Chapter 4
A Process-Based Vegetation Model for Estimating Agricultural Bioenergy Potentials

Markus Tum, Kurt P. Günther, and Martin Kappas

Abstract We present an approach to estimate sustainable straw energy potentials by means of a modelled net primary productivity (NPP) product validated against empirical data on the managed area and mean yields of the main crops in Germany. We used the Biosphere Energy Transfer Hydrology Model (BETHY/DLR) as a theoretical framework for estimating the NPP of agricultural areas in Germany. The BETHY/DLR was driven by remote sensing data from SPOT-VEGETATION, meteorological data from the European Centre for Medium-Range Weather Forecast (ECMWF) and additional static datasets such as land cover information (GLC2000), a soil map (ISRIC-WISE) and an elevation model (ETOP05). The output of the BETHY/DLR, i.e. the yearly accumulated NPP, was first converted into straw potentials through simple allocation rules (root-to-shoot and yield-to-straw ratios). Thereafter it was converted into energy potentials through species-specific lower heating values. The 2006 and 2007 results were compared with data from the literature. Using this method for estimating sustainable bioenergy potentials, we found good compatibility between the established approaches with only little overestimations (up to 12 %) and high correlations with the R^2 of up to 0.78. Our analysis shows that the presented approach fills an important gap in estimating energy potentials from the modelled NPP. The estimated straw biomass energy potentials play an important role in the sustainable energy debate.

Keywords Bioenergy potentials • Biosphere Energy Transfer Hydrology Model (BETHY/DLR) • NPP • Agriculture • Remote sensing

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M. Tum (✉) • K.P. Günther
German Aerospace Center (DLR), German Remote Sensing Data Center (DFD),
Oberpfaffenhofen, D-82234 Weßling, Germany
e-mail: markus.tum@dlr.de; kurt.guenther@dlr.de

M. Kappas
Institute of Geography, Department of Cartography, GIS and Remote Sensing, University of Göttingen, Goldschmidtstr. 5, D-37077 Göttingen, Germany
e-mail: mkappas@uni-goettingen.de; mkappas@gwdg.de

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4.1 Introduction

Over the last 60 years, the treatment of straw as a side product of cereal production has changed considerably in many developed countries. This is mainly due to a reduction in field straw burning, which used to be done to fertilise the soil, control pests and avoid nitrogen immobilisation (Børresen 1999). The decreasing demand for straw as bedding litter in feeding lots due to changes in housing systems (Jorden et al. 2008) also resulted in many regions experiencing an increase in the available straw on the fields. However, while leaving straw residues on fields has certain positive effects, like the stabilization of the topsoil, specific crop rotations require their removal (Zebarth et al. 2009). Cropping systems with a high straw supply rate thus offer the possibility of straw removal without changing the soil conditions.

The focus of the current – politically motivated – energy discussion has shifted toward renewable energy sources and the energetic use of agricultural by-products, such as straw. Since no competition with human food is related to its use, it has considerable potential, but is limited by several factors. Two major limiting factors apply to central Europe: animal husbandry and the demand for organic material for the humus balance. Over the last 10 years, several studies have been conducted to assess Germany’s total and regional straw potentials (e.g., Gauder et al. 2011; Zeller et al. 2011; Pacan and Dröge 2010; Thrän et al. 2009; Fritsche et al. 2004).

These studies’ general approach is to use empirical data on land use and mean yields to estimate the theoretically informed straw and sustainable energy potentials after considering the use competitions. Thus, there is always a spatial limitation of the area on which the empirical data source is based.

