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The MILESTONES modeling framework: An integrated analysis of national bioenergy strategies and their global environmental impacts

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A B S T R A C T

Bioenergy policies affect both the environment and biomass availability for food, feed, and fiber on a national and international scale. To support policy makers, knowledge and methods from different scientific disciplines in the form of integrated assessments is necessary. Therefore we developed the MILESTONES framework which models the links between the national bioenergy system and the global land-use system as an integrated modeling approach. It builds on a set of three well-tested models (MAGNET, LandSHIFT and BENSIM). The prototype's functionality was demonstrated by assessing the environmental impacts of future German bioenergy strategies on a global level and along the entire biomass provision chain. The results from the case study show that, on the one hand, German bioenergy strategies have little effect on international market prices, but on the other hand land-use policies on an international level strongly influence the environmental performance of any German bioenergy strategy.

1. Introduction: background and research agenda

Bioenergy is obtained from renewable biomass sources. Currently, these mainly include woody biomass from forests and food crops grown on agricultural land, but also consist of biogenic residues and waste. On the global scale, the provision of bioenergy is by far the most important renewable energy source and is considered to be one approach to reducing global greenhouse gas emissions (Chum et al., 2011; REN21, 2014; Smith et al., 2014). Energy carriers that are derived from biomass, whose composition and behavior are similar to fossil carriers, will play an ever increasing role in the future in the transport and power sectors (Eisentraut and Brown, 2014; OECD/IEA, 2011). Moreover, biomass enables flexible power supply and storage in the power sector. These characteristics of biomass, which have driven bioenergy policy in the past, provide an opportunity to overcome major challenges in climate protection and to enable the transition to a renewable resource base (EC, 2013; Inderwildi and King, 2009). At the same time, the provision and use of bioenergy from energy crops causes additional demand for agricultural land and may increase pressure on this limited resource (van Renssen, 2011; UNEP, 2012). Bioenergy policy is strongly accompanied by intensive debates on bioenergy use with regard to the effects on different dimensions of sustainability, such as the food versus fuel debate and the debate on environmental impacts of direct and indirect land-use change triggered by energy crop production. Possible effects on, for instance, food security and biodiversity preservation are also relevant in the design of bioenergy policies. These bioenergy policies are thus driven by some of the big challenges of global change (Fig. 1).

The ongoing discussion on biomass availability, and the direct and indirect effects of bioenergy policy, forces decision makers to not only define overall targets for bioenergy use, but also to prioritize in which energy sectors the limited resource should be used.

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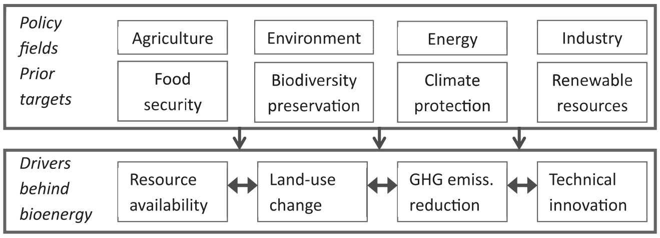

Fig. 1. Political framework and drivers behind a bioenergy strategy.

Due to international markets and transnational effects of changing demand patterns for bioenergy resources, national bioenergy policies also affect the international situation regarding biomass availability for food, feed, fiber and other purposes. At the same time, global trends can strongly impact national bioenergy strategies. Hence policymakers from different fields are faced with very complex decision-making issues.

To provide comprehensive, simplified and transparent information about the possible impact of future bioenergy policies, it is necessary to establish potential bioenergy development options and to assess their effects with regard to the different dimensions of sustainable development on different levels. To do this, we need to consider the feedback between different policy fields and the robustness of the effects within the context of changing framework conditions and priorities.

This requires a combination of data, knowledge and methods from different scientific disciplines in the form of integrated assessments (IA). Integrated models (IM) are important tools for supporting these assessments (Hamilton et al., 2015). In our case, they facilitate the analysis of the interactions between bioenergy technology pattern, the energy system, agricultural commodity markets and land-use change, and therefore help to improve our understanding of the system as well as to provide information that can be used in decision making.

There are a number of models that concentrate on specific elements of the entire bioenergy supply chain. For example van der Hilst et al. (2012) and Humpenöder et al. (2013) analyzed the effect of bioenergy policies on land-use change and the related environmental impacts on a regional level using spatially explicit land-use models that operate using a geographic raster. In both cases, projections for food, fiber and biofuel demands were based on external data sources. In contrast to the studies mentioned above, Laborde (2011) analyzed the effect of the EU bioenergy policy on direct and indirect land-use changes at a rough geographic level using an economic equilibrium model (MIRAGE) with a much lower resolution of land-use change (only calculated at the basic level of the MIRAGE regions). In contrast, integrated assessment models for bioenergy analysis can combine energy sector models with economic equilibrium models and land-use models. Popp et al. (2014) compare three different modeling approaches for the integrated analysis of energy and land systems on a global level: GCAM (Clarke et al., 2007), IMAGE (Bouwman et al., 2006) and REMIND/MAgPie (Popp et al., 2011). In their current form, these models are only of limited use in supporting the development of national bioenergy strategies as they operate using a rough spatial resolution (world regions). Unlike consequential life cycle assessments (e.g. Cherubini and Strømman, 2011) they do not take into consideration the whole biomass-to-bioenergy value chain, such as greenhouse gas emissions, when analyzing environmental impacts.

The key aspect of the research project “MILESTONES 2030” was to identify elements and milestones in order to develop a stable and sustainable German bioenergy strategy (Thrän et al., 2015). This required an integrated assessment that included socio-economic and technological processes as well as an analysis of environmental impacts. Regarding the aforementioned limitations of existing modeling approaches, one important aspect was the construction of an integrated modeling system to aid policymakers in designing a strategy for using bioenergy which (i) considers the complexity of drivers and processes, (ii) determines the environmental and economic effects of these strategies on the national and global level, and (iv) provides appropriate information for the different fields of policy. In order to illustrate the different elements of the assessment and, in particular, the development of the model, we have structured the paper according to the four phases of integrated assessment modeling described by Hamilton et al. (2015): (1) scoping the problem, (2) problem framing and formulation, (3) analysis and assessment of options and (4) communication of the findings.

In Section 2 we describe the scoping-phase by clarifying the objectives, system boundaries, stakeholders and issues of concern within the bioenergy policy field in Germany. In Section 3 we conceptualize the system concept and define management scenarios for a more in-depth analysis of problem framing and formulation. An analysis and assessment of the options make up the main body of the integrated analysis, and are therefore divided into two sections. In Section 4 we describe the structure and the elements of the model set-up and the model coupling. In Section 5 the defined scenarios are analyzed and assessed, including the results from the integrated modeling and a further assessment of those results. The last step of the integrated assessment - a communication of the findings - is examined in Section 6. Finally, in Section 7, we discuss the integrated assessment modeling approach in terms of the modeling framework, the quality of the scenario assessment results, and the potential to further improve the approach.

2. Scoping the problem

In the scoping phase, we defined the objectives, system boundaries, stakeholders and issues of concern. To support future bioenergy strategies, we need to address the stakeholders within the bioenergy policy field. Due to a close interrelationship between biomass and bioenergy, these bioenergy decision makers are typically placed in different ministries, i.e. the Ministry of Agriculture (biomass provision), the Ministry of Economic Affairs and Energy (bioenergy – power and heat), and the Ministry of Transport (bioenergy for transport) etc. In terms of the transition of the energy system, different expectations regarding future bioenergy utilization are expressed at the national level (BMELV/BMU, 2010; BMVBS, 2013). Today it is also expected that increased use of biomass might negatively impact land, environment and social effects in different ways. This applies not only to Germany but also to other regions of the world, which in turn also influences international sustainability issues surrounding future bioenergy utilization.

There is a growing need for clear, stable, long-term priorities to provide additional bioenergy within the different energy sectors (heat, power and transport). In the latter case, it is reasonable to ask which technologies would best utilize this potential. However, the representation of the bioenergy sector in existing studies is usually too general in order to answer such a question. The focus of this study is to assess the environmental, economic and technological effects of different bioenergy strategies in more detail.

The starting point for the creation of an overarching bioenergy strategy for Germany is the actual biomass for energy provision of 1100 PJ/year in 2010 (calculation based on AGEE-Stat (2013)). It should be noted that biomass utilization more than tripled in every energy sector between 2002 and 2012. In addition, many of the bioenergy conversion plants have an expected time of operation and, hence, a biomass demand that extends to 2025 or even beyond (Fig. 2).

At the same time, the normative limit has also been set so that the amount of biomass used for energy production in Germany does not exceed the sustainable biomass use of 1550 PJ of primary energy, which is assumed as the domestic production potential, according to (Nitsch et al., 2012). So the expected use of biomass for energy provision is a function of the installed capacities and their technical life time. The degree of freedom in using the limited biomass for different applications increases after the end of the lifetime of the currently established plants. Modern biomaterials and biochemicals are not part of this biomass potential so that available biomass potential for further bioenergy provision can be calculated from biomass potential and current use (about 450 PJ/year in 2010; see Fig. 2).

Under this framework, policy advice for a bioenergy strategy should consider long-term development potentials for the most relevant drivers such as land-use change, technological development, competitiveness of bioenergy provision concepts and the role of bioenergy in the overall energy system. Any trend in bioenergy also affects the overall energy supply and vice versa. Hence, the trends in the overall energy system need to be considered when framing the problem.

Many future settings are possible when it comes to these drivers. In order to provide valuable information for policy decision-making processes on the longer term, it is necessary to clearly address the model system with dedicated research questions. As part of the ongoing bioenergy discussion in Germany there are special concerns about national priorities for the provision of power versus transport fuels, and the global impact of a national bioenergy strategy – especially with regard to the related biomass demand. We translated these concerns into two key questions to further develop a bioenergy strategy. These should be answered with help of the MILESTONES framework:

(1) Based on future biomass potentials for flexible power provision or for transport – how do resource demand, technology development, expected installation and environmental impacts differ over the longer term?

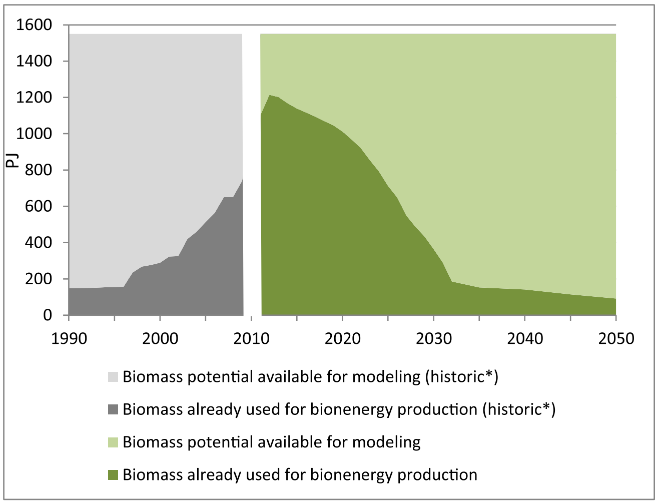

Fig. 2. Development of biomass potentials (Nitsch et al., 2012) and bioenergy use (both in petajoules) in Germany (based on AGEE-Stat (2013), Nitsch et al. (2012) and our own assumptions).

