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Article

Uncertainty of biomass contributions from agriculture and forestry to renewable energy resources under climate change

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Abstract

In the future, Germany's land-use policies and the impacts of climate change on yields will affect the amount of biomass available for energy production. We used recent published data on biomass potentials in the federal states of Germany to assess the uncertainty caused by climate change effects in the potential supply of biomass available for energy production. In this study we selected three climate scenarios representing the maximum, mean and minimum temperature increase for Germany out of 21 *CMIP5*-projections driven by the Representative Concentration Pathways (*RCP*) 8.5 scenario. Each of the three selected projections was downscaled using the regional statistical climate model *STARS*. We analysed the yield changes of four biomass feedstock crops (forest, short-rotation coppices (SRC), cereal straw (winter wheat) and energy maize) for the period 2031–2060 in comparison to 1981–2010. The mean annual yield changes of energy wood from forest and short-rotation coppices were modelled using the process-based forest growth model *4C*. The yield changes of winter wheat and energy maize from agricultural production were simulated with the statistical yield model *IRMA*. Germany's annual biomass potential of 1500 PJ varies between minus 5 % and plus 8 % depending on the climate scenario realisation. Assuming that 1500 PJ of biomass utilisation can be achieved, climate change effects of minus 75 (5 %) PJ or plus 120 (8 %) PJ do not impede overall bioenergy targets of 1287 PJ in 2020 and 1534 PJ in 2050. In five federal states the climate scenarios lead to decreasing yields of energy maize and winter wheat. Impacts of climate scenarios on forest yields are mainly positive and show both positive and negative effects on yields of SRC.

Keywords: Climate change, uncertainty, biomass yields, bioenergy potential, scenario

1 Introduction

Climate change is one of the greatest challenges facing mankind in the coming decades. Reducing carbon dioxide emissions – the main driver of climate change – will only be successful if energy can be supplied at a level of global emissions much lower than the 67.2 Gt fossil-fuel-related CO_2 emissions produced in 2010 (Boden et al., 2013). Securing energy supplies on a sustainable basis, in line with climate mitigation targets, is a target of Germany's government (Bmwi, 2011). The government's energy concept ascribes bioenergy a significant role alongside other energy generation techniques such as hydro power and wind power (see Koch et al. (2015)). Two main advantages of bioenergy highlighted by the energy concept are the wide range of its applications and its storage ability. One objective of this concept is to better exploit the biomass potential of Germany in order to benefit from its mitigation potential (Dhillon and von Wuehlisch, 2013). Besides energy consumption, land-use change is another main source of greenhouse gas emissions (Jain et al., 2013). In this light there is increasing responsibility to optimise food production and efficient green energy generation, in the form of down-streamed use of by-products and residues like slash wood from forests, straw from cereal production and harvested material from energy crops (i.e. maize, biomass from short-rotation coppices) (Schulze et al., 2012).

The biomass potentials of different sectors in Germany have been estimated by a number of studies in the past (Aretz and Hirschl, 2007; Lasch et al., 2010; Dunger and Rock, 2009; Thrän et al., 2011; Kaltschmitt, 2011). Recently, the Renewable Energies Agency (Aee, 2013) published an extensive summary of bioenergy potential for each of the federal states of Germany (below only the term "state" is used) based on a study by Dbfz (2010). This report calculates the technical potential of several bioenergy feedstocks on the basis of a land-use scenario for 2020. Future land-use is a key issue since using land for energy production often conflicts with other ecosystem services such as food production and biodiversity conservation (Koh and Ghazoul, 2008; Ajanovic, 2010; Dale et al., 2010; Mueller et al., 2012; Lamers et al., 2013). The study explicitly considers the limits to the amount of land available to produce energy feedstocks (Dbfz, 2010).

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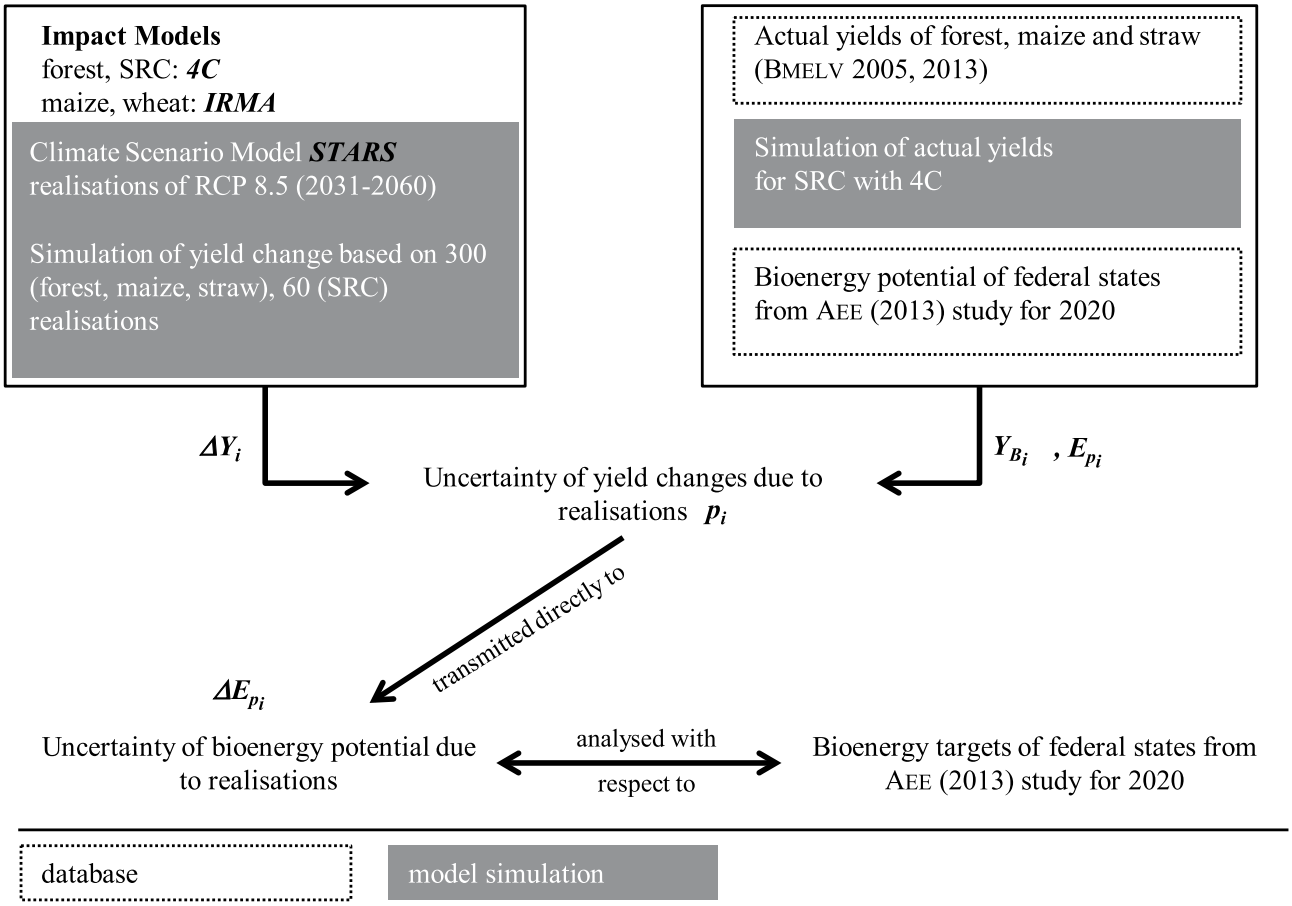

