Cropping systems for biomethane production: a simulation based analysis of yield, yield potential and resource use efficiency

Dissertation zur Erlangung des Doktorgrades der Agrar- und Ernährungswissenschaftlichen Fakultät der Christian-Albrechts-Universität zu Kiel

vorgelegt von M.Sc. Babette Maria Wienforth aus Bad Wildungen

Kiel, Mai 2011
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Lebenslauf
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<th>Description</th>
<th>Unit</th>
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<tbody>
<tr>
<td>AC&lt;sub&gt;root&lt;/sub&gt;</td>
<td>Root dry matter allocation coefficient</td>
<td>[-]</td>
</tr>
<tr>
<td>ACE&lt;sub&gt;root&lt;/sub&gt;</td>
<td>AC&lt;sub&gt;root&lt;/sub&gt; at emergence</td>
<td>[-]</td>
</tr>
<tr>
<td>Autoirrm&lt;sub&gt;amount&lt;/sub&gt;</td>
<td>Irrigation amount</td>
<td>[mm]</td>
</tr>
<tr>
<td>Autoirrm&lt;sub&gt;nfKcrit&lt;/sub&gt;</td>
<td>Critical plant available field capacity (percentage) for triggering irrigation</td>
<td>[%]</td>
</tr>
<tr>
<td>BS</td>
<td>Braunschweig, site in Central Germany</td>
<td></td>
</tr>
<tr>
<td>CD</td>
<td>Coefficient of determination</td>
<td>[-]</td>
</tr>
<tr>
<td>CompF</td>
<td>Root competition factor</td>
<td>[-]</td>
</tr>
<tr>
<td>Coty</td>
<td>Cotyledon</td>
<td>[-]</td>
</tr>
<tr>
<td>Cropheight</td>
<td>Crop height</td>
<td>[m]</td>
</tr>
<tr>
<td>cum. ETI</td>
<td>Cumulative Evapotranspiration including interception</td>
<td>[mm]</td>
</tr>
<tr>
<td>cum. E&lt;sub&gt;act&lt;/sub&gt;</td>
<td>Cumulative Evaporation</td>
<td>[mm]</td>
</tr>
<tr>
<td>cum. TI&lt;sub&gt;act&lt;/sub&gt;</td>
<td>Cumulative Transpiration including interception</td>
<td>[mm]</td>
</tr>
<tr>
<td>D&lt;sub&gt;W&lt;/sub&gt;, D&lt;sub&gt;W(θ)&lt;/sub&gt;</td>
<td>Diffusivity of water</td>
<td>[cm&lt;sup&gt;2&lt;/sup&gt; d&lt;sup&gt;-1&lt;/sup&gt;]</td>
</tr>
<tr>
<td>DevRateS0</td>
<td>Development rate valid from sowing till emergence</td>
<td>[1 °C&lt;sup&gt;-1&lt;/sup&gt; d&lt;sup&gt;-1&lt;/sup&gt;]</td>
</tr>
<tr>
<td>DevRateS1</td>
<td>Development rate, valid from emergence till tassel initiation</td>
<td>[1 °C&lt;sup&gt;-1&lt;/sup&gt; d&lt;sup&gt;-1&lt;/sup&gt;]</td>
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<td>DevRateS2</td>
<td>Development rate valid from tassel initiation till silking</td>
<td>[1 °C&lt;sup&gt;-1&lt;/sup&gt; d&lt;sup&gt;-1&lt;/sup&gt;]</td>
</tr>
<tr>
<td>DevRateS3</td>
<td>Development rate valid from silking till end of grain filling</td>
<td>[1 °C&lt;sup&gt;-1&lt;/sup&gt; d&lt;sup&gt;-1&lt;/sup&gt;]</td>
</tr>
<tr>
<td>DevRateS4</td>
<td>Development rate valid from end of grain filling till silage maturity</td>
<td>[1 °C&lt;sup&gt;-1&lt;/sup&gt; d&lt;sup&gt;-1&lt;/sup&gt;]</td>
</tr>
<tr>
<td>DOY</td>
<td>Day of Year</td>
<td>[d]</td>
</tr>
<tr>
<td>DM</td>
<td>Dry matter</td>
<td>[g m&lt;sup&gt;-2&lt;/sup&gt;]</td>
</tr>
<tr>
<td>DM&lt;sub&gt;cob&lt;/sub&gt;</td>
<td>Cob dry matter</td>
<td>[g m&lt;sup&gt;-2&lt;/sup&gt;]</td>
</tr>
<tr>
<td>DM&lt;sub&gt;ini&lt;/sub&gt;</td>
<td>DM&lt;sub&gt;ini&lt;/sub&gt; at emergence</td>
<td>[g m&lt;sup&gt;-2&lt;/sup&gt;]</td>
</tr>
<tr>
<td>DM&lt;sub&gt;leaf&lt;/sub&gt;</td>
<td>Leaf dry matter</td>
<td>[g m&lt;sup&gt;-2&lt;/sup&gt;]</td>
</tr>
<tr>
<td>DM&lt;sub&gt;root&lt;/sub&gt;</td>
<td>Root dry matter</td>
<td>[g m&lt;sup&gt;-2&lt;/sup&gt;]</td>
</tr>
<tr>
<td>DM&lt;sub&gt;seed&lt;/sub&gt;</td>
<td>Seed weight</td>
<td>[g m&lt;sup&gt;-2&lt;/sup&gt;]</td>
</tr>
<tr>
<td>DM&lt;sub&gt;shoot&lt;/sub&gt;</td>
<td>Shoot dry matter</td>
<td>[g m&lt;sup&gt;-2&lt;/sup&gt;]</td>
</tr>
<tr>
<td>DM&lt;sub&gt;stem&lt;/sub&gt;</td>
<td>Stem dry matter</td>
<td>[g m&lt;sup&gt;-2&lt;/sup&gt;]</td>
</tr>
<tr>
<td>DM&lt;sub&gt;tot&lt;/sub&gt;</td>
<td>Total plant dry matter</td>
<td>[g m&lt;sup&gt;-2&lt;/sup&gt;]</td>
</tr>
<tr>
<td>DS</td>
<td>Development stages for root growth</td>
<td>[-]</td>
</tr>
<tr>
<td>DS&lt;sub&gt;stop&lt;/sub&gt;</td>
<td>Development driven stop of root growth</td>
<td>[-]</td>
</tr>
<tr>
<td>Duration</td>
<td>Duration of root activity</td>
<td>[d]</td>
</tr>
</tbody>
</table>
$E_{\text{act}}$ Actual evaporation [mm d$^{-1}$]

$E_{\text{pot}}$ Potential evaporation [mm d$^{-1}$]

EEG Renewable Energy Sources Act

EF Modelling efficiency [-]

$E_{T_{\text{act}}}$ Actual evapotranspiration [mm d$^{-1}$]

$E_{T_{\text{pot}}}$ Potential evapotranspiration [mm d$^{-1}$]

$f_{\text{cob}}$ Proportion of shoot dry matter growth minus leaf growth which is allocated to the cob [-]

$f_{\text{cobslope}}$ Coefficient for calculating $f_{\text{cob}}$ [-]

$f_{\text{cob0}}$ Coefficient for calculating $f_{\text{cob}}$ [-]

$f_{\text{cropheight}}$ Coefficient for calculating crop height [m]

$f_{\text{evap}}$ Reduction factor for calculating $E_{\text{act}}$ from $E_{\text{pot}}$ [-]

$f_{\text{hypo}}$ Fraction of DM$_{\text{seed}}$ allocated into the hypocotyl [-]

$f_{\text{leaf}}$ Proportion of shoot dry matter growth allocated to the leaves [-]

$f_{\text{PAR_glob}}$ Constant factor between $k_{\text{glob}}$ and $k_{\text{PAR}}$ [-]

$f_{\text{phy}}$ Correction factor for calculating the actual phyllochron [-]

$f_{\text{Sen}}$ Senescent proportion of GAI* [-]

$f_{\text{sinkred}}$ Reduction factor of the sink term [-]

$f_{\text{stemmin}}$ Minimum ratio between DM$_{\text{stem}}$ and DM$_{\text{shoot}}$ [-]

$f_{T}$ Temperature factor [-]

$f_{\text{trans}}$ Fraction of DM$_{\text{seed}}$, which is lost by transformation and translocation processes [-]

FF Cropping system

FF1 Cropping system: maize monoculture

FF2 Cropping system: maize, silage wheat, Italian ryegrass

FF3 Cropping system: silage maize, grain wheat, catch crop (mustard)

FF4 Cropping system: perennial grassland

g Coefficient of the allometric relation between DM$_{\text{leaf}}$ and (DM$_{\text{stem}}$ + DM$_{\text{cob}}$) [-]

GAI Green area index [m² m$^{-2}$], [-]

GAI* Green area index, not accounting for green area loss due to senescence [-]

GAI$_{\text{leaf}}$ Green area index of leaf [-]

GAI$_{\text{stem}}$ Green area index of stem [-]

GAD Green area duration [d]

GAI$_{\text{crit,ExtPAR}}$ Critical GAI for calculating $k_{\text{PAR}}$ [-]

GDD$_{\text{emer}}$ Temperature sum between sowing and emergence [°C d]