(2) Does the picture change if the currently discussed impacts on land-use change and the related environmental impacts are reduced by an internationally sustainable land-use policy in the coming decades?

3. Problem framing and formulation

3.1. System conceptualization

At this point, a conceptual model that describes the main elements and processes of the studied system is derived as a basis for the modeling framework. The conceptual model includes the national bioenergy system (Germany in our case study) and its links to national and global biomass markets. The relevant processes follow the biomass-to-bioenergy value chain from cradle to grave. These elements comprise (i) land-use systems that define the resource basis for biomass production from forestry and agriculture, (ii) global trade and biomass markets (economic system) and (iii) the respective national bioenergy system (see also Fig. 3).

3.2. Definition of management scenarios

To assess the key questions identified in Section 2, we conducted an analysis of four scenarios describing German bioenergy policy options up to 2050. In order to achieve robust results for advising policy, we decided to clearly show the effects of different political decisions by assessing scenarios with extreme framework conditions for the two key questions (in the sense of "policy decided to implement option A or B").

Scenarios were defined in which (i) biomass is either used to produce fuels or combined heat and power (CHP) and where (ii) different sustainability criteria limit land-use change and thus biomass availability (Table 1). Briefly, in contrast to the business-as-usual (BAU) scenarios, the sustainability scenarios (S) show (i) a stronger protection of primary forests, (ii) no conversion of forest to cropland or pasture land, (iii) a protection of areas with high biodiversity, (iv) an implementation of the Aichi biodiversity target 11 that conservation areas should cover at least 17% of the terrestrial Earth surface (Tittensor et al., 2014), (v) protected carbon-rich areas and prohibited use of wetlands or peatland, (vi) a ban on converting pastureland into cropland in the European Union (EU) from 2020 onwards, (vii) a more rapid increase in CO_2 costs up to 100€/tCO_2 in 2050 and (viii) faster cost reductions through research and development (corresponding to one learning rate in 3 instead of 10 years). These assumptions were translated into four extreme scenario settings.

These scenarios were embedded in a German transition strategy towards a highly efficient energy supply based on renewable resources in 2050 (BMU, 2009; Nitsch, 2008; Nitsch et al., 2010, 2012; Schlesinger et al., 2010). Output data from existing energy system models and the national bioenergy policy framework were used as a starting point. This takes into account the future pattern of energy demands for heat, power and transport, and the role of other renewables and fossil fuels, as well as other parameters from a well renowned study (Nitsch et al., 2012) covering the entire German energy system. This information was supplemented with data updates, e.g. for the power sector, mobility scenarios, and trends in fertilizer production (IFEU, 2015; Thrän et al., 2013). Within this context, the bioenergy sector and the effects of bioenergy use are analyzed in more detail. This enables the specific bioenergy results of this study to be interpreted in the context of the overall energy system with only moderate computational burden.

In addition to the above-mentioned points, we considered a global trend towards an energy supply in 2050 that is increasingly

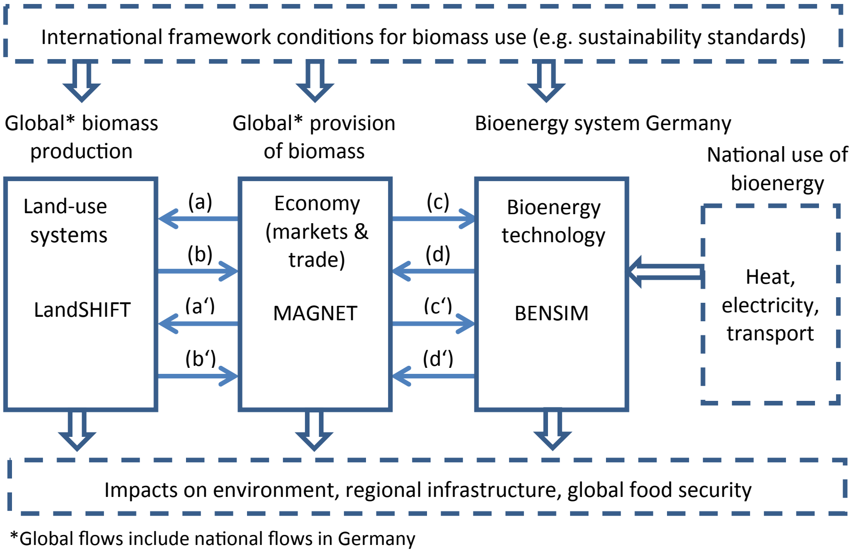

Fig. 3. Structure of the MILESTONES modeling framework. The framework combines the three models MAGNET, LandSHIFT and BENSIM. Data exchange between the models includes: (a, a′) Agricultural production and yield developments; (b, b′) medium yield and area of the different land-use types; (c, c′) feedstock price changes for the German market; (d, d′) national biomass-for-energy demand. Important exogenous model drivers comprise international framework conditions for biomass use and assumptions regarding the use of bioenergy in Germany. Based on the model output the impacts on the environment, regional infrastructure and global food security can be analyzed.

Table 1
The four extreme scenarios for long-term bioenergy options in Germany.

Biomass for combined heat and power provision for Germany under an international, business-as-usual land-use policy **CHP-BAU**	Biomass for transport fuel provision for Germany under an international, business-as-usual land-use policy **Fuel-BAU**
Biomass for combined heat and power provision for Germany under an international, more sustainable land-use policy **CHP-S**	Biomass for transport fuel provision for Germany under an international, more sustainable land-use policy **Fuel-S**

based on wood and advanced, lignocellulose-based biofuels (IEA, 2014) for all scenarios with higher global production quantities in the two sustainability scenarios (IINAS, 2014).

4. Model set-up

4.1. Structure of the modeling framework

The software prototype of the MILESTONES modeling framework is an implementation of the conceptual model that we described in Section 3 as an operating computer model (see Magliocca et al., 2015). It provides an integrated assessment tool (1) to analyze different scenarios of bioenergy use in Germany taking into account global framework conditions and (2) to evaluate options for a sustainable bioenergy strategy.

Fig. 3 shows the structure of the modeling framework. It combines (1) the global economic equilibrium model MAGNET to describe international markets and trade, (2) the grid-based global land-use model LandSHIFT to determine the location and extent of global land-use change, and (3) the bioenergy market model BENSIM to simulate the competition between bioenergy options at the national level in Germany. Models were coupled using a soft-link approach. This means that the models still operate as standalone tools that exchange data via defined interfaces. In the next 3 sections we describe the individual models, their respective input requirements and the generated output data. Then the procedures for model coupling and data exchange are outlined (Section 4.5).

Additionally, we implemented a set of analytical tools to assess the impacts of the modeled bioenergy options on the environment, regional infrastructure and global food security (Thrän et al., 2015). In section 5 of this paper we describe results from an analysis of selected environmental impacts.

4.2. Modeling the global provision of biomass

One central aspect of our modeling framework is the general equilibrium model MAGNET (Modular Applied GeNeral Equilibrium Tool) which is used to calculate future economy and trade. It explicitly determines supply, demand and prices of agricultural products in a macroeconomic context taking into account competition over inputs between all economic sectors.

MAGNET is a recursive dynamic computable general equilibrium (CGE) model that focuses on agricultural sectors within the world economy. The current version uses the GTAP 8 database (Narayanan et al., 2012) which represents the world economy in 2007 in US dollars. It distinguishes between 134 regions (which were aggregated into 35 world regions within our framework) and 57 sectors. The GTAP core of MAGNET was subsequently extended by several modules (for details see Woltjer et al., 2014). Two of these modules are a detailed representation of agricultural land supply (Eickhout et al., 2009) and the inclusion of biofuel sectors and biofuel policies (Banse et al., 2008). The biofuel module is refined to include exogenously given absolute demand of biofuel in metric tons of oil equivalent (mtoe).

MAGNET is mainly driven by changes in human population, gross domestic product and technological change over time. Additional exogenous drivers are trade, agricultural and biofuel policies, constraints on land supply, factor mobility (the ability to move production factors from one sector to another), and the possibilities for substituting inputs and products. The exogenous drivers are derived from recognized international statistics.

In MAGNET, scenarios differ with regard to demand for bioenergy and sustainable land-use policies (Table A6). The sustainable land-use policy is interpreted as a reduction in available land for crop cultivation. Additionally, the conversion of grassland to cropland is not allowed in the European Union from 2020 onwards. In MAGNET, the bioenergy demand is distinguished between conventional biofuels and bioenergy options using lignocellulosic biomass and is formulated in absolute demand and land demand, respectively. The land demand for lignocellulosic biomass further reduces the available land for crop cultivation. For all world regions except Germany, the two BAU scenarios CHP-BAU and Fuel-BAU use the same assumptions for bioenergy demand and sustainable land use policies in contrast to the two S scenarios (Table A7). Only the bioenergy mix varies between all four scenarios in Germany (Table A7).

4.3. Modeling the bioenergy system in Germany

In order to model the competition between different bioenergy technology options, a myopic least-cost simulation model with endogenous technological learning (BioENergy SImulation Model, BENSIM) was developed. A detailed description can be found in Millinger et al. (2015).

BENSIM simulates the least-cost mix of biofuel or bioenergy production options on a yearly basis. Investment costs, operation and maintenance costs, as well as black box input and output variables for the processes (feedstock, power, byproducts, GHG-emissions etc.) coupled with costs serve as a data basis for the modeling.

The main drivers of the model are bioenergy provision costs that are mainly influenced by costs for biomass, technical learning (a reduction in investment costs with increased capacity and/or through research and development) and efficiency improvements. Biomass potentials also serve as a limit for some pathways. The model's main output consists of production shares of the different options resulting from competition that is based on the internally generated cost trends (based on technological learning effects under competition) to satisfy a bioenergy target or until biomass limits are reached. The model also assesses the sensitivity of markets to different parameters and assumptions. Path dependencies are also captured through the recursive elements of learning effects and previously built capacities.

In terms of simulating the bioenergy provision in BENSIM, the main differences between the scenarios are that there is a more rapid increase in CO_2 costs towards 100€/tCO_2eq in 2050 in the S scenarios (roughly corresponding to a logarithmic and an exponential curve respectively, with the end-point being the same). At the same time, cost reductions through research and development are more rapid (one learning rate in 3 years instead of 10), as well as differing feedstock prices obtained from MAGNET.