Figure 1: Methodological approach of the analysis.

It also discusses different management options to avoid counter effects (ZANCHI et al., 2012; ZONA et al., 2013) and to optimise trade-offs between climate mitigation objectives and maximum energy yields (LIPPKE et al., 2011; POUDEL et al., 2011; ROUTA et al., 2012). On the other hand, climate change itself has the potential to alter the technical potential of biomass. Depending on future climate conditions, the growth of trees, maize, cereals and other potential biomass feedstocks and consequently their yield will change (WOLF and VANDIEPEN, 1995; JAGGARD et al., 2010; LASCH-BORN et al., 2015).

In our study, we aggregate the analyses of climate scenario effects on different kinds of agricultural and forest species (GERSTENGARBE et al., 2015; LASCH-BORN et al., 2015) to get insights into their importance in terms of bioenergy potential. Our analysis aims at quantifying possible climate-change-induced variation of reported bioenergy potential for Germany's states. Thus, we do not consider different land-use scenarios or management strategies. We analyse the range of bioenergy yields based on a set of regional climate scenario realisations of the Representative Concentration Pathways (*RCP*) 8.5 scenario in the context of reported energy potentials and targets of the states. The main question we address is whether the energy targets on national and state levels for 2020 and later will be at risk under climate change according to *RCP* 8.5 by the middle of this century.

2 Data and methods

The analysis consists of two main parts. The first part encompasses a review of the data concerning actual yields of bioenergy feedstocks (baseline yields, Y_B) and bioenergy potentials (E_P) of the states in 2020 (AEE, 2013). The second part combines the bioenergy potentials with model simulations of future yield changes (ΔY) of the four considered bioenergy feedstocks (i = *forest*, *short-rotation coppices (SRC)*, *maize*, *straw*). The yield changes in terms of absolute change of dry matter (DM) production are used to calculate relative changes (p) from baseline yields. These relative changes are transmitted directly to relative changes of bioenergy potentials in 2020 (ΔE_p) based on the values given in AEE (2013). This approach, using only simulated yield changes, allows a robust estimation of the climate-induced uncertainty considering existing bioenergy scenarios with reliable potentials and baseline yields. The different working steps of the analysis and used data are summarised in Fig. 1.

Table 1: land-use, yield and bioenergy potential used in this study. Land-use [$\times 10^3$ ha], bioenergy potentials and targets [TJ] are from AEE (2013) and THRÄN et al. (2011) (SRC). Yields [tDM ha^{-1} year^{-1}] are from literature review (BMELV, 2005; BMELV, 2013) and own calculations (SRC).

	Federal state	Land-use 2011				Yield 2006–2011				Potential 2020					Target 2020
		Forest	SRC	Maize	Straw	Forest	SRC	Maize	Straw	Forest	SRC	Maize	Straw	total	
SH	Schleswig-Holstein	165.7	9.9	194.0	292.6	4.62	5.14	13.06	8.03	9072	957	31402	6456	47887	33000
NI	Lower Saxony	1033.9	28.3	515.3	776.8	4.60	5.36	16.01	6.88	42972	2859	75798	14953	136582	68750
NW	North Rhine-Westphalia	873.2	16.2	177.0	520.5	5.31	5.63	16.47	7.25	27266	1715	42403	9659	81043	37367
HE	Hesse	847.3	7.4	38.2	299.7	5.16	5.35	17.56	6.87	45540	744	24832	5194	76310	86450
RP	Rhineland-Palatinate	833.0	6.0	30.7	230.3	5.21	5.41	16.22	6.09	35329	613	16787	3552	56281	139000
BW	Baden-Württemberg	1368.8	12.7	109.1	451.8	5.74	6.50	16.31	5.44	71597	1552	30821	7539	111509	114000
BY	Bavaria	2472.0	31.6	399.4	1049.3	5.90	5.88	17.75	6.14	139650	3498	90496	16080	249724	163150
SL	Saarland	87.0	0.6	3.7	21.6	5.12	5.78	15.58	5.67	5535	62	2064	347	8008	8000
BB	Brandenburg	1045.1	15.7	165.4	485.5	3.93	5.04	11.37	4.74	40980	1493	37620	7589	87682	80556
MV	Mecklenburg-Vorpommern	503.2	16.5	155.2	564.5	4.51	5.25	12.50	6.58	25368	1631	57866	11021	95886	64294
SN	Saxony	500.7	20.8	74.6	383.8	4.76	5.55	14.28	6.19	26541	2172	34225	4863	67801	9000
ST	Saxony-Anhalt	498.5	15.1	113.2	549.7	4.33	5.90	13.17	6.67	25323	1684	45681	9338	82026	5000
TH	Thuringia	516.2	9.3	51.9	373.4	4.56	5.36	14.70	6.54	16266	940	31932	6530	55668	45006
G	Germany	10744.6	190.0	2027.7	5999.5	4.90	5.55	15.00	6.39	511439	19920	521927	103121	1156407	853572