Besides these empirical approaches, remote sensing-driven vegetation models, established to assess the carbon uptake of plants, can also provide information on the straw potential, but at a significantly higher – raster-based – resolution. Vegetation models have become an important tool for answering questions on the mechanisms that drive the carbon cycle and the roles of terrestrial carbon sinks and sources (Cox et al. 1999). Models, such as the Biosphere Energy Transfer Hydrology (BETHY/DLR)[1] model, have already been tested to estimate the sustainable energy potentials of forests in Germany (Tum et al. 2011) and have shown reasonably good results. More detailed information on the local availability of straw potentials is needed if a sustainable and cost-efficient use is to be achieved in terms of the current political discussion on renewable energy sources.

The primary objective of this study is to investigate an approach to estimate straw potentials by using the modelled net primary productivity (NPP) from the BETHY/DLR in a 1 km^2 area. Statistical data on the land use and the main crops’ yields, which are at Level 3 of the ‘Nomenclature des Unités Territoriales Statistiques’ (NUTS), are used to calibrate the estimated straw potentials. Specific allocation schemes, such as the root-to-shoot and yield-to-straw ratios, are used to

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[1] The BETHY/DLR was originally designed for global applications (Knorr and Heimann 2001), after which Wisskrichen (2005) adapted it for regional use.

estimate the straw potentials. Germany was selected as the test area due to its data availability. Computing time and hard disk storage issues restricted our modelling to 2006 and 2007.

4.2 Model Description

The BETHY/DLR is a special soil-vegetation-atmosphere-transfer (SVAT) model of photosynthesis that takes environmental conditions that affect it into account. SVAT models track the plant-mediated transformation of atmospheric carbon dioxide into energy-storing hydrocarbons, such as sugars; this process is called carbon fixation.

The process of photosynthesis is parameterised following a combined approach based on methodologies by Farquhar et al. (1980) and Collatz et al. (1992). Photosynthetic reactions to dark and light are calculated on the leaf level and treated separately. With this approach, the photosynthesis rate can be limited either by light availability or the carboxylation enzyme Rubisco – the key player in the Calvin cycle, which fixes carbon. Owing to the significant differences between their carbon fixation physiologies, a distinction is made between C3 and C4 plants. –In the BETHY/DLR, C4 plants, such as sugar beet and corn, can fix more atmospheric carbon dioxide at higher temperatures than C3 plants, such as barley and wheat.

To extrapolate photosynthesis from the leaf to the canopy level, the canopy structure and the soil-atmosphere-vegetation interaction is taken into account. The photosynthetic rate of closed and open canopies (forests, shrubs, grassland and crops) depends on the Leaf Area Index (LAI). Self-shading is considered by reducing the photosynthetic rate from the canopy top to the soil by using Sellers's (1985) 'two-flux scheme' with three canopy layers.

In addition to photosynthesis, other energy transfers, such as heat fluxes between vegetation and the atmosphere as well as the cooling effect of evapotranspiration, are taken into account. Furthermore, we consider the soil heat flux and the storage of heat in the canopy. The coupling of these processes is of great importance, since temperature-dependent photosynthesis transforms light energy into chemical energy and finally into carbohydrates by using water and CO_2.

The water cycle is also modelled and included in the interaction scheme. Three reservoirs are considered: soil water, snow, and 'skin' or 'intercepted' water on leaves and other parts of the vegetation, which change in space and time. Soil water is available for vegetation, while evapotranspiration from vegetation and evaporation from soil determine the water loss to the atmosphere. Water limitation is modelled by calculating the demand for evapotranspiration. We do so by using Monteith's (1965) approach, to which we have applied criteria by Federer (1979) which assume that evapotranspiration cannot be greater than the limit determined by the soil water supply and the water uptake of a plant's roots. Thus, when the dynamic interaction of, for instance, the soil water balance and photosynthesis is examined, this reflects the natural behaviour of vegetation, which motivated us to use the SVAT approach.

Using the BETHY/DLR, autotrophic respiration is modelled as the sum of the maintenance respiration and the growth respiration. Maintenance respiration is limited by vegetation-specific dark respiration rates. Growth respiration is assumed to be a constant fraction of the NPP.