4.4. Modeling the global land-use system

The global land-use system is represented by the LandSHIFT model which is used to calculate spatial and temporal land-use change due to the cultivation of food and energy crops, grazing and urbanization. A detailed description can be found in Schaldach et al. (2011) and Alcamo et al. (2011). LandSHIFT operates on a global spatial grid with a cell size of 5 arc-minutes (~9 × 9 km at the equator). Each cell is assigned to a world region (regional level). Model drivers are specified separately for each world region. These include the production quantities of different crop types, yield improvements due to technological change, change in livestock numbers and human population growth. Cell-level information comprises land-use type, human population density, and a set of parameters that describe the landscape characteristics (e.g. terrain slope, potential yields, road infrastructure) and land-use restrictions (e.g. protected areas). The model is initialized with a global land-cover map for 2007. Additional information on the spatial location of crop types and pasture is introduced by merging this map with statistical data on cropland and grazing land area on a regional level. During the simulation, LandSHIFT translates the regional model drivers into spatial land-use patterns. At the beginning of every time step the suitability of each raster cell for the different land-use types is determined based on cell-level information. Thereafter the model uses region-level data to determine and allocate the land needed for each crop type, pasture and settlement in the most suitable cells. Model results are raster maps that depict the spatial and temporal patterns of land-use change within the different regions. Additionally, statistical data on the regional level is calculated that consists of information on the area used for crop cultivation, grazing, settlements, mean crop yields and the area that is potentially available for new cropland and pasture. The potentially available land is determined based on assumptions regarding land-use restrictions, e.g. the protection of forests and natural reserves.

In LandSHIFT the scenarios differ in respect of crop production, livestock numbers and the development of crop yields as well as in respect of their assumptions regarding land-use policies. In the sustainability scenarios land-use policies are modeled in form of land-use constraints that define the extent of protected land which is not available for the expansion of cropland and pasture. GIS-maps of primary forests, nature protection areas etc. are used to specify the location of protected land (Table A6). The Aichi targets were implemented by randomly selecting unprotected cells with natural vegetation and exclude them from being converted to agricultural land. Additionally, the transition of particular land-use types is disabled, e.g. from pasture to cropland in the EU after 2020.

4.5. Model coupling and exchange of data

The first step of model coupling is the adjustment of MAGNET and LandSHIFT with respect to their spatial resolution and represented agricultural commodities, in order to facilitate the exchange of data between the models. Both models are modified to use the same aggregation of world regions (Table A1) and differentiate between the agricultural commodities of wheat, coarse grains, oilseeds, sugar crops, rice, other crops and pasture.

In the second step, interfaces for data exchange between the models are defined and a workflow for running the models in coupled mode is developed. Two tables form the interface between MAGNET and LandSHIFT. The LUCC DRIVER table (Table A2) specifies the model input for a LandSHIFT simulation based on MAGNET output. This includes the production of each agricultural commodity for each region in each time step, as well as information on how crop-specific yields change over time as a result of technological progress. It also includes information on the cultivated area of each crop type. The LUCC-RESULTS table (Table A3) contains the LandSHIFT output that serves as the input for MAGNET simulation runs, including information on the average yields of the different crops and the area of all land-use types. The interface between MAGNET and BENSIM is organized in a similar way. Using the PRICE CHANGES table (Table A4), MAGNET provides data to BENSIM for the prices of wheat, coarse grains, oilseeds and sugar crops. In return, BENSIM provides information on the demand of first and second generation biofuels via the table BIOFUEL DEMANDS (Table A5).

Model coupling is currently carried out in a semi-automated way. This means that the models are run manually by the scientists on independent computer systems while the exchange of data between two coupled models (source, target) via the described interfaces is automated. For the MAGNET-LandSHIFT coupling we implemented a set of R scripts that are responsible for semantic mediation between the models. They extract the relevant information from the respective source model output, generate ASCII files with the interface tables and then copy this information from these files to the input data structure of the coupled target model. The data between BENSIM and MAGNET is exchanged in the same manner through excel files. Models do not exchange data until the simulation runs have been completed (in our case the scenario simulations cover the period from 2010 to 2050, with simulated bioenergy provision in BENSIM starting in 2014 based on the latest available data for technology capacities and feedstock costs). This means that modifications to the model source code were unnecessary for achieving interoperability.

4.6. Simulation runs

At the beginning of each simulation run consistent initial conditions for all models are defined. MAGNET and LandSHIFT are initialized with the same statistical data (FAO, 2013) for cultivated area and crop production in the different world regions. Moreover, the assumptions regarding the amount of potentially available land for crop cultivation and pasture are consistent in MAGNET and LandSHIFT (see 4.4). MAGNET and BENSIM use consistent assumptions with regard to initial bioenergy (biofuel) production, expected increases in conversion efficiency, and maximum cost reductions.

The sequence of a simulation run with the coupled models is illustrated in Fig. 3. It starts with the definition of a set of global assumptions on income and population change as well as trade, agriculture, and environmental and bioenergy policies that include global and national bioenergy targets (as an important part of a bioenergy strategy). Based on these assumptions MAGNET projects the resulting biomass production, demand, trade and commodity price developments until the end of the simulation period. In BENSIM, the projections for feedstock price changes for the German market (both domestic and imported feedstocks) from MAGNET (c) are directly used for wheat, oilseeds and sugar crops, and from “other grains” and wheat to represent maize silage and wood. The projections are interpolated to accommodate for the yearly resolution in BENSIM, which simulates least-cost bioenergy technology developments for Germany. After this initial step we established 2 feedback loops between the models.

Feedback loop 1: Using the national biomass-for-energy demand (d) as an additional input, iterative simulation runs of MAGNET and LandSHIFT are conducted. First, MAGNET calculates agricultural production and initial yield developments until 2050 and provides this information (a) to LandSHIFT where the corresponding land-use changes are also simulated until 2050. LandSHIFT uses the initial yield development as exogenous technical progress per area and distributes the agricultural production of MAGNET. LandSHIFT reports back to MAGNET (b) with information on medium yield and area of the different land-use types on a regional level. Using the average yield from LandSHIFT, MAGNET is run again and feeds back new agricultural production to LandSHIFT once again. LandSHIFT calculates land-use changes based on this new agricultural production and the initial yield developments. At this point the calculated cropland areas from both models are compared. If their difference exceeds a defined threshold (in the case of our experiments we typically used 10%) exogenous assumptions about crop yield developments within MAGNET are adjusted and a new iteration is initiated (a′, b′). If the difference between the calculated area in both models is below the defined threshold, the iteration is halted. In the scenario analysis described above, we typically required between 2 and 6 iterations until the model results converged.

Feedback loop 2: Based on the results from feedback loop 1 another BENSIM simulation is started using the commodity price changes from MAGNET as input data (c′). BENSIM simulates a production technology mix for the depletion of a given supply of biomass for bioenergy. The resulting biofuel supply for Germany is then handed to MAGNET, distinguishing between bioenergy options using lignocellulosic biomass and options using food crops. The conventional biofuel supply is provided to MAGNET in absolute amounts while the advanced biofuel supply is translated into a land demand which is subtracted from the available area for crop cultivation in MAGNET as well as in LandSHIFT (d′). Using this data, MAGNET is rerun and the calculated commodity prices are compared to the commodity prices from feedback loop 1. If differences are above a certain threshold (in the case of our experiments 1%), feedback loop 1 and, consequently also feedback loop 2 are repeated. Otherwise the simulation is finalized. Our simulation experiments show that German biomass demands have a relatively small impact on global commodity prices and the simulations can be finalized without repeating feedback loop 1.

4.7. Model evaluation

The plausibility of the underlying model assumptions and the simulation results was evaluated by a scientific advisory board with 13 experts from different disciplines (forestry, agriculture, market modeling, land-use modeling, energy scenario development, environment etc.). For this reason 3 workshops were carried out between 2012 and 2014 where the structure of the modeling framework, the design of the simulation studies as well as the input data and simulation results from the scenario analysis were presented and discussed. The experts confirmed that the MILESTONES framework portrays most of the relevant processes, that the data used for the model initialization and the scenario analysis were scientifically sound and that the scenario simulation results (as described in Section 5) seemed plausible and internally consistent. The identified model limitations are addressed in the discussion section of this article. We have chosen this qualitative evaluation method instead of a comparison against independent data (e.g. Bennett et al., 2013) as at this stage of prototype development our major aim was to ensure that the modeling framework fits its purpose of use (Jakeman et al., 2006). This approach of model evaluation is often applied in the context of integrated assessment modeling since independent numerical data is often not available to quantitatively test the model performance (e.g. Parker et al., 2002; Jakeman et al., 2006).

5. Analysis and assessment of options

5.1. Modeling protocol

The MILESTONE modeling framework was applied for conducting four simulation runs covering the different scenarios. Table A6 provides an overview of the scenario assumptions and data sources. In the following sections we describe our key findings with respect to the system components covered by the three models (energy system, global markets and trade, and land-use system). Then we provide an overview of selected environmental impacts.

5.2. Main findings for the energy system

The resulting share of bioenergy provision for each option is summarized for the German energy system in Table 2.

Conventional biofuels continue to dominate with an almost complete dominance of biodiesel in the BAU scenarios. In the S scenarios, biomethane gains large market shares towards the end of the simulation time span. In the CHP cases (S and BAU), options based on biogas and vegetable oil achieve large shares.

Notably, options based on lignocellulosic biomass do not achieve large market shares in any of the cases, neither in the fuel sector nor in the power sector. In the latter case, the reason is largely due to higher investment costs combined with expected lower capacity factors (due to increasing shares of variable renewable energy sources in the power system). In the former case, the fact that there is an expected decrease in cost due to learning does not sufficiently compensate for the increase in feedstock costs needed for these options to become competitive against conventional options.

In the Fuel-S scenario (biofuel provision under stricter land use restrictions) there is a continuously strong increase of biomethane from the year 2025 onwards (see Fig. 4). This is partly caused by more steeply increasing biomass prices as well as differing price developments between feedstock from MAGNET, depending, to some extent at least, on land-use costs. This leads to an improved competitiveness of options that are more land and resource effective, such as biomethane from maize silage, which is a process that utilizes the whole crop.

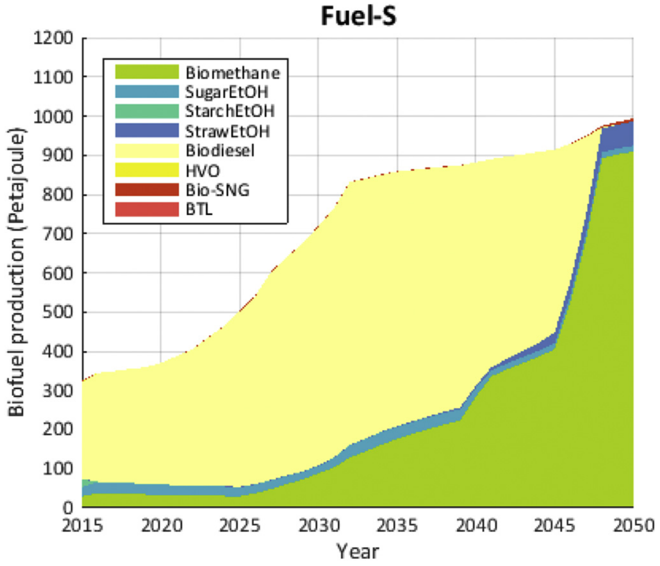

Fig. 4. Development of bioenergy provision for Germany in the Fuel-S scenario. Of all the biofuel options included, only HVOs (hydrogenated vegetable oils) and BTL (biomass-to-liquid) do not show up on the market. Biodiesel dominates but is overtaken by biomethane towards the end of the simulation. Bio-SNG (synthetic natural gas) is the only advanced biofuel which retains a (small) share of the market. Bioethanol is produced from starch at the beginning, sugar over the medium term and straw over the long term.