GDD$_{S3}$ Temperature sum between silking and grain filling [°C d]
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>GDD_silk</td>
<td>Temperature sum between emergence and silking</td>
<td>°C d</td>
</tr>
<tr>
<td>GDD_tasini</td>
<td>Temperature sum between emergence and tassel initiation</td>
<td>°C d</td>
</tr>
<tr>
<td>GDD_total</td>
<td>Temperature sum between sowing and silage maturity</td>
<td>°C d</td>
</tr>
<tr>
<td>GlobRad</td>
<td>Global radiation</td>
<td>MJ m⁻² d⁻¹,</td>
</tr>
<tr>
<td>h</td>
<td>Coefficient of the allometric relation between DM_(leaf) and (DM_(stem) + DM_(cob))</td>
<td>-</td>
</tr>
<tr>
<td>harvestdate_latest</td>
<td>Latest date of crop harvest</td>
<td>d</td>
</tr>
<tr>
<td>HA</td>
<td>Holtenau, site in the North of Germany</td>
<td></td>
</tr>
<tr>
<td>HO</td>
<td>Hohenheim, site in the South-West of Germany</td>
<td></td>
</tr>
<tr>
<td>HS</td>
<td>Hohenschulen, site in the North of Germany</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>Interception</td>
<td>mm d⁻¹</td>
</tr>
<tr>
<td>k, k(θ)</td>
<td>Unsaturated hydraulic conductivity</td>
<td>cm d⁻¹</td>
</tr>
<tr>
<td>k_a</td>
<td>Fit parameter for calculating kr</td>
<td>-</td>
</tr>
<tr>
<td>k_DMini</td>
<td>Constant rate of DM_(ini) decrease</td>
<td>g m⁻² d⁻¹ °C⁻¹</td>
</tr>
<tr>
<td>k_glob</td>
<td>Extinction coefficient for global radiation</td>
<td>-</td>
</tr>
<tr>
<td>k_PAR</td>
<td>Extinction coefficient for PAR</td>
<td>-</td>
</tr>
<tr>
<td>k_RL</td>
<td>Increase of rooting depth per growing degree day</td>
<td>cm cm⁻² (°C d⁻¹)</td>
</tr>
<tr>
<td>k_zr</td>
<td>Coefficient for calculating root depth growth</td>
<td>cm (d °C⁻¹)</td>
</tr>
<tr>
<td>KD</td>
<td>Karkendamm, site in Northern Germany</td>
<td></td>
</tr>
<tr>
<td>KL</td>
<td>Kleve, site in the Mid-West of Germany</td>
<td></td>
</tr>
<tr>
<td>kr</td>
<td>Fractional decrease in RLD per unit increase of soil depth</td>
<td>-</td>
</tr>
<tr>
<td>KS</td>
<td>Saturated water conductivity</td>
<td>cm d⁻¹</td>
</tr>
<tr>
<td>Leaf_No</td>
<td>Number of leaves</td>
<td>-</td>
</tr>
<tr>
<td>LUE</td>
<td>Light use efficiency</td>
<td>g MJ PAR⁻¹</td>
</tr>
<tr>
<td>m</td>
<td>Fit parameter of Van-Genuchten equation</td>
<td>-</td>
</tr>
<tr>
<td>MA</td>
<td>Magdeburg, site in the Mid-East of Germany</td>
<td></td>
</tr>
<tr>
<td>Meth 1</td>
<td>Approaches for quantifying parameters, mainly from literature</td>
<td></td>
</tr>
<tr>
<td>Meth 2</td>
<td>Approaches for quantifying parameters, mainly by regression analysis from data sets</td>
<td></td>
</tr>
<tr>
<td>Meth 3</td>
<td>Approaches for quantifying parameters, a model parameter optimisation method</td>
<td></td>
</tr>
<tr>
<td>n</td>
<td>Fit parameter of Van-Genuchten equation</td>
<td>-</td>
</tr>
<tr>
<td>N_min</td>
<td>Mineral soil nitrogen</td>
<td>kg N ha⁻¹</td>
</tr>
<tr>
<td>N_0lt_first</td>
<td>Number of leaves, for those the phyllochron is not constant</td>
<td>-</td>
</tr>
<tr>
<td>N_0lt_notform</td>
<td>Number of leaves, which will never be formed</td>
<td>-</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Unit</td>
</tr>
<tr>
<td>------------</td>
<td>------------------------------------------------------------------------------</td>
<td>------------</td>
</tr>
<tr>
<td>No_{f tasini}</td>
<td>Number of already formed leaves at XStage 2</td>
<td>[-]</td>
</tr>
<tr>
<td>No_{fini_emer}</td>
<td>Number of leaves, which already have been initiated till emergence</td>
<td>[-]</td>
</tr>
<tr>
<td>No_{phy_first}</td>
<td>Phyllochrons needed for the formation of the first leaves</td>
<td>[-]</td>
</tr>
<tr>
<td>No_{phy_flag}</td>
<td>Number of phyllochrons which are needed for the period between the time of the appearance of the last leaf and silking</td>
<td>[-]</td>
</tr>
<tr>
<td>PAR</td>
<td>Photosynthetic active radiation</td>
<td>[MJ m^{-2} d^{-1}]</td>
</tr>
<tr>
<td>PA</td>
<td>Paulinenaue, site in the North-East of Germany</td>
<td></td>
</tr>
<tr>
<td>phy</td>
<td>Phyllochron</td>
<td>[° C d leaf^{-1}]</td>
</tr>
<tr>
<td>phy_{ini_rel}</td>
<td>Initial proportion of phy</td>
<td>[-]</td>
</tr>
<tr>
<td>pla</td>
<td>Plastochron</td>
<td>[° C d leaf^{-1}]</td>
</tr>
<tr>
<td>psi</td>
<td>Soil water potential</td>
<td>[hPa]</td>
</tr>
<tr>
<td>psi_{o}</td>
<td>Soil water potential at which crop water uptake is 0</td>
<td>[hPa]</td>
</tr>
<tr>
<td>psi_{larr[1]}</td>
<td>Soil water potential in the top soil layer compartment</td>
<td>[hPa]</td>
</tr>
<tr>
<td>psi_{crit}</td>
<td>Soil water potential at which crop water uptake is reduced</td>
<td>[hPa]</td>
</tr>
<tr>
<td>psi_{critevap}</td>
<td>Soil water potential at which evaporation is reduced</td>
<td>[hPa]</td>
</tr>
<tr>
<td>psi_{ini}</td>
<td>Initial soil water potential</td>
<td>[hPa]</td>
</tr>
<tr>
<td>Q</td>
<td>PAR radiation uptake of a crop</td>
<td>[MJ m^{-2} d^{-1}]</td>
</tr>
<tr>
<td>r^2</td>
<td>Coefficient of correlation</td>
<td>[-]</td>
</tr>
<tr>
<td>ra</td>
<td>Aerodynamic resistance</td>
<td>[s m^{-1}]</td>
</tr>
<tr>
<td>rc0</td>
<td>Canopy resistance at water saturation</td>
<td>[s m^{-1}]</td>
</tr>
<tr>
<td>rc</td>
<td>Canopy resistance</td>
<td>[s m^{-1}]</td>
</tr>
<tr>
<td>RE</td>
<td>Regensburg, site in the South-East of Germany</td>
<td></td>
</tr>
<tr>
<td>rgr</td>
<td>Relative growth rate</td>
<td>[d^{-1}]</td>
</tr>
<tr>
<td>RL</td>
<td>Root length</td>
<td>[cm cm^{-2}]</td>
</tr>
<tr>
<td>RL_{o}</td>
<td>Initial root length</td>
<td>[cm cm^{-2}]</td>
</tr>
<tr>
<td>RL_{max}</td>
<td>Maximal root length</td>
<td>[cm cm^{-2}]</td>
</tr>
<tr>
<td>RL_{tot}</td>
<td>Total root length</td>
<td>[cm]</td>
</tr>
<tr>
<td>RL_{toteff}</td>
<td>Effective total root length</td>
<td>[cm]</td>
</tr>
<tr>
<td>RLD</td>
<td>Root length density</td>
<td>[cm cm^{-3}]</td>
</tr>
<tr>
<td>RLD_{o}</td>
<td>Initial root length density at z = 0</td>
<td>[cm cm^{-3}]</td>
</tr>
<tr>
<td>RLD_{eff}</td>
<td>Effective root length density</td>
<td>[cm cm^{-3}]</td>
</tr>
<tr>
<td>RMSE</td>
<td>Root Mean Square Error</td>
<td></td>
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<tr>
<td>rRMSE</td>
<td>Relative root mean square error</td>
<td>[-]</td>
</tr>
<tr>
<td>RZ_{eff}</td>
<td>Effective rooting zone</td>
<td>[cm]</td>
</tr>
<tr>
<td>S, S(psi)</td>
<td>Sink term describing water uptake by the plant roots</td>
<td>[cm d^{-1}]</td>
</tr>
<tr>
<td>SD</td>
<td>Standard deviation</td>
<td></td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Definition</td>
<td>Unit</td>
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<td>SE</td>
<td>Standard error</td>
<td>[-]</td>
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<tr>
<td>Sen_a</td>
<td>Coefficient for calculating ( f_{\text{Sen}} )</td>
<td>[-]</td>
</tr>
<tr>
<td>Sen_b</td>
<td>Coefficient for calculating ( f_{\text{Sen}} )</td>
<td>[-]</td>
</tr>
<tr>
<td>SLA_leaf</td>
<td>Specific leaf area</td>
<td>[m² g⁻¹]</td>
</tr>
<tr>
<td>SLA_stem</td>
<td>Specific stem area</td>
<td>[m² g⁻¹]</td>
</tr>
<tr>
<td>SLA_leaf</td>
<td>Coefficient for calculating ( \text{SLA}_{\text{leaf}} )</td>
<td>[-]</td>
</tr>
<tr>
<td>SLA_stem</td>
<td>Coefficient for calculating ( \text{SLA}_{\text{stem}} )</td>
<td>[-]</td>
</tr>
<tr>
<td>SLA_leaf</td>
<td>Coefficient for calculating ( \text{SLA}_{\text{leaf}} )</td>
<td>[-]</td>
</tr>
<tr>
<td>SLA_stem</td>
<td>Coefficient for calculating ( \text{SLA}_{\text{stem}} )</td>
<td>[-]</td>
</tr>
<tr>
<td>SLAini_leaf</td>
<td>Initial specific leaf area</td>
<td>[m² g⁻¹]</td>
</tr>
<tr>
<td>SLAini_stem</td>
<td>Initial specific stem area</td>
<td>[m² g⁻¹]</td>
</tr>
<tr>
<td>Slope_PAR</td>
<td>Rate of ( k_{\text{PAR}} ) decrease</td>
<td>[-]</td>
</tr>
<tr>
<td>SRL</td>
<td>Specific root length</td>
<td>[cm g⁻¹]</td>
</tr>
<tr>
<td>ST</td>
<td>Steinach, site in the South-East of Germany</td>
<td></td>
</tr>
<tr>
<td>SW_pa</td>
<td>Plant available soil water</td>
<td>[mm]</td>
</tr>
<tr>
<td>SWDF</td>
<td>Soil water deficit factor</td>
<td>[-]</td>
</tr>
<tr>
<td>t</td>
<td>Time</td>
<td>[d]</td>
</tr>
<tr>
<td>( T_1 )</td>
<td>Base temperature</td>
<td>[°C]</td>
</tr>
<tr>
<td>( T_2 )</td>
<td>Lower optimum cardinal temperature for calculating ( f_T )</td>
<td>[°C]</td>
</tr>
<tr>
<td>( T_3 )</td>
<td>Upper optimum cardinal temperature for calculating ( f_T )</td>
<td>[°C]</td>
</tr>
<tr>
<td>( T_4 )</td>
<td>Maximum cardinal temperature for calculating ( f_T )</td>
<td>[°C]</td>
</tr>
<tr>
<td>( T_{\text{act}} )</td>
<td>Actual transpiration</td>
<td>[mm d⁻¹]</td>
</tr>
<tr>
<td>( T_{\text{mean}} )</td>
<td>Daily mean temperature</td>
<td>[°C]</td>
</tr>
<tr>
<td>( T_{\text{pot}} )</td>
<td>Potential transpiration</td>
<td>[mm d⁻¹]</td>
</tr>
<tr>
<td>T_eff</td>
<td>Effective daily mean temperature</td>
<td>[°C]</td>
</tr>
<tr>
<td>TLNO</td>
<td>Total number of leaves that will eventually appear</td>
<td>[-]</td>
</tr>
<tr>
<td>TUE</td>
<td>Transpiration use efficiency</td>
<td>[g L⁻¹]</td>
</tr>
<tr>
<td>TSUM_{crit}</td>
<td>Critical Temperature (logistic growth curve equation)</td>
<td>[°C d]</td>
</tr>
<tr>
<td>WUE</td>
<td>Water use efficiency</td>
<td>[g L⁻¹]</td>
</tr>
<tr>
<td>XStage_1</td>
<td>Crop development stage: emergence</td>
<td>[-]</td>
</tr>
<tr>
<td>XStage_2</td>
<td>Crop development stage: tassel initiation</td>
<td>[-]</td>
</tr>
<tr>
<td>XStage_3</td>
<td>Crop development stage: silking</td>
<td>[-]</td>
</tr>
<tr>
<td>XStage_4</td>
<td>Crop development stage: end of grain filling</td>
<td>[-]</td>
</tr>
<tr>
<td>XStage_5</td>
<td>Crop development stage: silage maturity</td>
<td>[-]</td>
</tr>
<tr>
<td>( z )</td>
<td>Soil depth</td>
<td>[cm]</td>
</tr>
<tr>
<td>( zr )</td>
<td>Root depth</td>
<td>[cm]</td>
</tr>
<tr>
<td>( zr_0 )</td>
<td>Sowing depth</td>
<td>[cm]</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Unit</td>
</tr>
<tr>
<td>---------</td>
<td>-----------------------------------------------</td>
<td>------------------</td>
</tr>
<tr>
<td>$z_{r_{\text{max}}}$</td>
<td>Maximal root depth</td>
<td>[cm]</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Fit parameter of Van-Genuchten equation</td>
<td>[cm$^{-1}$]</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Volumetric soil water content</td>
<td>[cm$^3$ cm$^{-3}$]</td>
</tr>
<tr>
<td>$\theta_r$</td>
<td>Residual soil water content</td>
<td>[cm$^3$ cm$^{-3}$]</td>
</tr>
<tr>
<td>$\theta_s$</td>
<td>Saturated soil water content</td>
<td>[cm$^3$ cm$^{-3}$]</td>
</tr>
<tr>
<td>$0_{PAR}$</td>
<td>Constant value of $k_{PAR}$</td>
<td>[-]</td>
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Chapter 1

