Sustainable Bioenergy Potentials for Europe and the Globe
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Abstract
In the framework of the EU FP7 project EnerGEO (Earth Observation for Monitoring and Assessment of the Environmental Impact of Energy Use) sustainable energy potentials for agricultural and forest areas were estimated by applying three different model approaches. The EPIC (Environmental Policy Including Climate) yield forecast model was used to estimate crop yields. The Global Forest Model (G4M) was applied to estimate global woody biomass growth. Both models were driven on the European and global scale. Additionally the Biosphere Energy Transfer Hydrology (BETY/DLR) model was applied to assess Net Primary Productivity (NPP) for agricultural and forest areas in Europe. We transferred our biomass and NPP estimations to energy potentials using conversion factors (i.e. above to below ground and yield to straw ratios), which we also present in this study. For agriculture we focussed on the straw potentials of selected crops (barley, grain maize, oats, rapeseed, rye and wheat), taking into account use competitions. For forests we calculated maximum available energy potentials per year, excluding the tropical belt. Our results for Europe show energy potentials of 9.3 – 15.0 EJ a⁻¹ (forests) and 2.5 – 3.8 EJ a⁻¹ (straw). On a global scale we calculated a maximum available energy potential for forests of 170.0 EJ a⁻¹ and 32.9 EJ a⁻¹ for straw. These results are in concordance with previous studies, albeit somewhat conservative.

Keywords
Bioenergy; Modelling; Straw potential; Sustainability

Introduction
During recent decades the use of renewables has come increasingly into focus to substitute fossil energy sources. In the last sixty years the treatment of straw as a side product of cereal production changed considerably in many developed countries. This is mainly caused by the reduction of on-field straw burning, which used to be done to improve soil fertilization, control pests and to avoid nitrogen immobilisation [1]. Biomass burning was found as one major impact to air quality, which was investigated by many groups [2,3]. The decreasing demand for straw as bedding litter in feeding lots due to changes in animal husbandry systems [4] also resulted in many regions in an increasing availability of straw on fields. However, while leaving straw on fields has positive effects (e.g. stabilization of the topsoil), specific crops (e.g. barley) or climatic conditions (e.g. wet spring conditions) require their removal to increase yields [1,5]. Cropping systems with high straw supply rates thus offer the possibility of straw removal without changing the soil conditions and thus might be used for bioenergy production.

Aside from crop residues, forests biomass is widely used for energy generation, which is particularly done in developing countries [6,7]. However its availability highly depends on its sustainable use. The discussion of a sustainable forest management (SFM) concept has continued to evolve since 1992, when it was triggered by the international forest policy dialogue within the Intergovernmental Forum on Forests (IFF), the Intergovernmental Panel on Forests (IPF), the United Nations Forum on Forests (UNFF), and further country-led and eco-regional activities [8]. A generally accepted definition of SFM currently does not exist [9]. The tendency is to propose management practices to be sustainable if responsibility for future generations is recognized [10], and generally health and well-being of mankind and the forest ecosystem can be maintained [11]. The Roundtable on Sustainable Biofuels (RSB) specifies sustainable use of forest and agricultural residues to happen, if the long-term soil stability and organic matter content is not compromised [12]. Current use practices show that mainly the stem wood share of biomass increase is harvested. However large amounts of residues and stumps are left in the forest to meet the SFM [13].

The current politically motivated energy discussion has refocused the attention on renewable energy sources and thus on the energetic use of agricultural and forest products and by-products such as straw and woody biomass. During the last fifteen years several studies have been conducted to assess bioenergy potentials, which were carried out for various temporal and geographical scopes, also including future scenarios. A good overview of studies conducted until 2010 is given in [14]. However more recent studies can be found in e.g. [15,16]. Most studies are based on empirical data on land use and yield tables, which were used to estimate theoretical energy potentials and sustainable energy potentials after respecting use competitions and constraints. They are mostly carried out on a country, or state level. Thus a spatial limitation to the resolution of the empirical data source is usually given. However, when bioenergy use scenarios are assessed, more detailed information about local availability of e.g. straw is needed. This is especially needed for planning of bioenergy power plant locations.