5.3. *Main findings for biomass market developments*

In terms of the global economy, our focus lies on agricultural production and price developments for crops which are potential bioenergy feedstock. In general, crop production increases strongly by 2050. In contrast to the BAU scenarios, the increase in the sustainability scenarios is hampered by land restrictions (Table 3), which leads to overall production reduction. While all real prices are expected to increase over time for agricultural products, this increase is much higher in the sustainability scenario than in the BAU scenarios. These trends are mainly driven by an increasing global demand for food and feed. The demand on international markets to provide additional feedstock for bioenergy provision in Germany will not significantly affect the international markets and prices for agricultural products. Land restrictions and increasing global agricultural prices are expected to stimulate technical progress in agriculture and lead to higher overall yields and an intensification of agricultural production in the remaining area in all scenarios. Increasing prices for land around the world clearly show that land will be a growing limiting factor in agricultural production in general. In the sustainability scenarios after 2025, land restrictions, such as the protection of natural ecosystems (e.g. primary forests and nature reserves), will cause a change in food consumption as well as in the trade and production patterns of agricultural commodities due to price increases for land as well as agricultural commodities.

In Germany, the Fuel-BAU scenario triggers an increase in vegetable oil demand for the production of biodiesel. Oilseed production and vegetable oil imports increase over time. In the other three scenarios, vegetable oil imports decrease over time because other technologies replace biodiesel.

5.4. *Main findings for land-use change*

Table 4 provides an overview of the key model results. Under the BAU scenarios, global cropland area is expected to increase from 1400 million hectares (M ha) in 2010 to 2800 M ha in 2050. This increase is lower in the sustainability scenarios, rising to 2400 M ha in 2050. The main reasons for these expected trends are increasing global demands for food and feed in all scenarios. Two important hot spots of land-use change in the BAU scenarios will be Brazil and Southeast Asia. In Brazil, cropland area almost triples, leading to a drastic loss in natural vegetation.

While we can clearly identify the benefit of applying the sustainability criteria to globally protect natural vegetation, there are no significant differences between the respective fuel and CHP

Table 2
Share of sector bioenergy from bioenergy carriers in the scenarios [%].

	2015[d]		2030				2050			
	Fuel	CHP	Fuel-BAU	Fuel-S	CHP-BAU	CHP-S	Fuel-BAU	Fuel-S	CHP-BAU	CHP-S
Vegetable oil/biodiesel	77	3	97	85	54	32	100	0	80	0
Biogas/biomethane	9	69	3	12	37	60	0	93	20	86
Bioethanol	14	–	0	3	–	–	0	6[b]	–	–
Bioenergy from woody feedstock[a]	0	29	0	0.3	8	8	0	7[c]	0	14

[a] CHP in different systems, Bio-SNG (synthetic natural gas).

[b] Straw based.

[c] Sum of straw-based ethanol and Bio-SNG).

[d] Simulation of the current situation: values for bioenergy production simulated by BENSIM based on capacities including most current data (Naumann et al., 2014; Scheftelowitz et al., 2014; Zeymer et al., 2012).

Table 3
Overall global crop production in M tons in the four scenarios for the years 2010, 2030 and 2050.

	2010	2030				2050			
		Fuel-BAU	Fuel-S	CHP-BAU	CHP-S	Fuel-BAU	Fuel-S	CHP-BAU	CHP-S
Sugar beet and cane	2036	3084	2834	3078	2828	4116	3495	4108	3495
Oilseeds	639	1160	911	1136	894	1981	1373	1953	1373
Wheat	654	977	962	977	962	1498	1310	1499	1310
Coarse grains	1175	1898	1770	1898	1771	2820	2294	2822	2294

Table 4
Expansion of cropland and loss of natural vegetation (forest and other types of vegetation) in 2030 and 2050. LandSHIFT simulation results at a global level, for Brazil and Germany in 1000 km^2. Grazing and urban areas are not shown in the table. In Germany, cropland expands into grassland and areas set aside are taken back into production.

In 1000 km^2	2010	2030				2050			
		Fuel-BAU	Fuel-S	CHP-BAU	CHP-S	Fuel-BAU	Fuel-S	CHP-BAU	CHP-S
Global									
Cropland	13,935	19,732	16,556	19,740	16,596	28,184	23,920	28,271	24,062
Forest	43,231	42,817	43,070	42,819	43,071	40,374	43,039	40,330	43,040
Natural vegetation	54,902	51,398	51,514	51,395	51,499	47,171	46,481	47,151	46,406
Brazil									
Cropland	685	1182	763	1180	763	1976	1124	1993	1137
Forest	4205	4200	4204	4200	4204	3909	4204	3886	4204
Natural vegetation	1256	746	1089	741	1088	458	965	459	955
Germany									
Cropland	94	108	100	123	117	115	100	121	114
Forest	147	147	147	147	147	147	147	147	147
Natural vegetation	22	22	22	22	22	22	22	22	22

scenarios. This can be explained by the scenario assumption that additional biomass production for CHP is limited to territory in Germany (see Section 3.2). Consequently, the slight increase in cropland area in Germany that is simulated in all scenarios is higher in the CHP scenarios. Taking into account imports and exports of agricultural commodities to and from Germany as modeled by MAGNET, it becomes obvious that in the BAU scenarios, the cropland area appropriated in other countries (land footprint) to fulfill the German biomass demands for bioenergy production is almost as high as the total domestic cropland area in Germany. In contrast, the sustainability scenarios assume that all biomass for bioenergy in Germany is produced domestically leaving no direct land footprint outside the country. In this case the direct expansion of cropland is located on existing cropland, causing displacement of grassland and areas that have been set aside are taken back into production. Assuming that mainly wheat is displaced and using modeled trade patterns the sum of land needed for biomass production for bioenergy in Germany and missing wheat outside of Germany is estimated. The total amount of needed land is about 30% lower than in the CHP-scenarios.

5.5. Global consequences of German bioenergy provision

5.5.1. Further processing of the modeling output

The modeled biomass-to-bioenergy flows enable related impacts to be assessed. This is possible, in principle, for different aspects (i.e. resource use, emissions and associated environmental impacts, impacts on national energy infrastructure, risks to food security, biodiversity, soil quality etc.). There are a number of standardized methods to quantify these impacts. Life cycle assessments (LCA) are most commonly used to identify environmental impacts of a product system, especially those on a global scale (e.g. climate change) or regional scale (e.g. acidification). However, although methodological developments are under way, environmental impacts at local scale (e.g. land use-related impacts on biodiversity and soil) are not yet covered in state-of-the-art LCA studies. Therefore, the screening LCAs are complemented by spatially explicit analyses of land-use-related impacts on biodiversity (see Section 5.5.3) as a key concern in the context of increased biomass production (Hennenberg et al., 2010; Immerzeel et al., 2014).

5.5.2. Life cycle environmental impacts

Mass flows and the corresponding final energy provision obtained by coupling MAGNET and BENSIM formed the basis for the assessment of environmental impacts of the future bioenergy chains which covered the entire life cycle from cradle to grave. In addition, changes in soil organic carbon due to land-use changes (LUC), as modeled in LandSHIFT, were used to calculate the corresponding greenhouse gas (GHG) emissions in a spatially explicit way. However, within the scope of the MILESTONES project, no reference or baseline scenario was calculated and therefore, only a simplified calculation of LUC effects was possible. Furthermore, LUCs were only modeled in an exemplary fashion due to the fact that the wood sector and biogas plants are not intrinsically included in MAGNET and thus part of the LUC effects of the CHP scenarios cannot be accounted for within the current version of the modeling framework. Screening life cycle assessments (LCA) were performed for all future bioenergy chains. These were closely in line with the international standards ISO 14040 & 14044 on product life cycle assessment (ISO, 2006).

A system expansion was applied where possible when there were processes with a number of co-products. The same calculation was carried out for all corresponding fossil energy chains. The mixes for electricity, heat and transport fuels were mainly taken from (Nitsch et al., 2012) and remained consistent between the scenarios. Base data was taken from different LCA databases and studies, harmonized and compiled into coherent systems, especially from Knörr et al. (2012), Ecoinvent (2010) and GEMIS (2014), and supplemented by studies on future parameter trends such as Gärtner (2014) and Gärtner et al. (2014).

These screening LCAs were subsequently applied to the final energy output derived by BENSIM (for bioenergy) and (Nitsch et al., 2012) (for fossil energy) in the different scenarios. This quantified the environmental impacts of the energy system and was done in the following way: Since the focus of the case study is on bioenergy, non-biogenic renewable energies (wind power, photovoltaics etc.) were excluded from the assessment. For each year, the total final energy (Table 5, row 1) was defined to be the sum of the final energy from fossil fuels and biomass based on numbers from (Nitsch et al., 2012). The final energy from biomass was provided by BENSIM (Table 5, rows 2–4), substituting fossil energy carriers by up to 45%. However, a considerable share of final energy still has to be provided by fossil energy. Finally, the cumulated environmental impacts (global warming potential, acidification potential and particulate matter emissions) of these energy snapshots (scenarios at a certain point in time) were obtained for the four analyzed scenarios by multiplying the specific environmental impacts with the amount of final energy in the corresponding technology (Table 5, rows 6–11).

Table 5 shows that, for all scenarios, all environmental impacts (in terms of cumulated emissions) associated with the baskets of products decrease over time (see Table 5, rows 6–11). However, this is, to a large extent, due to the decreasing final energy supply from fossil and bioenergy carriers (see Table 5, row 1), which is made possible by the increasing proportion of non-biogenic renewable energy in the system and decreasing demand. Due to the difference in final energy supply, the four scenarios can only be compared *within* each point in time but not *between* 2030 and 2050.

Within the energy snapshots, the *relative* contribution of bioenergy to the overall emissions varies between the environmental impact categories. While less significant in terms of global warming potential (2–12%, except for scenario CHP-S in 2050), bioenergy contributes disproportionately to acidification potential and particulate matter emissions. Here we can observe a *relative* increase over time, at times amounting to more than 50%. In the 2050 CHP-S scenario, for instance, bioenergy makes up roughly three quarters of the acidifying emissions and is responsible for roughly one third of GHG emissions while providing just under 50% of the final energy. These results confirm the well-known fact that bioenergy from dedicated crops typically emits less greenhouse gases (and non-renewable resources) compared to fossil energy carriers, but cause additional burdens in terms of other environmental impacts (Rettenmaier et al., 2010). GHG emissions associated with land-use change (LUC) effects are not included in Table 5 because they could only be determined properly for the FUEL scenarios. This is due to data quality and sector details of the MAGNET model in its current state of development (see also list of limitations and shortcomings in the discussion section of this paper). Calculations for the FUEL scenarios (not shown here since the focus of this paper is rather on the modeling framework itself than on LCA results) indicate that under unfavorable circumstances, land-use change (LUC) effects significantly increase the amount of greenhouse gases emitted from bioenergy pathways, leading to emissions that are comparable to those from fossil energies (Thrän et al., 2015).

