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Bioenergy potential in Germany – assessing spatial patterns of biomass production with aspen short-rotation coppice

C. Kollas[1]*, P. Lasch[1], J. Rock[1,2], and F. Suckow[1]

[1]Potsdam Institute for Climate Impact Research, Telegraphenberg P.O. Box 601203, D-14412 Potsdam, Germany
[2]Johann Heinrich von Thünen-Institute, Federal Research Institute for Rural Areas, Forests and Fisheries
Institute for Forest Inventory and Forest Ecology, A.-Möller-Str. 1, D-16225 Eberswalde, Germany

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A b s t r a c t. The aim of this work is to provide policymakers with a tool to explore the actual and future energy potential of short-rotation coppice (SRC) in Germany. The ecophysiological model 4C was used to estimate mean annual yields of SRC with the species *Populus tremula* L. on arable land. The total potentially suitable area was calculated with GIS to be up to 12.9 mln ha. Growth simulations were performed on 7 010 patches in Germany for a basis period (1987-2006) and 21 climate scenarios of different temperature increases (period 2041-2060). The simulations showed yearly mean timber yields of 5.86 tons dry mass per hectare in the basis period and 5.77 to 7.25 in the scenario periods. The variability of yields throughout Germany is also presented and overall annual potential yields of primary energy from different shares of agricultural lands allocated to SRC in Germany are analyzed. If 4 mln ha were used as SRC, between 415 and 522 PJ a^{-1} of primary energy could be produced in the scenario periods.

K e y w o r d s: biomass, short rotation coppice, climate change scenario, bioenergy, poplar

INTRODUCTION

The production of 'renewable energies' or 'bioenergy' in order to mitigate CO_2 emissions, reduce dependence on imported fossil fuels and improve energy supply security is strongly supported by the European Union. In 2010, about 21% of consumed electricity should be generated by the member states (EU, 2007) through renewable resources.

The German government strives to increase the share of electricity produced by renewables to 30% by 2020 (Bundesregierung, 2008). In 2007, the share was 14.2, 1.2 % being produced by renewable solid fuels, or biomass (Nitsch, 2008). To increase this production the quality and quantity of raw material has to be increased. Two processes are commonly used to make use of biomass as an energy source: direct combustion to produce heat and/or electricity, and biomass-to-liquid (via Fischer-Tropsch process) to produce liquid biofuels.

To provide the requisite quantities of biomass, short rotation coppice plantation (SRC) can be a promising option. Suitable fast growing tree species have been investigated in several German field studies (Bemmann *et al*., 2007; Hofmann, 1999; Landgraf *et al*., 2007a). For Germany, estimations of current SRC potentials have been directed at acreage and given only very rough yield approximations (Rock, 2008). These range from 0.5 to 4.6 mln ha (Burschel *et al*., 1993; Flaig and Mohr, 1993).

Analyzes of other European countries are also rare. Aylott *et al*. (2008) used GIS (geographic information system) analysis with embedded empirical techniques to assess possible yields of willow and poplar SRC in the UK, and Andersen *et al*. (2005) used GIS-based approaches to distinguish SRC-suitable from unsuitable land in Scotland. Varela *et al*. (2001) located technically suitable sites for SRC in Spain, emphasising especially power plant specific factors. In this study, however, an approach based on the ecophysiological modelling of aspen (*Populus tremula* L.) SRC growth with the model 4C (FORESEE-Forest Ecosystems in a Changing Environment (Lasch *et al*., 2005)) was applied, incorporating soil conditions and changing climate conditions. Other process-based studies of SRC were made by Deckmyn *et al*. (2004) for yield prediction in Belgium, and by Grogan and Matthews (2002) who calculated soil carbon sequestration by SRC in UK.

*Corresponding author's e-mail: chris.kollas@unibas.ch

The first aim of this study was to analyze the potential supply of SRC biomass on a national scale and to identify regions of best growing conditions, under current and probable future climatic conditions.

The second aim involved an estimation of the recent and prospective potential of SRC as renewable energy source, depending on the amount of land used as SRC culture. Both results provide decision support for farmers who have to decide whether to grow food or energy crops, and for policymakers and investors who need estimates of yield potentials in larger regions *eg* for landscape planning or investment decisions.

MATERIAL AND METHOD

The regions of potential suitability for SRC were calculated using GIS and the land use map (CORINE Landcover, 2000). Non-irrigated arable land was extracted within the German borders. With the help of the German soil map (BÜK 1 000; BGR, 1998) areas with organic soils (fen soils and raised bog soils) were excluded because of their unsuitability for SRC due to soil moisture and climate mitigation aspects (Rock, 2008). Areas smaller than 100 ha have been excluded due to computational capacity. For the resulting 7010 patches of arable land the soil information of reference profiles was extracted from the BÜK 1 000. Climate information was derived from the next climate station by nearest-neighbour interpolation and related to the patches. In total, 12.9 mln ha (about 76%) of Germany agricultural land (that is 17 mln ha after CORINE Landcover, excluding grassland) was incorporated in this analysis.

