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Optimizing Land use and the Yields of Bio-Energy Crops by using site specific Biomass Calculations: Introduction of the Crop Modelling Software BioSTAR

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Abstract: With the trend of a growing production and use of agricultural substrates in bio-gas facilities in Lower Saxony (Germany), the competition between the production of food crops, environmental conservation issues and, sustainability goals in general, has seen an increase in the last decade. To mitigate the conflict, accurate knowledge of agricultural potentials can be of help. When questions of medium or long range regional planning are concerned, policy makers and other stakeholders often lack reliable yield data. From statistical data sources, usually only limited information with low spatial resolutions on agricultural biomass potentials is available in Lower Saxony (administration district level).To overcome this hindrance in the assessment of biomass potentials, a software tool for the computation of such potentials has been developed (BIS, 2012). The tool BioSTAR (**Bio**mass **S**imulation **T**ool for **A**gricultural **R**esources) can be classified as a generic crop model and it is currently tested and validated for several agricultural biomass crops grown in Lower Saxony. The model uses climate and soil input data and calculates carbon accumulation rates on a daily or monthly basis. The model belongs to the family of carbon based models (Azam-Ali, et al., 1994). Climate input data are precipitation, solar radiation, temperature, humidity and wind speed. Soil data can be either of the FAO soil texture classification type or of the more differentiated German classification of the KA5 (DIN, 4220, 2008). Special features of the model BioSTAR are the ability to process either single or multiple sites in one calculation procedure, and a simple, and user friendly graphic interface. The program uses MS-Access data base tables to read in and write out data. The model has been kept simple enough to avoid some of the difficulties (e.g. unavailable input parameters and input data) often associated with more complex models which are often overburdened for simple biomass analysis.

Keywords: Bio Energy; Bio-Gas; Biomass Potentials; Crop Modeling

1. INTRODUCTION

The demand for biomass from agricultural resources as an energy source is currently seeing a strong increase. This is particularly true for Germany, as the country is trying to double the share of bio energy (agricultural, forest and waste biomass combined) to the country's energy total by the year 2020 (BMWI-BMU, 2010).
In 2011, 2.2 million ha of the total agricultural area (17 Mio. ha) were already in use for either energy crop production or renewable primary products. 800.000 hectares of this area were in use for bio gas crops, mainly maize, 900.000 hectares were used for oilseed rape for the country's bio-diesel production and, the smallest share, 250.000 ha. for starch and bio-ethanol production. By 2020 the agricultural

area in use for renewable resources production in Germany is projected to be further expanded and will then have a share of around 20% of the country's total agricultural area. Even though Germany's food production is close to self-sufficient today, a growing competition between food production, environmental issues, sustainability goals, and the production of energy and renewable primary products is moving into the focus of policy makers and researchers. At present, the production of bio-gas from energy crops and agricultural wastes (manure and other residual materials) appears to be the most (land resource) efficient way to use agricultural areas for energy production. This is due to the relatively high energy yield of bio-gas per hectare (FNR, 2011). This advantage of bio gas is even higher when power-heat cogeneration technology is applied.
In an intensively used agricultural landscape like the one existing in Germany, good management and farming practices and diverse crop rotation cycles are of importance and the introduction of new energy crops into the existing crop rotation cycles can be beneficial for ecological reasons (Karpenstein-Machan, 2010) (Ruppert, 2010). By using a crop modeling tool, yield differences of different crop rotations and crops can be approximated and optimized solutions, with economical as well as ecological perspectives in view, can be found out. The 21^{st} century is predicted to be a century of climate change and the regionalized CLM –Model (A1B scenario) shows a decrease in precipitation and a temperature increase for Lower Saxony towards the end of the century (Krause, et al., 2011)
By feeding a crop model with climate change data, possible statements on how different crops will react to climate change can be made (von Buttlar, et al., 2011) and possibly adverse effects on agriculture can be mitigated by planning ahead of time.

