Identifying the regional straw potential for energetic use on the basis of statistical information

Martin Gauder*, S. Graeff-Hönninger1, W. Claupein2

Institute for Crop Production and Grassland Research, University of Hohenheim, Fruwirthstr. 23, 70599 Stuttgart, Germany

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Abstract
The amount of cereal straw that can be recovered from arable land and its potential usage for energy production in the state of Baden-Württemberg (Germany) was assessed using statistical data from the general agricultural surveys in 2003 and 2007. Based on these surveys, the occurrence of straw, the demand by animal husbandry and the restrictions regarding humus balances were evaluated. The results indicated that the resources of straw for energetic use are not equally distributed within the state, they are rather primarily concentrated in the eastern municipalities. Altogether, an amount of 2,022,995 Mg DM straw is produced in Baden-Württemberg annually. A proportion of nearly one third of the total straw occurrence in the state could theoretically be available without endangering the supply of litter for animal husbandry and the long-term humus soil contents. The amount of these 584,564 Mg DM straw could be used as a biomass feedstock with an energy content of 10113 TJ. After transportation and conversion, 3200.6 TJ of electric energy could be generated, representing the mean consumption of 230.551 persons. Three scenarios with a higher straw availability were evaluated. The effect of a higher share of intermediate crops on arable land, the effect of a higher share of cereal crops on arable land and the combination of both modifications was calculated. The evaluation of these potential scenarios showed that the augmentation of intercropping and cereal production on arable land leads to an increased straw availability within the state.

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1. Introduction

During the second half of the 20th century the conditioning of straw as a by-product of cereal production changed considerably in most of the developed countries. One major factor was the reduction of straw burning on the field. The burning was done to facilitate the sowing and establishment of the next crop, control pests and avoid the immobilisation of nitrogen during the decay of the straw [1,2]. This practice has been reduced sharply in order to prevent environmental damages and pollution [3,4]. The intensification in animal husbandry with housing systems based on slatted floors [5,6] has lead to a diminishing demand for straw as bedding litter. In accordance, in many regions most of the cereal straw is left on the fields or is incorporated in the soil. Some long-term studies could show a tendency to an alteration of soil organic matter content by the retention of straw [2,7,8]. Another positive effect which is connected to straw retention is reduced soil erosion, especially in hillside situations [9,10]. Despite these positive effects, agricultural practice requires the removal of crop residues like straw in decent situations, depending on crop rotation, mechanization and site conditions [11–14].
Cropping systems which are characterized by a high supply of organic material offer the possibility to remove straw, without lowering the soil organic matter content.

As highly unstable energy and commodity prices in the first decade of the 21st century have refocused the attention on renewable energy sources, the use of straw as a feedstock for energy production has caught interest again. Agricultural by-products such as straw provide a considerable potential for energetic use without the competition with human food production. Straw from cereal crops is the major by-product from agricultural fields in Europe [15] as well as worldwide [16]. However, the availability of straw is limited by several factors. Two major limiting factors in the western European context are the demand for straw in animal husbandry and the demand for organic material in field soils to ensure sustainable crop production. Several studies have been conducted in order to assess general and regional straw availabilities [4,17–19]. Though, a comparison between different studies is not possible as diverse approaches have been conducted. The emphasis in this study was to locate regions in the federal state of Baden-Württemberg (Germany), which offer a high abundance of straw resources that can be converted into bioenergy without endangering the soil quality of the fields. Therefore, statistical information about the agricultural circumstances in the state was analysed. Based on the estimations of straw demand from animal husbandry and of humus balances, the amount of straw which could be disposable was calculated.

2. Material and methods

2.1. General approach

This study was conducted with statistical information from the state Baden-Württemberg in Southwest Germany. The state is located in the transition zone of maritime and continental climate, with a mean temperature of 8.9 °C. 40% of the total land area of 35,751 km² is attributed to agricultural land, 60% of this area is used as crop land and 40% as permanent grassland. Main crops are winter wheat, winter barley, silage maize, winter rape and grain maize. Intensive crop management is conducted, as primary tillage is done generally with the mouldboard plough and fertilizers are given adjusted to the crop requirements. The mean grain yield of winter wheat was 6.9 Mg per hectare in the period of 1997–2007, the mean yield of rapeseed was 4.2 Mg in the same period.