Climate information for the period 1987 to 2006 (recent climate) was taken from the PIK-DWD-Database. This database contains checked and, if necessary, amended weather data from 2342 climate stations of the DWD (German Wheather Service, Österle *et al*. (2006) for details). This data was used as a basis scenario. Future climate scenarios for the timeframe 2041-2060 were generated with the statistical regional climate model STAR2 (Orlowsky *et al*., 2008; Werner and Gerstengarbe, 1997). It used +0.5 K stepwise temperature increase trends (0.0, 0.5, … 3.0 K for the time period 2007 till 2060) comparable to IPCC scenarios as driving forces to build up a suite of scenarios. For every temperature increase trend a set of 1000 realizations (Monte Carlo simulation) were available, describing different precipitation characteristics. Three scenarios were chosen from these sets (Table 1): Regarding the climatic water balance at all available climate stations in Germany, the driest (dry), a medium (medium) and the wettest (wet) realization were selected. In total 22 climate scenarios (basis and temperature increase scenarios) were used in this work. STAR2 provides a time series of 10 climatic variables covering the timeframe from 2007 to 2060 with a daily resolution. The spatial resolution is defined by the 2342 climate stations irregularly located throughout Germany. Visualization of the medium realizations of mean annual temperature of four selected climate scenarios and their trends and variation is given in Fig. 1. The range of precipitation scenarios is mainly characterized by decreasing (dry), steady (medium) and increasing (wet) precipitation (Fig. 2). The annual precipitation varies strongly from year to year and the precipitation sum over one year of a wet scenario can even be lower than that of the same year in the dry scenario. The overall means of annual precipitation sums (P) increased slightly with a rising temperature trend for the wet realizations from 801 mm (0.0 K trend) to 807 mm (3.0 K trend), but for the dry realization P decreased by about 90 mm from the 0.0 K to the 3.0 K scenario (Table 2).

Scenarios of increasing CO_2 concentration were taken from the data of the BERN-CC model (IPCC 2001). For every temperature increase trend we chose the SRES CO_2 scenario that corresponds to mean temperature in 2060 (Table 1).

The process-based forest dynamics model 4C (FORESEE – Forest Ecosystems in a Changing Environment, (Lasch *et al*., 2005) was applied to analyze aspen-SRC productivity. The model works on the forest stand level and describes growth, regeneration and mortality of tree groups with identical characteristics (species type, dimensions), called cohorts. Being a physiological model, the processes for plant growth *eg* photosynthesis, water and nutrient uptake by roots and leafs, wood production and allocation, are incorporated. Forest management measures such as planting, thinning and harvesting as well as short rotation coppice culture are implemented.

The model requires daily weather data (temperature, precipitation, air vapour pressure, relative humidity, solar radiation, wind speed, CO_2-concentration in the air) as environmental drivers and soil data must be provided.

Table 1. Temperature increase scenarios and corresponding IPCC scenarios (IPCC 2001)

Climate scenario	Basis	+0.0 K	+0.5K	+1.0 K	+1.5K	+2.0 K	+2.5 K	+3.0 K
Realization	dry / medium / wet							
Corresponding IPCC scenario			B2	B1	A1B	A2	A1F1	A1F1

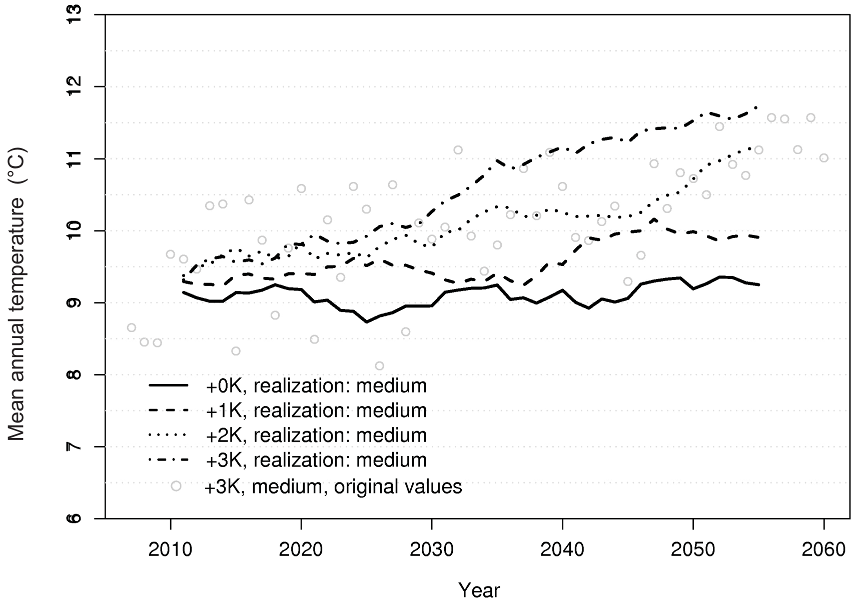

Fig. 1. Mean annual temperature of 2 342 climate stations in Germany in the scenario period: circles – simulated means of the years, lines – 10-year-moving averages.