In terms of cumulated emissions, the 2050 CHP-S scenario shows the strongest decrease in GHG emissions owing to the fact that power and heat are associated with larger specific GHG emission savings than fuels. In terms of acidification potential, however, the three other scenarios clearly outperform the CHP-S scenario. Due to these conflicting results, it is impossible, from a scientifically objective perspective, to identify one single scenario that is associated with the least amount of environmental impact across *all* impact categories.

5.5.3. Impacts on biodiversity

The highest risks to biodiversity loss relate to the loss of valuable habitats (Groom et al., 2006). Thus, the impact assessment on biodiversity is built upon information on land-use change. This analysis is achieved using the interlinked modeling approach presented in this paper. Information on global production and import patterns from MAGNET, together with disaggregated land use patterns and information on land with high biodiversity value from LandSHIFT, are used to determine global impacts from German bioenergy demands. For each grid cell, we checked if there was a land-use change in terms of cropland replacing a valuable natural land cover. The loss of primary forests and protected areas is assumed to be associated with high risks to biodiversity, and the loss of unmanaged grasslands, wetlands, forests and peatland is associated with medium to high risk. Risks from the conversion of managed grassland can range from low to high, depending greatly on how the grassland was previously managed. Land-use change within already cultivated land is assumed to be of low risk to biodiversity. If a grid cell contains raw material production (e.g. crop commodities), we assess the type of land-use change which took place since 2007. For countries producing a raw material, we add up the volume of raw material associated with a specific land-use change, e.g. primary forest to cropland, natural grassland to cropland, etc. We assume that exported raw materials show the same proportion of land-use change. Based on import flows and domestic use of raw materials (derived from MAGNET) the associated amount of land and its specific land-use change patterns are

Table 5
Trends of final energy from fossil and bioenergy carriers in Germany for the four scenarios in 2010, 2030 and 2050 and the environmental impacts of fossil and biogenic energy provision. For land-use change (LUC) effects, see text.

	2010	2030				2050			
		Fuel-BAU	Fuel-S	CHP-BAU	CHP-S	Fuel-BAU	Fuel-S	CHP-BAU	CHP-S
Final energy (sum of fossil + bioenergy) [PJ/yr]	8028	5269	5269	5269	5269	3239	3239	3239	3239
Consisting of:									
- biofuels [PJ/yr]	129	717	719	0	0	904	994	0	0
- biopower [PJ/yr]	103	39	39	468	562	3	3	543	1124
- bioheat [PJ/yr]	567	202	202	354	373	59	59	204	333
Share of bioenergy [%]	10	18	18	16	18	30	33	23	45
Global warming potential (w/o LUC) [Tg CO_2 eq./yr]	845	486	488	459	452	260	254	229	155
Share of bioenergy [%]	2	6	7	7	10	11	12	7	32
Acidification potential [Gg SO_2 eq./yr]	1708	992	1014	1014	1085	645	682	688	845
Share of bioenergy [%]	14	40	42	38	45	66	71	52	73
Particulate matter emissions [Gg PM10 eq./yr]	1671	913	917	893	892	598	525	627	543
Share of bioenergy [%]	13	35	36	32	35	60	58	49	63

assessed. Such a characteristic for land-use change is illustrated in Table 6 for Germany in 2030 compared to 2007, and for 2050 compared to 2007, where imports to Germany are distinguished between imports from European countries (EU) and countries outside of Europe (non-EU). In the Fuel-BAU scenarios (2030, 2050) and Fuel-S scenario (2030) about two-thirds of the used land already belonged to the low-risk category, i.e. already cultivated land, in 2007. The strongest land-use change patterns occur for unused grassland (up to 3.5 M ha) followed by used grassland (up to 1.3 M ha) and forest (up to 0.7 M ha). The assumed protection of land categories after 2015 in the Fuel-S scenario results in low conversion of forests, peatland, primary forests and protected areas in 2030. In the 2050 Fuel-S scenario almost all bioenergy used in Germany is biogas that has been produced domestically. The area required - about 4 M ha - is much smaller than the land area needed when biomass is imported for biofuel production due to the comparably high productivity of land in Germany and the area efficiency of biogas compared to some biofuels.

6. Communication of findings

The different model results enable us to provide decision makers, who are active in the field of national bioenergy policy, with a comprehensive picture of the four scenarios. It should be noted that these scenarios are extrema. It is important to clearly communicate that these results only represent an interim step towards a more realistic picture of possible bioenergy futures, which need to be concluded from the scenario bundle as a whole. Following this research design, we will have to intensively assess and further develop the scenario results to create support elements for a bioenergy strategy. Three approaches for further processing the scenario results are described in an exemplary fashion below:

- Example 1: Even under extreme scenarios conditions, in terms of environmental impacts, it is impossible, from a scientifically objective perspective, to identify one single scenario which is associated with the least amount of environmental impact across all impact categories. Stationary bioenergy use (for combined heat and power), for example, shows a stronger decrease in GHG emissions but higher emissions affecting acidification potential. This conflict of goals can only be resolved in a political debate in which alternatives to biomass also need to be taken into account. In the power sector, non-biogenic renewables could potentially play a bigger role, whereas in the transport sector (especially aviation), alternatives to biofuels will most likely be very costly.
- Example 2: When assessing the power and transport scenarios, if competing technologies are found in both scenarios (i.e. biodiesel, ethanol from straw and biomethane), we will have to decide whether such robust elements should have a higher relevance in the bioenergy strategy. One relevant finding for these elements is that new technologies using woody biomass as a feedstock for biofuel provision do not achieve a relevant market share until 2050 in all four scenarios. This result leads to two conclusions: (1) there is a need for further investigation, under what conditions biofuels from lignocellulosic material achieve higher market shares and (2) that there is a need for action if food crop based on biofuels should be limited. In this sense, the 7% cap for biofuels produced from food crops (implemented via Directive 2015/1513) is a measure, which is in line with the results of our study. However, from an environmental point of view, this measure is debatable: the bottom line is the land use associated with energy crops cultivation (and thus increasing competition) and not the fact that some of those crops are edible.
- Example 3: Another relevant finding is obtained when answering the question of which national bioenergy strategy under investigation has no effect or only minor effects on risks related to land-use change. Here, it is clearly demonstrated that international agreements on land use and land-use change are much more relevant for the overall environmental impacts of bioenergy use than the differentiated national policy strategies to support biofuels or power generation on a national level. Consequently, the international governance on land use has to be supported intensively from bioenergy supporting nations. In conclusion for national bioenergy strategies, increasing bioenergy from energy crops should only be supported in the longer term once international land-use policies will have improved.

With regard to the intended bioenergy strategies, these findings provide parts and pieces for a bioenergy strategy. In addition to

Table 6
Land-use change in 1000 ha towards cropland as an indicator for biodiversity risks for the Fuel-BAU and Fuel-S scenarios.

Former land category used as cropland	Bioenergy type	Origin	Fuel-BAU (1000 ha)		Fuel-S (1000 ha)	
			2030[a]	2050[b]	2030[a]	2050[b]
Already cultivated land	Biogas	DE	489.6	39.8	806.2	3805.6
Already cultivated land	Biofuels	DE	983.4	1218.1	1115.7	0.0
	Biofuels	Import (EU)	2541.7	3068.3	2237.4	1.2
		Import (non-EU)	4398.4	3445.2	3341.4	0.4
Used grassland	Biofuels	DE	390.6	353.2	277.8	0.0
	Biofuels	Import (EU)	443.3	320.7	111.9	0.0
		Import (non-EU)	315.5	1004.6	399.0	0.0
Unused grassland	Biofuels	DE	5.1	5.0	8.0	0.0
	Biofuels	Import	254.0	448.5	829,0	0.2
		Import (non-EU)	2161.0	3110.5	2605.7	0.2
Wetlands	Biofuels	Import (non-EU)	0.0	0.0	0.0	0.0
Forest	Biofuels	Import (EU)	0.2	64.9	0	0.0
		Import (non-EU)	173.5	647.9	13.5	0.0
Peatland	Biofuels	Import (EU)	3.6	5.0	0.9	0.0
		Import (non-EU)	4.2	10.9	0.1	0.0
Primary forest	Biofuels	Import (non-EU)	1.8	5.3	0.0	0.0
Protected areas	Biofuels	Import (non-EU)	3.2	36.8	0.1	0.0
Total			12,169.1	13,784.9	11,746.8	3807.6

[a] 2030 compared to 2007.
[b] 2050 compared to 2007.

these parts and pieces, modeling findings should also be linked to relevant aspects not or only partly considered in the study (i.e. trends in heat provision from biomass, assessment of land-use change) should be discussed in order to provide transparent and more complete information for decision makers.

7. Discussion

The MILESTONES modeling framework can provide comprehensive information on bioenergy conversion plants, related feedstock markets, and the land where the feedstock is produced. This facilitates the assessment of biomass flows with regard to many different potential environmental impacts along the entire provision chain.

Up to now, this has been the first attempt to design a modeling framework based on system models which explicitly focuses on the national perspective of bioenergy planning. It builds on three well tested sectoral models that are coupled by defined interfaces and use consistent initial conditions. Compared to other approaches, which couple economic, land-use and energy sector models that focus on global aspects (see Popp et al., 2014), the MILESTONES framework allows us to illustrate the specifics of the German policies and regulations in much greater detail. As it also considers cross-scale dependencies between the German bioenergy system and the international biomass trade (e.g. Scholes et al., 2013), it provides a testbed for evaluating national strategies in light of international policy settings, for example with regard to the implementation of protected areas and future biomass demands for food and energy. In the case study, we were able to explore both the effects of national policy making on global land-use change and, vice versa, the effect of declining global land availability on the decision-making processes within the German bioenergy system (selection of technologies). By investigating the relatively simple extreme scenarios, we have demonstrated that the developed approach can be applied to provide crucial information in the development of long-term bioenergy strategies.

The results from the case study made it clear that, on the one hand, the effects from German bioenergy strategies do not affect international market prices, but on the other hand land-use policies on an international level strongly influence the environmental performance of any German bioenergy strategy. This effect is again underlined by the scenario assumption that Germany will increase its biofuel production to a much larger extend than other countries. The conclusion is that the establishment of international governance on land use should be a prior element of a national bioenergy strategy that aims to have a more sustainable use of resources. A second relevant finding is that, in all scenarios, bioenergy production from annual energy crops was more cost-competitive than biofuels from woody sources, even when considering the rather high CO_2 abatement credits. The conclusion for a national strategy is that, if biofuels from woody resources should enter the market, it is necessary to have dedicated market introduction support schemes that are stable over the long term. This is only realistic if there are clear advantages from those fuels in terms of technical and environmental performance, and promising utilization sectors are derived from those advantages (i.e. aviation). Hence, the model results for Germany show that a more specific bioenergy strategy is necessary for the transport sector, which also includes, for example, a dedicated analysis of different transport sectors (public and private road transport, heavy vehicles, aviation, shipping etc.), the related demand on fuel qualities and quantities, the substitution potential from different biofuels, the related environmental and social impact, and the stakeholder-related aspects of market implementation. At the same time, the actual use of woody biomass in heat provision might have a higher strategic relevance than it was assumed when the scenarios were set.