Based on the statistical data from the last two general agricultural surveys in 2003 and 2007 [20,21], the regional situation of crop production and animal husbandry was analysed. The scope for this study was on municipalities, as each municipality has an extent of arable land with a mean of 752 ha, which ensures a small inter-annual cropping diversity. On the other hand, this regional level gives an adequate spatial resolution with respect to regional differences. The arithmetic mean of both surveys was considered for the amount and proportion of the field crops on the arable land and the number of animals held in each municipality; the amount of intermediate crops in every municipality was conferred from the associated district. To assess the straw potential for energetic use, the occurrence of straw was calculated for each municipality, then the demand for animal husbandry was deducted. The remaining straw was expected to be left on the fields or incorporated into the soil. Using a humus balance, the amount of straw that could be recovered from the fields without lowering long-term humus contents was calculated. Graphical illustration of the results was created by editing the administrative map of the state with ArcView™ software (ESRI, Inc., Redlands, California). The recovery of straw was calculated with the standard values of the KTBL dataset [22], a mean distance from the field to the farm of 4 km was assumed. Transportation to the power plant was calculated with a 40 Mg truck using the GEMIS dataset [23], a mean distance of 50 km was assumed from the farm to the power plant.

2.2. Occurrence of straw in the municipalities

The amount of cereal straw, excluding maize straw, was calculated by using the straw-to-grain ratios, provided by the ministry of agriculture in Baden-Württemberg. One tonne of barley or wheat grain yield is currently related to 0.8 tonnes of straw. Rye and triticale have a straw-to-grain ratio of 0.9 and oat has a ratio of 1.1. The straw occurrence was calculated by multiplying the mean yields from 2003 to 2007 with the relevant straw-to-grain ratios and the area of cultivation in every municipality for spring and winter wheat, spring and winter barley, triticale, rye and oat. The mean yields of the years 2003–2007 were chosen in order to adjust high variability between the years. Two percent of the area of cereal production was excluded as it is used for whole-crop silage with dedication to biogas plants [24]. The resulting equation which was used for each crop in every municipality was:

\[ S = Y \times (A - (A \times W)) \times R, \]

where \( S \) is the straw occurrence, \( Y \) is the mean grain yield of the years 2003–2007, \( A \) is the mean cultivated area in the years 2003 and 2007, \( W \) is the proportion of cultivated area which is dedicated to whole-crop silage production and \( R \) is the straw-to-grain ratio of the crop.

2.3. Straw demand by animal husbandry

The demand for straw by animal keeping in the municipalities is determined by the demand for straw bedding and straw feeding. Cattle, pigs, sheep, horses and poultry of every municipality were considered in respect to straw litter demand with classification to age and assignment. For pig keeping the demand for straw as bedding was calculated by the following equation:

\[ D_{\text{swine}} = \left( \frac{P_1}{C_1} \times S_{\text{swine}} + B_{\text{swine}} \right) + \left( \frac{P_2}{C_2} \times S_{\text{swine}} + B_{\text{swine}} \right) + \left( \frac{P_3}{C_3} \times S_{\text{swine}} + B_{\text{swine}} \right) + \left( \frac{P_4}{C_4} \times S_{\text{swine}} + B_{\text{swine}} \right) + \left( \frac{P_5}{C_5} \times S_{\text{swine}} + B_{\text{swine}} \right) \times M. \]

Where \( D_{\text{swine}} \) is the demand for straw bedding of pig keeping in Mg per year and municipality, \( P_i \) is the number of piglets up to 20 kg in the state, \( P_2 \) is the number of piglets who have a weight between 20 and 50 kg in the state, \( P_3 \) is the number of feeder pigs in the state, \( P_4 \) is the number of gilts in the state, \( P_5 \) is the number of other sows in the state, \( P_6 \) is the number of boars in the state and \( P_7 \) is the number of all pigs in the state.