General introduction

1. Background

1.1. German and European energy policies

Climate change and energy security are the driving forces of German and European energy policies (BMELV and BMU, 2009). At the same time the global energy demand is growing rapidly, increasing atmospheric greenhouse gas concentrations can be observed, with fossil fuel-derived CO$_2$ emissions being the most important contributor (Weiland, 2010). For reaching the target of holding the increase in global average temperature below 2°C above pre-industrial levels, which was appointed by the international community at the 16th United Nations Climate Change Conference 2010 in Cancún, the greenhouse gas emissions have to be reduced dramatically till 2050 (WGBU, 2011). Renewable energy sources, such as bioenergy out of biogas (biomethane) production, will play an important role in this context (Ericsson et al., 2009, Weiland, 2010). European Council endorsed in 2007 the binding targets for 2020 to increase the proportion of renewable energy sources to at least 20% of the EU’s final energy consumption (BMELV and BMU, 2009; Ericsson et al., 2009). The German government underlined 2007 this target by manifesting the will to cover 30% of the German electricity use and 14% of the German heat use by renewable energy sources in 2020 (BMELV and BMU, 2009). From biogas both can be produced, power and/or heat (FNR, 2010; Weiland, 2010) and it is currently contributing approx. 11% to the electricity and approx. 9% to the heat production from renewable energies in Germany (FNR, 2010). German government now supports biogas production since 20 years, starting in 1991 with a law which ensured the feed-in of power from renewable energy sources into the public grid. In 2000 the Renewable Energy Sources Act (EEG) was adopted, which vital stimulated the biogas sector (Horbelt, 2011). By the first amendment of the EEG in 2004 the biomass bonus for plants was introduced, which increased economic efficiency of agricultural biogas production clearly (Fig. 1). With the second amendment of the EEG in 2009 again an increase of the number of biogas units could be observed (Schüsseler, 2011) and the German government reinforce the economic efficiency of biogas production by a policy of financial support.
1.2. Biogas

Biogas (biomethane), a renewable energy source of the second generation, is gained by anaerobic digestion of organic materials. Methane fermentation, carried out by different microorganisms, is a complex process which can be divided up into four phases: hydrolysis, acidogenesis, acetogenesis respectively dehydrogenation, and methanation (Herrmann and Taube, 2006; Weiland, 2010). Key factors for the anaerobic digestion are, among others, temperature, pH, particle size of the substrate and production of enzymes, moreover the methane yield is influenced by the substrate quality (specific methane yield), the digestion system and the retention time (Amon, et al., 2007b; Herrmann and Taube, 2006; Weiland, 2010). All organic biomass consisting of carbohydrates, proteins, fats, cellulose and hemicelluloses can be used as a substrate for biogas production (Weiland, 2010). Currently, the major part of substrates are derived from agricultural resources, like farm waste (mainly animal manures), crop residues and dedicated energy crops, but also agri-food and municipal waste can be an important biogas production sources (Pöschel et al., 2010).

However, the most important substrates are energy crops (Weiland, 2010), because methane yields from energy crops are much higher compared to e.g. animal manure (IE, 2008). According to the biogas plants (Tab. 1) the acreage cultivated for biogas production increased steadily in Germany within the last years and amounts actual (2010) to approx. 650000 ha (Schüsseler, 2011). If the acreage for biogas production would increase up to 2 million hectares, over 50 % of the potential energy yield from biogas could be realised by
energy crops (Weiland, 2010). Together with the other mentioned agricultural resources, biogas from energy crops would provide approx. 8 % of the German electricity use (Schüsseler, 2011). Crops which are currently used in biogas plants are silage maize, grain and silage cereals, perennial grasses and with less proportion fodder beets, potatoes or dedicated energy crops, like Sudan grass (Amon et al., 2007b; Schüssler, 2011; Weiland, 2010). However, maize is dominating energy cropping for biogas production (Bauer et al., 2010; Schittenhelm, 2008; Amon et al., 2007b), with 80 % (Schütte, 2010) to 90 % (DMK, 2006), cultivated in monoculture or in crop rotations with very high percentage of maize. This predominance is due to its high methane yield on a hectare basis, resulting from both high specific methane yields [l methane per kg organic matter] and high biomass yields (Murphy and Power, 2009; Amon et al., 2007b; Weiland, 2010). Among others, the increase in biogas production led in Germany since 2004 (first amendment of EEG) to a significant increase of silage maize acreage (39 %) up to approx. 1.83 Mio. ha (DMK, 2011).

2. Requirements for bioenergy cropping systems
Due to the limited availability of arable land, food and feed as well as bioenergy cropping compete for agricultural resources (Bauer et al., 2010). World wide actual agriculture is driven by a sudden rise in the price of petroleum and a rapid expansion of global biofuel production, which tend to amplify the problems of regions with consistently experience of food shortages (Cassman and Liska, 2007). The critical challenge is to cover the increasing food demand from population increase and the increasing feed and energy demand simultaneously and in an environmental friendly way (Bauer et al., 2010; Cassman and Liska, 2007). Facing the rapid increase in these demands and the need to reduce greenhouse gas emissions expeditiously (WGBU, 2011), require an increase in research towards increasing rates of gain in crop yields (Cassman and Liska, 2007; Bauer et al., 2010). Therefore, it will be necessary to explore yield potentials around the world and to calculate the methods and the probability to close the yield gaps between average farm yields and yield potentials (Cassman, 2010).

Criteria to evaluate energy cropping systems are various and may differ with the explored system level. However, generally energy cropping systems producing biomass have to be sustainable in terms of climatic, environmental and socio-economic conditions (Lewandowski and Faaij, 2006; de Vries et al. 2010; Bauer et al., 2010). Socio-economic requirements might have a high variability between regions and refer mainly to the whole composition of the agricultural sector in each region. However, a bioenergy cropping system has to be economic efficient for the farmer, which is highly linked to high energy yields per hectare (Amon et al., 2007a). De Vries et al., 2010 defined different indicators to evaluate the production-ecological sustainability of biofuel crops. These indicators refer to energy yield, as
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input output ratio and per unit of land, to the potential of saving greenhouse gas emissions, considering also N₂O or CH₄ emission from production line, and to the agro-environment, including soil erosion, soil organic matter, risk of soil borne diseases, eutrophication, pesticide usage and water use. These indicators give quite a full picture of the subjects needed to be considered for assessing bioenergy cropping systems towards productivity and ecological aspects.

3. Objectives of this study
The objective of this study is the quantification of the production potential and the analyses towards resource use efficiencies of energy cropping systems for biogas production. Only a site adapted choice of bioenergy cropping system can contribute to both, high yields and reduced environmental effects. Additionally, as mentioned before, the economic profitability, but also the greenhouse gas reduction effect depends on high biomass yields.

As silage maize is dominating energy cropping systems for biogas production (Bauer, et al. 2010; Schittenhelm, 2008; Amon et al., 2007b), first focus was set on the evaluation of silage maize grown in monoculture. Therefore, an empirical dynamic crop growth model for silage maize was developed, featuring dry matter production, dry matter partitioning into root, leaf, stem and cob, leaf area expansion and spatial root distribution, and was linked to modules calculating potential evapotranspiration and soil water balance (Chapter 2). It was parameterised for North Western European conditions and validated considering different cultivars and sites. Crop growth models are for a better understanding of site - cultivar (respectively species) interaction appropriate tools. They provide the ability to analyse dynamically the influence of resource limitations on dry matter production and can provide important parameters, like transpiration, which are hardly measurable, but which are important in terms of water balance and resource use efficiencies. Moreover, crop growth simulation models allow quantifying yield potentials at different sites and, by controlled simulation experiments, evaluating yield gains possible with specific management changes (Lobell et al., 2009). For analysing and evaluating the yield potential of silage maize in three typical regions of Germany and to quantify the yield gap between attainable yield and yield potential, in order to discuss chances and limitations of possible yield increase in these regions, a simulation study was conducted using the developed crop growth model (Chapter 3). As high biomass yields of silage maize might be most often limited by either low temperatures or drought stress, the simulation study focused on temperature and water supply effects on crop growth at the different sites. Additionally, different water supply scenarios towards yield and water, transpiration and light use efficiencies were conducted.

Maize grown in monocultures can cause several environmental problems, like reduction of crop species diversity, increase of pest pressure or possible increase of nutrient losses and
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soil erosion (Schittenhelm, 2010; Frede, 2010). For reducing these problems alternative cropping systems, like crop rotations consisting of more than corn and a fallow, may play a key role (Bauer et al., 2007 and Schittenhelm, 2010). Under Northern German conditions, so low mean temperatures and high amount of precipitation, one possible alternative might be provided by intensive crop rotations, which might reach comparable or even higher dry matter yields as maize monocultures due to a prolonged leave area. These crop rotations could in turn reduce e.g. soil erosion processes or the risk of soil born disease. In order to investigate, if alternative cropping systems grown under Northern German conditions can provide biomass yields comparable to maize monocultures, a combined experimental-modelling evaluation of light and water use efficiencies of different bioenergy cropping systems was conducted (Chapter 4). Perennial ryegrass and intensive crop rotations including winter intercrops and combining C$_4$- and C$_3$-crops were compared with maize monocultures with respect to their productivity and nitrogen use efficiency. To provide the needed data a two years field experiment at two different sites in Northern Germany was conducted within the cooperative project BIOGAS-EXPERT.

References

Chapter 1


A new crop growth model for silage maize: development, parameterisation and validation

Babette Wienforth, Ulf Böttcher, Antje Herrmann, Klaus Sieling, Siegfried Schittenhelm, Friedhelm Taube and Henning Kage

Keywords: crop growth model, silage maize, energy cropping, cultivar site specific interaction, drought stress, low temperature regions, biogas

Abstract
A new empirical, dynamic crop growth model for silage maize was developed and adapted to North Western European (low temperature) conditions in order to provide an appropriate tool for analysing and evaluating the production potential of silage respectively energy maize cropping under different environmental conditions. Under the German and European energy policy of the last decade, the concern of an economical and ecological efficient silage maize production has increased strongly. The new maize model was modular structured and calculates for plant development, dry matter production, dry matter partitioning as well as green area expansion, root growth and soil water balance. This model was parameterised using data from three different field experiments, including a data set of an irrigation field trail. Model performance concerning above ground dry matter was with a RMSE of 190 g m$^{-2}$ appropriate. Conducted sensitivity analyses underlined the importance, but also the ability of adequate green area calculations, especially in context of differing water supply levels in specific year site cultivar combinations, caused by feedback reactions on dry matter production. The validation of the model showed, that the model calculations for silage maize biomass production are for a large range of site year cultivar combinations satisfactory (RMSE of 324 g m$^{-2}$).
1. Introduction
A strong promotion of renewable energy production by the European and German energy policy led to a substantial increase of crops grown for biogas (methane) production in Germany. The actual acreage cultivated for biogas production amounts to approx. 650000 ha (Schüsseler, 2011). An economically and ecologically sustainable expansion of biogas production requires high methane yields. Methane yield on a hectare basis is the product of specific methane yield [l methane per kg organic matter] and biomass yield (Amon et al., 2007). As silage maize provides both, high biomass and a high specific methane yield, it is dominating energy cropping with approx. 80% (Schütte, 2010) and energy cropping systems are tending to maize monocultures or rotations with very high percentage of maize. Among others, the expansion of energy cropping led to a significant increase of silage maize acreage (39%) in Germany up to approx. 1.83 Mio. ha (DMK, 2011) between 2004 (first amendment of the Renewable Energy Sources Act) and 2009. This development comprised an expansion of silage maize production to highly productive regions, where forage production so far was of little importance. Furthermore, maize production increased on minor productive sites. This includes sites, which might be less favourable for maize, due to low mean temperatures or other sites with generally insufficient water availability.

Following Krauter and Claupein, 2004 and summing up the already mentioned points, some open fields of work can be identified: Requirements of biomass quality in terms of specific methane yield; biomass yield potential considering the given limits in water availability and thermal time; as well as integration of energy maize in sustainable cropping systems to minimise negative environmental effects and to maximise net energy yield. Chemical composition of maize has been shown to effect specific methane yield (Weiland, 2010), the main driver of methane hectare yield, however, is biomass yield (BMELV, 2008). Efforts to improve biomass yield per hectare led to a high intensification of maize dominated energy crop rotations by e.g. intercropping or bi-cropping, as well as to the introduction of late maize hybrids, which are supposed to increase biomass yield of energy cropping systems by prolonged leaf area duration. Amon et al., 2007 showed the predominance of late maize hybrids concerning biomass yields by field data. However, in many regions of Germany and North Western Europe thermal time might be insufficient for late hybrids to achieve full maturity, which may reduce biomass yields or at least reduce dry matter content, needed for effective ensiling. In other regions these strategies may fail due to increased leaf area duration and therefore higher water demand of these cultivars or intensified energy crop rotations, because of low water availability.