2.1 Data

Land-use data

In our study we focus on bioenergy production from the silvicultural and agricultural land-use sector. The actual shares of the different land-use classes and different agricultural crops are taken from the official statistics of the federal agriculture ministry BMELV (2013) and a recently published study at the state level (DBFZ, 2010; AEE, 2013) (Tab. 1), except for short-rotation coppice plantations (SRC). Currently, only a small portion of arable land area used for SRC in Germany. Hence, following the approach of THRÄN et al. (2011), we develop a hypothetical land-use scenario with 190,000 ha SRC both for the present day and for the year 2020 for Germany as a whole. The distribution of the total SRC area among the states is based on their ratio of agricultural land to total agricultural land of Germany.

Baseline yield data

For the forest sector the average yields of the states stem from a study which is based on the second national forest inventory (*BWI*^{2}) in 2002 (BMELV, 2005) and estimates the mean annual stem increment for the period 2008–2012 (*Holzaufkommensmodellierung (HAM)*[1], BMELV (2005) (Tab. 1). The values are given in cubic metres per hectare per year and are divided by 2 to get tonnes dry matter per hectare per year. We choose the overall parameter 0.5 [g cm^{-3}] for wood density, due to lacking information about the tree species composition of the estimated mean annual stem increment. The conversion from dry matter to the technical energy potential is based on the heat value and is 18.8 [MJ kg DM^{-1}].

[1] 1HAM = Projection modelling of forest development and timber harvesting potential

As with area information, there is currently no information about average yields of SRC. We therefore calculate the average yield for the states with the process-based forest growth model *4C* (LASCH-BORN et al., 2015) (Tab. 1). The simulation concept for SRC plantations is described later in Section 2.2.

The annual statistics of the federal ministry BMELV (2013) for maize yields and different types of cereal yields are used. We select the mean yield of silage maize and for all reported types of grain yields excluding maize to represent straw for the period 2006–2011 (Tab. 1). In the case of straw yields we have to make two assumptions:

1. The ratio of straw to grain yield is one (data are only given for grain mass).
2. 20 % of straw yield is available for bioenergy, since the main part remains in the field (DBFZ, 2010).

The conversion factor for the energy potential is 17.2 for straw and 18.21 [MJ kg DM^{-1}] for maize.

Data for estimating bioenergy potentials and bioenergy targets in 2020

The data for the state-specific bioenergy potentials and targets for 2020 are derived from the study carried out by the Agency of Renewable Energy (AEE, 2013) (Tab. 1). One general problem exists since the targets for 2020 are given as ultimate energy consumption (after conversion) and not as primary energy potential. To allow comparisons between bioenergy potentials (without considering losses due to energy transformation) and targets we use a conversion factor. The ratio between ultimate and primary bioenergy is 0.72 based on data given in NITSCH et al. (2010) (p.45).

The estimated bioenergy potential of present-day land use is simply the average yield of the four bioenergy feedstocks multiplied by the current area. In the

Table 2: The annual statistics of used daily climate data (observed and scenario data) for the states (Gerstengarbe et al., 2015). Minimum/maximum are calculated on the base of the 100 realisation of each temperature scenario (low, medium, high). T=mean annual temperature [°C], P=mean annual precipitation sum [mm], R=mean annual radiation [J cm^{-2}].

state	Base 1981–2010			RCP 8.5 low 2031–2060						RCP 8.5 medium 2031–2060						RCP 8.5 high 2031–2060					
	T	P	R	T		P		R		T		P		R		T		P		R	
	mean	mean	mean	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max
SH	9.0	817	972	9.7	9.9	785	858	990	1016	10.1	10.5	770	838	1002	1030	10.5	10.8	763	809	1025	1048
NI	9.4	760	966	10.3	10.5	711	787	986	1017	10.8	11.2	720	769	1004	1031	11.3	11.6	714	757	1026	1053
NW	9.7	878	981	10.6	10.8	807	904	1006	1035	11.2	11.6	820	886	1021	1050	11.8	12.0	821	872	1036	1071
HE	9.2	753	999	10.2	10.3	687	780	1020	1048	10.8	11.1	709	776	1038	1075	11.4	11.6	720	758	1056	1088
RP	9.7	727	1030	10.7	10.8	685	751	1049	1081	11.3	11.7	677	743	1069	1098	11.9	12.1	686	737	1075	1111
BW	9.2	871	1064	10.1	10.3	813	886	1084	1107	10.9	11.2	787	875	1104	1133	11.4	11.6	793	855	1121	1151
BY	8.5	818	1051	9.5	9.6	768	823	1061	1086	10.2	10.5	746	826	1082	1113	10.7	11.0	741	795	1107	1136
SL	9.7	922	1070	10.6	10.8	861	939	1089	1131	11.3	11.6	856	925	1111	1142	11.9	12.1	853	925	1111	1152
BB	9.3	568	1003	10.3	10.5	538	593	1015	1048	10.8	11.3	529	589	1037	1067	11.4	11.7	515	561	1065	1092
MV	8.9	620	984	9.8	10.0	583	645	1000	1033	10.2	10.6	588	638	1020	1045	10.8	11.0	577	619	1043	1068
SN	8.9	716	1033	9.8	10.0	657	735	1039	1077	10.5	10.9	644	733	1070	1103	11.1	11.3	649	701	1091	1129
ST	9.3	569	1007	10.3	10.5	549	600	1014	1048	10.8	11.3	539	590	1034	1067	11.4	11.7	549	574	1064	1091
TH	8.5	681	1012	9.5	9.7	637	704	1013	1050	10.1	10.5	633	695	1037	1073	10.7	11.0	640	678	1063	1096
G	9.2	746	1013	10.1	10.3	699	770	1028	1060	10.7	11.1	694	760	1048	1079	11.3	11.5	694	741	1068	1099

case of straw we assume a 20 % use and for forest the actual ratio between total timber use and energy timber use is the basis for the assumed energy yield per hectare.