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\( A \)
\( C \)
\( D \)
\( P \)
\( S \)
\( B \)
Each share of pig category was multiplied with the related share of litter management, $S$ and the need for straw litter in Mg per year, $B$. The result, the average straw litter demand by a pig in Baden-Württemberg, was multiplied with the number of pigs in each municipality $M$. This calculation was done similarly for assessing the litter demand of cattle, sheep, horses and poultry (equations not shown).

Age and assignment of the animals was taken from the agricultural surveys [20,21], the share of straw bedding for cattle was based on the assessments of Dr. Over from the State Agency of Food and Agriculture (personal communication), share of straw bedding in pig industry was taken from the annual swine-report of the state [25]. For sheep and horses, a typical free range period of 250 and 105 days was expected [22]. The amount of straw bedding was calculated by the detailed table of standard values for the appearance of organic manure and the demand of litter, provided by the Ministry of Agriculture in Bavaria [26]. The need for straw as fodder was deduced by the mean fodder use for every livestock unit in Germany [27] and calculated for each municipality by multiplying the number of all livestock units with the mean straw fodder requirement.

### 2.4. Humus balance

The evaluation of the humus balance on arable land was conducted with the method of balancing the supply of organic material and the humus decomposition. This method is used in praxis and for legal formalities [28–30]. The guidelines were consolidated by a commission from the Association of the German Agricultural Research Institutes in 2004 [31]. In this study, the higher values for humus decomposition were consulted in order to lower the risk of underestimating the rate of humus decomposition, in this context the humus effect of the remaining straw was set to 80 kg C per Mg, which is the lowest value. The humus alterations generated by cropping measures were calculated by the following equation:

$$B = \left( \frac{S_{\text{crop}} + S_{\text{crop}} + S_{\text{crop}} + \ldots + S_{\text{crop}} + S_{\text{crop}} + \ldots}{S_{\text{cover}} + S_{\text{cover}} + S_{\text{cover}} + \ldots + S_{\text{cover}} + S_{\text{cover}} + \ldots} \right) - D$$

where $B$ is the humus alteration per hectare in the municipality, $S$ is the share of crops on cropland in the municipality, with crop being all major crops, cover being cover crops in winter and summertime, $C$ is the humus coefficient, which can be positive or negative, for the relevant crop $(1 - n)$, residue $(1 - n)$ or manure $(1 - n)$. $R$ is the amount of crop residues resulting from the cultivated crops $(1 - n)$, $D$ is the demand for straw as litter and food for animal husbandry in the municipality. $M$ is the amount of organic manure which is produced by the animals in the municipality, with the different types of slurry and solid manure $(a - n)$. $N$ is the number of biogas plants in the municipality, $O$ is the mean output of digestates and $C_{\text{biogas}}$ the humus coefficient for the digestates. $A$ is the total agricultural land of the municipality.

All crop residues were assumed to remain on the fields, except one third of beet leaves for cattle feeding and the straw for animal husbandry. In return all farmyard manure, calculated by the standard values of the Bavarian Ministry of Agriculture [26], was assumed to be applied on arable land and grassland. The amount of fermented residues from biogas plants was calculated by the number of plants in every district [32] and the mean input of substrates (Berg, 2008, unpublished) and the resultant output of digestates with a mean dry mass of 7% [33]. The application of the digestates was assumed to be arranged on arable land and grassland.

When the results indicated that straw remained on the fields and the humus balance was positive, the amount of straw which could be recovered without lowering the balance to negative values was expected as surplus straw. Accordingly, the calculated potential of straw for energetic use contains only straw which is not needed for animal husbandry and could be recovered without lowering the humus balance to negative values.