For a better understanding of site cultivar interactions on maize growth, system oriented crop growth models are appropriate tools. These models provide the ability to analyse dynamically the influence of resource limitations on dry matter production and can provide important
parameters, like transpiration, which are hardly measurable, but which are important in view of water balance and resource efficiencies.

During the last decades a number of models usable for simulating maize crop growth have been developed. However, these models differ in various terms, like model complexity, degree of process-orientation or system levels the models apply for. Models focusing on crop growth are for example CERES-Maize (Jones and Kiniry, 1986), HYBRID-Maize (Yang et al., 2004b) or MAISPROG (Herrmann et al., 2005), whereas e.g. DSSAT (Jones et al., 2003), EPICphase (Cabelguenne et al., 1999), APSIM (Robertson et al., 2009), CropSyst (Stöckle et al., 2003), DAISY (Abrahamsen and Hansen, 2000), WOFOST (Boogard et al., 1998) or STICS (Brisson et al., 1998) are models focusing on farming- or agro-ecosystems. These models are coping crop growth processes by integrating generic crop growth models, that can be applied to several species and cropping systems. For the more specific maize growth models, a distinction between models focusing on maize growth for grain or for silage production can be made. Almost all process-orientated, dynamic models such as CERES-Maize, MAIZE (Muchow et al., 1990), SUCROS97 (van Laar et al., 1997), WOFOST, APSIM, CropSyst and STICS calculate maize grown for grain, even so aboveground biomass is calculated, too (Herrmann et al., 2005). However, only few models, like MAISPROG or the adaptation of SPN to silage maize (Bleken et al., 2009) have directly been developed with respect to silage maize production. Certainly, these models have been adapted to cool-temperate climates (according to Wilson et al., 1995 < 18 °C mean temperature during main growing season). Even though appropriate silage maize growth models may be available, a heuristic benefit can be given, according to Sinclair and Seligman, 1996 and Brisson et al., 1998, by building own models, although only well known model concepts and formalisms from existing models are integrated. This applies especially, because, only programmable and modularly structured models allow for the integration of fragmented research efforts and for focussing on specific purposes.

The aim of this study was to develop, parameterise and validate a dynamic crop growth model for silage maize in order to analyse and evaluate the production potential of energy maize cropping under different environmental conditions. This involves the development of procedures to calculate dry matter production, dry matter partitioning into different plant organs (roots, leaf, stem, and cob), leaf area expansion and spatial root distribution, as well as the link to modules calculating potential evapotranspiration and soil water balance. In particular, it requires the consideration of North Western European conditions, in terms of low temperatures during the main growth period of maize, the ability to calculate the impact of water limitation on dry matter production and the sensitivity for cultivar specificity concerning maturity groups.
To assure the possibility of regionalising research efforts and to benefit by analyses towards scenario calculations, the model has to be easily transferable into other environmental conditions and should be adoptable to a range of cultivars. Therefore, the chosen model concepts are simple but easy to parameterise using commonly available data and information. Additionally, the presented model is modularly structured to allow, later on, its integration into a linked model, which focuses beside crop productivity also issues concerning the impact of silage maize and especially energy maize cropping on the environment.

2. Material and Methods

2.1. The model
The maize crop growth model we developed is an empirical dynamic model which is divided into sub models for calculating plant development, dry matter production, dry matter partitioning as well as green area expansion, root growth and soil water balance. The soil water balance is calculated by a potential based layer module, thereby the potential evapotranspiration is calculated according to Penman-Monteith (Monteith, 1973) in an extra module. Some details concerning this approach are given in Kage et al., 2003.

The model runs on daily time steps. External data inputs required for running the model are daily mean temperature [°C] (T mean), incoming globe radiation [W m^-2 d^-1], precipitation [mm], wind speed [m s^-1], air humidity [%] and resulting values like vapour pressure [mbar] and saturation deficit [mbar].

Main calculations in the crop growth model are based on effective daily mean temperature (Teff) described as the difference between T mean and a base temperature (T_1) and on photosynthetic active radiation (PAR) derived from the global radiation using a factor of 0.5 (Szeicz, 1974).

The model was implemented using an object orientated component library (Kage and Stützel, 1999a), which uses the concept of visible software components of the Delphi®/C++ Builder®, Borland.

2.1.1. Evapotranspiration module
For the calculation of potential evapotranspiration [mm d^-1] (ET pot) the Penman-Monteith equation (Monteith, 1973) is implemented within the model. The potential evaporation [mm d^-1] (E pot), as a fraction of ET pot, is calculated from an estimate of global radiation, reaching the soil surface relative to total available global radiation. The potential transpiration [mm d^-1] (T pot) is simply the difference between ET pot and the sum of E pot and the Interception (I).
The used variables concerning environmental conditions, such as global radiation, wind speed, saturation deficit and daily mean temperature, are derived from the input weather data. Whereas the crop variables green area index \([ \text{m}^2 \text{m}^{-2}] \) (GAI) and crop height \([\text{m}]\), which are necessary for calculation of canopy resistance \([\text{s} \text{m}^{-1}] \) (rc) and aerodynamic resistance \([\text{s} \text{m}^{-1}] \) (ra), are provided by the partitioning module. Important parameters of the model component are \(r_{c0} \) \([\text{s} \text{m}^{-1}]\), describing the canopy resistance at water saturation and \(f_{\text{PAR}, \text{glob}} \), describing a constant factor between the extinction coefficient for glob radiation \((k_{\text{glob}})\) and the extinction coefficient for PAR \((k_{\text{PAR}})\) \([\cdot]\), which is calculated in the dry matter production module.

2.1.2. Soil water module

The calculation of vertical soil water movement is a potential based approach using the water content based formulation of the Richards equation.

\[
\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[ D_{\theta}(\theta) \left( \frac{\partial \theta}{\partial z} \right) + k(\theta) \right] - S(\theta) \quad \text{(Eq. 1)}
\]

\(\theta\) is the volumetric soil water content \([\text{cm}^3 \text{cm}^{-3}]\), \(t\) the time \([\text{d}]\), \(z\) the soil depth \([\text{cm}]\), \(D_{\theta}(\theta)\) the diffusivity of water \([\text{cm}^2 \text{d}^{-1}]\), \(k(\theta)\) the unsaturated hydraulic conductivity \([\text{cm d}^{-1}]\) and \(S(\theta)\) is a sink term \([\text{cm d}^{-1}]\) describing water uptake by the plant roots. The relationship between \(D_{\theta}\) and \(\theta\), \(k\) and \(\theta\) is described according the functions proposed by van Genuchten, 1980 in the formulation revised by Wösten and van Genuchten, 1988. The Van-Genuchten-parameter \(m\) is calculated according to Mualem, 1976.

\(S[i]\), the sink term describing water uptake by the plant roots in a certain layer \([i]\), depends on \(T_{\text{pot}}\), a reduction factor \([\cdot]\) \((f_{\text{sinkred}})\) and a term, which describes the reduction of water uptake by roots due to competition. This term is calculated by the root length in the layer \([\text{cm cm}^{-2}]\) \((RL[i])\), an exponential factor for root competition \([\cdot]\) \((\text{CompF})\) divided by the sum of root length in all layers \([\text{cm cm}^{-2}]\) \((RL[j])\) and \(\text{CompF}\). 0.1 is simply the conversion from cm to mm.

\[
S[i] = 0.1 \cdot T_{\text{pot}} \cdot \sum_{j} RL[i]^{\text{CompF}} \cdot f_{\text{sinkred}} \quad \text{(Eq. 2)}
\]

\(f_{\text{sinkred}}\) is calculated by the soil water potential in each soil layer \(\text{psi}_i \) \([\text{hPa}]\), the soil water potential \([\text{hPa}]\) \(\text{psi}_0\) from which on water uptake is 0 and \(\text{psi}_{\text{crit}} \) \([\text{hPa}]\), a parameter for the soil water potential from which on water uptake decrease.
Chapter 2

\[ f_{\text{sinkred}}[i] = \begin{cases} 1 & |\psi_i < \psi_{\text{crit}}| \\ \frac{\log(\psi_i) - \log(\psi_0)}{\log(\psi_{\text{crit}}) - \log(\psi_0)} & |\psi_i \geq \psi_{\text{crit}}| \end{cases} \quad \text{(Eq. 3)} \]

The sum of the sink terms of the different soil layers is the actual transpiration [mm d\(^{-1}\)] (\(T_{\text{act}}\)).

\[ T_{\text{act}} = \sum_j S[j] \quad \text{(Eq. 4)} \]

Actual evaporation [mm d\(^{-1}\)] (\(E_{\text{act}}\)) is calculated by a reduction factor (\(f_{\text{evap}}\)), which corrects \(E_{\text{pot}}\) by the influence of low soil water content in the top soil layer.

\[ E_{\text{act}} = E_{\text{pot}} \cdot f_{\text{evap}} \quad \text{(Eq. 5)} \]

\[ f_{\text{evap}} = \frac{-1 \cdot (\log 10(psi_{\text{arr}[1]}) - 4.2)}{4.2 - \log 10(psi_{\text{crit evap}})} \quad \text{(Eq. 6)} \]

Thereby \(psi_{\text{arr}[1]}\) is the soil water tension in the top soil compartment and \(psi_{\text{crit evap}}\) is the soil water tension at which evaporation is reduced.

The initiation of soil water potential (\(\psi\)) is simply done by a parameter \(\psi_{\text{ini}}\).

2.1.3. Development

The calculation of crop development is, with slight adaptation, based on the calculations of the HYBRID-Maize model (Yang et al., 2004b). Five main developmental stages, so called XStages, are considered in the model. Thereby, integer values of these stages represent cardinal points of crop development. XStage 1 [\(\cdot\)] is reached at the date of emergence. XStage 2 [\(\cdot\)] simulates the date of tassel initiation, which is followed by silking (XStage 3 [\(\cdot\)]). XStage 4 [\(\cdot\)] represents the end of the effective grain filling. XStage 5 [\(\cdot\)] is the date of maturity, which in the present mode, is defined as dough stage (maturity criterium for silage maize), but not physiological maturity as used by Yang et al., 2004b. The progress of development is quantified by development rates. DevRateS0 [1 °C \(^{-1}\) d\(^{-1}\)] is the development rate from sowing till emergence. It is a simple ratio of \(T_{\text{eff}}\) and a parameter GDD\(_{\text{emer}}\) [°C d] describing the temperature sum which is needed for reaching emergence. As this step of development is not included in the HYBRID-Maize model we adopted equation 7.

\[ \text{DevRateS0} = \frac{T_{\text{eff}}}{GDD_{\text{emer}}} \quad \text{(Eq. 7)} \]
The development rate ($\text{DevRateS}_1 \, [1 \, \text{°C}^{-1} \, \text{d}^{-1}]$), valid for the period between emergence and tassel initiation, is calculated from $\text{Teff}$ and a temperature sum $\text{GDD}_{\text{tasini}} \, [\text{°C} \, \text{d}]$, which is required from emergence till tassel initiation.

$$\text{DevRateS}_1 = \frac{\text{Teff}}{\text{GDD}_{\text{tasini}}} \quad \text{(Eq. 8)}$$

$\text{GDD}_{\text{tasini}}$ is described by the number of leaves, which have to be initiated between emergence (XStage 1) and tassel initiation (XStage 2), multiplied by the plastochron ($\text{pla}$) [°C d leaf$^{-1}$], which is a model parameter. The number of leaves, which have to be initiated between XStage 1 and XStage 2, are calculated by the term in brackets of equation 9. Thereby the ratio between $\text{GDD}_{\text{silk}}$ [°C d], a parameter describing the temperature sum needed from emergence to silking (XStage 3) and phy [°C d leaf$^{-1}$], a parameter describing the constant phyllochron, calculates the number of leaves in total which have to be formed. All remaining parameters in this term are correction factors. However, $\text{No}_{\text{fini\_emer}}$ is the number of leaves, which already have been initiated till emergence. $\text{No}_{\text{lf\_notorm}}$ is the number of leaves, which will never be formed. $\text{No}_{\text{lf\_first}}$ is describing the first five leaves and $\text{No}_{\text{phy\_first}}$ is the amount of phyllochrons needed for formation of the first leaves. This correction is necessary because the model computes an increasing phyllochron for the first leaves but a constant one (phy) for all following leaves (see Eq. 13 and Eq. 14). $\text{No}_{\text{phy\_lflag}}$ is the number of phyllochrons which is needed for the period between the time of the appearance of the last leaf and silking. Parameter Coty indicates that the cotyledon is already formed at emergence.