The model output of the BETHY/DLR is given as a time series of the NPP in daily steps with a spatial resolution and a projection of the land cover classification. For this study, we used the Global Landcover Classification 2000 (GLC2000) with an area size of 1 km^2.

4.3 Input Data

The inputs for the BETHY/DLR model include two remote sensing datasets derived from SPOT-VEGETATION, meteorological time series data provided by the ECMWF and two static datasets describing the soil type and land elevation.

4.3.1 Meteorological Data

The BETHY/DLR requires a meteorological time series with a temporal resolution of at least once per day. The European Centre for Medium-Range Weather Forecasts (ECMWF) provides the data, which indicate a spatial resolution of $0.25° \times 0.25°$ and a temporal resolution of up to four times per day. The ECMWF INTERIM dataset contains a broad variety of parameters of which air temperature (at 2 m height), wind speed (at 10 m height), soil water content (in the four uppermost layers), cloud cover and precipitation are used. The INTERIM reanalysis combines the meteorological station, satellite and airborne-based measurements. We used these data to calculate the daily mean minimum and maximum temperatures as well as the daily mean cloud cover at three heights. The daily temperatures were adjusted to the 1 km^2 resolution of the model output to compensate for the elevation difference between the ECMWF data and the elevation of each model pixel. We did this by using a 1 km^2 elevation map and the temperature gradient of the international standard atmosphere (−0.65 K per 100 m).

Using Burridge and Gadd's method (1974), we calculated the daily average photosynthetically active radiation (PAR) from the global radiation. We estimated the PAR by using the incident sunlight for the given day and year, limited by atmospheric transmissions, which depend on the degree of cloudiness. The daily average cloud cover was calculated using a weighted sum of each cloud layer. The advantage of this approach is that it produces more accurate results than the direct use of radiation forecast data (Wisskirchen 2005).

Daily volumetric soil water content data were needed to calculate the model's soil water budget. The soil type information was taken from the International Soil Reference and Information Centre-World Inventory of Soil Emission Potentials

(ISRIC-WISE) dataset, which is a harmonization of the global FAO-UNESCO Soil Map of the World (FAO-UNESCO 1974) and is available with a 5 × 5 arc-minutes resolution.

4.3.2 *Remote Sensing Data*

In addition to meteorological data, the BETHY/DLR is driven by two remote-sensing-based datasets. These consist of the LAI time series and a detailed and homogenous land cover/land use product. The LAI time series are used to indicate the phenology of vegetation and are based on the CYCLOPES 10-day composites dataset that the POSTEL (Pole d'Observation des Surfaces continentales par Teledetection) database provides.

For each 1 km^2 pixel, a time series analysis, namely the harmonic analysis, was applied to fill the data gaps and eliminate outliers. The harmonic analysis decomposes a time series into a linear combination of suitable trigonometric functions (sine and cosine oscillations) of particular periodicities. In principal, the power spectrum is deconvolved by iteratively finding and subtracting the highest peak of the time series power spectrum.

The CYCLOPES database also provides land cover and land use information, indicated as the GLC2000 (Fritz et al. 2003; Bartholome and Belward 2005). To derive the GLC2000 land cover classes, the FAO's Land Cover Classification System (LCCS) (DiGregorio and Jansen 2001) was used. The GLC2000 dataset represents the year 2000 and includes 22 different land cover classes. The CYCLOPES dataset was chosen because it is thought to be the most accurate dataset for agricultural areas (Garrigues et al. 2008).

4.4 Energy Potentials

The main objective of this study is to derive sustainable straw energy potentials from the modelled and validated NPP (Tum and Günther 2011) of agricultural areas in Germany, and to compare these with recently published estimates. Straw energy potentials are of considerable importance for the sustainable energy discussion and the development of a sustainable energy policy.