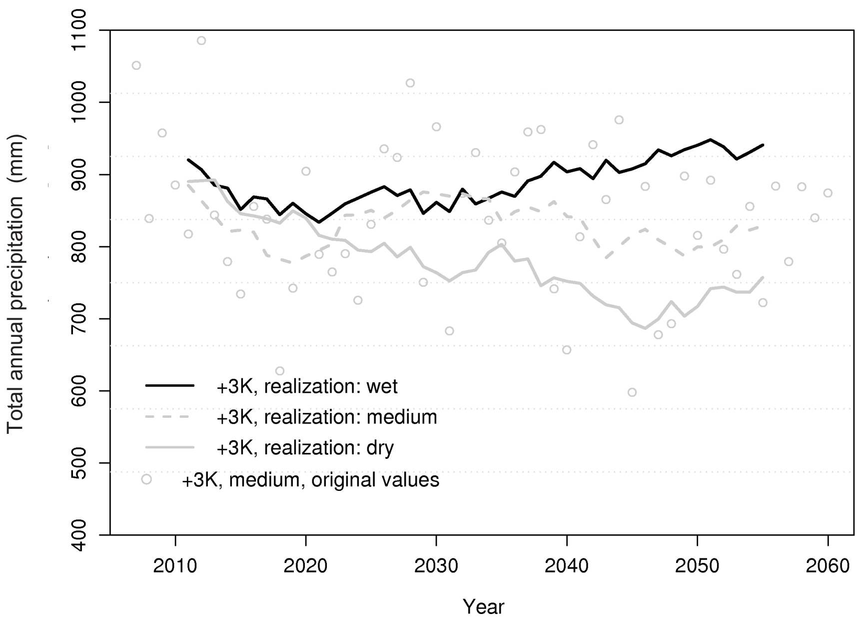

Fig. 2. Mean total annual precipitation of 2 342 climate stations in Germany in the scenario period: circles – simulated means of the year, lines – 10-year-moving averages.

Calculations are done in daily time-steps and results can be given in daily, weekly, or yearly resolution. The model describes the water budget of the stand and the soil including the actual evapotranspiration and potential evapotranspiration according to Priestley/Taylor.

Currently, the model is parameterized for the tree species European beech, (*Fagus sylvatica* L.), Norway Spruce (*Picea abies* L. Karst.), Scots pine, (*Pinus sylvestris* L.), oaks *(Quercus robur* L. and *Quercus petraea* Liebl.), silver birch (*Betula pendula* Roth), Aleppo pine (*Pinus halepensis* Mill.), ponderosa pine (*Pinus ponderosa* Dougl.), and aspen (*Populus tremula* L., P. *tremuloides* Michx.). The model was validated for these species at various sites (Lasch and Suckow, 2007; Lindner *et al*., 2005; Suckow *et al*. 2001). The short rotation coppice management was especially validated (Rock, 2008). Aspen was chosen as model species

Table 2. Characteristics and simulation results of the 22 climate scenarios: *T* – mean temperature 1987-2006 (basis) and 2041-2060; T_m – average over the mean temperatures of three scenarios dry, medium and wet; *P* – mean precipitation sum over the simulation periods; P_m – mean precipitation sums over the three climate scenarios; AET/PET – ratio of averaged annual actual and potential evapotranspiration; *Y* – mean annual biomass yield over the simulation periods; Y_m – averaged mean annual biomass yield over the three climate scenarios; *SD* – standard deviation; *CV* – coefficient of variation; $Energy_{4\ mln\ ha}$ – mean energy potential on 4 mln ha

Scenario	CO_2 (ppm)	*T* (°C)	T_m (°C)	*P* (mm)	P_m (mm)	AET/PET	*Y* (t d.m. ha^{-1} a^{-1})	Y_m (t d.m. ha^{-1} a^{-1})	*SD*	*CV*	$Energy_{4\ mln\ ha}$ (PJ)
Basis	370	9.16	9.16	751	751	0.441	5.86	5.88	1.28	0.22	422
+0.0 K m*	370	9.48		759		0.441	6.03		1.32	0.22	434
+0.0 K d	370	9.31		732		0.435	6.04		1.28	0.21	435
+0.0 K w	370	9.52	9.44	801	764	0.440	5.77	5.94	1.24	0.21	415
+0.5 K m	499	9.77		739		0.419	6.41		1.53	0.24	462
+0.5 K d	499	9.82		698		0.418	6.44		1.46	0.22	464
+0.5 K w	499	9.67	9.75	845	761	0.426	6.46	6.44	1.51	0.23	465
+1.0 K m	503	10.19		757		0.432	6.60		1.52	0.23	475
+1.0 K d	503	10.04		703		0.416	6.37		1.53	0.24	458
+1.0 K w	503	10.07	10.10	805	755	0.436	6.60	6.52	1.53	0.23	475
+1.5 K m	563	10.58		716		0.418	6.98		1.62	0.23	502
+1.5 K d	563	10.50		684		0.402	6.75		1.64	0.24	486
+1.5 K w	563	10.59	10.56	804	735	0.435	6.97	6.90	1.62	0.23	502
+2.0 K m	568	11.00		744		0.408	7.11		1.72	0.24	512
+2.0 K d	568	11.10		680		0.393	6.82		1.67	0.24	491
+2.0 K w	568	10.88	10.99	813	746	0.424	6.86	6.93	1.70	0.24	494
+2.5 K m	625	11.30		754		0.419	7.25		1.75	0.24	522
+2.5 K d	625	11.42		648		0.375	6.29		1.75	0.27	453
+2.5 K w	625	11.45	11.39	790	731	0.414	6.96	6.84	1.69	0.24	501
+3.0 K m	625	11.78		705		0.382	6.65		1.74	0.26	479
+3.0 K d	625	11.83		641		0.369	6.32		1.71	0.27	455
+3.0 K w	625	11.79	11.80	807	718	0.415	7.13	6.70	1.80	0.25	513