$$\text{GDD}_{\text{tasini}} = \left(\frac{\text{GDD}_{\text{silk}}}{\text{phy}} - \text{No}_{\text{fini\_emer}} + \text{No}_{\text{lf\_notorm}} + \text{No}_{\text{lf\_first}} - \text{No}_{\text{phy\_first}} - \text{No}_{\text{phy\_lflag}} + \text{Coty}\right) \cdot \text{pla}$$

$$\quad \text{(Eq. 9)}$$

$\text{DevRateS}_2 \, [1 \, \text{°C}^{-1} \, \text{d}^{-1}]$ is the development rate for the period between tassel initiation and silking. It is calculated from the ratio of $\text{Teff}$ and the temperature sum from XStage 2 until the appearance of the last leaf plus the temperature sum from the appearance of the last leaf up to XStage 3. Thereby the temperature sum from XStage 2 till the appearance of the last leaf is calculated by the term in brackets in the denominator of equation 10 multiplied with phy. The fraction describes the number of leaves, which have to be formed from tassel initiation. $\text{No}_{\text{lf\_tasini}}$ is the number of already formed leaves at XStage 2. The multiplication of $\text{No}_{\text{phy\_lflag}}$ and phy describes the temperature sum needed from the last leaf appearance till silking.
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\[
DevRateS2 = \frac{Teff}{\left(No_{ini \_emer} + \frac{GDD_{\text{tasin}i}}{pla} - No_{\text{notform} - \_tasin} \cdot \text{phy} + No_{\text{phy \_flag} \cdot \text{phy}} \right)}
\]

(Eq. 10)

DevRateS3 [1 °C⁻¹ d⁻¹], used between XStage 3 and XStage 4, is calculated by Teff and the parameter GDDS3 [°C d], which is the duration of silking till grain filling.

\[
DevRateS3 = \frac{Teff}{GDD_{S3}}
\]

(Eq. 11)

DevRateS4 [1 °C⁻¹ d⁻¹] is obtained from Teff and the remaining period between the end of grain filling and maturity. Thereby the duration of this period is the difference between the whole thermal time needed till maturity, described by the parameter GDDtotal [°C d] and the thermal times for prior development phases, described by the, already mentioned, parameters GDDemer, GDDSilk and GDDS3.

\[
DevRateS4 = \frac{Teff}{GDD_{\text{total}} - GDD_{\text{emer}} - GDD_{\text{silk}} - GDD_{S3}}
\]

(Eq. 12)

Besides describing crop development, the development module also calculates the number of leaves (LeafNo) [-]. Eq. 13 gives the change of LeafNo, which is calculated by the ratio of Teff and the phyllochron (denominator). As already mentioned, the model computes an increasing phyllochron for the first leaves but a constant one (phy) for all following leaves. To determine the actual phyllochron phy is corrected by \(f_{\text{phy}}\) [-] (Eq. 13), which is the ratio of the phyllochron during the initial leaf appearance period and the later, constant phyllochron (Eq. 14). As long as LeafNo is smaller than No_{l\_first}, \(f_{\text{phy}}\) results from the initial proportion of phy (\(\text{phy}_{\text{ini\_rel}}\)) [-] plus the constant increase of this relative value (ratio of Eq. 14). If LeafNo equals No_{l\_first} or exceeds No_{l\_first}, \(f_{\text{phy}}\) becomes 1 and therefore the phyllochron becomes constant (see Eq. 13).

\[
\frac{d\text{Leaf}_{\text{No}}}{dt} = \frac{Teff}{\text{phy} \cdot f_{\text{phy}}}
\]

(Eq. 13)
2.1.4. Dry matter production

Production of total plant dry matter [g m\(^{-2}\)] (DM\(_{\text{tot}}\)) starts with emergence. The growth rate for DM\(_{\text{tot}}\) [g m\(^{-2}\) d\(^{-1}\)] is computed as a function of absorbed photosynthetic radiation [MJ m\(^{-2}\) d\(^{-1}\)] (Q) and light use efficiency [g MJ PAR\(^{-1}\)] (LUE) corrected by a temperature factor (f\(_T\)) [-] and a soil water deficit factor [-] (SWDF).

\[
\frac{dDM_{\text{tot}}}{dt} = Q \cdot LUE \cdot f_T \cdot SWDF
\]  

(Eq. 15)

Q is a function of PAR, GAI and an extinction coefficient for PAR [-] (k\(_{\text{PAR}}\)).

\[
Q = PAR \cdot (1 - e^{-k_{\text{PAR}}^GAI})
\]  

(Eq. 16)

Canopy reflection thereby is lumped into the k\(_{\text{PAR}}\). The calculation of GAI is given within the description of the partitioning sub model (Eq. 36 – 43). k\(_{\text{PAR}}\) describes the light extinction coefficient as a negative linear-plateau function of GAI. Thereby Slope\(_{\text{PAR}}\) [-] is the slope of the negative linear part of the equation which switches to a constant value [-] (0\(_{\text{PAR}}\)) at GAI\(_{\text{crit}}\)\(_{\text{ExpPAR}}\). [-]

\[
k_{\text{PAR}} = \begin{cases} 
Slope_{\text{PAR}} \cdot (\text{GAI} - \text{GAI}_{\text{crit}}_{\text{ExpPAR}}) + 0_{\text{PAR}} & | \text{GAI} \leq \text{GAI}_{\text{crit}}_{\text{ExpPAR}} \\
0_{\text{PAR}} & | \text{GAI} > \text{GAI}_{\text{crit}}_{\text{ExpPAR}}
\end{cases}
\]  

(Eq. 17)

LUE is assumed to be constant.

The temperature function (f\(_T\)) for calculating dry matter productivity is described by an optimum function with 4 cardinal temperatures [°C] (T\(_1\), T\(_2\), T\(_3\) and T\(_4\)), as followed.
The function is zero if $T_{\text{mean}}$ is below the base temperature $T_1$ or exceeding the upper threshold $T_4$. Temperatures equal or higher $T_1$ lead to a linear rise of $f_T$ until $T_2$ is reached. Between $T_2$ and $T_3$ a temperature optimum is reached and $f_T$ is 1. Higher temperatures than $T_3$ lead to a linear decrease of $f_T$ until $T_4$ is reached.

The soil deficit factor (SWDF), which influences dry matter productivity, is obtained as the simple ratio of actual and potential transpiration.

$$SWDF = \frac{T_{\text{act}}}{T_{\text{pot}}} \quad (Eq. \ 19)$$

At emergence total plant dry matter production is initialised in addition to Eq. 15 by the seed weight ($DM_{\text{seed}}$) [g m$^{-2}$] minus the fraction ($f_{\text{hypo}}$) [-] of $DM_{\text{seed}}$ found in the hypocotyl and minus the fraction ($f_{\text{trans}}$) [-] of $DM_{\text{seed}}$, which is assumed to be lost by transformation and translocation processes.

$$DM_{\text{ini}} = DM_{\text{seed}} - DM_{\text{seed}} \cdot f_{\text{trans}} - DM_{\text{seed}} \cdot f_{\text{hypo}} \quad (Eq. \ 20)$$

Thereby $DM_{\text{ini}}$ is calculated as provided in Eq. 20 and decreases with time by a constant rate $k_{DM_{\text{ini}}}$ [g m$^{-2}$ d$^{-1}$ °C$^{-1}$] and $f_T$ [-] (Eq. 21).

$$\frac{dDM_{\text{ini}}}{dt} = -\min(DM_{\text{ini}}, k_{DM_{\text{ini}}} \cdot f_T) \quad (Eq. \ 21)$$

The growth rate of $DM_{\text{tot}}$ is then calculated as the difference of the growth rate of $DM_{\text{tot}}$, calculated for the last time step and the rate of $DM_{\text{ini}}$. 

\[
\begin{align*}
f_T &= \begin{cases} 
0 & |T_{\text{mean}} < T_1 \\
\frac{T_{\text{mean}} - T_1}{T_2 - T_1} & |T_1 \leq T_{\text{mean}} \leq T_2 \\
1 & |T_2 \leq T_{\text{mean}} \leq T_3 \\
\frac{T_4 - T_{\text{mean}}}{T_4 - T_3} & |T_3 \leq T_{\text{mean}} \leq T_4 \\
0 & |T_{\text{mean}} > T_4
\end{cases}
\end{align*}
\]
\[
\frac{dDM_{\text{tot}}}{dt} = \frac{dDM_{\text{tot}}}{dt} - \frac{dDM_{\text{ini}}}{dt}
\]  
(Eq. 22)

2.1.5. Dry matter partitioning and green area expansion

All dry matter components of the plant are calculated in \([g \text{ m}^{-2}]\), their rates are given in \([g \text{ m}^{-2} \text{ d}^{-1}]\). The principle of the partitioning module is the simple idea, that total plant dry matter is the sum of its single components, which also can be separated in subcomponents. The first separation of DM\(_{\text{tot}}\) is between root (DM\(_{\text{root}}\)) and shoot dry matter (DM\(_{\text{shoot}}\)).

\[
DM_{\text{tot}} = DM_{\text{root}} + DM_{\text{shoot}}
\]  
(Eq. 23)

Correspondingly, the growth rate of DM\(_{\text{tot}}\) is the sum of the growth rates of DM\(_{\text{root}}\) and DM\(_{\text{shoot}}\).

\[
\frac{dDM_{\text{tot}}}{dt} = \frac{dDM_{\text{root}}}{dt} + \frac{dDM_{\text{shoot}}}{dt}
\]  
(Eq. 24)

The growth rate of the root is computed from the growth rate of DM\(_{\text{tot}}\), given by the module for dry matter production and a dry matter allocation coefficient for the root \([-\text{]}\) (AC\(_{\text{root}}\)).

\[
\frac{dDM_{\text{root}}}{dt} = \frac{dDM_{\text{tot}}}{dt} \cdot AC_{\text{root}}
\]  
(Eq. 25)

AC\(_{\text{root}}\) is assumed to have its maximum at emergence \([-\text{]}\) (ACE\(_{\text{root}}\)) and to decrease until root growth stops. It is calculated following HYBRID-Maize with a separate scale of development stages for root growth (DS), ranging from 0 to 2, with 1 at silking. The development driven stop \([-\text{]}\) (DS\(_{\text{stop}}\)) of root growth is timed short after silking (Yang et al., 2004b).

\[
AC_{\text{root}} = \frac{ACE_{\text{root}} - DS \cdot ACE_{\text{root}}}{DS_{\text{stop}}}
\]  
(Eq. 26)

Shoot growth rate is then obtained as

\[
\frac{dDM_{\text{shoot}}}{dt} = \frac{dDM_{\text{tot}}}{dt} \cdot (1 - AC_{\text{root}})
\]  
(Eq. 27)

DM\(_{\text{shoot}}\) is separated into the dry matter of leaf (DM\(_{\text{leaf}}\)), stem (DM\(_{\text{stem}}\)) and cob (DM\(_{\text{cob}}\)).
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\[ DM_{\text{shoot}} = DM_{\text{leaf}} + DM_{\text{stem}} + DM_{\text{cob}} \]  
(Eq. 28)

Corresponding to Eq. 24, the growth rate of \( DM_{\text{shoot}} \) is the sum of the growth rates of the single organs.

\[ \frac{dDM_{\text{shoot}}}{dt} = \frac{dDM_{\text{leaf}}}{dt} + \frac{dDM_{\text{stem}}}{dt} + \frac{dDM_{\text{cob}}}{dt} \]  
(Eq. 29)

The growth rate of \( DM_{\text{leaf}} \) is calculated as a function of the growth rate of \( DM_{\text{shoot}} \) and the proportion of shoot dry matter growth allocated to the leaves [\(-\)] \( f_{\text{leaf}} \).