Before the energy content of straw is estimated, the modelled NPP needs to be transferred to dry above-ground biomass. This can be done by using simple crop-specific allocation schemes. Since the GLC2000 only contains information about general land use, an additional dataset, describing the area use and yields of the main crops, had to be implemented in order to differentiate between straw crops, such as wheat and barley, and non-straw crops, such as sugar beet and potatoes. We used empirical data from the German Federal Statistical Office, which conducts a yearly farm structure survey. It contains yield and area use information on the main crops grown in each NUTS 3 region. The NUTS hierarchical spatial classification starts with the member states of the European Community (EU) (NUTS 0), followed by the regions of the EU (NUTS 1), which are separated into basic administrative units (NUTS 2), and ends with the subdivisions of these basic administrative units (NUTS 3). However, a criterion was needed to fill the gaps in the dataset. We thus assumed that the gaps in a given crop could be filled by using the mean yield of the given crop from the German NUTS 3 units.

In a first step, the modelled NPP of the BETHY/DLR was aggregated into NUTS 3 units and compared to the NPP values of each NUTS 3 unit, which, as described by Tum and Günther (2011) were calculated from the empirical data. To calculate the NPP of straw-providing crops (NPP_s) the NPP of non-straw-providing crops (NPP_{ns}) was subtracted from the aggregated modelled NPP per NUTS area (NPP_N). The percentage of land use was taken into consideration as described in the empirical dataset.

$$NPP_s = NPP_N - NPP_{ns} \tag{4.1}$$

The remaining NPP_S was then transferred to above-ground NPP (NPP_a) by subtracting the below-ground NPP part (NPP_b), using crop-specific root-to-shoot ratios:

$$NPP_a = NPP_s - NPP_b \tag{4.2}$$

In a next step, the straw content (NPP_{st}) of NPP_a was calculated by subtracting the yield content (NPP_{yi}), using crop-specific yield to straw ratios:

$$NPP_{st} = NPP_a - NPP_{yi} \tag{4.3}$$

The final sustainable straw potential (S_{pot}) was then calculated by adding non-carbon (${}_{non}C$) and water (H_2O) contents to NPP_{st}. We used Gauder et al.'s (2011) empirical factor of 0.29 in respect of the use competitions of the harvested straw.

$$S_{pot} = (NPP_{st} + H_2O + {}_{non}C) \times 0.29 \tag{4.4}$$

In addition, we applied Tum and Günther's (2011) crop-specific root-to-shoot and yield-to-straw ratios, water and non-carbon contents.

The recently available S_{pot} values per NUTS 3 region can be used directly to estimate sustainable straw energy potentials. To do so, species-specific lower heating values (H) are needed to convert dry above-ground biomass into energy. The heating values represent the maximum energy output from burning biogenic solid fuels and are measured in megajoules per kilogram. Since the GLC2000 does not provide any information on crop species, we calculated a mean heating value per NUTS 3 unit (<*H*>). Kaltschmidt and Hartmann's (2001) heating values for rye, wheat, barley and rapeseed straw were used in this study.

We calculated the energy potential (J_n) of each NUTS 3 unit, as shown in Eq. 4.5.

$$J_n = S_{pot} * \langle H \rangle \tag{4.5}$$

In a last step, the energy potentials per NUTS 3 unit were spatially reallocated, using the modelled NPP values. To do so, we assumed that the high NPP values of the model output represented high energy potentials and vice versa. We calculated the energy content (J_i) of each pixel (i), as presented in Eq. 4.6.

$$J_i = \frac{NPP_i}{NPP_N} \times J_n \tag{4.6}$$

With this approach, we assumed that each pixel's percentage of straw-providing crops is similar to that of the full NUTS 3 region.