### 2.5. Scenarios

Three future scenarios were computed in order to evaluate the possible increment of straw availability by modified cropping practices. Scenario 1 represents increased intercropping practices on arable land by 25%. In this scenario, the cultivation of intermediate summer crops rises from 10% to 12% and the cultivation of intermediate winter crops from 5% to 7%. Other cultivation factors were retained unchanged. Scenario 2 represents an augmentation of cereal crops on arable land by 15%. Cultivation of the other main crops on arable land was reduced proportionally. All other factors remained unchanged. Scenario 3 combines the augmentation of intercropping by 25% and the increased cereal production on arable land by 15%.

### 3. Results and discussion

#### 3.1. Straw occurrence and demand

As shown in Fig. 1, the mean cropping area of the most important small grains remained relatively stable during the last 57 years, fluctuating between 432,000 and 496,000 ha, totalled. Whereas the mean grain yield of the most important small grains increased 2.9 times from the average of 2.2 Mg per hectare in 1952 to 6.5 Mg per hectare in 2008 (Fig. 2). In the consulted years, 2003 and 2007, a mean area of 438,000 ha was observed for small grains. The mean grain yield of the consulted years between 2003 and 2007 was 6.2 Mg, which equals the ten year average from 1998 to 2007. According to the calculations, an amount of 2,022,995 Mg dry matter (DM) of straw occurred in the state of Baden-Württemberg on average per year. Similar results were found by Kappler [34] who calculated a straw occurrence of 2,446,700 Mg DM for the year 2003 in Baden-Württemberg.

Altogether, the municipalities in the eastern regions of the state showed higher occurrence of straw than western municipalities (Fig. 3). In addition, straw demand by animal husbandry was higher in the eastern regions. Overall, 488, 738 Mg DM of straw were required by animal husbandry,

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which accounts to 24% of total straw occurrence. Consequently, about 76% of the cereal straw remains on arable land.

The highest straw demand was derived by cattle farms accounting to more than 65% of the straw demand by animal husbandry. Since cattle breeding is concentrated in the southeastern part of the state, the highest demand was seen in these municipalities (Fig. 3). The humus balance showed an equated ratio of accumulation and decomposition for most of the municipalities. Nevertheless, 14% of the municipalities had a negative balance, thus an increased straw removal would probably lead to a long-term reduction of humus contents in the soils of these municipalities. The humus balance also showed spatial variability among the geographical regions. Row and root crops like maize, beet and potatoes were negatively correlated with the humus balance output. Animal husbandry, catch and forage crops showed a positive correlation to the humus balance outcome. Thus, municipalities with a high share of root and row crops like in the Rhine Valley had a lower humus balance output than most municipalities in the lower mountain range of the Black Forest or in the Swabian Mountains (Fig. 3).

According to humus balances, 595 of 1109 municipalities have a well-balanced humus turnover. 128 municipalities and 275 municipalities showed a low and high humus balance, respectively. Only 20 municipalities had a very low humus balance and 6 municipalities had a very high humus balance. In the case of 85 municipalities no humus balance could be calculated, due to incomplete database.

### 3.2. Straw availability

Merging the calculations of straw occurrence, the demand by animal husbandry and the restrictions by the humus balance led to the individual straw potential for every municipality in the state. The allocation of the straw potential of each municipality with the total area of the municipality turned out the straw potential per unit of land (Fig. 4).
Altogether, an amount of 584,564 Mg DM straw was available for recovery dedicated for usage beyond agricultural purposes. This potential accounts for 29% of the total straw occurrence in the state. The study indicated a large regional difference in the share of straw that can be recovered from the fields without endangering the long-term loss of humus in the soil. In one quarter of all municipalities which had been included in the calculations, no straw could be recovered, since there is no straw left or humus balances are negative. In half of the municipalities between 0% and 37%, with a median of 12%, of the straw could be recovered for energetic use. In one quarter of the municipalities between 38% and 87% of the straw could be recovered. The share of 29% straw availability throughout the whole state indicates that municipalities with a lot of straw occurrence offer the possibility to recover a high share of the straw. Whereas mostly all of the straw should remain on the fields if only a small part of the crops are cereals. Areas with a high amount of straw that could be used for energetic purposes are concentrated in the north-eastern and the middle-eastern part of the state. This is shown in Fig. 4 by the straw potential per unit of land.