\[ \frac{dDM_{\text{leaf}}}{dt} = \frac{dDM_{\text{shoot}}}{dt} \cdot f_{\text{leaf}} \]  
(Eq. 30)

Thereby \( f_{\text{leaf}} \) is calculated by assuming an allometric relation between \( DM_{\text{leaf}} \) and \( (DM_{\text{stem}} + DM_{\text{cob}}) \) (Kage and Stützel, 1999b). This means that the ratio of the relative growth rates of both fractions is constant and results in a linear relation between the natural logarithms of \( DM_{\text{leaf}} \) and \( (DM_{\text{stem}} + DM_{\text{cob}}) \). Parameters \( g [-] \) and \( h [-] \) denote the coefficients of the linear regression.

\[ \ln(\text{DM}_{\text{stem}} + \text{DM}_{\text{cob}}) = g \cdot \ln \text{DM}_{\text{leaf}} + h \]  
(Eq. 31)

After transformation and differentiation of Eq. 31 and considering that leaf growth does not proceed over the entire period of plant development, \( f_{\text{leaf}} \) is computed as follows:

\[ f_{\text{leaf}} = \begin{cases} 
\frac{1}{(1 + e^{h \cdot g \cdot DM_{\text{leaf}}^{g-1}})} & \text{Leaf}_{\text{no}} < \text{TLNO} - \text{No}_{\text{lf_notform}} \\
0 & \text{Leaf}_{\text{no}} \geq \text{TLNO} - \text{No}_{\text{lf_notform}}
\end{cases} \]  
(Eq. 32)

\( \text{Leaf}_{\text{no}} \) is the number of leaves, \( \text{TLNO} \) is the total number of leaves that will eventually appear and \( \text{No}_{\text{lf_notform}} \) is the amount of leaves which will never appear.

As the allocation of dry matter into the leaf is calculated firstly, the cob growth rate is calculated by the proportion [\(-\)] \( f_{\text{cob}} \) of shoot dry matter growth minus leaf growth which is allocated to the cob.

\[ \frac{dDM_{\text{cob}}}{dt} = \frac{d(\text{DM}_{\text{stem}} + \text{DM}_{\text{cob}})}{dt} \cdot f_{\text{cob}} \]  
(Eq. 33)
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\( f_{cob} \) is calculated development dependent by a linear function of \( X_{Stage} \) with the two parameters, \( f_{cob\text{slope}} \) [-] and \( f_{cob0} \) [-].

\[
f_{cob} = \begin{cases} 
    X_{Stage} \cdot f_{cob\text{slope}} + f_{cob0} & |DM_{stem} / DM_{shoot} > f_{stem\text{min}} \\
    \min(X_{Stage} \cdot f_{cob\text{slope}} + f_{cob0}, 1) & |DM_{stem} / DM_{shoot} \leq f_{stem\text{min}}
    \end{cases}
\]

(Eq. 34)

If \( f_{cob} \) becomes > 1, additionally to the partitioning of the remaining shoot dry matter growth into the cob, also a retranslocation of dry matter out of the stem is calculated. This retranslocation stops (\( f_{cob} \) becomes \( \leq 1 \)), if the ratio of \( DM_{stem} \) and \( DM_{shoot} \) gets smaller than the parameter value of \( f_{stem\text{min}} \) [-].

The growth rate of \( DM_{stem} \) is calculated as a resultant of shoot growth rate, \( f_{leaf} \) and \( f_{cob} \).

\[
\frac{dDM_{stem}}{dt} = \frac{dDM_{shoot}}{dt} \cdot (1 - f_{leaf}) \cdot (1 - f_{cob})
\]

(Eq. 35)

The green area index, here \((GAI^*)\) [-], is calculated at first as the sum of the green area indices for leaf \((GAI_{leaf})\) [-] and stem \((GAI_{stem})\) [-]. Consequently, the growth rate of \( GAI^* \) is the sum of the growth rates of \( GAI_{leaf} \) and \( GAI_{stem} \) (equation not provided). The growth rates for \( GAI_{leaf} \) and \( GAI_{stem} \) are calculated as the products of the growth rate of leaf DM and the specific leaf area \([m^2 \; g^{-1}] \) \((SLA_{leaf})\) as well as product of stem growth rate and the specific stem area \([m^2 \; g^{-1}] \) \((SLA_{stem})\), respectively. Both, \( SLA_{leaf} \) and \( SLA_{stem} \) are assumed to be negative exponential functions of \( GAI_{leaf} \) respectively \( GAI_{stem} \) with the parameters \( SLA_{a\text{leaf}} \) \([m^2 \; g^{-1}] \) and \( SLA_{b\text{leaf}} \) [-] as well as \( SLA_{a\text{stem}} \) \([m^2 \; g^{-1}] \) and \( SLA_{b\text{stem}} \) [-] and initiated by the parameters \( SLA_{ini\text{leaf}} \) and \( SLA_{ini\text{stem}} \) \([m^2 \; g^{-1}] \), respectively.

\[
\frac{dGAI_{leaf}}{dt} = \frac{d(SLA_{leaf} \cdot DM_{leaf})}{dt}
\]

(Eq. 36)

\[
\frac{dGAI_{stem}}{dt} = \frac{d(SLA_{stem} \cdot DM_{stem})}{dt}
\]

(Eq. 37)

\[
SLA_{leaf} = \min(SLA_{ini\text{leaf}}, SLA_{a\text{leaf}} \cdot GAI_{leaf}^{-SLA_{b\text{leaf}}})
\]

(Eq. 38)

\[
SLA_{stem} = \min(SLA_{ini\text{stem}}, SLA_{a\text{stem}} \cdot GAI_{stem}^{-SLA_{b\text{stem}}})
\]

(Eq. 39)
After transformation of Eq. 36 and Eq. 38, differentiation of Eq. 38 and insertion of this equation into Eq. 36 leaf area growth is calculated as follows. Thereby the minimisation towards SLA_{ini} was neglected, simply caused by a lack of space. The calculation of leaf dry matter growth was already described by Eq. 30 till Eq. 32: The growth rate of stem area is computed according to Eq. 41 which equals Eq. 40. Thereby the calculation of the growth rate of stem dry matter was already given with Eq. 35.

\[
\frac{d\text{GAI}_{\text{leaf}}}{dt} = (\text{SLA}_{\text{leaf}} \cdot \text{GAI}_{\text{leaf}}^{\text{SLA}_{\text{leaf}} - \text{SLA}_{\text{leaf}}} - \text{SLA}_{\text{leaf}} \cdot \text{SLA}_{\text{leaf}} \cdot \text{GAI}_{\text{leaf}}^{\text{SLA}_{\text{leaf}}}) \cdot \frac{d\text{DM}_{\text{leaf}}}{dt}
\]  
(Eq. 40)

\[
\frac{d\text{GAI}_{\text{stem}}}{dt} = (\text{SLA}_{\text{stem}} \cdot \text{GAI}_{\text{stem}}^{\text{SLA}_{\text{stem}} - \text{SLA}_{\text{stem}}} - \text{SLA}_{\text{stem}} \cdot \text{SLA}_{\text{stem}} \cdot \text{GAI}_{\text{stem}}^{\text{SLA}_{\text{stem}}}) \cdot \frac{d\text{DM}_{\text{stem}}}{dt}
\]  
(Eq. 41)

To account for green area loss caused by senescence, a development driven reduction of GAI*, which represents an intermediate variable, is calculated. The resulting photosynthetic active green area index (GAI) [-] is described by a senescent proportion of GAI* ($f_{\text{Sen}}$ [-]).

\[
\text{GAI} = (1 - f_{\text{Sen}}) \cdot \text{GAI}^*
\]  
(Eq. 42)

$f_{\text{Sen}}$ is described by the two parameters $\text{Sen}_a$ [-] and $\text{Sen}_b$ [-]. It is assumed to be exponential over time and starts with silking.

\[
f_{\text{Sen}} = (X_{\text{Stage}} - 2) \cdot \text{Sen}_a^{\text{Sen}_b}
\]  
(Eq. 43)

Crop height [m] (Cropheight) is a function of the GAI* and a constant crop height factor $f_{\text{cropheight}}$ [m].

\[
\text{Cropheight} = \text{GAI}^* \cdot f_{\text{cropheight}}
\]  
(Eq. 44)
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2.1.6. Rooting depth and root length density

The total root length ($RL_{tot}$) [cm] is a function of $DM_{root}$ and the specific root length (SRL) [cm g$^{-1}$], which is assumed to be constant over time and rooting depth.

$$RL_{tot} = DM_{root} \cdot SRL$$  \hspace{1cm} (Eq. 45)

Root depth growth begins with the beginning of dry matter allocation into the root and stops if either $z_{r_{max}}$ [cm], a site and species dependent parameter, or the end of root dry matter allocation ($DS_{stop}$) is reached. Root depth growth is computed to be linear over the root depth $z_r$ [cm]. It increases temperature dependent and with $k_{z_r}$ [cm (d °C)$^{-1}$] denoting simply a coefficient. $z_r$ is initiated with $z_{r_0}$ [cm], which defines sowing depth.

$$\frac{dz_r}{dt} = k_{z_r} \cdot Teff \quad | \quad z_r \leq z_{r_{max}}$$  \hspace{1cm} (Eq. 46)

The vertical root distribution is calculated according to Kage et al., 2000. Thereby root length density $RLD$ [cm cm$^{-3}$] decreases exponentially with soil depth (z) [cm].

$$RLD = RLD_0 \cdot e^{-kr \cdot z}$$  \hspace{1cm} (Eq. 47)

$kr$ is the fractional decrease in $RLD$ per unit increase of soil depth. Thereby $kr$ is calculated as the negative logarithm of the fit parameter [-] ($k_a$) divided by $z_r$.

$$kr = \frac{-\ln(k_a)}{z_r}$$  \hspace{1cm} (Eq. 48)

$RLD_0$ is the root length density at $z=0$. Thereby $RLD_0$ is calculated from $RL_{tot}$, which is inserted in the transformed Eq.47.

$$RLD_0 = \frac{RL_{tot} \cdot kr}{1 - e^{-kr \cdot z_r}}$$  \hspace{1cm} (Eq. 49)

Root turnover is considered by the duration of root activity (Duration) [d], here $RL_{tot}$ becomes $RL_{toteff}$ [cm], which is the effective total root length. This applies also for $RLD$ which becomes $RLD_{eff}$.
2.2. Experimental data sets

Data sets from three different field experiments have been used for model parameterisation. A short description of each experiment, including environmental conditions, experimental design and crop management is given below. Additionally, a characterisation of the data sets used for model validation is provided in this section.

2.2.1. Data sets from experiment 1

Part of the data were obtained from a multi-factorial (location, crop rotation, nitrogen-amount, nitrogen-form) field experiment. The field trial was conducted at two different sites, Hohenschulen (HS) (54°18'N, 9°58'E) and Karkendamm (KD) (53°55'N, 9°56'E) in Northern Germany, during 2007 and 2008. The sites mainly differed concerning soil types. The soil of HS is sandy loam (Luvisol) with a plant available water-holding capacity of about 166 mm. Main soil texture in KD is sand (Gleyic Podzol) with a plant available water-holding capacity of about 125 mm, assuming an effective rooting depth of 100 cm for both sites. The weather data were recorded directly on the field sites. Gaps within the weather data sets were filled in HS with data from a weather station in approx. 500 m distance, whereas in KD the alternate weather stations were in a distance of at least 15 km to the field site. In general both sites are characterised by annual precipitation of approx. 750 – 800 mm with a uniform allocation over the year and a relatively low mean air temperature of approx. 8.5 °C. For the main growing season 2007 and 2008 main characteristics of weather conditions are given in Tab. 1 for HS and KD, respectively. For a better comparability the main growing season was defined to start with beginning of Mai and end in the end of September. In both years the two sites differ mainly by slightly lower mean temperatures and 1.0 m s⁻¹ higher wind speed for HS during the main growing period. The growing periods of 2007 and 2008 differ by lower mean global radiation (15.0 vs. 16.3 MJ m⁻² d⁻¹ for HS and 14.7 vs. 16.8 MJ m⁻² d⁻¹ for KD), slightly higher mean air temperatures (+ 0.4 °C for HS and + 0.1 °C for KD) and higher sum of precipitation (+ 189 mm for HS and + 299 mm for KD) for 2007. Still in 2007, April was with rainfall values of in total 2 mm for HS and 9 mm for KD very dry. In 2008 a dry period occurred in May with 17 mm HS and 12 mm for KD, respectively.