4.5 Results and Discussion

Figure 4.1 depicts the estimated 2006 and 2007 annual straw energy potentials in Germany in accordance with the study's spatial resolution of 1 km^2. In both years, central Germany was identified as the area with the highest energy potential values. This area is located in the Magdeburger Börde, which is well known for its extensive agricultural use. Other areas, such as the Münsterland in northwest Germany and parts of southeast Germany, show significant variability over the 2 years of observation. Overall, the calculated energy potentials in 2006 were lower than in 2007, which we assume was caused by climate conditions. The mean annual energy potential in 2006 was 0.52 [TJ km^{-2} year^{-1}] with a maximum of 2.85 [TJ km^{-2} year^{-1}]. In 2007, the mean annual energy potential was 0.70 [TJ km^{-2} year^{-1}] with a maximum of 2.75 [TJ km^{-2} year^{-1}]. The total annual estimated energy potential was thus 156 PJ in 2006 and 217 PJ in 2007.

Our estimates agree well with the values of the mean straw potentials reported in the literature (Zeller et al. 2011). Three methods were used to estimate the annual straw potentials in Germany and its 16 federal states. These methods consider the humus balance, which is required for sustainable crop and soil management as well as forming the basis of the direct payment obligation, i.e. the accounting regulation. Depending on the method of estimation, the mean annual energy potentials of 112–186 [PJ year^{-1}] are calculated for Germany by applying a mean heating value H of 14.05 MJ kg^{-1}. The heating value represents dry matter with 14 % moisture.

In addition to the annual sum, we analysed the correlation between the modelled sustainable energy potential of both years and the mean sustainable energy straw potential of each Federal State in Germany as presented by Zeller et al. (2011).

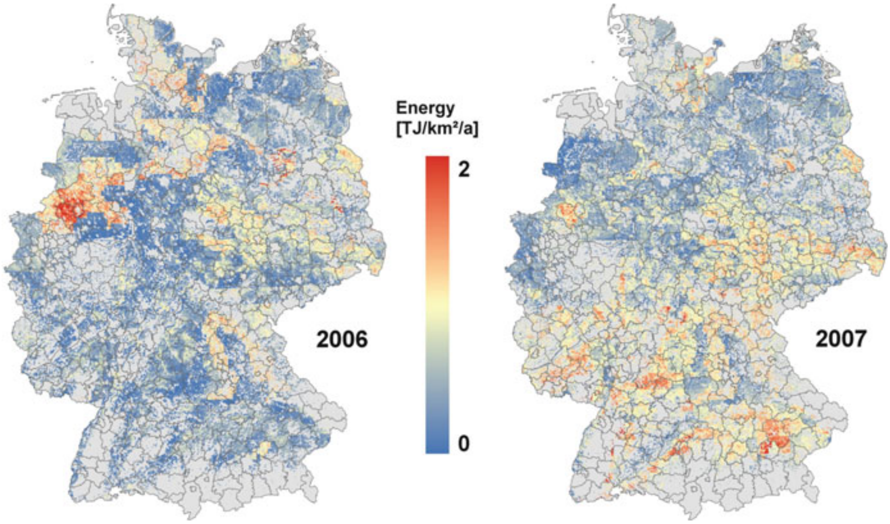

Fig. 4.1 Sustainable energy potential in terajoules per 1 km^2 pixels of agricultural areas in Germany in 2006 and 2007 modelled by the BETHY/DLR. Low energy potentials are indicated in *blue*, intermediate in *beige*, and high energy potentials in *red*. *Grey* represents areas that the GLC2000 has not designated as managed regions

Therefore, the biomass potential was converted into energy potentials, again using a mean H value of 14.05 MJ kg^{-1}. The results are presented as linear regressions in Fig. 4.2.