2. STATE OF THE ART

Crop models have been in existence for about four decades now (Bouman, et al., 1996). During the evolution period of crop models, new insights from field and lab crop breeding, as well as from the parent models themselves have been used to further improve new model developments. If crop models tended to be highly complex in the past, there is a growing trend of structuring them more simply nowadays.
A typical example for the reduction of complexity in crop models is the use of empirically gained parameters and relations instead of attempting to model plant physiological processes more mechanistically with chemical or physical equations. A commonly found parameter in crop modeling to achieve such a simplification is the radiation use efficiency (RUE) parameter (Monteith, 1977). The RUE parameter relates the amount of biomass fixed to the solar radiation intercepted by the plant, expressed in equation 1 in the term:

$$NPP = \epsilon * APAR \qquad \text{Equation 1}$$

Where:

NPP = net primary production
ϵ = photosynthetic radiation use efficiency
APAR = absorbed photosynthetic active radiation

Most crop models contain a mixture of mechanistic and empirical functions though (Whistler, et al., 1986).
If compared with their approach of resource capture (the growth engine), crop models can be grouped into three main categories. Carbon based models calculate biomass accumulation by relating CO_2-accumulation to the amount of light quantum received. Radiation based models use the RUE parameter for measuring resource capture, and the third type, the water- or transpiration based models, use a water use efficiency (WUE) parameter to calculate the amount of dry mass

accumulated per gram of water transpired and evaporated. Though all three model types are in use in one or several of the most widely used crop models today, the RUE method is probably the one most commonly used. As a relatively new model, AquaCrop (Steduto, 2009) is the only model relying only on the WUE parameter for calculating biomass accumulation.

3. MATERIALS AND METHODS – THE CROP MODEL BiOSTAR

The model BioSTAR uses a carbon based growth engine to calculate an initial light- and temperature dependant carbon accumulation rate (equation 2), from which photo respiration (maintenance and growth) is deducted. The remaining fraction of CO_2 is then used to calculate a photosynthesis-dependant transpiration rate. This is done using the gradients of the water vapour pressure and of the CO_2-concentration inside the leave to the corresponding pressures of the atmosphere (equations 3-6).

$Pg = Pmax * (1-exp^{(-Qe*PPFDI /Pmax)}$ Equation 2

Where:

Pg = gross-photosynthesis rate in mmol $CO_2 * m^{-2} * s^{-1}$
Qe = initial light use efficiency in mmol $CO_2 * mol^{-1}$ light quantum
$PPFDI$ = intercepted photosynthetically active radiation in mmol $* m^{-2} * s^{-1}$
$Pmax$ = maximum photosynthesis rate in mmol $CO_2 * m^{-2} * s^{-1}$

$H_2O_{grad} = (VP_{def} * Vol_{mol}) / 18) * 1000$ Equation 3

$CO_{2grad} = (CO_{2con} – (CO_{2con} * C_i/C_a)) / 1000$ Equation 4

$Wat_{use} = (H_2O_{grad} / CO_{2grad}) * 1.56$

$Trans_{pot} = (P_{rate} * 3600 / 1000 * L_{day} * 44 * 1000) * Wat_{use}$ Equation 6

Where:

H_2O_{grad} = H_2O-gradient from leaf to atmosphere in mmol * mol-1
VP_{def} = vapour pressure deficit of the air in gram $* m^{-2}$
Vol_{mol} = volume of 1 mol dry air
CO_{2grad} **=** the CO_2-gradient from leaf to atmosphere in mmol $* mol^{-1}$
$CO2_{con}$ = CO_2-concentration of the atmosphere in ppm
C_i/C_a = internal-external CO_2-ratio dimensionless, range 0.5-1.0
Wat_{use} = the H_2O-CO_2 evolution ratio dimensionless
$Trans_{pot}$ = CO_2-assimilation dependent potential transpiration rate in liters $* day^{-1}$
P_{rate} = CO_2-assimilation rate in mmol $CO_2 * m^{-2} * s^{-1}$
L_{day} = daylight hours