*m – medium, d – dry, w – wet.

for SRC as it shows comparatively good growth even on poor soils and is less sensitive to differences in soil quality than most poplar species and clones normally used for SRC (Liesebach *et al*., 1999). In addition, it was the only species for which enough information about eco-physiology and growth behaviour could be found to parameterize 4C (Rock, 2008). In this study, management was assumed to be conducted as follows: a stand was initialised by planting of 8300 aspen saplings with a mean height of 40 cm per hectare at the beginning of each simulation period. After five years of growth the total aboveground biomass (stems, twigs and branches) was harvested. In the year following the harvest re-sprouting of the remaining stools was used for regeneration and the second 5-year-cutting period started. Four five year periods were simulated (as recommended from field experiments, (Rydberg, 2000). For the basis scenario the 20 year time period started in 1987 and for the temperature increase scenarios the time period started in 2041. The harvests were summed up over the 20-year period and averaged to tons dry mass (d.m.) per hectare and year. The results were also organised according to the borders of the municipalities of Germany to facilitate spatial analysis.

RESULTS

The modelled mean annual biomass yield was organized into 3 classes: more than 7 t d.m. ha^{-1} (the actual threshold for profit-making (Schwarz, 2005; Rock, 2007); 5-7 t d.m. ha^{-1} (low biomass yield, but SRC can be competitive on poor soils), and less than 5 t d.m. ha^{-1}, referring to lowest yields. Figure 3 shows the potential yields under current climate, aggregated on municipal scale to facilitate interpretation. The annual yield of aspen SRC depends strongly on the underlying soil conditions. The highest yields are found, as expected, in regions of high soil quality such as the 'Magdeburger Börde' (a fertile loess plain), 'Oberrhein' (upper Rhine valley) and central Bavaria. The averaged annual yields on municipal scale range from 1 t d.m. ha^{-1} on sandy soils in the state of Brandenburg to 9 t d.m. ha^{-1} in the Magdeburger Börde.

To demonstrate growth potentials under changed climatic conditions the modelled yields of the strongest temperature increase scenario (+3.0 K, medium realization) were chosen and are shown in Fig. 4, also aggregated for municipalities. Hardly any decline in expected yields was found. Instead, regions in a broad belt from the NW to the SE of central Germany and in the states of Bavaria and Baden-Württemberg may be better suited for SRC in future decades.

The average biomass yields throughout Germany were higher under all future scenarios, independent of the realization (dry, medium, wet) (Table 2). Following the temperature increase trends a certain threshold can be observed: the average mean biomass yields (Y_m) declined if temperature rose more than 2 K (Fig. 5c, Table 2). If the realizations are regarded separately, the same threshold can be seen in the dry scenario realization (Fig. 5a, Table 2). It is only in the wet scenario realizations (Fig. 5b) that a steady increase of the averaged mean biomass yield Y from one temperature trend scenario to the next one can be seen. With increasing temperature trend scenarios the standard deviation (SD) and the coefficient of variation (CV) increased indicating an increasing variability of yields (Table 2), which is also shown by the increasing span between the yield values of the 5th and the 95th percentiles as well as between the yield values of 10th and 90th percentiles for the dry but even more significantly for the wet realizations (Fig. 5). It is important to mention that for each temperature increase scenario the dry realization had the lowest and the wet realization had the highest yield, as seen for the 0.0 K temperature trend scenario and occasionally the medium realization showed higher yields than the wet realization (+2.0 K scenario).

The potential yields mentioned above were estimated using all agricultural lands without restrictions from other agricultural products (12.9 mln ha). Mean overall annual