Figure 4.2 shows that, in both years, the sustainable energy potential, which was calculated using the BETHY/DLR model, tended to be slightly overestimated on the Federal State (FS) level. The R^2 values of 0.78 and 0.70 indicate a high degree of correlation between 2006 and 2007. In order to quantify the correlation between our estimations and the literature data, the root mean square error (RMSE) was calculated for both years; the RMSE for 2006 is 3.9 PJ FS^{-1} $year^{-1}$ and, for 2007, it is 6.5 PJ FS^{-1} $year^{-1}$. Figure 4.1 clearly indicates that, in 2006, the sustainable energy potentials for most regions in Germany were lower than in 2007. Our assumption that this finding is related to meteorological conditions is supported by a note in the agro-meteorological bulletin posted by the MARS (Monitoring Agriculture with Remote Sensing) project (MARS 2006). The MARS project characterised 2006 as ‘a below-average cereal season explained by hot and dry summer followed by over-wet conditions at harvest’. A mean wheat yield (including soft and durum wheat) of 6.6 tons per hectare was reported for Germany, while the 5-year moving average was 7.4 tons per hectare. This indicates a reduction of about 11 %. On the other hand, barley and grain maize show the same yields as in previous years. Thus, in 2006, Germany’s total cereal yield was slightly lower than the 5-year average. In 2007, the cereal production in “Germany was again limited by wet conditions at harvest (winter cereals) but not on the same amplitude as in 2006” (MARS 2007). In 2007, the wheat yield was more or less on par with the

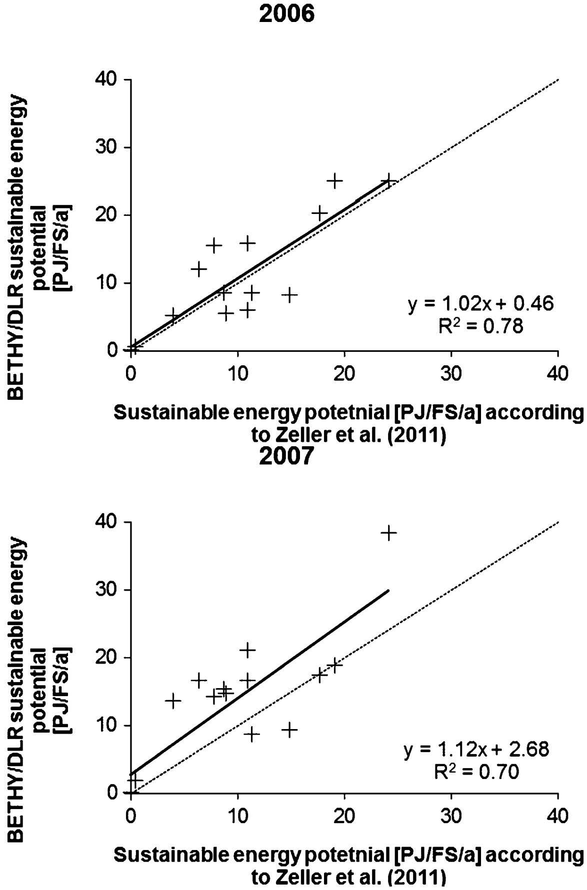

Fig. 4.2 Correlation between sustainable energy potentials of the 16 Federal States of Germany, derived from the modelled NPP with data from Zeller et al. (2011). The 2006 and 2007 energy potentials are modelled. Data points indicate the Federal States' energy potentials. *Dotted lines* indicate a perfect correlation while *solid lines* indicate the correlation found by means of a linear regression. Energy potentials are given in PJ per Federal State (FS) and year

5-year average. The barley yield estimates were about 3 % lower, while that of grain maize was about 8 % higher than the average yields. According to the MARS bulletins, 2007 was overall a more productive year than 2006. Our results support this finding.

Revisiting Fig. 4.1, the Magdeburger Börde can clearly be identified as an area in central Germany with high energy potentials. This is also an area with extensive agricultural use. The ISRIC-WISE dataset reports large amounts of cambisols and chernozems, which are very fertile soils. Areas rich in chernozems, which are among the most fertile soils, are especially sought after as agricultural land. Thus, a constantly high straw potential is expected for areas with these types of soils, as seen in both years.