Climate data and scenarios

We use daily weather data (temperature, precipitation, relative humidity, global radiation, air pressure and wind speed) from 1218 meteorological stations in Germany available at *PIK* for recent (1981–2010) climate. We then apply climate scenario projections for the time period 2031–2060 based on the Representative Concentration Pathways (*RCP*) scenario 8.5 of the IPCC. Outputs of three different *GCM*s with different temperature trends (high, medium, low) are used to create daily meteorological variables with the regional statistical climate model *STARS* (Gerstengarbe et al., 2015) (Tab. 2). For each of the three *RCP* 8.5 temperature trend scenarios 100 realisations were produced giving a total of 300 realisations, except for the SRC bioenergy feedstock simulation where we select 20 realisations of each climate scenario, summing up to 60 realisations. This reduction in applied realisations is necessary because of the high computational time of SRC model simulations. In the case of the other three feedstocks we are able to consider all 300 realisations.

Soil data

We apply the digital national soil data base BÜK 1000 (Bgr, 2004) to the *4C*-model simulation of forest stands and SRC plantations. This database is available as a map and provides soil-layer-specific information about soil texture, physical and chemical properties for main soil types in Germany. It is joined with the spatial data on the area of forest and SRC to incorporate the existing soil type to the simulated forest stand or SRC plantation.

2.2 Calculations of future yield change and climate change uncertainty

Forests and SRC plantations

The future yield changes of forest stands are simulated with *4C* (Lasch et al., 2005). The annual forest stem increment is simulated for hypothetical 55-year-old monospecies forest stands of five main tree species (spruce (Picea abies (L.) H.Karst.), beech (Fagus sylvatica L.), pine (Pinus sylvestris L.), oak (Quercus robur L.) and douglas fir (Pseudotsuga menziesii (Mirbel) Franco)). The simulations are conducted on a grid ($0.11\,^\circ \times 0.11\,^\circ$) with 4183 sites in Germany for two periods (1981–2010, 2031–2060) and three climate scenarios each with 100 realisations. We assume a constant CO_2 concentration of 380 ppm to exclude the CO_2 fertilisation effect. The forest analysis is the main topic of a second paper by Lasch-Born et al. (2015), also within this issue.

The mean annual stem increment change is calculated as the difference between each simulation result of the future period 2031–2060 and the recent period 1981–2010. The grid cells are assigned to the states. To get the mean, maximum and minimum change due to climate change, we calculate:

1. the mean change over all realisations and grid cells of each state
2. maximum and minimum changes for each grid cell based on the 300 realisations
3. the mean of the maxima and minima over the grid cells of each state.

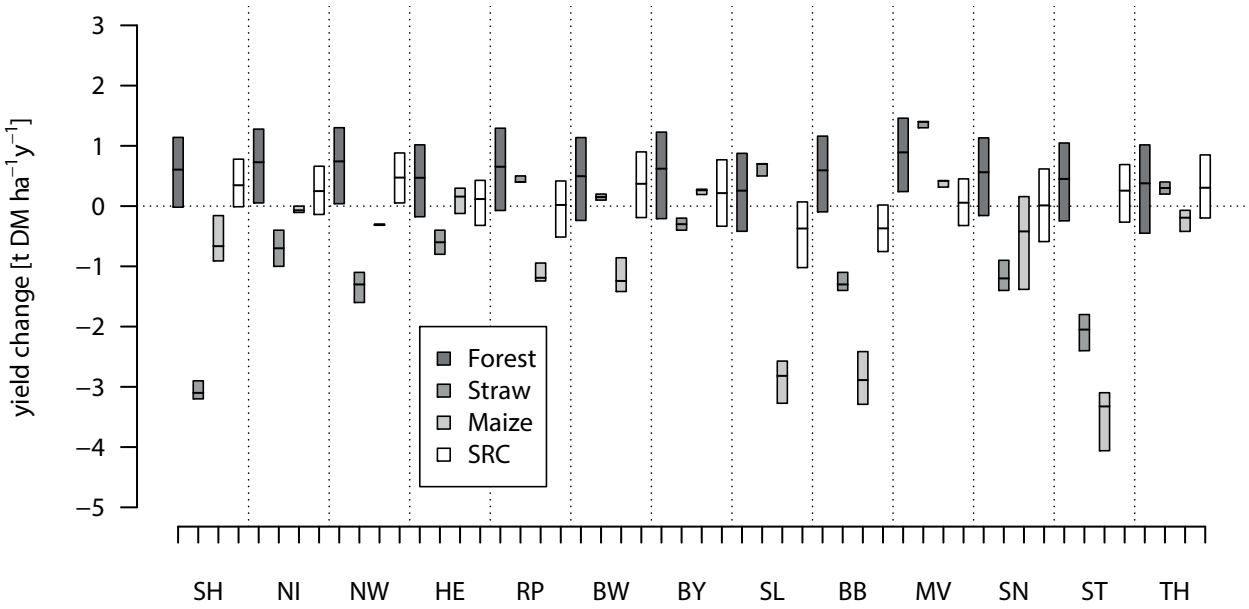

Figure 2: Simulated yield changes (Y_i) of biomass from forest, SRC plantations, straw and maize for the period 2031–2060 compared with 1981–2010 aggregated for the states. The black line indicates the median value, the box around the line indicates the range ($min(Y_i), max(Y_i)$).