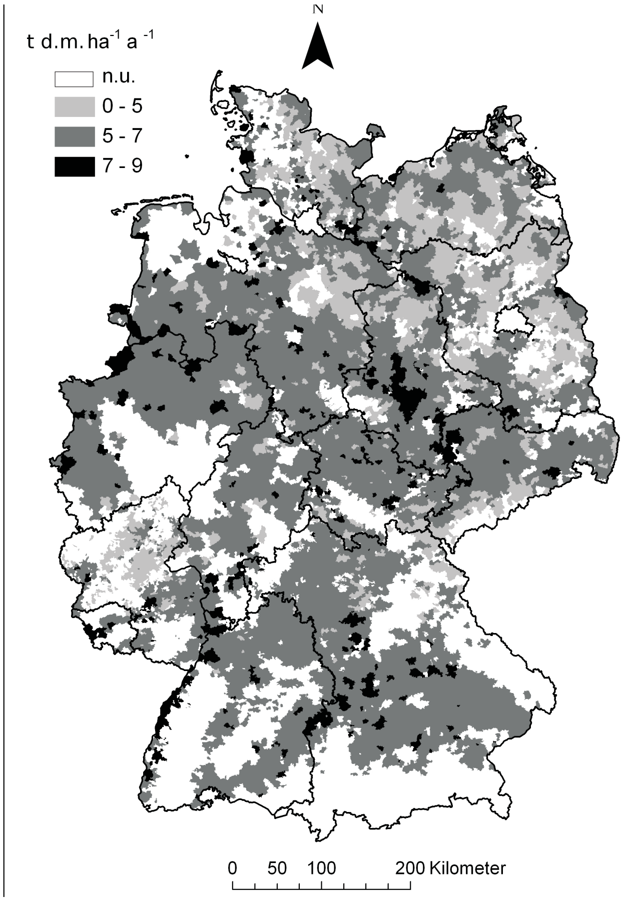

Fig. 3. Yearly biomass yield for the basis period 1987-2006, aggregated at municipality level; n.u. – not utilized, municipalities which contain too little land suitable for aspen SRC.

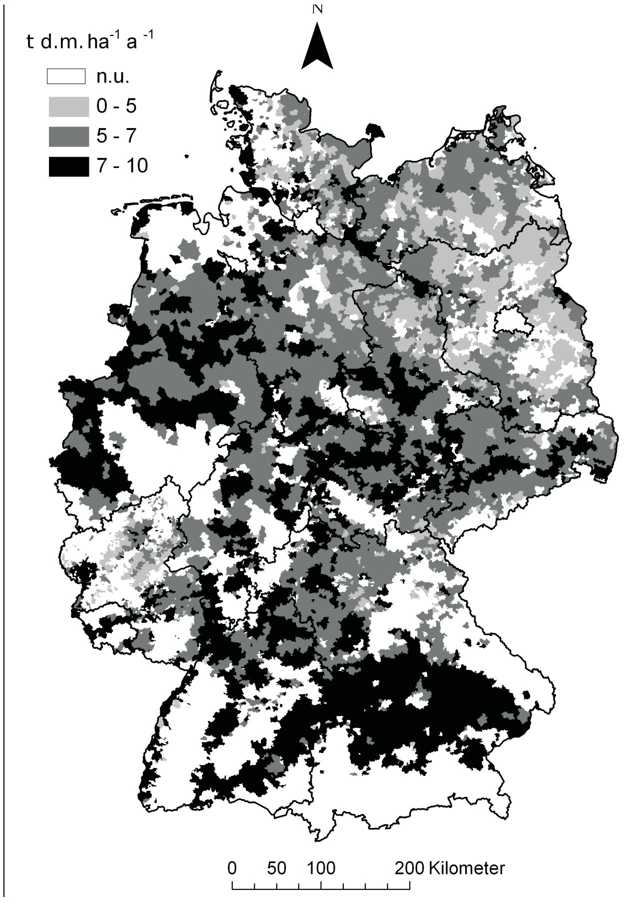

Fig. 4. Yearly biomass yield for the scenario +3 K, medium realization (period 2041-2060), aggregated at municipality level, n.u. – not utilized, municipalities which contain too little land suitable for aspen SRC.