Due to this calculation procedure, BioSTAR does not need a separate ETo-calculation (e.g. Penman, FAO, Turc or other).The transpiration rate calculated by equation 5 plus a leaf area dependant soil evaporation value is then further used in the soil sub-model to check if enough water for evapotranspiration is available in the rooted layers of the soil profile. Soil water availability is defined by each layers individual soil water retention curve. If the available soil water content is smaller than the calculated ETo, evapotranspiration and the photosynthesis rate are lowered correspondingly.
Crop development and leaf area index development (LAI) are temperature driven and divided into two main stages: emergence till anthesis (development stages 0-1) and anthesis till ripeness (development stages 1-2). Maximum LAI is reached at

development stage one and the curve of LAI-development is modeled as a Gaussian integral (normal distribution).
The software tool which was developed to process data according to the models algorithms is written in Java and uses the open source programming tool Eclipse for its execution with a user friendly and simple interface (figure 1). Input and output data is read from and written into Microsoft Access data base tables (figure 2) and can therefore easily be imported from and exported to a GIS via a spread sheet and the dbf-format.

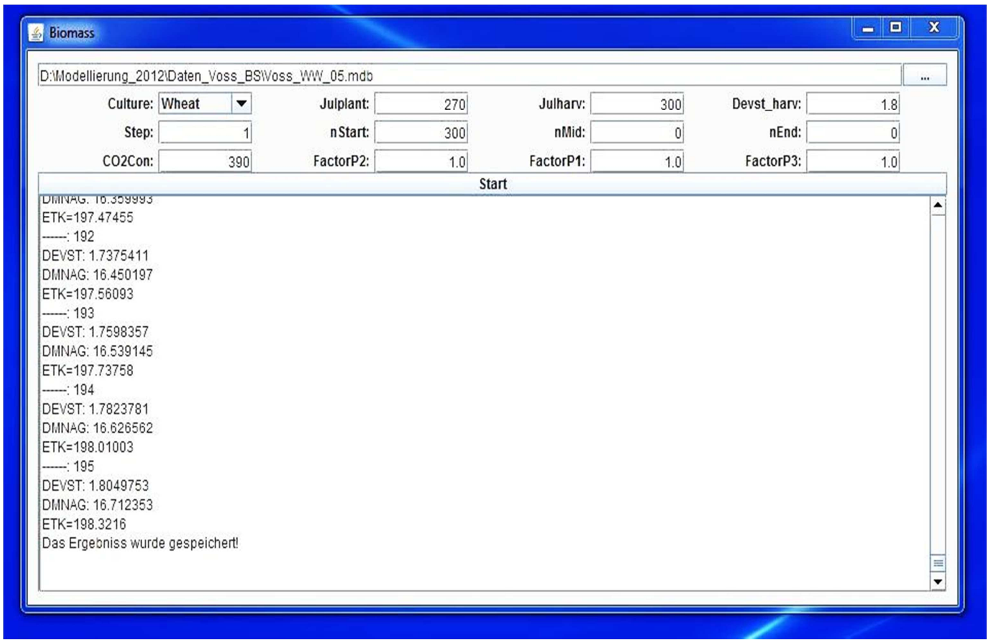
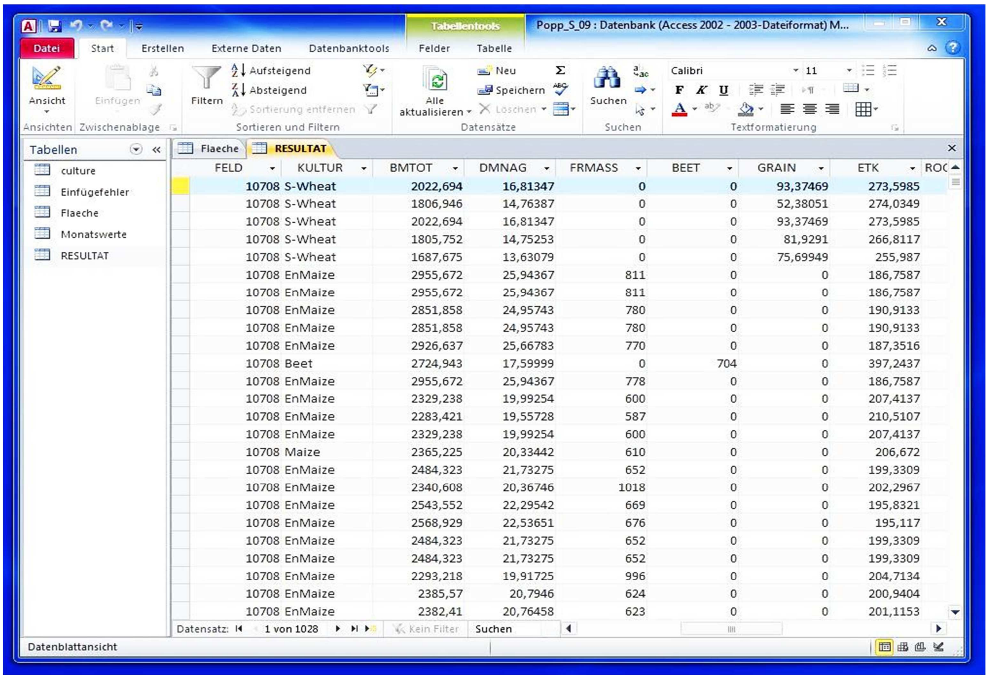