SRC of aspen (Populus tremula (L.), P. tremuloides (Michx.)) and black locust (Robinia pseudoacacia L.) are simulated using *4C* on a total agricultural land area (land-use cover CORINE 2000 (Dlr-Dfd, 2004)) of about 12.5 million hectares (except on organic soils given by BÜK 1000 (Bgr, 2004)). In addition to soil and land-use information, the nearest of the 1218 climate stations is assigned to each agricultural field polygon for the simulation. Every five years the total aboveground biomass is harvested and regrowth from the stump takes place. The total rotation period is 20 years. The SRC plantation plots are assigned to states based on their calculated centroid. The plot yields from aspen SRC and black locust SRC are averaged per state to one single value. The concept and results of this model study have been published by Kollas et al. (2009). The change in harvested dry matter is calculated as described for forest, with the exception that we have agricultural plots instead of regular grid cells. The second difference is that instead of 100 realisations for each climate scenario we use only 20 realisations, due to limitations of computational power. To preserve the climate variability, the 100 realisations are sorted with respect to the mean annual climatic water balance and we selected every fifth realisation (1,6,...,96).

Straw and maize

The yield changes of winter wheat (representing cereal straw) and silage maize are simulated with the Integrated Regional Model Approach (*IRMA*). This statistical approach represents a separated time-series model (Eq. 2.1) and connects inter-annual changes of weather variables to observed yearly changes of yields. We use the period 2001–2010 to fit the regression model. The yields have to be transformed into relative yield changes ($\Delta y_t = y_t - y_{t-1}$) to account for possible yield trends due to technological progress. The weather variables ($j = 1, \ldots, J$) of the regression are selected within yield sensitive developing stages of winter wheat (i.e. germination, vernalisation impulse, stem elongation, anthesis) for each year ($t = 2, \ldots, M$). The regression model is calculated for each county (i) in Germany which has a significant amount of agricultural area (urban counties such as Potsdam are left out). In total 303 counties were selected for the analysis. The estimated yield changes of the counties are averaged for greater areas ($i = 1, \ldots, N$) by the arithmetic mean. β and ϵ indicate the regression coefficients and the rest variance of the regression model.

$$N^{-1} \sum_{i=1}^{N} \Delta \log y_{it} = N^{-1} \sum_{i=1}^{N} \left(\beta_{i0} + \sum_{j=1}^{J} \beta_{ij} \log x_{itj} + \log \epsilon_{it} \right) \quad (2.1)$$

The simulations of future wheat and maize yields are undertaken on the level of counties with three *RCP* 8.5 scenarios (minimum, medium and maximum increase of mean annual temperature) each with 100 realisations. The mean of the observed yields per county from 2001–2010 is used for a retrograde calculation from the simulated yield changes per year to absolute yields from 2011 onwards. The changes are averaged for 2031–2060 as done for forest and SRC. No future technological progress nor fertilisation effect through higher CO_2-concentration is considered.

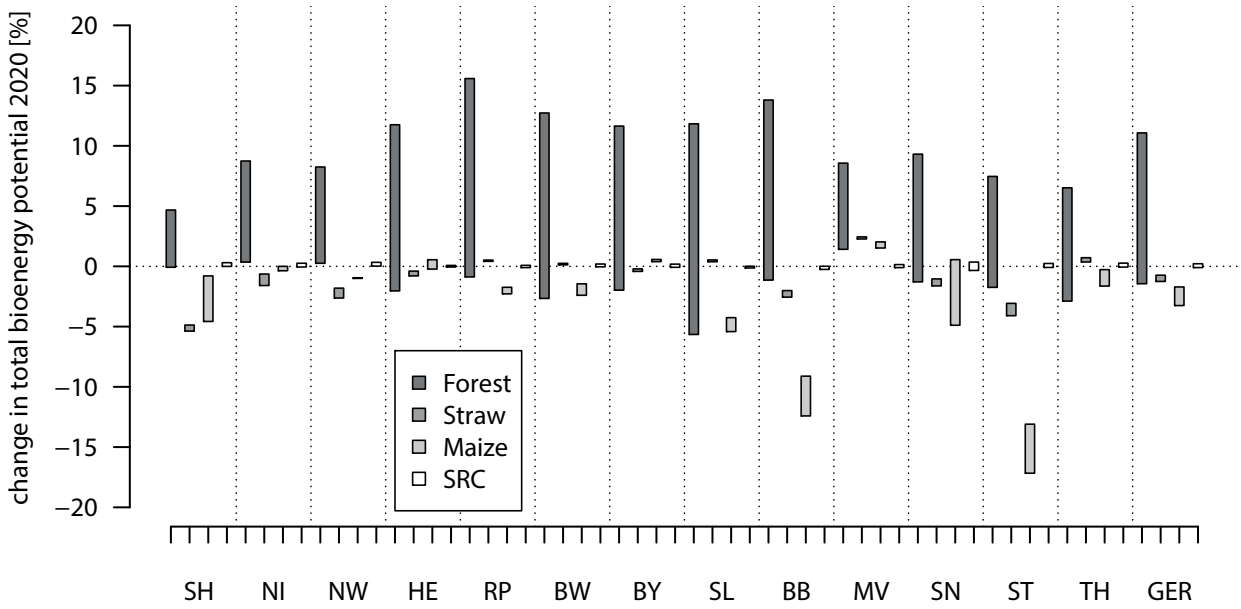

Figure 3: Changes in total bionergy potential in 2020 for four selected biomass feedstocks (forest, straw, maize and SRC) calculated specifically on state level on the base of simulated yield changes and given potential of AEE (2013).