In northwest Germany, namely the Münsterland, high energy potentials are observed for 2006 and, to a lesser degree, 2007. In the Münsterland, the total

Table 4.1 The precipitation rates of the Münsterland and Landshut areas in millimetres and the 2006 and 2007 mean temperatures in °C

	Münsterland		Landshut area	
10-year mean precipitation sum [mm]	781		779	
10-year mean precipitation sum [mm] for the growing season (15 March–30 September)	432		422	
10-year mean temperature (15 March–30 September) [°C]	15.2		14.7	
	2006	**2007**	**2006**	**2007**
Precipitation sum (1 January–31 December) [mm]	732	831	736	971
Mean temperature (1 January–31 December) [°C]	11.4	11.4	9.4	10.1
Precipitation (15 March–30 September) [mm]	475	496	427	558
Mean temperature (15 March– 30 September) [°C]	14.9	15.4	13.9	15.0

amount of precipitation in 2006 (732 mm) was considerably lower than in 2007 (831 mm) – even lower than the 10-year average (781 mm). A similar precipitation pattern is seen in 2006 and 2007 in the area around Landshut in southeast Germany. In the Landshut area, the precipitation was about 736 mm in 2006 and 971 mm in 2007, as shown in Table 4.1. When discussing the energy potential of straw and biomass development, the most important meteorological parameters are the precipitation and the mean temperature during the growing season. For our analysis, we defined the growing season as the period between 15 April and the end of September. During the growing season, the precipitation in both years was higher than the 10-year average of both regions.

An analysis of the monthly mean temperatures, which we calculated using the daily values taken from the ECMWF data, was performed for both regions to investigate the potential warming or cooling effects on the plant growth and, ultimately, on the straw energy potential. Figure 4.3 presents the time series of the mean monthly temperature of the Münsterland and Landshut areas in both years.

The 2006 and 2007 monthly mean temperatures differed significantly in the nonproductive time period (from January to mid-March and from October to December) in both regions. However, there were slight differences in the temperature between the growing seasons (mid-March to September) in the two areas. The mean temperature during the growing period from mid-March to September was lower in the Landshut region in 2006 than in 2007 and equal in the Münsterland region. Compared to the 10-year average, the 2006 mean temperature was lower in both regions. An explanation for the high energy potentials in the Münsterland in 2006 and in the Landshut region in 2007 is found when examining the scatterplot of the mean temperature and precipitation in the growing season from 1999 to 2010, as shown in Fig. 4.4. All the mean values of the meteorological parameters are based on the daily ECMWF data. It is evident that the 2006 growing season was relatively cold and wet in the Landshut region, while the 2007 growing season was relative warm and wet (compared to the 10-year average – shown in Fig. 4.4 as an open

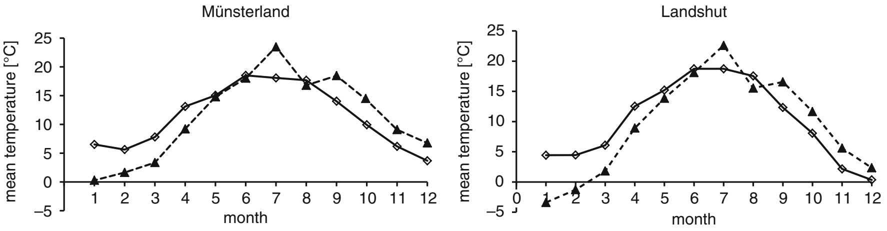

Fig. 4.3 The 2006 (*triangles*) and 2007 (*diamonds*) monthly mean temperatures of the Münsterland (*left*) and Landshut areas (*right*) in °C