Figure 1: User interface of the BioSTAR software with pull-down menus, the log window (bottom) and the data base connectivity (top)



FELD	KULTUR	BMTOT	DMNAG	FRMASS	BEET	GRAIN	ETK
10708	S-Wheat	2022,694	16,81347	0	0	93,37469	273,5985
10708	S-Wheat	1806,946	14,76387	0	0	52,38051	274,0349
10708	S-Wheat	2022,694	16,81347	0	0	93,37469	273,5985
10708	S-Wheat	1805,752	14,75253	0	0	81,9291	266,8117
10708	S-Wheat	1687,675	13,63079	0	0	75,69949	255,987
10708	EnMaize	2955,672	25,94367	811	0	0	186,7587
10708	EnMaize	2955,672	25,94367	811	0	0	186,7587
10708	EnMaize	2851,858	24,95743	780	0	0	190,9133
10708	EnMaize	2851,858	24,95743	780	0	0	190,9133
10708	EnMaize	2926,637	25,66783	770	0	0	187,3516
10708	Beet	2724,943	17,59999	0	704	0	397,2437
10708	EnMaize	2955,672	25,94367	778	0	0	186,7587
10708	EnMaize	2329,238	19,99254	600	0	0	207,4137
10708	EnMaize	2283,421	19,55728	587	0	0	210,5107
10708	EnMaize	2329,238	19,99254	600	0	0	207,4137
10708	Maize	2365,225	20,33442	610	0	0	206,672
10708	EnMaize	2484,323	21,73275	652	0	0	199,3309
10708	EnMaize	2340,608	20,36746	1018	0	0	202,2967
10708	EnMaize	2543,552	22,29542	669	0	0	195,8321
10708	EnMaize	2568,929	22,53651	676	0	0	195,117
10708	EnMaize	2484,323	21,73275	652	0	0	199,3309
10708	EnMaize	2484,323	21,73275	652	0	0	199,3309
10708	EnMaize	2293,218	19,91725	996	0	0	204,7134
10708	EnMaize	2385,57	20,7946	624	0	0	200,9404
10708	EnMaize	2382,41	20,76458	623	0	0	201,1153