However, there are several limitations and shortcomings of the modeling approach that need to be addressed in future research in order to improve the reliability of the simulation results.

(1) A fundamental challenge for modeling the biomass flows is the fact that many different biomass resources from agriculture, forestry and waste management are suitable for bioenergy provision but market models are only well established for agricultural products. Thus a lot of additional assumptions are necessary to describe the other biomass flows, which decreases the coherence of the results.
(2) Additionally, the ability of the different models to consider and process the many assumptions is limited. For example, MAGNET, as a typical CGE model, does not represent the renewable energy provision in detail. Thus, the developed modeling approach needs more testing in order to understand the relevance of the model-related uncertainties.
(3) With regard to the coupling of BENSIM and MAGNET, the link was restricted to internationally traded energy crops which are the biomass resources most sensitive in terms of future potentials (Chum et al., 2011). For other resources, we had to work with external assumptions, which we assessed through expert knowledge and comprehensive sensitivity analysis (Millinger et al., submitted). While we provided coherent modeled results for internationally traded energy crop related bioenergy, there are still uncertainties surrounding the quality of the results for systems using woody biomass and/or domestic resources.
(4) A more comprehensive assessment of the direct and indirect effects of the modeled biomass flows is necessary to interpret the scenarios. This is especially crucial for land-use change where the displacement of natural land by cropland and pasture can happen both on a regional and global level through the trade of agricultural commodities (see Lambin and Meyfroidt, 2011). Data quality and sector details in MAGNET so far only allowed calculations of LUC-related GHG emissions in the FUEL scenarios. Moreover, the assumption that land-use restrictions are implemented and followed is crucial for the outcomes of our study and it should be assessed whether this is a realistic assumption (see e.g. Andam et al., 2008; Bryngelsson and Lindgren, 2013; Leverington et al., 2010).
(5) Up to now we have used a qualitative approach for model evaluation (4.7). In order to learn more about the dynamics of the modeled system and the robustness of the simulation results, it will be necessary to systematically explore and quantify model uncertainties.

In conclusion, the case study demonstrates that the MILESTONES modeling framework can provide valuable information to support policy makers in designing national bioenergy strategies. Nevertheless, further significant improvements, with respect to both the concept and the software, are required to provide a coherent assessment tool that can also be applied outside the scientific context. This includes the updating of input data, the consideration of a wider range of biomass by model routines, the development of a more sophisticated automated mechanism of model coupling, and the joint assessment of biomass use for power and heat production in combination with the transport sector. Beyond the bioenergy perspective we see a great potential to adapt the modeling framework for identifying robust utilization options for other biomass-based value chains (i.e. bio-materials) in the context of Germany's national bio-economy strategy (BMBF, 2010).

Competing interests

The authors declare that they have no competing interests.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.envsoft.2016.09.005.

Appendix 1

Table A1
Regional aggregation.

MILESTONE framework		GTAP classification (Narayanan et al., 2012)	
Name	Abbreviation	Name	Abbreviation
Oceania	OCE	Australia, New Zealand, Rest of Oceania	aus, nzl, xoc
China+	CHN	China, Hong Kong, Taiwan	chn, hkg, twn
India	ind	India	ind
Japan, Korea	JKO	Japan, Korea	jpn, kor
Pakistan	pak	Pakistan	pak
Thailand, Philippines, Malaysia, Indonesia	SEA	Thailand, Philippines, Malaysia, Indonesia	idn, mys, phl, tha
Rest of Asia	XAS	Mongolia, rest of East Asia, Cambodia, Lao People's Democratic Republic, Singapore, Vietnam, Rest of Southeast Asia, Bangladesh, Nepal, Sri Lanka, rest of South Asia	mng, xea, khm, lao, sgp, vnm, xse, bgd, npl, lka, xsa
Argentina	arg	Argentina	arg
Bolivia	bol	Bolivia	bol
Brazil	bra	Brazil	bra
United States of America	usa	United States of America	usa
Rest of South and Central America	XLA	Chile, Colombia, Ecuador, Paraguay, Peru, Uruguay, Venezuela, Rest of South America, Costa Rica, Guatemala, Honduras, Nicaragua, Panama, El Salvador, Rest of Central America, Caribbean	chl, col, ecu, pry, per, ury, ven, xsm, cri, gtm, hnd, nic, pan, slv, xca, xcb
Rest of North America	XNA	Canada, Mexico, Rest of North America	can, mex, xna
Benelux	BNL	Belgium, Luxembourg, Netherlands	bel, lux, nld
Germany	deu	Germany	deu
France	fra	France	fra
United Kingdom	gbr	United Kingdom	gbr
Italy	ita	Italy	ita
Rest of new European Member States (2004)	NEU	Czech Republic, Hungary, Malta, Slovakia, Slovenia	cyp, cze, hun, mlt, svk, svn
Poland	pol	Poland	pol
Rest of EU15	REU	Austria, Greece, Ireland	aut, grc, irl
EU2 Bulgaria and Romania	ROB	Bulgaria, Romania	bgr, rou
Scandinavia and Baltics	SCA	Denmark, Estonia, Finland, Latvia, Lithuania, Sweden	dnk, est, fin, lva, ltu, swe
Spain and Portugal	SPO	Spain, Portugal	prt, esp
Rest of Europe	XER	Switzerland, Norway, Rest of EFTA, Albania, Belarus, Croatia, Ukraine, Rest of Eastern Europe, Rest of Europe	che, nor, xef, alb, blr, hrv, ukr, xee, xer
Russian Federation	rus	Russian Federation	rus
Rest of the former Soviet Union	XSU	Kazakhstan, Kyrgyzstan, Rest of the former Soviet Union, Armenia, Azerbaijan, Georgia	kaz, kgz, xsu, arm, aze, geo
Western Asia Oil Producers (excluding Iraq)	WAS	Islamic Republic of Iran, Kuwait, Oman, Qatar, Saudi Arabia, United Arab Emirates	irn, kwt, omn, qat, sau, are
Rest of Western Asia	XWS	Bahrain, Israel, Turkey, Rest of Western Asia	bhr, isr, tur, xws
Kenya	ken	Kenya	ken
Mozambique, Ethiopia	MOE	Ethiopia, Mozambique	eth, moz
North Africa	NAF	Egypt, Morocco, Tunisia, Rest of North Africa	egy, mar, tun, xnf
Tanzania	tza	Tanzania	tza
South Africa	zaf	South Africa	zaf
Rest of Sub Saharan Africa	SSA	Cameroon, Ivory Coast, Ghana, Nigeria, Senegal, Benin, Burkina Faso, Togo, Guinea, Rest of Western Africa, Central Africa, South Central Africa, Madagascar, Malawi, Mauritius, Uganda, Zambia, Zimbabwe, Rwanda, Rest of Eastern Africa, Botswana, Namibia, Rest of South African Customs, rest of the world	cmr, civ, gha, nga, sen, ben, bfa, tgo, gin, xwf, xcf, xac, mdg, mwi, mus, uga, zmb, zwe, rwa, xec, bwa, nam, xsc, xtw

Table A2
LUCC DRIVER.

Region	Period	Commodity	Variable	Unit	Scenario	Scenario run
All regions see Table A1	2010 to 2050 in 5-year increments	Wheat, coarse grains, oilseeds, sugar crops, rice and other crops	Yields	t/ha	CHP-BAU, CHP-S, Fuel-BAU, Fuel-S	Only in inital run
All regions see Table A1	2010–2050 in 5-year increments	Pasture	Yield changes	Percentage of change to 2007		Only in inital run
All regions see Table A1	2010 to 2050 in 5-year increments	Wheat, coarse grains, oilseeds, sugar crops, rice and other crops	Production	t		In each iteration
All regions see Table A1	2010–2050 in 5-year increments	Pasture	Production changes	Percentage of change to 2007		In each iteration
All regions see Table A1	2010 to 2050 in 5-year increments	Wheat, coarse grains, oilseeds, sugar crops, rice and other crops, pasture	area	km^2		In each iteration (just for comparison)

Table A3
LUCC RESULTS.

Region	Period	Commodity	Variable	Unit	Scenario	Scenario run
All regions see Table A1	2010 to 2050 in 5-year increments	Wheat, coarse grains, oilseeds, sugar crops, rice and other crops, pasture	Average yields	t/ha	CHP-BAU, CHP-S, Fuel-BAU, Fuel-S	In each iteration
All regions see Table A1	2010 to 2050 in 5-year increments	Wheat, coarse grains, oilseeds, sugar crops, rice and other crops, pasture	Area	km^2		In each iteration (just for comparison)

Table A4
PRICE CHANGES.

Region	Period	Commodity	Variable	Unit	Scenario
Germany	2010 to 2050 in 5-year increments	Wheat, coarse grains, oilseeds, sugar crops	Price	Index with 2007 = 1	CHP-BAU, CHP-S, Fuel-BAU, Fuel-S

Table A5
BIOFUEL DEMANDS.

Region	Period	Variable	Unit	Scenario
Germany	2010 to 2050 in 5-year increments	Crop based biofuel demand	in PJ	CHP-BAU, CHP-S, Fuel-BAU, Fuel-S
Germany	2010 to 2050 in 5-year increments	Land based biofuel demand	in ha	CHP-BAU, CHP-S, Fuel-BAU, Fuel-S

Table A6
Assumptions within the models across scenarios.