Besides these empirical approaches vegetation models (established to assess the carbon uptake by terrestrial plants) can also be used to calculate bioenergy potentials [17] on a global scale. Vegetation models are among the methods frequently used to estimate ecosystem carbon fluxes on a high temporal frequency and spatial resolution. Since terrestrial vegetative carbon sequestration can be directly linked with biomass, these tools are promising to estimate bioenergy potentials without limitations of e.g. political boundaries. This is particularly the case if remote sensing data is used to drive these models. An example would be the Biosphere Energy Transfer Hydrology (BETY/DLR) model, which has already been used to estimate sustainable energy potentials for Germany’s forests and agricultural areas on a high spatial resolution [18,19].

The primary objective of this study is to estimate sustainable...
bioenergy potentials for agricultural side products (i.e. straw) and forest for Europe and the globe. For Europe we used the three models BETHY/DLR, Environmental Policy Including Climate (EPIC), and the Global Forest Model (G4M) on a 1 km² resolution. For global estimations we used EPIC (10 km x 10 km resolution) and G4M (0.5° x 0.5° resolution) only. All estimations were carried out for the year 2000. We believe our study to contribute to the identification of opportunities for the use of bioenergy.

Method

Models

To calculate sustainable energy potentials, three models were used as shown in Figure 1. In a first step woody biomass, crop yield and Net Primary Productivity (NPP) were computed and then transferred to energy units using a post-processing module for each model. The EPIC (Environmental Policy Including Climate) model was used to assess agricultural yields on a European and global scale. EPIC was originally developed by a modelling team of the USDA to assess the status of U.S. soil and water resources [20] but continuously expanded and refined to allow simulation of many processes important in agricultural land management. The major components in EPIC are weather simulation, hydrology, erosion-sedimentation, nutrient and carbon cycling, pesticide fate, plant growth and competition, soil temperature and moisture, tillage, cost accounting, and plant environment control. EPIC operates on a daily time step and can simulate plant growth for hundreds of years. The spatial resolution of EPIC is adjusted to Homogeneous Response Unit (HRU) because EPIC does not work directly on a GIS platform and therefore the transformation of GIS-based information to the model interface is necessary. HRUs have been delineated by geographically clustering of 5 arcmin pixels according to only those parameters of the landscape, which are generally not changing over time and are thus invariant with respect to land use and management or climate change. At the global scale, we have included five altitude classes, seven slope classes, and six soil classes, resulting into 157 HRUs.

In a second step, the HRU layer is intersected with a 0.5° × 0.5° grid and with country boundaries to delineate more than 100 000 Simulation Units (SimU) which contain other relevant information such as global climate data, land category/use data, irrigation data, etc. For each SimU a number of land management options are simulated using the bio-physical process model EPIC [20,21]. Heterogeneous landscapes can be modelled by identifying a reasonable number of representative HRUs. For the European run the model resolution was set to 1 km², for the global run to 10 km x 10 km. EPICs primary output is the crop yield for more than 20 species. However for this study only the six crops (barley, grain maize, oats, rapeseed, rye and wheat) which yield straw as a side product were used.

The input data for EPIC are weather (precipitation, minimum

Figure 1: Overview of the three models used in the study, the input data, the intermediate output, the post-processing component and the final energy potential output used for a comparison for Europe.
and maximum air temperature, and solar radiation), physical and chemical soil parameters describing the soil layer with depth, topography (field size, slope length and steepness) and management practices (e.g. planting day, harvesting day, harvesting index, date and depth of each tillage operation, scheduling options for timing and rate of irrigation water, fertilizer, lime, pesticide, grazing, and drainage systems).