The experimental design was a randomized block design with four replications for each treatment. Plot size was 12 x 12 m. For the parameterization of the model only data from plots, on which in both years maize was grown, were used. The cultivated hybrid was Ronaldino (S 240, KWS) a mid early variety; with the maturity index (BSA, 2008) and breeder given in brackets. A plant density of 10 plants m⁻² was established; row-spacing was 0.75 m. Sowing was conducted on both sites in both years in the End of April, which is typical for these regions. Crops were harvested at maturity for silage maize production. Harvest dates had been the 5th of October in 2007 and the 9th of October in 2008. Only the data of the
highest nitrogen level (360 kg N ha\(^{-1}\)) were used in our analysis, in order to ensure sufficient N-supply during the vegetation period. Nitrogen fertilizer was applied at two equal rates as calcium ammonium nitrate. First application was given shortly before sowing; second one was given at the three-leave-stage. Otherwise, plants were treated according to local best practice recommendations.

2007 and 2008, seven respectively eight plant samplings were carried out over the whole vegetation period. At each sampling date ten plants were manually harvested for analysing DM\(_{\text{shoot}}\), and the fractions DM\(_{\text{leaf}}\), DM\(_{\text{stem}}\) and later on DM\(_{\text{cob}}\). In addition leaf and stem areas were determined from these samples using the LAI-3100 (LI-COR, Inc., Lincoln, NE). In parallel to destructive samplings but at least fortnightly the parameters crop height, development stage according to the BBCH-Monograph (BBA, 1997) and GAI were measured. Thereby GAI was measured by using two non-destructive methods. For early determination of GAI, pictures have been taken with a standard digital camera. Using a digital image analysis techniques (Böttcher, personal communication), the canopy closure was determined. Out of these canopy closure values the GAI was calculated by a transformation of the Lambert-Beer law. The extinction coefficient (0.515) thereby was estimated by minimization of the difference between the GAI values, measured by LAI-3100 and the GAI values, estimated from the transformed Lambert-Beer law and the canopy closure data. For higher GAI values (GAI>1), GAI was determined using the LAI-2000 (LI-COR LAI-2000 meter; LI-COR, Inc., Lincoln, NE). All LAI-2000 values have been multiplied by a coefficient (1.22), resulting out of a linear regression between LAI-3100 and LAI-2000 values. Additionally, in 2008 number of leaves was directly counted fortnightly on ten plants. For 2007 the number of leaves was calculated from the development stages, confined to the stages of leaf development. Soil water content was measured fortnightly with time domain reflectometry (TDR) technique (Dobson et al., 1985) in 30 cm thick layers down to 120 cm. A soil profile classification was done at three soil pit dugs for both sites. For each soil horizon analyses of soil texture, soil bulk density and of the matrix potential dependent water contents were conducted. Additionally the saturated soil conductivity was determined.

2.2.2. Data sets from experiment 2

For the parameterisation of root depth growth and distribution of root length density a data set collected in 1987 and 1988 was used. In order to investigate cultivar specific differences of maize in the exploitation of soil nitrate a field experiment had been conducted by Wiesler and Horst, 1994 on the Agricultural Experimental Station of the University of Hohenheim (HO) (48°42’N, 9°11’E). Soil texture is clayey silt and the soil type is classified as a Gleyic Luvisol. The effective rooting zone was assumed to be 120 cm depth with a plant available soil water capacity of 153 mm. The main characteristics of weather conditions during the
main growing season of 1987 and 1988 are given in Table 1. The mean temperatures for the experimental years in this period had been 15.4 and 16.2 °C in 1987 and 1988, respectively. The mean precipitation in these periods was 502 mm in 1987 and 447 mm in 1988. Saturation deficits of 5.8 and 7.1 mbar in 1987 and 1988 respectively had been quite high compared to HS or KD.

The experimental design was a randomised block design with four replicates and a plot size of 6 m x 10.5 m. Crop management was comparable to experiment 1, except of N rates, which amounted to 238 kg N ha\(^{-1}\) in 1987 and 265 kg N ha\(^{-1}\) in 1988. Three maize cultivars of differing maturity groups were selected from this experiment for model parameterisation: Alize (S 180, Dynamais) an early cultivar, Brummi (S 240, I.N.R.A.) and Dent (NA (mid late), NA) (BSA, 1988). Sowing took place in the beginning of May and harvesting in the beginning of October, in both years.

Main crop characteristics, which had been determined, included development stages, DM\(_{\text{shoot}}\) and RLD in different soil layers. In 1987 samplings for analysing RLD had been conducted at the beginning of stem elongation, at silking, and at milky / dough stage. DM\(_{\text{shoot}}\) was measured at the beginning of stem elongation, at silking, and at silage maturity. In 1988 root samples have been taken at silking, whereas DM\(_{\text{shoot}}\) was determined at silking and maturity. For determination of DM\(_{\text{shoot}}\) in general 3 m\(^{-2}\) but for the sampling at maturity 18 m\(^{-2}\) had been harvested. To study root growth, vertical soil cores (h = 30 cm, d = 10 cm) were extracted to a depth of 150 cm. RL was determined by the line intersect method (Tennant, 1975). \(z_r\) had not been explicit determined in this experiment but was derived from the sampling depths of RLD. Data concerning soil properties including soil classification, soil bulk density and matrix potential dependant water content were available. For further details towards this experiment see Wiesler and Horst, 1994, experiment A.

2.2.3. Data sets from experiment 3

Within a study on yield and quality aspects of biomass for energy production (Schittenhelm, 2008), conducted by the Federal Research Centre for Cultivated Plants (JKI), an irrigation field trial with maize cultivars of differing maturity groups was carried out near Braunschweig (BS) (52°17’N, 10°26’E) during 2005 to 2007. The soil on this site is a loamy sand, classified as a Haplic Luvisol. Plant available water holding capacity is estimated to be 110 mm, considering an effective rooting depth of 60 cm. Precipitation during the main growing season was with 290 mm and 275 mm comparably low in 2005 and 2006, while it was comparably high in 2007 (573 mm), as shown in Tab. 1. The mean temperature during May till September was 15.9 °C in 2005, 17.5 and 16.3 °C in 2006 and 2007. Thereby the year 2006 can be characterised as very dry and warm and 2007 as quiet wet.
Three maize cultivars were tested under two different water supply levels: Flavi a mid early hybrid (S250, Caussade), the mid late PR36K67 (S 350, Pioneer), and Mikado (ca. S500, KWS), which is a late hybrid representing a prototype for energy maize, although it is not adapted to the cool Northern German climate. Irrigation was done by drip irrigation with pressure compensated drip lines and a dripper distance of 30 cm. The two water supply levels were defined as a ‘rain fed’ and an ‘irrigated’ treatment. The rain fed treatment was occasionally irrigated in 2006 in order to prevent total crop failure. The irrigated treatment was irrigated in order to assure a plant available soil water >50 % of the plant available water holding capacity. The amount of irrigation differed widely between the years: 145 mm in 2005, 184 mm in 2006, 50 mm in 2007 for the irrigated treatments and 31 mm in 2005, 41 mm in 2006 and 0 mm in 2007 for the rain fed treatments.

The experiment was conducted in a split-plot-design with four replications. The plots consisted of eight rows of 20 m length, with a row spacing of 0.75 m. Plant density was 10 plants m$^{-2}$. Nitrogen fertiliser was applied at a single rate of 180 kg N ha$^{-1}$ as calcium ammonium nitrate directly before sowing. In 2005 sowing took place in the end of April, 2006 and 2007 in the beginning of May for all cultivars. In 2005 all cultivars were harvested at October 25th, which is a relatively late harvest date for this region. In 2006 and 2007 harvesting was conducted cultivar specific according to the maturity group with the aim to harvest at silage maturity. In 2006 the mid early hybrid Flavi was harvest at September 26th whereas the late hybrid Mikado was harvest at the 10th of October. In 2007 harvest date for Flavi had been the 9th and for Mikado the 22th of October.

In 2005 six manual samplings starting at silking had been conducted for determining DM$_{shoot}$ and crop height. In 2006 and 2007 DM$_{shoot}$ was only analysed at final harvest. Additionally to manual samplings, GAI was determined over the whole vegetation period using the SunScan canopy analysing system (Delta-T Devices, Cambridge). In 2005 GAI measurements were done in approximately weekly intervalls, while in 2006 and 2007 measurements have been conducted at least fortnightly. Main development stages, like emergence or silking had been recorded in terms of BBCH. Soil water content was measured in the upper 60 cm at least once a week using ML2x Probes (Delta-T Services, Cambridge). Data about soil classification, soil texture, soil bulk density had been available for that specific site. Data concerning the pF curves were taken from another study, conducted in approx. 1 km distance to the experimental site.
Tab. 1: Weather conditions of each experimental year provided for the different experimental sites. Average air temperature, wind speed and saturation deficit values as well as sum of global radiation and precipitation are given for the main growing season of maize, from beginning of May till end of September. NA assigns data which were not available.

<table>
<thead>
<tr>
<th>Number of</th>
<th>Site</th>
<th>Year</th>
<th>Air temperature [°C]</th>
<th>Global radiation [MJ m(^2)]</th>
<th>Precipitation [mm]</th>
<th>Wind speed [m s(^{-1})]</th>
<th>Saturation deficit [mbar]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>HS</td>
<td>2007</td>
<td>15.3</td>
<td>2297</td>
<td>493</td>
<td>2.5</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2008</td>
<td>14.9</td>
<td>2488</td>
<td>304</td>
<td>2.5</td>
<td>4.1</td>
</tr>
<tr>
<td></td>
<td>KD</td>
<td>2007</td>
<td>15.6</td>
<td>2255</td>
<td>519</td>
<td>1.5</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2008</td>
<td>15.5</td>
<td>2581</td>
<td>299</td>
<td>1.5</td>
<td>4.3</td>
</tr>
<tr>
<td>2</td>
<td>HO</td>
<td>1987</td>
<td>15.4</td>
<td>2180</td>
<td>502</td>
<td>NA</td>
<td>5.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1988</td>
<td>16.2</td>
<td>2436</td>
<td>447</td>
<td>NA</td>
<td>7.1</td>
</tr>
<tr>
<td>3</td>
<td>BS</td>
<td>2005</td>
<td>15.9</td>
<td>2525</td>
<td>290</td>
<td>0.9</td>
<td>5.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2006</td>
<td>17.5</td>
<td>2699</td>
<td>275</td>
<td>0.9</td>
<td>6.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2007</td>
<td>16.3</td>
<td>2409</td>
<td>573</td>
<td>0.9</td>
<td>4.9</td>
</tr>
</tbody>
</table>

2.2.4. Data set for model validation

For validation purposes data sets from three different sites were used. The field experiments were conducted in order to test cultivars’ maturation behaviour under different environmental conditions and were coordinated by the German Committee of maize (DMK). The main criteria for selecting data sets of these three sites for model validation were the representativeness of the sites for different German environmental conditions of silage maize cropping.

The field trials took place in Paulinenaue (PA), Kleve (KL) and Steinach (ST) during the years 2001 to 2003. PA is located in the North-East of Germany (52°47’N, 12°42’E) and the soil type at this site is sand. Location of KL is in the Mid-West of Germany (51°47’N, 06°07’E); soil type is sandy loam. ST represents the South-East of Germany (50°25’N, 11°09’E) and soil texture of this site is classified as sandy loam. PA has an average annual precipitation of approx. 550 mm and therefore PA is regarded as a ‘dry location’, especially compared to KL and ST (approx. 880 mm and 800 mm, respectively). However, annual precipitation of KL and ST is quite high compared to the German average. ST is the coldest site with an annual mean air temperature of approx. 8.7 °C, whereas KL is characterised by a generally slow soil warming in spring. Analysing the weather conditions during the main growing seasons (May to September) for the given site year combinations (Tab. 2), shows that the sum of precipitation was lowest at PA, at least in 2001 and 2002 (248 mm and 293 mm). For KL and ST experimental year 2003 had the driest main growing season with precipitation sums of 262 mm and 249 mm. Saturation deficits were highest in 2003 for all sites. The main growing season of 2002 showed for all sites the lowest global radiation sum.