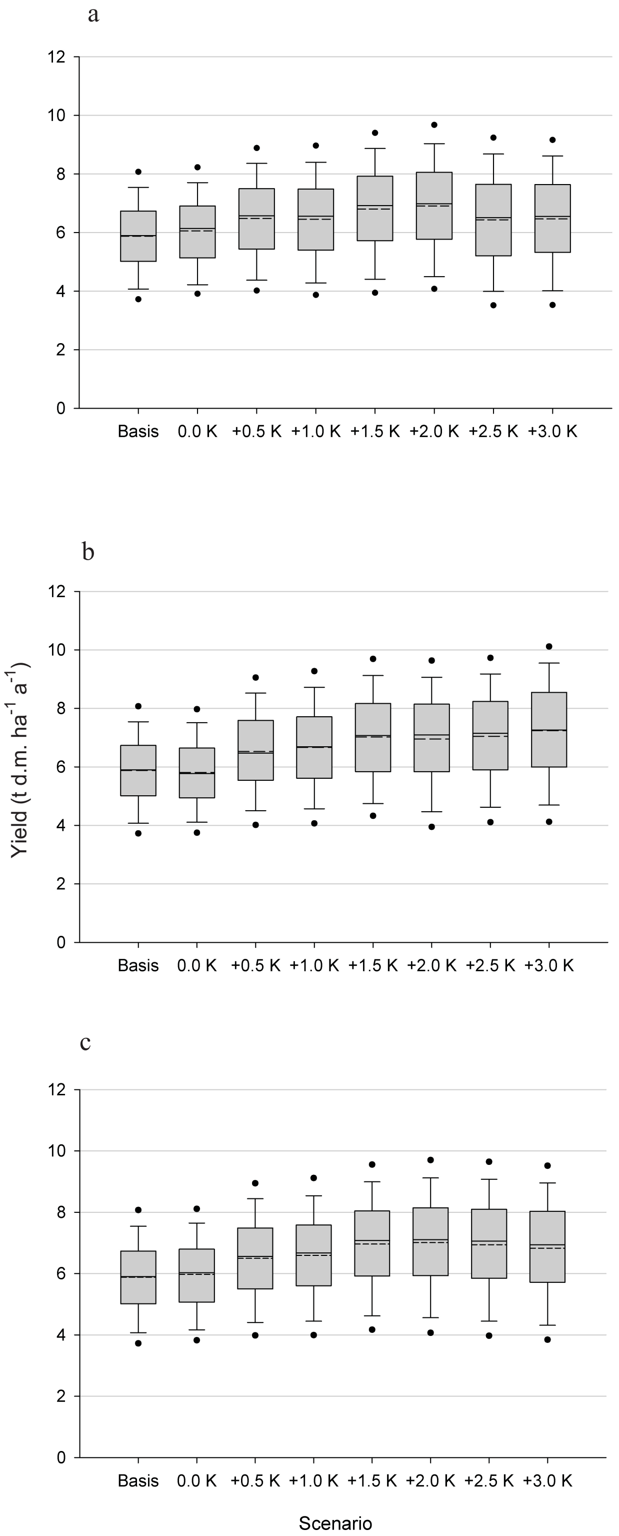

Fig. 5. The 25th and 75th (box), the 10th and 90th (whisker) and the 5th and 95th (point) percentiles of the averaged mean yields over time and all patches; the median (solid line) and mean value (dotted line) for the a) dry realizations, b) wet realizations and c) mean of three realizations.

yield is 5.9 t d.m. ha^{-1} in the basis period and 7.1 t d.m. ha^{-1} a^{-1} in the +3.0 K (wet) scenario, respectively 6.3 t d.m. ha^{-1} in the +3.0 K (dry) scenario, averaged over all soil types (Table 2). According to recent official documents (Nitsch 2008), estimations of land potentially available for SRC are about 4 mln ha. If this number is taken as the total amount planted, the overall yield will vary according to the shares of good and poor soils planted. The range is reflected in the mean yield per hectare and year (Fig. 6). If only that 4 mln ha of the agricultural land would be used, mean annual yields between 4.5 t d.m. ha^{-1} a^{-1} (using the poor suitable sites) and 7.3 (using the best suitable sites) can be achieved in the basis period, 4.4 to 8.1 t d.m. ha^{-1} a^{-1} in the +3 K (dry) and 5.1 to 9.1 t d.m. ha^{-1} a^{-1} in the +3 K (wet) scenario period (Table 2).

In reality, not all soil types are suitable for aspen-SRC and in fact food crop production with very fertile soil types is more likely than bioenergy crop production (Wechsung *et al*., 2008). Most probably set-aside land of poor soil quality will be chosen.

Linking biomass to potential energy a net calorific value of 18 000 MJ t^{-1} d.m. (DIN 51 900) was assumed. Analogous to mean yields, the energy potentials depend on whether primarily good or poor soil types are cultivated with SRC and on the amount of land used in total (Fig. 7). Accordingly, Germany's overall potential is about 1 370 PJ under recent climatic conditions and between 1 510 (+3 K dry scenario) and 1 690 PJ (+3 K wet scenario) under climatic conditions possible in 2041-2060. Depending on site quality used, the energy potential produced on the 4 mln ha mentioned above varied from 321 to 525 PJ in the basis period, from 321 to 586 PJ in the +3.0 K dry scenario period and from 368 to 657 PJ in the +3.0 K wet scenario period.

DISCUSSION

Aspen yields in SRC tend to be slightly lower than those of other poplar species better suited to specific sites, as has been shown in the experiments by Hofmann-Schielle *et al*. (1999). Therefore, the real potential of SRC using a variety of other fast growing tree species such as balsam poplar, willow or black locust in Germany might be underestimated. On the other hand, aspen SRC shows good yield level under low nutrient and low water conditions (Kauter *et al*., 2003; Mohrdiek, 1977). Therefore it can be assumed that aspen will suffer less from changing climate conditions than a drought-sensitive species like balsam poplar. Yields between 8 and 10 t d.m. ha^{-1} a^{-1} were described by Bemmann *et al*., 2007, on sites with medium and good soil quality for poplar and willow and on sites with low soil quality yields of 3.5 to 7 t d.m. ha^{-1} a^{-1} were found. On post-mining land Bungart and Hüttl (2004) measured an average of 2.3 t d.m. ha^{-1} a^{-1} for 8 aspen progenies, while Landgraf *et al*. (2007a, 2007b), reported yields below 1 t d.m. ha^{-1} a^{-1} on similar sites. In