Climate change uncertainty in bioenergy potentials

The formulas given in equation 2.2 are used to investigate the climate-induced potential bioenergy changes. First, we calculate the ratios p_i ($i = forest, SRC, straw, maize$) of simulated yield changes ΔY to baseline yields Y_B (simulated yields for SRC and database for the other feedstocks). With the given bioenergy potentials E_{P_i} for 2020 (AEE, 2013) and the ratios (p_i) we get the bioenergy potential changes ΔE_{P_i}. The total change of the bioenergy potential ΔE_{tot} is summed for all four bioenergy feedstocks. The minimum and the maximum result from simulations of feedstock-specific number of climate realisations of ΔE_{tot} represents the climate-induced uncertainty.

$$
\begin{aligned}
p_i &= \frac{\Delta Y_i}{Y_{B_i}} \\
\Delta E_{P_i} &= p_i \cdot E_{P_i} \\
\Delta E_{\text{tot}} &= \sum_{i=1}^{4} \Delta E_{P_i}
\end{aligned}
\tag{2.2}
$$

3 Results

Projections for 2031–2060 for all four kinds of simulated biomass feedstocks, aggregated by state, show mainly positive yield changes for biomass from forests and also mainly positive but lower changes for biomass from SRC plantations (Fig. 2). The yield changes of straw and maize biomass are clearly negative in some states (BB, ST, SL, SH), largely positive in MV and vary from −1 to +1 [tDM ha^{-1} year^{-1}] in states such as NI, HE, BY and TH.

The yield changes relative to bioenergy potentials of 2020 (Tab. 1) for the period 2031–2060 are given in Fig. 3. In the case of bioenergy coming from harvested timber residues the resulting range in total bioenergy potential change over all states is from −5 % (SL) to 15 % (RP). In most states the range encompasses roughly 10 % of total bioenergy potential, which is much higher than for the other three feedstocks (< 5 %). The median of forest-related total bioenergy change is an increase of 4.3 % over all states. The SRC-related bioenergy potential changes do not affect total bioenergy potentials (Fig. 3) due to small yield changes and especially due to the small share in the total bioenergy potential of the states. In the case of straw there are noticeable effects on total bioenergy potential in five states (Fig. 3). In SH, NW, BB, and SN yield changes lead to a decrease in total bioenergy potential of up to −5 %, while in MV yields increase by 3 %. In BB and ST negative yield changes of maize cause a decrease in total bioenergy potential of up to −15 %. In other states there are only minor reductions, while in MV there is a small increase in bioenergy coming from maize crops.

Finally, we present the potential bioenergy supply of the four considered biomass feedstocks for each state in 2020 from the AEE (2013) (Fig. 4, dark column). Our estimated climate uncertainty (upper and lower potential) depending on the climate change scenario for each state is given as black lines. Comparing the potential bioenergy amount with the target values for 2020 (AEE, 2013), it can be seen that most states will be able to exceed their targets, with the exception of RP, BW and HE. The effect of climate change uncertainty has little influence on this overall result. Only for Saxony-Anhalt is the bioenergy potential slightly reduced under the assumed cli-

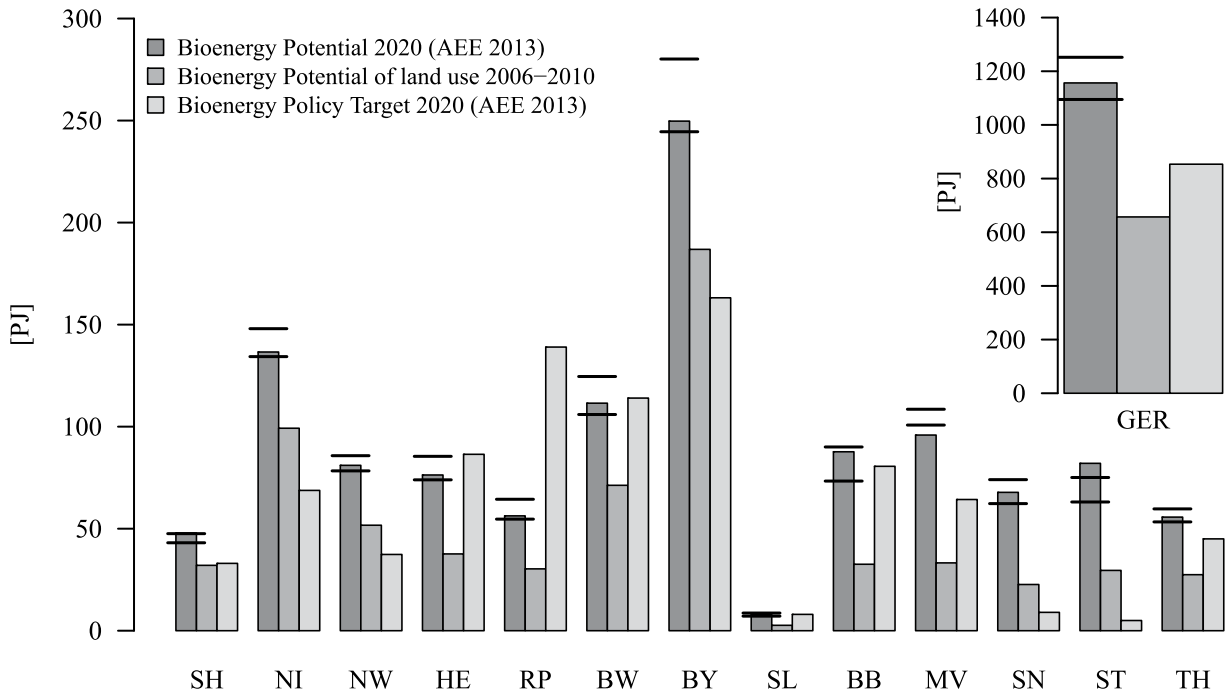

Figure 4: Potential (E_{tot}), target and current (relating on mean land-use of 2006–2010) bioenergy supply of the four selected biomass feedstocks. Black lines ($max(E_{tot})$, $min(E_{tot})$) indicate climate change uncertainty of the bioenergy potential, calculated with the scenario realisations.

mate change scenario *RCP* 8.5. The total bioenergy for all four biomass feedstocks and states is about 1156 PJ with a range of 1095–1252 PJ for 2031–2060, assuming the *RCP* 8.5 climate scenario (embedded barplot in Fig. 4).