Figure 2: Export database table with calculated parameters: Total yield=BMTOT, culture=KULTUR, yield above ground=DMNAG, grain yield=GRAIN, liters of water per kg=ETK

3.1 Model Calibration and Validation

The model is currently calibrated and validated for the winter cereals wheat, rye and triticale, for maize, sorghum b. and for sunflower.
For model calibration and validation, harvest and climatic data from two locations (Poppenburg and Werlte) in Lower Saxony has been used. At the two locations regular field trials are carried out by the LWK (Landwirtschaftskammer Niedersachsen / Chamber of Agriculture, Lower Saxony).
Werlte has a medium range soil quality (loamy sand, agricultural comparative figure 30-40, 120 mm field capacity), receives about 770 mm of precipitation per year and the annual average temperature is 9°Celsi us.
Poppenburg has a higher soil quality (silty loam, agricultural comparative figure 80, 180 mm field capacity), receives about 600 mm of precipitation per year and the annual average temperature is 8.2°Celsius.
For calibration of a crop model, curve and parameter fitting for best matches with one data set are performed. The model is then tested afterwards with another data set for model validation.
Example data used for calibration and validation of the model are displayed in table 1.

Table 1: Measured and calculated BioSTAR yields (tons/ha) used for model calibration for the cultures winter wheat (WW), winter rye (WR) and winter triticale (WT) (data from Werlte)

Calibrate	Measured	Calculated	Error %
WW-2009-1	14,1	13,9	-1
WW-2009-2	14,1	14,7	4
WR-2009-1	12,6	13,7	9
WR-2009-2	14,6	17,1	17
WT-2009-1	12,6	13,9	10
WT-2009-2	16,7	16	-4
Mean			**6**

Tables 2-4: Measured and calculated BioSTAR yields (tons/ha) used for model validation for the cultures winter rye (WR), winter wheat (WW) and winter triticale (WT) (data from Poppenburg)

Table 2: Measured, Calculated and Error for Rye

Validate	Measured	Calculated	Error %
WR-2008-1	19,7	19,3	-2
WR-2009-1	16,8	16,8	0
WR-2009-2	19,3	18,2	-6
WR-2009-3	18,6	18,7	1
WR-2010-1	19,3	19,4	1
Mean			**-1**

Table 3: Measured, Calculated and Error for Wheat

Validate	Measured	Calculated	Error %
WW-2008-1	21	18	-14
WW-2009-1	13,5	12,9	-4
WW-2009-2	15,7	14,3	-9
WW-2009-3	15,1	14,8	-2
WW-2010-1	16,6	17	2
Mean			**-5**

Table 4: Measured, Calculated and Error for Triticale

Validate	Measured	Calculated	Error %
WT-2008-1	21,7	19,8	-9
WT-2009-1	18,8	16,9	-10
WT-2009-2	16,2	15,1	-7
WT-2009-3	18,5	16,4	-11
WT-2010-1	20	18,9	-5
Mean			**-9**

4. RESULTS

The validated model can now be used to make predictions about potential yields for locations with known soil properties and known or projected climate properties.
As part of the research project “Climate Change Mitigation Strategies for the Metropolitan Area Hannover-Braunschweig-Göttingen” (KFM, 2012), the model BioSTAR has been used to calculate potential biomass yields for three districts in Lower Saxony which were chosen for their representativeness of an agricultural area with certain traits, like climate and soil types.
The northernmost of the three is Uetze (Celle). Here sandy soils are most common and water supply can be short in the summer. The second district is Alfeld (Hildesheim). Here loamy soils with good water retention capacities are dominant. The third district is Krebeck (Göttingen). Out of the three, Krebeck has the best soils but, due to its higher altitude, yields can be lower than in Alfeld.