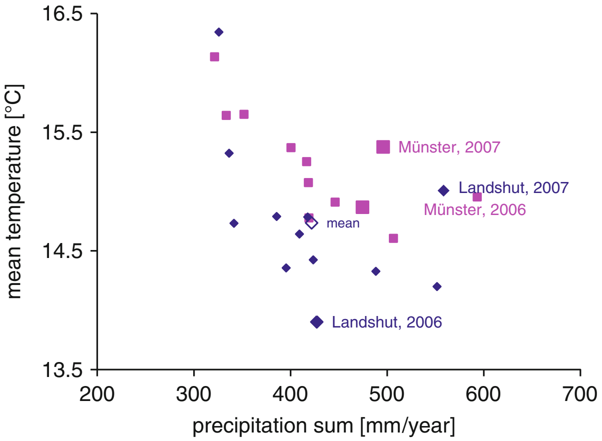

Fig. 4.4 Scatterplot of the precipitation sum [mm] and the mean temperature [°C] of the growing season (15 March–30 September) over 11 years (1999–2010). The Münsterland data are presented as *squares* (*magenta*) while the Landshut region data are indicated by *diamonds* (*blue*). The average values of both regions is presented as *open symbol*

diamond). The 2006 growing season in the Münsterland region was only a little colder and wetter than the 10-year average, but the 2007 growing season was a little warmer and significantly wetter than the 10-year average. In sum, in 2006, the meteorological conditions in the Münsterland region were more favourable than in 2007. In 2006, the cold conditions in the Landshut region reduced the biomass growth and, thus, the energy potential of straw.

The mean yields of the two NUTS 3 units we investigated were derived from an agricultural statistical survey. When the mean yields of the two NUTS 3 units, which are representative of the two described regions, are studies, it becomes evident that our modelled NPP data show lower yields and, thus, lower straw potentials (Table 4.2) for the Landshut region in 2006 and for the Münsterland in 2007.

Table 4.2 Mean 2006 and 2007 yields of important straw-providing crops in two NUTS 3 units in Germany

	Winter-wheat	Rye	Winter-barley	Summer-barley	Oats	Triticale	Other cereals
Landshut							
2006	70.4	54.3	56.8	46.7	49.6	68.8	57.8
2007	78.6	62.1	65.3	51.0	50.0	76.2	63.9
Steinfurt							
2006	68.4	60.4	59.2	44.5	39.7	54.7	54.5
2007	60.7	40.7	48.5	34.3	38.3	47.3	45.5

Steinfurt is representative of the Münsterland area, while Landshut represents the area surrounding Landshut. The values are given in dt ha^{-1}

4.6 Conclusion

Germany's sustainable straw energy potentials in 2006 and 2007 were calculated using the modelled NPP from the BETHY/DLR vegetation model. Inputs for the model were the LAI time series from the VEGETATION satellite, meteorological data from the ECMWF and land cover/land use data from the GLC2000. In this chapter, we presented an approach to estimate sustainable energy potentials by using empirical data on average grain yields and on the acreage of main crops on the NUTS 3 level. Using conversion factors (root-to-shoot and corn-to-straw ratios), the modelled NPP data were converted into harvested straw per NUTS unit. Thus, the NUTS's specific land use practices were taken into account. Compared to recently published straw potential values (Zeller et al. 2011), this method yielded reasonably high coefficients of determination (R^2 up to 0.78), combined with a slight overestimation (up to 12 %), therefore allowing strong conclusions to be drawn about the usability of the presented method.

We indicated the differences between two areas' rate of precipitation and mean annual temperature. We furthermore proved that lower mean temperatures and wet conditions, especially during the growing season, correspond to lower mean grain yields. We hypothesised that significantly cooler mean temperatures during the growing seasons, combined with high precipitation rates, cause yield losses. This phenomenon also corresponds to our calculated sustainable energy potential, which is a good indicator of our method's usefulness.

This study illustrated an approach to calculate sustainable straw energy potentials that we believe will be useful in estimating the energy potentials of the modelled NPP products with a medium resolution. This method could also be used as a downscaling approach to empirically derived straw potential data on a NUTS level, as the model's results could help to spatially represent the NUTS information.

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