A correlation analysis of agricultural characteristics in the municipalities with the straw potential per unit of land showed a high correlation with several factors. The amount of pig breeding in a municipality is highly correlated with the straw potential (Table 1). Although, it is not necessarily that pig breeding leads to a lot of straw, but a large number of pig industries in Baden-Württemberg is located in regions where a major proportion of cereals are grown and a lot of the land is arable land. The humus balance, the share of arable land on total land and the amount of cereal crops on arable land are also positively correlated to the straw potential in the municipalities. However, grain maize production and root crop production is negatively correlated to the straw potential. These results indicated that the positive effect on humus balances by animal husbandry exceeds the demand of straw for litter and forage. Hence, in the case of Baden-Württemberg,
regions with a high animal density can offer more straw for energetic use than those with minor densities.

3.3. **Straw availability in modified scenarios**

If farmers get incentives to furnish straw for energy use, they will likely shift management practices in order to increase the straw recovery. One simple option could be the augmentation of intermediate cropping for green-manure, which is currently realised on 10% and 5% of the cropping land with summer and winter crops, respectively. Hence, three different scenarios were investigated in order to evaluate the alteration of surplus straw by modified crop rotations. Scenario 1 simulates an increase of intermediate crops by 25%, thus 12% of the cropping land would be cropped with intermediate summer crops and 7% of the land would be cropped with intermediate winter crops. According to the higher humus return, more of the cereal straw could be recovered, leading to a total potential within the state of 636,320 Mg DM. This is 8.8% more than in the current situation. An increase of cereal production by 15%, as it is computed in scenario 2, would lead to an elevated straw surplus of 14%. This is due to a higher production of straw along with a nearly unchanged humus balance with a median of 42.9 kg C/ha·a instead of 42.6 kg C/ha·a. Together with an intensified intercropping, in scenario 3, the increase of surplus straw would account to 24% compared to the current situation (Table 2). Further advancements could be achieved by a wider implementation of conservation tillage or no-tillage practices, as the reduced soil management generally leads to higher accumulation of soil organic matter and soil organic carbon content [35].

3.4. **Energetic value of the available straw**

One tonne of totally dry wheat straw has a lower heating value (LHV) of 17.3 GJ, rye straw has an LHV of 17.6 GJ and barley straw an LHV of 17.4 [36]; consequently the current potential of 584,564 Mg DM straw contains about 10,113 TJ of energy. This energy equals 340,504 t of black coal and represents 3.8% of the total electricity consumption in the state [37].

The energetic value of the surplus straw could be utilised for direct heating, electricity production or biofuel production. The energetic conversion efficiency from straw or similar feedstocks to ethanol or Fischer–Tropsch fuels is calculated between 35% and 52% [38–40]. Whereas biofuel production from straw is not practiced in a commercial scale yet, several power plants fuelled by straw already exist in Europe and many plants are co-fired with straw [41,42]. Direct combustion

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**Table 2** – Actual situation and scenarios of the straw production and the straw demand in Baden-Württemberg. A: actual situation, 1: actual situation with 25% more intercropping, 2: actual situation with 15% more cereal cropping, 3: actual situation with 25% more intercropping and 15% more cereal cropping.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Total straw production</th>
<th>Straw demand by animal husbandry</th>
<th>Straw demand for a stable humus balance</th>
<th>Surplus straw</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mg DM/year</td>
<td>Mg DM/year Proportion [%]</td>
<td>Mg DM/year Proportion [%]</td>
<td>Mg DM/year Proportion [%] Alteration to actual situation [%]</td>
</tr>
<tr>
<td>A</td>
<td>2,022,995</td>
<td>488,738  24</td>
<td>949,692  47</td>
<td>584,565  29  0</td>
</tr>
<tr>
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<td>2,022,995</td>
<td>488,738  24</td>
<td>897,937  44</td>
<td>636,320  31 +9</td>
</tr>
<tr>
<td>2</td>
<td>2,326,331</td>
<td>488,738  21</td>
<td>1,173,449 50</td>
<td>664,144  29 +14</td>
</tr>
<tr>
<td>3</td>
<td>2,326,331</td>
<td>488,738  21</td>
<td>1,113,670 48</td>
<td>723,922  31 +24</td>
</tr>
</tbody>
</table>