The Global Forest Model (G4M) was used to calculate theoretical energy potentials for forests on a European and global scale. G4M was developed at IIASA [22] and predicts the annual above ground wood increase and stocking biomass. Currently the species beech, birch, fr, larch, oak, pine and spruce are parameterised. G4M needs a yield description as an input parameter as e.g. NPP, which was supplied by the Biosphere Energy Transfer Hydrology (BETHY/DLR) model for the European run and the mean annual NPP map from [23] for the global run. The mean global map of annual NPP was derived from 17 models. Additionally the current forest and leaf type cover (GLC2000), the initial stocking biomass or the stand density [24] and the management target are needed as input. The age structure is derived from the initial forest biomass in combination with the NPP. For the European run the model resolution was set to 1 km² and for the global run to 50 km x 50 km.

The BETHY/DLR [25] model is a Soil-Vegetation-Atmosphere (SVAT) model which was used to compute the carbon uptake by vegetation and to estimate sustainable energy potentials for agriculture and forests on an European scale. At the German Aerospace Center (DLR) the model was modified by [26,27] to use satellite remote sensing data as input. Its main output is the calculation of carbon exchange between biosphere and atmosphere, which is based on a photosynthetic parameterisation of the canopy. In addition the water balance is regarded, taking into account precipitation as the primary input and canopy interception as secondary input. The soil water balance is calculated by quantifying the uptake of water by the roots, the transpiration of the soil and the evapotranspiration of the plant.

The model is driven by time series of air temperature at two meters height, precipitation, wind speed at ten meters above ground, cloud cover taken from the European Center for Medium Range Weather Forecasts (ECMWF) and remote sensing based time-series of the Leaf Area Index (LAI), which are derived from SPOT-VEGETATION data. Cloud cover information is used to calculate the fraction of incoming photosynthetic active radiation (PAR) which is one driver of photosynthesis. In addition static datasets, e.g. information about the soil type (FAO/IIASA), land cover / land use (GLC2000) and elevation (SRTM) are needed. The models output spatial resolution is 1 km². The temporal resolution is 1 hour but can be aggregated to daily or yearly time steps.

**Table 1:** Parameter used for post-processing including a mean value and standard deviation resulting from literature study on a global scale. The used parameters are typical for Europe.

<table>
<thead>
<tr>
<th>Residue : Yield Ratio</th>
<th>Shoot : Root Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean</td>
<td>std.</td>
</tr>
<tr>
<td>Wheat</td>
<td>1:1.4</td>
</tr>
<tr>
<td>Maize</td>
<td>1:2.0</td>
</tr>
<tr>
<td>Barley</td>
<td>1:1.0</td>
</tr>
<tr>
<td>Rapeseed</td>
<td>1:3.0</td>
</tr>
<tr>
<td>Rye</td>
<td>1:1.5</td>
</tr>
<tr>
<td>Oats</td>
<td>1:1.5</td>
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</tbody>
</table>

**Estimation of energy potentials**

As seen in Figure 1 a post-processing module was developed for each model to estimate sustainable energy potentials using a two-step approach. First the model outputs (crop yield for EPIC, wood increase and stocking biomass for G4M and NPP for BETHY/DLR) need to be transferred to straw content (agriculture, EPIC and BETHY/DLR) or above ground woody biomass harvests (forest, G4M and BETHY/ DLR) by using conversion factors of e.g. yield to straw and above to below ground biomass also referred to as shoot to root ratio. This post-processing is needed because of two reasons, first: BETHY/ DLR’s output is given in values of Net Primary Productivity (tons carbon per unit time and per unit area), G4M in biomass increase in (tons dry matter per unit time and unit area) and EPIC’s in crop yields (tons dry matter per unit time and per unit areas). The conversion factors used are presented in Table 1. Here we also show mean values, the standard deviations and medians for the conversion factors. The median is included to demonstrate that the literature data are in most cases not normally distributed. The statistical results are based on a literature survey reflecting the mean, standard deviation and median for global application including all treatments e.g. applying high or low manure. As an example, [28] reported for wheat a shoot to root ratio of 10.6:1 when high manure levels are applied while the ratio is 4.3:1 for low application. The values used in our study reflect the typical residue to yield ratio and the typical shoot to root ratio for Europe. The papers from [28-36] formed the basis for our literature survey.