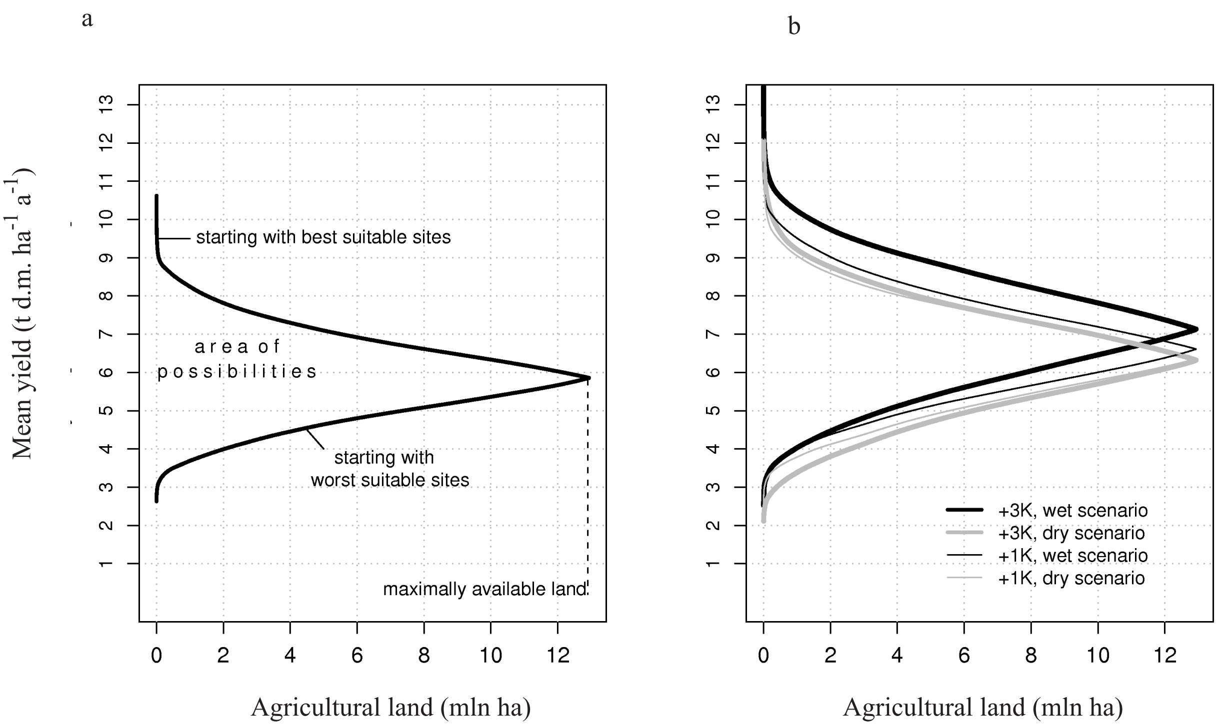

Fig. 6. Mean biomass yield depending on the amount of agricultural land used and whether good or poor site conditions are used first: a – basis period (1987-2006), b – scenario periods (2041-2060).

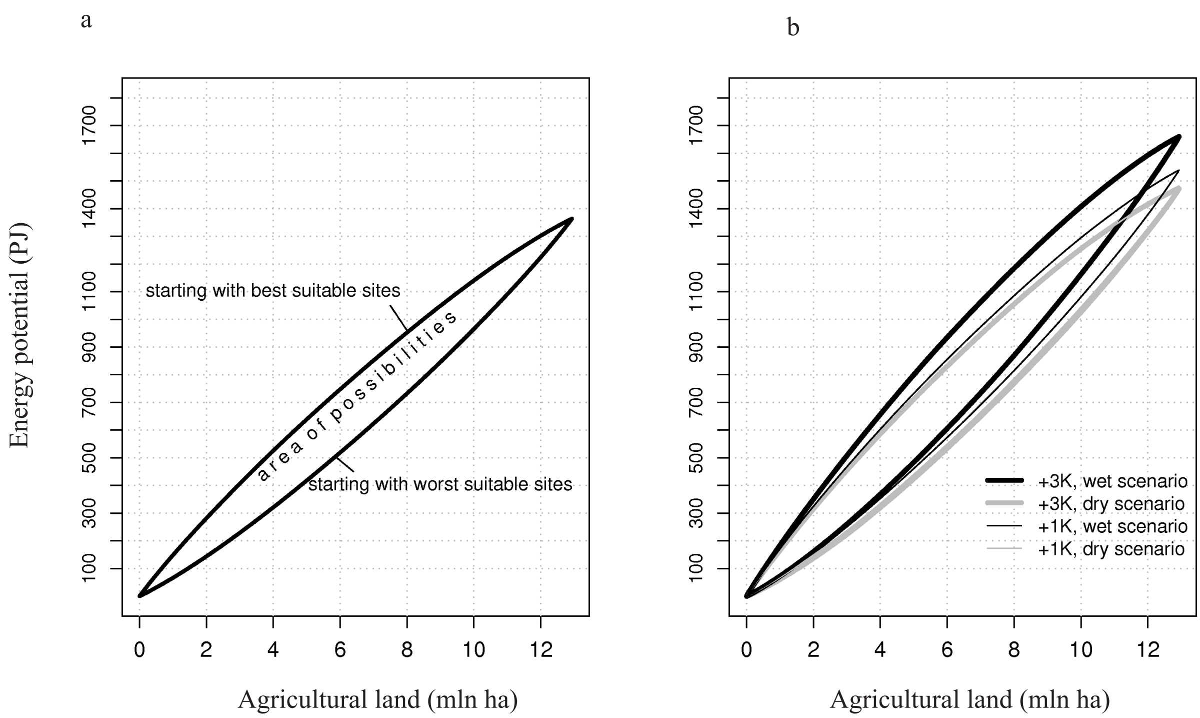

Fig. 7. Energy potential from woody biomass depending on the amount of agricultural land used and whether good or poor site conditions are used first: a– basis period (1987-2006), b – scenario periods (2041-2060).