Table 5: Relative yield changes (2021-50, 2071-100) for Uetze as compared to the base scenario (1961-90) and climatic parameters for the scenarios

Region Celle (Uetze)			
Scenario	1961-90	2021-50	2071-100
Culture	Base	rel. [%]	rel. [%]
Maize	100	97	96
Sunflower	100	106	103
Sorghum b.	100	104	104
W-Wheat	100	106	93
W-Triticale	100	100	85
W-Rye	100	102	87

Mean Agr. Comp. Figure: 35 **Mean Field Capacity in mm: 113**			
Scenario	**1961-90**	**2021-50**	**2071-100**
CO_2 [ppm]	380	450	600
Prec. [mm]*	372	356	315
Temp. Σ [°C]*	2620	2958	3244

*in the growing period

Table 6: Relative yield changes (2021-50, 2071-100) for Krebeck as compared to the base scenario (1961-90) and climatic parameters for the scenarios

Region Göttingen (Krebeck)			
Scenario	1961-90	2021-50	2071-100
Culture	Base	rel. [%]	rel. [%]
Maize	100	105	111
Sunflower	100	105	100
Sorghum b.	100	104	106
W-Wheat	100	98	89
W-Triticale	100	98	89
W-Rye	100	98	87

Mean Agr. Comp. Figure: 62 **Mean Field Capacity in mm: 183**			
Scenario	**1961-90**	**2021-50**	**2071-100**
CO_2 [ppm]	380	450	600
Prec. [mm]*	367	358	324
Temp. Σ [°C]*	2524	2904	3282

*in the growing period

Table 7: Relative yield changes (2021-50, 2071-100) for Alfeld as compared to the base scenario (1961-90) and climatic parameters for the scenarios

Region Hildesheim (Alfeld)			
Scenario	1961-90	2021-50	2071-100
Culture	Base	rel. [%]	rel. [%]
Maize	100	107	113
Sunflower	100	108	102
Sorghum b.	100	106	101
W-Wheat	100	98	88
W-Triticale	100	97	89
W-Rye	100	98	85

Mean Agr. Comp. Figure: 54 **Mean Field Capacity in mm: 132**			
Scenario	**1961-90**	**2021-50**	**2071-100**
CO_2 [ppm]	380	450	600
Prec. [mm]*	414	407	367
Temp. Σ [°C]*	2526	2880	3221

*in the growing period

As a brief summary of the data interpretation, it can be said that the summer cultures (maize, sunflower and sorghum b.) will presumably profit from overall higher summer temperatures and longer growing periods. One exception is maize in Uetze. Here the low water retention capacities of the soils will limit growth in the second half of the century.
The winter cereals (C3-cultures) will profit from the CO_2-fertilizer effect in the second half of the century, but due to higher summer temperatures the ripening period for these cultures will be speeded up and they will not reach their optimum yields any longer.
Further uses and applications of the model BioSTAR are detailed biomass potential analyses on a regional scale with adapted crop rotation cycles, exclusion of nature conservation areas or with the modeled effects of cross compliance measures (e.g. flower strips, lark windows) on biomass yields.

5. CONCLUSIONS AND RECOMENDATIONS

Crop models can be useful tools when site specific and large scale biomass potentials are needed to make detailed biomass analyses with varying input parameters (crops, rotations, restrictions, climate parameters).This is especially true when the model is built into a software tool which enables the user to easily and quickly modify input variables and process tasks in single or batch style.
The output data of these biomass analyses can then be used by other models or planers to optimize biomass yields and land use allocation.

6. OUTLOOK AND FURTHER IMPROVEMENTS

The model BioSTAR and the software in which the model code is embedded in have proven to work soundly and to deliver satisfactorily simulated yields for the validated crops. Further development and research for the model and the software will include calibration and validation for more crops (sugar beet, miscanthus, sylphium perfoliatum, and fast growing tree species like willow and poplar). Improvements in the software are to be made in the user interface (more options and menus) and the data base structures to speed up processing of data.

7. ACKNOWLEDGEMENTS

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8. LITERATURE

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