4 Discussion

Yield change and bioenergy potential of selected feedstocks

Yield changes due to climate change are reported differently in the literature for the feedstocks we analysed in this study. On average over the whole area of Germany, maize and straw yields experience a decrease under the climate change scenario used in our study. The *IRMA* model only uses climate factors for estimating future yield trends and neglects effects of other important drivers such as socio-economic and technological development (Ewert et al., 2005). Especially for the eastern parts of Germany, our results are in line with other model studies which find decreasing potential yields in these regions (Wolf and Vandiepen, 1995; Angulo et al., 2013). However Supit et al. (2012) using the Crop Growth Monitoring System (CGMS), calculated yield changes to 2100 for a variety of agricultural crops. For Germany their results concerning maize indicate stable yields in the middle and decreasing potential yields at the end of this century. Simulations indicate increasing winter wheat yields, except for the scenario with low CO_2 concentration. Ewert et al. (2005) combine the European climatic stratification of Metzger et al. (2005) with yield statistics and simulate stable wheat yields until 2080 for most German regions except the eastern states. Given the positive yield development brought about by technological progress, they conclude a further positive development of wheat yield trends will occur. On the other hand, this study highlights the knowledge gaps concerning interactions between climate and soil factors which might affect the biological limits of further yield increases. Another limitation of yield studies at a higher level of spatial aggregation (i.e. the European NUTS-2 level with 39 regions in Germany) emerges from a study examining the effects of driving forces on yields (Bakker et al., 2005). Here the authors found that significant correlations between wheat yields and the used economical and bio-physical variables increased further when using data on NUTS-2 level instead of NUTS-3 level. But this high level of correlation carries the risk of confounding and misinterpreting statistical model results. We executed our statistical analysis at the county level, on a much lower aggregation level, where these problems are of less importance. Asseng et al. (2013) show that model intercomparison reveals large uncertainties in future wheat yields. They conclude that projections of individual crop models do not represent crop responses to climate change. Large

uncertainties exist regarding interactions between heat responses, water stress and effects of CO_2 concentration (Angulo et al., 2013; Asseng et al., 2013). Another study of impacts of changing climatic conditions on yields studied the relationship between temperature and wheat yield (Reidsma et al., 2007). They found a clear mean temperature optimum for the first half year of 4–6 °C and a decline of wheat yields at higher temperatures, and described this relationship with a quadratic term. This optimum temperature is exceeded by most of the counties simulated with *IRMA* and the climate scenarios of *RCP* 8.5. This suggests that higher temperatures in Germany increase the risk of lowering yields.

On average over all states we project that the biomass potential of forests will increase due to the increasing annual stem increment of 0.57 tDM $ha^{-1}year^{-1}$. The minimum and maximum of this increment change, depending on the realisation used, are −0.13 and 1.16 tDM $ha^{-1}year^{-1}$. This change only takes into account tree growth changes due to changing climate factors as described in Lasch-Born et al. (2015) and reflects the probability of increasing growth as analysed also by Reyer et al. (2013). In general there is a positive view about using forest biomass for energy purposes as well as for wood production (Stupak et al., 2007). Whittaker et al. (2011) presented a life cycle assessment of harvesting residues for use as a biomass resource in Great Britain and deduced a positive effect for CO_2 reduction. On the other hand Domke et al. (2012) calculated a time delay of 10–30 years before the use of residues for bioenergy surpasses wood decay in the forest in terms of CO_2 mitigation. However, the future available forest biomass and the forest mitigation potential are strongly influenced by other factors, such as biotic and abiotic disturbances. There is some evidence showing that forests in Europe (in particular Germany) are at the saturation point of their carbon sink potential (Nabuurs et al., 2013). Future analysis of bioenergy and mitigation potential should therefore incorporate forest dynamics, life cycle assessment of management as well as climate change impacts which involve physiological responses and calamities (Klein et al., 2013).

The results of the SRC simulations show only minor changes due to climate change. Our simulated average yields of SRC are at the lower end of reported values (5–20 tDM ha^{-1} $year^{-1}$) for SRC in Saxony and other test areas in eastern Germany (Röhle and Skibbe, 2011). A comparable model study with the process-based model *3-PG* predicts poplar biomass productivity of Minnesota and Wisconsin (USA) of between 4 and 13 tDM ha^{-1} $year^{-1}$ (Headlee et al., 2013). Therefore, the biomass potential per hectare of SRC could be underestimated by *4C* and subsequently by our study. In spite of its relatively low importance in terms of total bioenergy supply, there are some arguments supporting SRC as one sustainable part of the future low-carbon energy portfolio. First, there is the potential for positive biodiversity effects within intensively managed agricultural systems dominated by areas of mono-specific crop types (Bfn, 2012). Second, there is also potential to reduce the pressure on timber utilisation in the forest. Zanchi et al. (2012) highlight the beneficial outcome regarding CO_2 mitigation of using harvest residues and transforming marginal agricultural area into SRC plantations. On the other hand, SRC increases pressure on cropland and thus food and feed production. In addition, recently published results of Zona et al. (2013) show significant greenhouse gas emissions from poplar plantations: they describe an 18-month-long experiment on poplars which revealed significant nitrogen emissions. Although the short interval of this experiment limits its explanatory power, the important issue of carbon footprint should be investigated and considered in future studies.

Total bioenergy potential

Here we analysed the effects of climate uncertainty on four main bioenergy feedstocks in Germany using the scenario *RCP* 8.5. Germany's reported potential (Aee, 2013) of maize, straw, SRC and forest of 1156 PJ varies between minus 5 % and plus 8 % depending on the realisation. This is close to another estimation of total bioenergy potential which includes feedstocks we omitted in our study (animal excreta, waste and industrial wood, grassland and organic waste) for Germany of about 1500 PJ under the environmental scenario of Dbfz (2010). Our calculated uncertainty due to climate change will not change significantly by adding these neglected feedstocks because of their small share in the total amount and their low climate sensitivity.

