farmers farming practices in that they try to find alternative sources/ways to maintain soil humus balances than using straw (e.g. increase in interest in alternative organic materials, changes in land use) or use different materials/ methods for animal bedding to free up straw for selling it on the market.

The model results also show that large-scale increases in straw demand for renewable energy production impacts existing actors that rely on straw for their business purposes in that it increases their straw procurement costs or makes them need to find alternative solutions to straw. At lower additional demand, existing users stay in the market, even though their straw procurement costs do increase.

Impact buying power
With regards to the impact of different buying power of the EtOH plant, the model results showed no major influence on straw supply. It does however result in the EtOH plant being able to maintain a more stable feedstock supply over the years with less fluctuation. The average aggregate straw use for soil is slightly reduced in cases of higher EtOH plant buying power emphasizing the impact of market forces on the system.

EUCC policy
Without EUCC policy there are larger fluctuations in yearly straw supply due to a larger degree of overexploitation of straw for market supply on the expense of straw use for humus supply and the resulting feedback on crop yields. The EUCC thus, besides promoting sustainable agriculture, also creates more stable market conditions. The EUCC policy is less important in only small additional demand scenarios, but becomes especially relevant in high additional demand scenarios, where market demand leads to continuous overexploitation of straw potentials on the expense of maintaining soil humus balances.

Ignoring feedback on soil humus balances
As a result of ignoring the feedback of soil humus balances on yields the total straw availability continues to decrease with the result being that less straw can be mobilized for biofuel production than in the case of farmers taking appropriate care of their soil humus balances. This is of course an extreme scenario, but helps to exemplify the long-term impacts if humus levels are ignored. It also demonstrates the impacts short-term profit-oriented thinking has for farmers in the long run, as it will hamper their lands quality with consequences for overall land productivity.

In conclusion, one can assert that market dynamics or market forces and farmer behaviour play a significant role in the mobilization of straw for renewable energy production and can lead to yearly variations in available feedstock potential for bioenergy purposes. In cases where straw demand for renewable energy production approaches the actual available surplus potential or exceeds the available potential this can risk the sustainability of using straw for renewable energy production by overharvesting damaging soil properties.

Discussion

The results of the model have to be seen in context with the assumptions that were made in the development of the model. In this research project the primary aim was to investigate the system behaviour/ dynamic impacts, if straw becomes a primary target for renewable energy/biofuel production. Hence, investigating the dynamic behaviour was the focus in the model development and considering the existing time constraints that came with the research project simplifications had to be made with regards to the detail in what specific elements in the system were modelled.

Theoretically straw could be used not only for biofuel production, but also in other energetic utilization pathways (i.e. biogas production, heating plants, combined heat and power production). These alternative pathways have been excluded from the scope of this research and the increase in demand for straw for renewable energy production has been instead solely exemplified by the operation of an EtOH plant that uses straw as feedstock for biofuel production.

Another limitation is the extent to which alternative options for humus supply to soils and the factors that influence humus balances itself could be incorporated into the model. Humus balances are influenced by a number of regional factors like soil type, water supply, temperature, and farmers farming practices with regards to land cultivation intensity, choice of crop cultivation and choice of organic fertilisers (Source: *LWK NRW).* This means that farmers in theory have other options available for humus supply than only straw. However, including these decision processes and regional factors into the model would require extensive additional work which exceeded the time available for this research project

While it was possible to identify different types of farmer attitude with regards to straw use (Kretschmer et al., 2012; personal communications with farmers), it was difficult to find empirical data to derive the distribution in farmer attitudes/straw use decision-behaviour among the farmers.

All in all, the model has to be regarded as a conceptual as certain important concepts could only be included in simplified fashion (e.g. conceptualisation of feedback loop of negative humus balance on crop yields) or had to be based on individual assumptions (e.g. straw demand, farm system distribution). However, the purpose of the model was not to make predictions about the future but to investigate the dynamic behaviour of the system and investigate the interrelationships and interdependencies between market dynamics, farmer decision behaviour and existing delays in feedback loops. The research results showed that market interactions and farmer behaviour can play a significant role in the bioenergy potential that can be won from straw. It also showed that market dynamics should not be underestimated in the endeavour to promote the use of agricultural residues for bioenergy production as it can lead to unsustainable developments (overharvesting of straw) and/or could lead to market movements in the agricultural sector.

For future research connecting the existing model with land use decision models and adding options for alternative choices for humus supply would bring valuable insights into how mobilising straw for energy production might further impact the agricultural sector and lead to market movements. Furthermore, it would be interesting to investigate if there are differences in system behaviour if also other energetic utilization pathways are included in model simulations. Other energetic utilization pathways have lower feedstock demands and would be more distributed in the area, which could result in different market dynamics.

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