		CHP-BAU	Fuel-BAU	CHP-S	Fuel-S
Macroeconomic indicators	Population	Percentage changes up to 2050 based on USDA ERS (2013) for all world regions except Germany, from Destatis (2009)			
	Gross domestic product (GDP)	Percentage changes up to 2050 based on USDA ERS (2013) for all world regions except Germany, from Destatis (2009)			
	World fossil energy price	European Commission (2013)			
	Change in exogenous part of yield for agricultural commodities (= technical progress)	Developed countries 2.5% over 5 years and developing countries 4.5% over 5 years			
Bioenergy policies (MAGNET)	Germany - bioenergy in PJ	From 125 PJ in 2010 to 0 PJ from 2025 onwards	From 125 PJ in 2010 to 900 PJ in 2050	From 125 PJ in 2010 to 0 PJ from 2025 onwards	From 125 PJ in 2010 to 670 PJ in 2035, then decreasing to 0 PJ in 2050
	Germany - land for bioenergy	From 0.9 M ha in 2010 to 3.2 M ha in 2020 to 0.8 M ha in 2050	From 0.9 M ha in 2010 to 1.3 M ha in 2015 to 0.04 M ha in 2050	From 0.9 M ha in 2010 to 3.1 M ha in 2020 to 2.5 M ha in 2040 to 3 M ha in 2050	From 0.9 M ha in 2010 to 1.3 M ha in 2015 to 1.1 M ha in 2050
	Rest of the world - bioenergy in PJ	IINAS (2014) for BAU scenarios.		IINAS (2014) for sustainability scenarios	
	Rest of the world - land for bioenergy	IINAS (2014) for BAU scenarios.		IINAS (2014) for sustainability scenarios	
Bioenergy policies (BENSIM)	Germany – available biomass for bioenergy	Aggregate biomass potential with deduced projections for the not simulated sector in the respective scenarios, based on AGEE-Stat (2013) and Nitsch et al. (2012), see Fig. 2.			
	CO_2-costs	Ca. exponential towards 100€/t in 2050	Ca. logarithmic towards 100€/t in 2050	Ca. exponential towards 100€/t in 2050	Ca. logarithmic towards 100€/t in 2050

Table A6 (*continued*)

		CHP-BAU	Fuel-BAU	CHP-S	Fuel-S
	Exogenous (Research & Development) investment cost reductions (for years of no capacity expansion of the respective technologies)	One learning rate (e.g. 2–10% reduction depending on technology) in 10 years		One learning rate (e.g. 2–10% reduction depending on technology) in 3 years.	
Land-use policies (MAGNET, LandSHIFT)		Protected area, rest of the world	Protected areas (WDPA, 2012) in countries with a low corruption index.		Protected areas excluded from LUCC (WDPA, 2012).
		Forest protection	Germany: no deforestation ROW: Deforestation allowed		Full protection of primary forests (Potapov et al., 2008), no deforestation allowed
		Soil protection	Not considered		Exclusion of land with high risk of degradation (Tóth et al., 2012)
		Wetland protection	Not considered		Exclusion from wetlands (Lehner and Döll, 2004) from LUCC.
		Aichi target 11	Not considered		17% of total territory of each world region protected.
		Grassland	No restrictions		Must not be ploughed up from 2020 onwards in the European Union.

Table A7
Biofuel demand and maximal available area for agriculture – assumptions in MAGNET for the various scenarios.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Germany - biofuel demand in PJ									
Fuel-BAU	125	291	326	436	651	822	852	881	901
Fuel-S	125	291	326	471	629	673	584	383	0
CHP-BAU	125	167	83	0	0	0	0	0	0
CHP-S	125	167	83	0	0	0	0	0	0
Germany - available area for crop production in Million hectare									
Fuel-BAU	15.5	15.0	15.1	15.3	15.9	16.2	16.3	16.3	16.3
Fuel-S	15.5	15.0	15.1	15.3	15.6	15.5	15.0	14.2	12.6
CHP-BAU	15.5	13.4	13.1	13.3	13.5	13.8	14.3	15.1	15.6
CHP-S	15.5	13.4	13.2	13.3	13.2	13.0	12.4	11.8	12.1
Rest of the world (excluding Germany) - biofuel demand in PJ									
Fuel-BAU and CHP-BAU	2262	3070	3865	4639	5318	6141	6772	7410	7887
Fuel-S and CHP-S	2262	3389	4386	5237	4762	4100	3642	3406	2921
Rest of the world (excluding Germany) - available area for crop production in Billion hectare									
Fuel-BAU and CHP-BAU	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1
Fuel-S and CHP-S	10.1	10.1	10.1	7.2	7.2	7.2	7.2	7.1	7.1

References

AGEE-Stat (Ed.), 2013. Zeitreihen zur Entwicklung der erneuerbaren Energien in Deutschland.

Alcamo, J., Schaldach, R., Koch, J., Koelking, C., Lapola, D., Priess, J., 2011. Evaluation of an integrated land use change model including a scenario analysis of land use change for continental Africa. Environ. Model. Softw. ISSN: 1364-8152 26 (No. 8), 1017–1027. http://dx.doi.org/10.1016/j.envsoft.2011.03.002.

Andam, K.S., Ferraro, P.J., Pfaff, A., Sanchez-Azofeifa, G.A., Robalino, J.A., 2008. Measuring the effectiveness of protected area networks in reducing deforestation. Proc. Natl. Acad. Sci. 105 (No. 42), 16089–16094. http://dx.doi.org/10.1073/pnas.0800437105. ISSN 0027-8424, 1091-6490.

Banse, M., van Meijl, H., Tabeau, A., Woltjer, G., 2008. Will EU biofuel policies affect global agricultural markets? Eur. Rev. Agric. Econ. 35 (No. 2), 117–141. http://dx.doi.org/10.1093/erae/jbn023.

Bennett, N.D., Croke, B.F., Guariso, G., Guillaume, J.H., Hamilton, S.H., Jakeman, et al., 2013. Characterising performance of environmental models. Environ. Model. Softw. 40, 1–20.

BMBF, 2010. Nationale Forschungsstrategie BioÖkonomie 2030-Unser Weg zu einer bio-basierten Wirtschaft. Federal Ministry of Education and Research (BMBF), Berlin.

BMELV/BMU, 2010. Nationaler Biomasseaktionsplan für Deutschland. Beitrag der Biomasse für eine nachhaltige Energieversorgung.

BMU, 2009. Leitszenario 2009-Langfristszenarien und Strategien für den Ausbau erneuerbarer Energien in Deutschland. BMU, Berlin.

BMVBS (Ed.), 2013. Die Mobilitäts- und Kraftstoffstrategie der Bundesregierung (MKS). Bundesministerium für Verkehr, Bau und Stadtentwicklung.

Bouwman, A.F., Kram, T., Klein Goldewijk, K., 2006. Integrated Modelling of Global Environmental Change: an Overview of IMAGE 2.4. Netherlands Environmental Assessment Agency (MNP), Bilthoven, The Netherlands.

Bryngelsson, D.K., Lindgren, K., 2013. Why large-scale bioenergy production on marginal land is unfeasible: a conceptual partial equilibrium analysis. Energy Policy. ISSN: 0301-4215 55, 454–466. http://dx.doi.org/10.1016/j.enpol.2012.12.036.

Cherubini, F., Strømman, A.H., 2011. Life cycle assessment of bioenergy systems: state of the art and future challenges. Bioresour. Technol. ISSN: 09608524 102 (No. 2), 437–451. http://dx.doi.org/10.1016/j.biortech.2010.08.010.

Chum, H., Faaij, A., Moreira, J., Berndes, G., Dhamija, P., Dong, H., Gabrielle, B., Goss Eng, A., Lucht, Wolfgang, Mapako, M., Masera Cerutti, O., McIntyre, T., Minowa, T., Pingoud, K., 2011. Bioenergy. In: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge/New York.

Clarke, L., Edmonds, H.J., Pitcher, H., Reilly, J., Richels, R., 2007. Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations. Sub-report 2.1 a of Synthesis and Assessment Product 2.1 by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Department of Energy, Office of Biological & Environmental Research, Washington, D.C., USA.

Destatis, 2009. Bevölkerung Deutschlands bis 2060-12. koordinierte Bevölkerungsvorausberechnung. Statistisches Bundesamt, Wiesbaden. www.destatis.de.

EC, 2013. On 16 October 2013 the European Parliament Intergroup on "Climate Change, Biodiversity and Sustainable Development" Held a Workshop Entitled "The Future of Biofuels as Alternative Fuel for the Transport Sector".

Ecoinvent, 2010. Ecoinvent data v2.2 – Ökoinventare für Energiesysteme. ESU-services, Uster (Schweiz).

Eickhout, B., van Meijl, H., Tabeau, A., Stehfest, E., 2009. The impact of environmental and climate constraints on global food supply. In: Hertel, T.W., Steven, K.R., Tol, R.S.J. (Eds.), Economic Analysis of Land Use in Global Climate

Change Policy, pp. 206–234. ISSN 978-1-135-97883-9.

Eisentraut, A., Brown, A., 2014. HEATING WITHOUT GLOBAL WARMING - Market Developments and Policy Considerations for Renewable Heat. International Energy Agency, Paris Cedex, France.

European Commission (Ed.), 2013. EU Energy, Transport and GHG Emissions Trends to 2050, ISBN 978-92-79-33728-4.

FAO, 2013. Statistical Database. Retrieved on 31.03.2014 from. http://faostat3.fao.org/home/E.

Gärtner, S., 2014. Ansätze zu den Entwicklungen hinsichtlich der Energieeffizienz und der Emissionen in den Konversionstechnologien. Erläuterung der Ökobilanzdaten für die Bereitstellung von Bioenergie bis zum Jahr 2050. ifeu – Institut für Energie- und Umweltforschung Heidelberg GmbH.

Gärtner, S., Cornelius, C., Müller-Lindenlauf, M., 2014. Ansätze zu den Entwicklungen in der Landwirtschaft. Erläuterung der Ökobilanzdaten für die Bereitstellung von Biomasse bis zum Jahr 2050. ifeu– Institut für Energie- und Umweltforschung Heidelberg gGmbH.

GEMIS, 2014. Globales Emissions-modell Integrierter Systeme. Öko-Institut, Darmstadt. http://www.iinas.org/gemis-de.html.

Groom, M.J., Meffe, G.K., Carroll, C.R., 2006. Principles of Conservation Biology, 3 edition. Sinauer Associates, Sunderland, Mass, ISBN 978-0-87893-518-5.

Hamilton, S.H., ElSawah, S., Guillaume, J.H.A., Jakeman, A.J., Pierce, S.A., 2015. Integrated assessment and modelling: overview and synthesis of salient dimensions. Environ. Model. Softw. 64, 215–229.

Hennenberg, K.J., Dragisic, C., Haye, S., Hewson, J., Semroc, B., Savy, C., Wiegmann, K., Fehrenbach, H., Fritsche, U.R., 2010. The power of bioenergy-related standards to protect biodiversity. Conserv. Biol. ISSN: 1523-1739 24 (No. 2), 412–423. http://dx.doi.org/10.1111/j.1523-1739.2009.01380.x.

Humpenöder, F., Schaldach, R., Cikovani, Y., Schebek, L., 2013. Effects of land-use change on the carbon balance of 1st generation biofuels: an analysis for the European Union combining spatial modeling and LCA. Biomass Bioenergy. ISSN: 0961-9534 56, 166–178. http://dx.doi.org/10.1016/j.biombioe.2013.05.003.

IEA, 2014. Energy Technology Perspectives 2014-Harnessing Electricity's Potential (ETP 2014). International Energy Agency, ISBN 978-92-64-20800-1.

IFEU, 2015. Own Data and Calculations.

IINAS, 2014. Datenzusammenstellung zu Biokraftstoffen auf Basis der IEA Energy Technology Perspectives 2014 für das Vorhaben “Meilensteine 2030”. Darmstadt.

Immerzeel, D.J., Verweij, P.A., van der Hilst, F., Faaij, A.P.C., 2014. Biodiversity impacts of bioenergy crop production: a state-of-the-art review. GCB Bioenergy. ISSN: 1757-1707 6 (No. 3), 183–209. http://dx.doi.org/10.1111/gcbb.12067.

Inderwildi, O.R., King, D.A., 2009. Quo vadis biofuels? Energy & Environ. Sci. 2 (No. 4), 343. http://dx.doi.org/10.1039/b822951c. ISSN 1754-5692, 1754-5706.

ISO, 2006. ISO Norms 14040:2006 (E) & 14044:2006 (E), Environmental Management – Life Cycle Assessment – Requirements and Guidelines. International Organization for Standardization, Geneva, Switzerland.