**Fig. 5** – Potential energy supply by the alternative processes FT fuel production or electricity generation with the available straw in Baden-Württemberg. Under A: current situation, 1: with 25% more intercropping, 2: with 15% more cereals on arable land and 3: with 25% more intercropping and 15% more cereals on arable land.

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in new power plants shows conversion efficiencies of around 32% and a demand of 150–200 Mg straw per year \cite{42, 43}. Three industrial power plants, similar to existing plants in Sangiesa (Energia Hidroelectrica de Navarra, S.A., Navarra, Spain) or Ely (Energy Power Resources Ltd., Woodbridge, UK) could utilise the calculated amount of available straw in the state. After transportation and combustion, the energy sustained in electricity is calculated to 3200.6 TJ per year (Fig. 5), this would represent the mean electricity consumption of 230.551 persons \cite{44}. The augmentation of intercropping and cereal cropping, in scenario 3, would lead to an electricity supply of 3963.6 TJ per year, which represents the current consumption of 285,513 persons. Alternatively, the conversion to Fischer–Tropsch (FT) fuels in pyrolysis plants would yield in higher energy outputs as the energy conversion factor for fuel; nevertheless conversion to fuel could be more efficient if the straw is calculated to 1.6% of the energy obtained in the FT fuels is calculated to 4500.8 TJ per year, which represents the current petroleum consumption of 429,603 persons \cite{44}. With an augmentation of intercropping and cereal production, the amount of available straw would increase, and lead to a potential energy amount of 5573.7 TJ per year retained in liquid fuels. This amount accounts for the current consumption of 532,018 persons in the state, representing 5% of the total population.

Energy consumption for collection and transportation of the straw is calculated to 1.6% of the energy obtained in the FT fuel; nevertheless conversion to fuel could be more efficient if the recovery of straw is limited to areas with a high abundance of straw. By focussing the recovery of straw-to areas with a high potential, transportation distances could be reduced to a minimum. The recovery of straw solely in the municipalities with more than 0.6 Mg straw, available in average of every hectare land, would cover 33.8% of the straw potential in the state, while only 7.7% of the whole area has to be regarded. Since this study is based on statistical data; the actual amount of available straw has to be assessed by the survey of every field with regard to soil, crop rotation and mechanization. Nevertheless, due to the findings in this study, the performance of individual surveys can be concentrated to selected regions within the state.

If the total amount of available straw is used as a feedstock in power plants, 3200 TJ of electricity could be generated per year. Even more energy could be generated by an efficient production of Fischer–Tropsch fuels, however high capital costs und uncertain upscaling effects have hindered the commercial implementation of Biomass-to-Liquid plants so far.

The simulation of a slightly intensified intercropping practice showed that 9% more straw would be available if intermediate crops are grown on 19% of the arable land instead of the current 15%. An increased cereal production would also lead to a higher straw availability, due to a higher straw production in combination with a nearly unchanged demand for organic matter in the soils. Nevertheless, it has to be verified in on-field surveys how much of the statistical potential can be realised in practice.

4. Conclusions

The amount of cereal straw that can be recovered for energetic or industrial use in the state of Baden-Württemberg is currently 584,564 Mg DM, based on statistical data. This accounts to 29% of the total straw occurrence. The implementation of a humus balance for every municipality avoided the use of a constant share of straw which needs to be returned as an organic input. In this study, it could be demonstrated that the share of straw which could be collected for energetic use varies highly with spatial distribution. Within the municipalities, the share of straw theoretically available to energetic use ranged from 0% to 87% of the total straw occurrence. Highest amounts of available straw were found in the north-eastern and middle-eastern municipalities of the state.

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