To better understand the different steps for converting the model output from BETHY/DLR, EPIC and G4M to energy units a schematic workflow is presented in Figure 2. The model data which are converted to energy potentials are represented as light grey boxes while the final result is represented as dark grey box. It is obvious from Figure 2 that the shoot to root parameter is only needed for the BETHY/DLR output in order to determine the above ground biomass after converting the assimilated carbon to total biomass. For BETHY/ DLR the workflow is split into two branches, one for calculating the energy potentials of agricultural areas, the other one for forest areas. For EPIC the first step is to estimate the straw potential for each species from the calculated crop yield. For G4M only one step is necessary to convert the annual wood increase to energy potentials. The application of sustainability criteria for agriculture and forest area is common for all models.

Secondly our approach considers a sustainable use of renewable energy sources. We assume as sustainability that only the straw content of a crop will be used for energy generation, but not the grain itself. In addition, the majority (80%) of the straw will be used...
for other purposes as e.g. cross-compliance (soil fertilization) and animal housing. For sustainable forest management we assume that only the annual increase of above ground woody biomass will be used for energy purposes, meaning: only this equivalent amount of wood can be harvested from a stand. In a second step lower heating values, giving specific energy potentials per kilogram biomass, are used to transfer the data. For agricultural areas technical potentials are estimated since use competitions for straw are taken into account, whereas for the forest areas only theoretical-sustainable potentials are estimated. In order to archive comparable results the study was performed for 2000 only. This was done to minimize computational time and to harmonize the different temporal resolutions of the models. A more detailed description of this approach regarding forests and agriculture are presented in [18] and [19].

For forests the NPP (in units of carbon) was converted to above-ground biomass (in units of dry weight) by applying a conversion factor:

\[ \text{CAI} = \frac{\text{NPP} \times a}{(1+R)} \]

where CAI represents the current annual increase of forest biomass, R represents the ratio of the increment of below- to aboveground biomass, while a is a conversion factor from NPP to total biomass. Species-specific values for R were taken from [37]. The value for a was set to 2, which is seen as representative for both deciduous and coniferous trees [38].

### Results and Discussion

For Europe we calculated energy potentials of 9.3 EJ to 15.0 EJ for forests (total model extent) and 2.5 EJ to 2.7 EJ for agriculture (EU27 only), and 3.8 EJ (total model extent). As can be seen from Figure 3 different areas for agriculture and forests were considered. The EPIC model run was restricted to the EU27 countries (excluding Malta and Cyprus), whereas the BETHY/DLR model was also run for the rest of Europe, including parts of northern Africa and Asia. The G4M model was used for the same extent as the BETHY/DLR model. The energy potential ranges from 0.01 [TJ pixel\(^{-1}\) a\(^{-1}\)] to 8.57 [TJ pixel\(^{-1}\) a\(^{-1}\)] (agriculture) and 0.01 [TJ pixel\(^{-1}\) a\(^{-1}\)] to 40.2 [TJ pixel\(^{-1}\) a\(^{-1}\)] (forest).

As can be seen from Figure 3 the energy yield for agricultural areas is generally lower compared with the values for forests. This is mainly due to the assumption that only 20% of the annual accrued straw can be used for energy production, if a sustainable use is considered. It can furthermore be stated that the land use information which was used for the BETHY/DLR model shows significant more pixel than the corresponding information of the G4M (29%) and EPIC (32%) model. This can especially be found for the area of Spain, France and Italy (agriculture) and Northern Portugal-Spain, the Carpathian forest (Ukraine, Rumania) and Southern France (forests).

Sensitivity analysis of BETHY/DLR and EPIC to input data showed congruent patterns to changes in input data [39]. For a small scale area the two models were driven with a variety of meteorological data and different land cover information. The analysis showed

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**Figure 2:** Schematic processing steps needed to convert model output to energy units.
variability in results of up to 39% when changing major input datasets. However both models showed comparable reactions to the change of individual datasets.