Jakeman, A.J., Letcher, R.A., Norton, J.P., 2006. Ten iterative steps in development and evaluation of environmental models. Environ. Model. Softw. ISSN: 1364-8152 21 (No. 5), 602–614. http://dx.doi.org/10.1016/j.envsoft.2006.01.004.

Knörr, W., Heidt, C., Schacht, A., 2012. Aktualisierung “Daten- und Rechenmodell: Energieverbrauch und Schadstoffemissionen des motorisierten Verkehrs in Deutschland 1960–2030” (TREMOD, Version 5.3) für die Emissionsberichterstattung 2013 (Berichtsperiode 1990–2011).

Laborde, D., 2011. Assessing the Land Use Change Consequences of European Biofuel Policies. Final Report. International Food Policy Institute (IFPRI).

Lambin, E.F., Meyfroidt, P., 2011. Global land use change, economic globalization, and the looming land scarcity. Proc. Natl. Acad. Sci. 108 (No. 9), 3465–3472. http://dx.doi.org/10.1073/pnas.1100480108. ISSN 0027-8424, 1091-6490.

Lehner, B., Döll, P., 2004. Development and validation of a global database of lakes, reservoirs and wetlands. J. Hydrol. 296/1–4, 1–22.

Leverington, F., Costa, K.L., Pavese, H., Lisle, A., Hockings, M., 2010. A global analysis of protected area management effectiveness. Environ. Manag. 46 (No. 5), 685–698. http://dx.doi.org/10.1007/s00267-010-9564-5. ISSN 0364-152X, 1432-1009.

Magliocca, N.R., van Vliet, J., Brown, C., Evans, T.P., Houet, T., Messerli, P., Messina, J.P., Nicholas, K.A., Ornetsmüller, C., Sagebiel, J., Schweizer, V., Verburg, P.H., Yu, Q., 2015. From meta-studies to modeling: using synthesis knowledge to build broadly applicable process-based land change models. Environ. Model. Softw. ISSN: 1364-8152 72, 10–20. http://dx.doi.org/10.1016/j.envsoft.2015.06.009.

Millinger, M., Thrän, D., 2016. Energy Crop Costs and Biofuel Competition in Germany (Unpublished) submitted to Journal of Cleaner Production.

Millinger, M., Arendt, O., Ponitka, J., Thrän, D., 2015. On Future Competitiveness of Advanced and Conventional Biofuels: Results from Least-cost Modelling of Biofuel Competition in Germany (Unpublished) submitted to Chemical Engineering Technology.

Narayanan, B., Aguiar, A., McDougall, R., 2012. Global Trade, Assistance, and Production: the GTAP 8 Data Base. Center for Global Trade Analysis. Purdue University.

Naumann, K., Oehmichen, K., Zeymer, M., Meisel, K., 2014. Monitoring Biokraftstoffsektor. DBFZ Deutsches Biomasseforschungszentrum gemeinnützige GmbH, Leipzig. ISBN 2197-4632.

Nitsch, J., 2008. Leitstudie 2008-Weiterentwicklung der Ausbaustrategie Erneuerbare Energien. BMU, DLR, Berlin.

Nitsch, J., Pregger, T., Scholz, Y., Naegler, T., Sterner, M., Gerhardt, N., von Oehsen, A., Pape, C., Saint-Drenan, Y.-M., Wenzel, B., 2010. Leitstudie 2010-Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global. BMU, DLR,IWES, IfnE.

Nitsch, J., Pregger, T., Naegler, T., Heide, D., de Tena, D.L., Trieb, F., Scholz, Y., Nienhaus, K., Gerhardt, N., Sterner, M., Trost, T., Oehsen, A., Schwinn, R., Pape, C., Hahn, H., Wickert, M., Wenzel, B., 2012. Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global - Schlussbericht. DLR, IWES, IFNE.

OECD/IEA, 2011. Technology Roadmap - Biofuels for Transport. International Energy Agency, Paris.

Parker, P., Letcher, R., Jakeman, A., Beck, M.B., Harris, G., Argent, R.M., Sullivan, P., 2002. Progress in integrated assessment and modelling. Environ. Model. Softw. 17 (3), 209–217.

Popp, A., Dietrich, J.P., Lotze-Campen, H., Klein, D., Bauer, N., Krause, M., Beringer, T., Gerten, D., Edenhofer, O., 2011. The economic potential of bioenergy for climate change mitigation with special attention given to implications for the land system. Environ. Res. Lett. ISSN: 1748-9326 6 (No. 3), 034017. http://dx.doi.org/10.1088/1748-9326/6/3/034017.

Popp, A., Rose, S.K., Calvin, K., Vuuren, D.P.V., Dietrich, J.P., Wise, M., Stehfest, E., Humpenöder, F., Kyle, P., Vliet, J.V., Bauer, N., Lotze-Campen, H., Klein, D., Kriegler, E., 2014. Land-use transition for bioenergy and climate stabilization: model comparison of drivers, impacts and interactions with other land use based mitigation options. Clim. Change 123 (No. 3–4), 495–509. http://dx.doi.org/10.1007/s10584-013-0926-x. ISSN 0165-0009, 1573-1480.

Potapov, P., Yaroshenko, A., Turubanova, S., Dubinin, M., Laestadius, L., Thies, C., Aksenov, D., Egorov, A., Yesipova, Y., Glushkov, I., Karpachevskiy, M., Kostikova, A., Manisha, A., Tsybikova, E., Zhuravleva, I., 2008. Mapping the world's intact forest landscapes by remote sensing. Ecol. Soc. 13 (2).

REN21, 2014. Renewables 2014 Global Status Report (Paris: REN21 Secretariat).

Rettenmaier, N., Köppen, S., Gärtner, S.O., Reinhardt, G.A., 2010. Life cycle assessment of selected future energy crops for Europe. Biofuels Bioprod. Biorefin. ISSN: 1932-1031 4 (No. 6), 620–636. http://dx.doi.org/10.1002/bbb.245.

Schaldach, R., Alcamo, J., Koch, J., Koelking, C., Lapola, D.M., Schuengel, J., Priess, J.A., 2011. An integrated approach to modelling land-use change on continental and global scales. Environ. Model. Softw. ISSN: 1364-8152 26 (No. 8), 1041–1051. http://dx.doi.org/10.1016/j.envsoft.2011.02.013.

Scheftelowitz, M., Thrän, D., Hennig, C., Krautz, A., Lenz, V., Liebetrau, J., Daniel-Gromke, J., Denysenko, V., Hillebrand, K., Naumann, K., Rensberg, N., Stinner, W., 2014. Entwicklung der Förderung der Stromerzeugung aus Biomasse im Rahmen des EEG. DBFZ Report Nr. 21. DBFZ Deutsches Biomasseforschungszentrum gemeinnützige GmbH, Leipzig. ISBN 2197-4632, (Online), 2190–7643 (print).

Schlesinger, M., Lindenberger, D., Lutz, C., 2010. Energieszenarien für ein Energiekonzept der Bundesregierung. Prognos AG, EWI, GWS, Köln.

Scholes, R., Reyers, B., Biggs, R., Spierenburg, M., Duriappah, A., 2013. Multi-scale and cross-scale assessments of social-ecological systems and their ecosystem services. Curr. Opin. Environ. Sustain. ISSN: 1877-3435 5 (No. 1), 16–25. http://dx.doi.org/10.1016/j.cosust.2013.01.004.

Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E.A., Haberl, H., Harper, R., House, J., Jafari, M., Masera, O., Mbow, C., Ravindranath, N.H., Rice, C.W., Robledo Abad, C., Romanovskaya, A., Sperling, F., Tubiello, F.N., 2014. Agriculture, forestry and other land use (AFOLU). In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge. United Kingdom and New York, NY, USA.

Thrän, D., Pfeiffer, D., Brosowski, A., Fischer, E., Herrmann, A., Majer, S., Oehmichen, K., Schmersahl, R., Schröder, T., Stecher, K., Stinner, W., Zeller, V., Zeymer, M., Ciroth, A., Zschunke, T., Fritsche, U.R., Hennenberg, K., Gödeke, K., 2013. Methodenhandbuch Stoffstromorientierte Bilanzierung der Klimagaseffekte. DBFZ, Leipzig. ISBN 2192-1806.

Thrän, D., Arendt, O., Ponitka, J., Braun, J., Millinger, M., Wolf, V., Banse, M., Schaldach, R., Schüngel, J., Gärtner, S., Rettenmaier, N., Hünecke, K., Hennenberg, K., Wern, B., Baur, F., Fritsche, U., Gress, H.-W., 2015. Meilensteine 2030-Elemente und Meilensteine für die Entwicklung einer tragfähigen und nachhaltigen Bioenergiestrategie. In: Thrän, D., Pfeiffer, D. (Eds.), Schriftenreihe des Förderprogramms “Energetische Biomassenutzung”, vol. 18. ISBN 2199-2762.

Tittensor, D.P., Walpole, M., Hill, S.L., Boyce, D.G., Britten, G.L., Burgess, N.D., et al., 2014. A mid-term analysis of progress toward international biodiversity targets. Science 346 (6206), 241–244.

Tóth, G., Kozlowski, B., Prieler, S., Wiberg, D., 2012. Global Agro-ecological Zones (GAEZ v3.0), GAEZ Data Portal, User's Guide [online] URL: http://www.gaez.iiasa.ac.at/docs/GAEZ_User_Guide.pdf.

UNEP, 2012. Land. In: The Fifth Global Environmental Outlook Report.

USDA ERS, 2013. USDA ERS - International Macroeconomic Data Set (accessed 24.09.13.). http://www.ers.usda.gov/data-products/international-macroeconomic-data-set.aspx#26198.

van der Hilst, F., Lesschen, J.P., van Dam, J.M.C., Riksen, M., Verweij, P.A., Sanders, J.P.M., Faaij, A.P.C., 2012. Spatial variation of environmental impacts of regional biomass chains. Renew. Sustain. Energy Rev. ISSN: 1364-0321 16 (No. 4), 2053–2069. http://dx.doi.org/10.1016/j.rser.2012.01.027.

van Renssen, S., 2011. A biofuel conundrum. Nat. Clim. Change. ISSN: 1758-678X 1 (No. 8), 389–390. http://dx.doi.org/10.1038/nclimate1265.

WDPA Consortium, 2012. World Database on Protected Areas [online] URL: http://www.iucn.org/about/work/programmes/gpap_home/gpap_biodiversity/gpap_ wdpa/.

Woltjer, G., Kuiper, M., Kavallari, A., van Meijl, H., Powell, J., Rutten, M., Shutes, L., Tabeau, A., 2014. The MAGNET Model - Module Description. LEI Wageningen UR, Wageningen.

Zeymer, M., Herrmann, A., Oehmichen, K., Schmersahl, R., 2012. Bundesmessprogramm zur Weiterentwicklung der kleintechnischen Biomassevergasung. No. 3430002. DBFZ, im Auftrag des Bundesministeriums für Umwelt. Naturschutz und Reaktorsicherheit, Leipzig.