earlier studies in western Germany yields varied between 1.4 and 11.2 t d.m. ha^{-1} a^{-1} depending on soil quality and site management (Hofmann 1999; Liesebach *et al.*, 1999). Aylott *et al.* (2008), calculated mean yields of poplar plantations ranging from 4.9 to 9.7 t d.m. ha^{-1} a^{-1} for crossings of clones *Populus deltoides* and *Populus trichocarpa* in UK. They used an empirical model driven by data of field trials and came to results quite similar to ours.

The most productive agricultural sites such as loess plains in the region 'Magdeburger Börde' will not be under consideration in coming decades for energy production purposes. Hence, high yields as reported from several (small-scale) experimental plots with good nutrient and water availability (Weisgerber (1984), for yields up to 29 t d.m. ha^{-1} a^{-1}) will not be achievable on large scale plantations.

Under the temperature increase scenarios the mean annual yield increased with rising temperature level up to the +2.0 K scenarios. In the +2.5 and 3.0 K scenarios the trend inverts (Fig. 5c, Table 2). This is caused by the decreasing or nearly unchanged precipitation sums for the +2.5 and +3.0 K scenarios which, together with the high temperatures in the vegetation period, cause higher drought stress than under the 0 to +2 K scenarios. This increasing drought stress is explicitly modelled in 4C and it is also given in Table 2 as the ratio of averaged annual actual evapotranspiration and potential evapotranspiration (AET/PET). On the other hand, yields of all scenarios were still higher than yields under the base scenario, which leads to the conclusion that the changing climatic conditions of the selected set of temperature scenarios combined with different precipitation realizations until 2060 did not cause clear losses in productivity of aspen SRC. This corresponds to model analysis for aspen stands in the boreal region (Grant *et al.*, 2006) where the net biome productivity of aspen stands was projected to rise gradually under conditions of increasing temperatures and CO_2 concentrations except under prolonged recurring drought conditions *eg* 6 years.

The amount of land available for energy crop production in Germany depends on different factors such as the development of food and oil prices and the political framework. In 2007, about 1.77 mln ha of arable land were used for bioenergy (mostly rapeseed and maize) in Germany (Nitsch, 2008). In the long run, around 4 mln ha are considered to be available under strong ecological restrictions (Fritsche *et al.*, 2004; Nitsch *et al.*, 2004), but 7.3 mln ha are mentioned by Thrän, 2005, and 11.8 mln ha by Nielsen *et al.* (2007), under weaker restrictions. Currently, there is no reliable information about the total available area for SRC plantations. According to this high uncertainty, mean annual yields and energy potential for the broad range of suitable land from 0 to 12.9 mln ha were calculated in this study.

In 2007 Germany produced 7.2 % (1 006 PJ) of its primary energy consumption (13 993 PJ) through renewable resources, mainly by wind, water and biomass (Energiebilanzen, 2008). The simulated mean aspen biomass production of 4 mln ha in Germany in the future scenario periods corresponds to a primary energy amount between 380 and 630 PJ a^{-1} in the dry and between 420 and 670 PJ a^{-1} in the wet scenario period. This represents 2.7 to 4.8% of afore-mentioned primary energy consumption and could increase the current portion of 7.2 %. Assuming a decrease of primary energy consumption by 2050 to 8 066 PJ a^{-1} (Nitsch, 2008), renewable energy from SRC could deliver 4.7-8.3% if 4 mln ha of arable lands were transformed into SRC.

CONCLUSIONS

1. The model-based analysis provided an initial insight into the potential of SRC for energy on arable land in Germany under current and hypothetical climate conditions.

2. The projected biomass yields of aspen are lower than the potential yields of a variety of other tree species carefully related to specific site conditions. The sustainable production of renewable energy by SRC over a period of 20 years should therefore be higher than the results presented here.

3. SRC can deliver a substantial contribution to the primary energy production in 2060. The use of SRC contributes to the reduction of CO_2 emissions by substitution and carbon sequestration.

4. Further impacts should be examined, including those concerning aspects of competition with other crops (food security) and energy demand (WBGU, 2008). Additionally, the effects on the regional water budget by increasing water demand of SRC due to changing temperature, precipitation and CO_2 concentration (Tricker *et al.*, 2009) should be considered. Initial contributions to an evaluation of the impacts of SRC on water and soil organic matter budgets as well as flora and fauna diversity have been published (Lasch *et al.*, 2009; Rowe *et al.*, 2009; Updegraff *et al.*, 2004) but need further enhancements.

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