On a global scale energy potentials of 170 EJ for forests and 32.9 EJ for agricultural areas were calculated (Figure 4). Note that the grid cell size varies from 0.5 x 0.5° (forests / G4M) to 0.05° x 0.05° (agriculture / EPIC). The highest potentials (up to 45 TJ ha⁻¹ a⁻¹) were calculated for dense forests as situated in Mexico, the South-East of the United States and parts of South Africa. Whereas the boreal forests of Canada, Scandinavia and Russia only show medium to low potentials (up to 20 TJ ha⁻¹ a⁻¹) which is due to the open forests, the short growing season and other unfavourable environmental conditions. Areas indicated with dark grey indicate tropical forests and savannahs, as reported in the World Wild Fund for Nature (WWF) terrestrial eco regions map, which can be downloaded at http://worldwildlife.org/biomes. Because it is believed that these areas should not be used for energy production, they were not included in the assessment.

For agricultural areas the highest values of up to 1 450 TJ were calculated for central United States, parts of northern Argentina, southern Brazil, East Europe and Russia (Figure 4). Intermediate values were calculated for wide areas of India, China, Brazil and Africa. All areas as modelled with EPIC were included to the energy calculation because our estimations are based on a very conservative approach.

The energy potentials as calculated with our approach are within the currently accepted range of theoretical to technical bio-energy potentials. Various studies showed that depending on the individual approach and scenarios 80 EJ to 1 450 EJ are available or will in near future be available from biomass [40-44]. Further case study analysis which we conducted for South Africa and Germany showed good agreements to regional studies. For Germany we found an energy potential of 156 PJ (EPIC) and 280 PJ (BETHY/DLR) for agricultural areas, compared to 112 PJ to 186 PJ reported in literature [16]. For South Africa we calculated 461 PJ (BETHY/DLR), compared with 546 PJ as reported in an independent study [45].

Conclusions

Sustainable straw and forest energy potentials for Europe and for the globe were estimated for 2000 using three models (EPIC, G4M and BETHY/DLR), which produce data with different resolutions in the form of raster data. To convert the model results (NPP for BETHY/DLR, crop yield for EPIC and wood increase for G4M) to energy potentials, conversion factors (shoot to root and residue to yield ratios) were used to compute straw and stem wood potentials. In a second step these potentials were transferred to energy units,

Figure 3: Energy potentials as computed with the EPIC (a), G4M (c) and BETHY/DLR (b + d) models. Values are given in terra joules per year. The resolution is 1km². High values are presented in dark green, medium values in olive and low values in grey colour. White areas represent all areas which were not considered as agricultural areas (a+b) or forests (c+d).
using lower heating values. We compared our results with data presented in recent studies and found our values to be within the range of published bioenergy potentials, however at the lower end of the spectrum. We believe this to be due to our conservative approach for agricultural areas of using only 20% of the straw potential and for forests of excluding the tropical belt from the assessment. Aside from our bioenergy estimations we also presented and described a post processing method to transfer model outputs of any vegetation model to energy potentials. We believe this approach to be very useful for application in future bioenergy studies.

Since biomass is a raw material, estimation of the annual biomass increase and potentially available energy is of great interest when discussing the renewable energy debate. With our new estimations we contribute with data to this debate and see potential in forecasting biomass availability which can be used for energy generation, without competing with food supply. We have shown that with our results, coming from three independent models and on different scales (global to regional/local) it is possible to obtain for any region of the world estimate of bio-energy potentials. These findings are thus potentially communicable to a broad range of policy makers.

**Acknowledgements**

This study was conducted under the “Energy Observation for monitoring and assessment of the environmental impact of energy use” (EnerGEO, Grant Agreement No.: 226364) project funded by the European Union. The authors would also like to thank ECMWF and Medias France for providing their data.

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