The numbers given by the National Biomass Action Plan of the German government (Bmelv and Bmu, 2010) aim for a share of energy from biomass of 11 % of primary energy consumption. With respect to the primary energy demand of 13757 PJ in 2012, 11 % represents 1513 PJ. After Nitsch et al. (2010) the primary energy demand from biomass in 2020 is 1287 PJ and rises to 1534 PJ in 2050. Providing that roughly 1500 PJ of biomass utilisation can be achieved, climate change effects of minus 75 (−5 %) PJ or plus 120 (8 %) PJ seems to be of small importance.

Our estimation of the bioenergy potential with respect to current land-use amounts to 657 PJ over the four feedstocks; while for the same feedstocks Dbfz (2010) gives a slightly higher potential of 742 PJ for the year 2007. The difference is mainly explained by the lower potential of forest biomass (245 versus 500 PJ) assumed in our study. This number is dependent on the assumed share of energy wood to total harvested wood. Thus, further growth of about 500 PJ for the analysed four bioenergy feedstocks is still needed to achieve the potential of 1156 PJ. Reflecting the methodology of the Aee (2013) study, which includes nature protection efforts and future food demands, 500 PJ seems to be a realistic and also sustainable target for additional bioenergy use in Germany.

Bioenergy potential in individual states

Our analysis reveals differences in climate change uncertainty between the states. Only those states with a more continental climate (BB, ST) and lower precipitation (SL) (Gerstengarbe et al., 2015) experience a higher risk of decreasing bioenergy yields. In southwestern states (BW, BY, RP, SL) and BB we observe larger ranges of uncertainty in the realisations of the *RCP* 8.5 scenario. In the case of BW, BY, HE and RP this uncertainty parallels a positive bioenergy potential trend, which is also estimated for MV and NI. Higher temperature and radiation in the climate scenario lead to higher yields at sites without water limitation. Forests and SRC in these states also profit from longer vegetation periods (Lasch-Born et al., 2015). In general though, the range of climate-change-induced uncertainty is low relative to energy targets and potential of 2020.

The comparison between current potential and potential for 2020 also reveals some differences between the states. There are states where the current potential is more than 50 % of the estimated potential for 2020 (SH, NI, NW, BY, BW). This has consequences for land-use and management strategies to meet future bioenergy targets. Relative to their potential some of the states have been assigned very low specific bioenergy targets. There is a gap of 433 PJ between the national target of 1287 PJ primary energy use and the sum of the state targets (854 PJ, Tab. 1). One reason for this could be that the formulation of specific targets lags behind actual development. The rough estimate of our ratio between ultimate and primary energy of 0.72 could be another reason. Data for both energy considerations in the official statistics would be very useful.

Methods, models and data aggregation

The environment scenario of Dbfz (2010) excludes forest clearance or land-use change for grassland. In addition, 10 % of forest and 2 % of agricultural area are removed from utilisation. These scenario guidelines are thought to counteract side-effects of intensified utilisation of forest biomass (i.e. increased CO_2 emissions in short and medium terms) as discussed by Schulze et al. (2012). In this study, we assume the bioenergy potentials of Aee (2013) to be sustainable in terms of climate, biodiversity and food supply. Therefore, our methods focus only on climate change uncertainty and leave out land-use, biodiversity and other bioenergy relevant scenarios. Our study therefore cannot uncover feedback processes between climate, land-use and bioenergy use.

The simulations of the bioenergy potential of SRC are based only on 60 realisations because of lacking computational capacities to consider all of the available realisations. But we think we reduce the error in comparison to the other feedstocks by considering only the minimum and maximum of the simulated potential. Further, we use realisations which are selected systematically with respect to their climatic water balance and therefore cover the whole range of possible climate-related impacts on growth and subsequently on bioenergy potential.

We use the process-based model *4C* for yield simulations of forests and SRC. On the other hand we use statistical model approaches such as *IRMA* for simulating wheat and maize yield changes. This method may be susceptible to inconsistency in total bioenergy results, since changes of maize and wheat yields are only dependent on statistical relationships between observed yields in official statistics and selected climate factors. Here we assume constant relationships in the future. In the case of process-based models, the relationship between yields and climate factors can vary due to underlying mechanisms of the growth processes. Because of the different trends of agriculture and forest-based bioenergy feedstocks, the uncertainty of climate-induced changes in total bioenergy potential could be much higher if all feedstocks show the same trend.

We also omit the calculations of uncertainty caused by the impact models themselves. There are current efforts to investigate model uncertainty by means of model inter-comparisons at regional scale (e.g. the ISI-MIP project (Schellnhuber et al., 2013; Warszawski et al., 2013)) which is an important step towards estimating the real uncertainties when looking at future bioenergy potential. In addition, averages on the spatial scale of states reduce the variance of results and subsequently the reported uncertainty in bioenergy potentials. Nonetheless, we think our model and data set approach is able to estimate general uncertainties due to climate change with respect to specific state and national bioenergy targets for 2020. We provide no information that is useful on the individual farm level.

Last, we want to point out our simplification of using the winter wheat yield change as an estimate of change in straw yield. Other straw materials will of course show different yield responses to climate change and alter our total bioenergy range, however without changing the whole picture.

5 Conclusions

The biomass potentials estimated by the Aee (2013) cover the target demand for bioenergy in 2020 and 2050 at the national level. The calculated changes of biomass yields from four feedstocks (forest, SRC, straw, energy maize) due to climate change effects, simulated for 2031–2060, do not pose a danger to the overall bioenergy target if the effects of disturbances and extreme events such as wind damage or massive outbreaks of pests are not considered. Climate change impacts differ between states and biomass feedstocks. The bioenergy yields of the drier eastern states and states with temperatures above the average exhibit a higher risk of being negative under the *RCP* 8.5 climate scenario. Maize and straw yields respond more strongly to climate change than SRC and forest yields. In addition, negative yields due to climate change are more frequent for maize and straw than for forests and SRC.

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