Weather data were recorded in a distance of approx. 40 km to the field site of PA, except for precipitation in all years and for air temperature in 2002 and 2003, which were directly recorded at the field site. In KL precipitation and air temperature were measured also directly
at the field site, remaining data were recorded in a distance of 5 km. All weather data for ST were collected directly at the field site.

The experimental design was a block design with two replications for each treatment. Plot size was 60 m², but the format of the plots was different from site to site, with a minimum of 4 rows being cultivated per plot. Six different silage maize hybrids were cultivated during the three years at all sites. Arsenal (S 210, Monsanto), Oldham (S 220, Syngenta Seeds) and Symphony (S 220, Limagrain Netherlands) are early varieties, Probat (S 230, Pflanzenzucht Oberlimburg), Attribut (S 240, NORDSAAT) and Fuego (S 250, KWS) are mid early varieties; with the maturity index (BSA, 2002) and breeder given in brackets. The established plant densities were chosen site specific and ranged from 7-8 plants m⁻² in PA, 9-11 plants m⁻² in KL to 10-12 plants m⁻² in ST; row-spacing was always 0.75 m. Sowing and harvest dates did not differ between cultivars at a given site, but between sites and years. Nitrogen level was 150 kg N ha⁻¹ and was applied as mineral N-fertiliser. Crop management was conducted according to the German best practice recommendations in order to achieve no effects by nutrition deficits or any pests and diseases.

Depending on site year combinations between 5 and 9 plant samplings were carried out during the vegetation period. Sampling generally began in June, but ST 2001 was starting in July and ST 2003 in August. Plants were harvested manually. At each sampling date DM_{shoot}, whole crop dry matter content and DM_{cob} was measured. Additionally, crop development was determined for main steps of development (emergence and silking).

Tab. 2: Weather conditions of each experimental year provided for the different experimental sites. Averaged air temperature and saturation deficit values as well as sum of global radiation and precipitation are given for the main growing season of maize, from beginning of May till end of September.

<table>
<thead>
<tr>
<th>Site</th>
<th>Year</th>
<th>Air temperature [°C]</th>
<th>Global radiation [MJ m⁻²]</th>
<th>Precipitation [mm]</th>
<th>Saturation deficit [mbar]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA</td>
<td>2001</td>
<td>16.0</td>
<td>2516</td>
<td>248</td>
<td>5.7</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>17.1</td>
<td>2414</td>
<td>293</td>
<td>5.3</td>
</tr>
<tr>
<td></td>
<td>2003</td>
<td>17.9</td>
<td>2713</td>
<td>290</td>
<td>8.0</td>
</tr>
<tr>
<td>KL</td>
<td>2001</td>
<td>16.6</td>
<td>2558</td>
<td>325</td>
<td>6.6</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>16.4</td>
<td>2383</td>
<td>396</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td>2003</td>
<td>17.7</td>
<td>2682</td>
<td>262</td>
<td>6.9</td>
</tr>
<tr>
<td>ST</td>
<td>2001</td>
<td>15.4</td>
<td>2757</td>
<td>483</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>16.1</td>
<td>2326</td>
<td>425</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>2003</td>
<td>18.0</td>
<td>3080</td>
<td>249</td>
<td>7.4</td>
</tr>
</tbody>
</table>

2.3. Model parameterisation and sensitivity analyses

Three different approaches for quantifying parameters have been used in this study. The first one was the parameter value acquisition from literature and in very few cases by setting parameter values, deduced from general considerations (Meth 1). The second one was parameter estimation mainly by regression analysis from data sets (Meth 2), using Microsoft
Office Excel 2003 © and the SAS statistical package. The third method was a model parameter optimisation method (Meth 3) implemented within the simulation environment HUME, based on the Levenberg-Marquard-Algorithm. The algorithm is supposed to be comparably robust and effective for non-linear parameter estimation (Kuhlmann, 1980) and allows for a simultaneous optimisation of several parameters. The abbreviations (see brackets above) to denote the method of parameterisation are given for each parameter in Tab 5.

Data sets from field experiment 1 mainly have been used for parameterisation of parameters concerning dry matter production and partitioning, as well as the parameters quantifying maize development, which were assumed not to be cultivar specific (e.g. phy, pla). The parameterisation of parameters relevant for computing rooting depth and distribution of root length density was based on the data set from experiment 2. Only parameter $\psi_{\text{crit}}$ [hPa], which is the critical soil water tension for water uptake by plant in case of water limitation, was optimised with data from the irrigation trial, experiment 3. Because most of the soil water parameters are site specific and the crop development parameters have been mainly estimated cultivar specific all data sets have been involved in these parameterisations.

As the interactions of modelled processes can influence the values of parameters, the order of parameterisation does affect model accuracy. Therefore the sequence of parameterisation is denoted in Tab. 5 by numbers (No) and is used in section 3.1 to guide through the single steps of parameterisation. The main order of parameterisation was (1) parameters of maize development, (2) parameters for dry matter partitioning, leaf expansion and root distribution, (3) parameters describing soil properties, (4) parameters for soil water balance including parameters for calculating potential evapotranspiration, but excluding $\psi_{\text{crit}}$, (5) parameters for dry matter production, including $\psi_{\text{crit}}$.

In order to obtain a robust parameterisation by minimisation of feedbacks between processes, fitted growth curves were used instead of mechanistic sub-models during some steps of parameter optimisation (Meth 3). For $\text{DM}_{\text{shoot}}$ data of experiments 1 and 2 expo-linear curve fits were used. These expo-linear functions were fitted using data from the early and linear growth phase. SLA parameters were optimised using $\text{DM}_{\text{shoot}}$ fits of experiment 1. Parameters for calculating rooting depth and distribution of RLD were also optimised using curve fits for $\text{DM}_{\text{shoot}}$ from experiment 2. Additionally, for optimisation of root parameters a strongly simplified model, without calculation of soil water balance, was used. To the GAI data of experiment 1 and 3 logistic growth curves were fitted, for which, additionally, a decay phase was added. Equation 50 provides a general formulation of this logistic growth including a decay phase, which is mainly temperature driven. For temperature sum below a critical value (TSUM$_{\text{crit}}$), change in $Y$ is the product of the actual value of $Y$, its relative growth rate (rgr), Teff, and the remaining proportion of $Y$ to reach its maximum value ($Y_{\text{max}}$). Thereby
TSUM\textsubscript{crit} is defined as the temperature sum at which Y becomes 99% of Y\textsubscript{max}. For temperature sum exceeding TSUM\textsubscript{crit} the change of Y is calculated by the product of –b, which is simply a curve parameter, Teff, the actual value of Y and the difference between Y\textsubscript{max} and Y.

\[
\frac{dY}{dt} = \begin{cases} 
Y \cdot \text{rgr} \cdot \text{Teff} \cdot \left(1 - \frac{Y}{Y_{\text{max}}}\right) & |\text{TSUM} < \text{TSUM}_{\text{crit}} \\
-b \cdot \text{Teff} \cdot Y \cdot (Y_{\text{max}} - Y) & |\text{TSUM} \geq \text{TSUM}_{\text{crit}}
\end{cases}
\]  
(Eq. 50)

CompF and LUE were parameterised with GAI fits for data of experiment 1, \(p_{\text{Sicr}}\) with curve fits for GAI data of experiment 3. Parameters were optimised on data of relevant time spans only. In the following text three different terms, describing different degrees of model simplifications used for parameterisation will be used. First one, ‘fixed DM\textsubscript{shoot}’, includes the parameterisation by curve fits for DM\textsubscript{shoot} or by parameter estimation directly from data sets (Meth 2). Second one, ‘fitted GAI’, means the use of curve fits for GAI to avoid interactions between dry matter production and green area expansion. The third one (‘complete model’) is not a simplification; it is just the complete mechanistic model version.

For parameters T\textsubscript{1}, T\textsubscript{2}, LUE, SLA\textsubscript{leaf} and ACE\textsubscript{root} sensitivity analyses were conducted in order to investigate the robustness of the parameterisation mainly with respect to DM\textsubscript{shoot}. Therefore, weather data of 35 years (1970 – 2004) from a site located approx. 10 km in the North-East direction of HS (experiment 1) were used. Certainly, the values of all non specific model parameter, which were not varied by a sensitivity analyses, were set according to the results of the parameterisation (see Tab. 5). Site specific parameters were adopted from HS (see Tab. 4). The used cultivar specific parameters were those given in Tab. 3 for Ronaldinio. For these sensitivity analyses only one parameter by time was varied. T\textsubscript{1} was varied in a range from 4 – 8 °C in 1 °C steps. The variation of T\textsubscript{1} was only conducted for the crop growth, not for the crop development processes. As T\textsubscript{1} is used in our model normally for both, crop development and crop growth processes, the implementation of an auxiliary parameter was necessary for conducting this sensitivity analysis. T\textsubscript{2} was also varied in 1 °C steps in a range from 14 – 18 °C. The variation of the LUE parameter was done in 10% steps, ranging from 2.215 – 5.316 g MJ PAR\textsuperscript{-1}. SLA\textsubscript{leaf}, which applies for the level of the SLA\textsubscript{leaf} function over GAI, was varied in a range between 0.01298 till 0.03298 in 0.005 wide steps. The variation of ACE\textsubscript{root} was done in irregular steps resulting in the following values: 0.35, 0.5, 0.6, 0.68 and 0.74. For ACE\textsubscript{root} not only the influence on DM\textsubscript{shoot}, but also on DM\textsubscript{tot} and DM\textsubscript{root} was tested.
In order to test the sensitivity of the model for cultivar specificity concerning maturity groups, the influence of the two cultivar specific parameters \( \text{GDD}_{\text{silk}} \) and \( \text{GDD}_{\text{total}} \) on dry matter production (\( \text{DM}_{\text{tot}} \)) and on dry matter partitioning (\( \text{DM}_{\text{shoot}} \) and \( \text{DM}_{\text{root}} \)) was also tested by a sensitivity analysis. Therefore, weather data from 2005 BS (experiment 3) and the site specific parameterisation of BS (see Tab. 4) were used. The sensitivity analysis was conducted for the irrigated as well as for the rain fed treatments. \( \text{GDD}_{\text{emer}} \) was set to a constant value of 100 °C d, while \( \text{GDD}_{\text{silk}} \) was varied in 50 °C d steps in a range from 650 – 1200 °C and \( \text{GDD}_{\text{total}} \) was varied simultaneously in a fixed ratio between \( \text{GDD}_{\text{total}} \) to \( \text{GDD}_{\text{silk}} \), resulting from the cultivar specific parameterisation from experiment 3 (see section 3.1 paragraph 1.2). To assure that the crop will be harvested in autumn, even if the temperature sum does not reach \( \text{GDD}_{\text{total}} \) a slight model adaptation was necessary. The parameter \( \text{harvestdate}_{\text{latest}} \) was implemented in the model to allow for a harvest if \( \text{GDD}_{\text{total}} \) is not achieved.

2.4. Statistics

Because a single statistical criterion may be insufficient for evaluating model accuracy against the parameterisation data sets, coefficient of correlation (\( r^2 \)) as well as slope and intercept including their standard errors (SE) of the linear regression (\( y = a + bx \)) between the measured and simulated results, root mean square error (RMSE), coefficient of determination (CD), and modelling efficiency (EF) are provided. RMSE is expressed in the unit of the observed variable or state variable. Low RMSE values indicate high absolute degree of precision of the estimated values. CD values serve as a measure of how much of the variance of the measured data can be explained by the model. CD is scaled from 0 with no upper limit, whereas 1 means no differences from measured to estimated values. EF reflects the quality of the simulation compared to the data points, especially in the temporal course. The values range from \(-\infty \) to 1, higher values indicating better model performance (Loague and Green, 1991). These measures had been calculated for evaluating the performance of the complete model version. The calculations had been conducted for \( \text{DM}_{\text{shoot}} \), \( \text{DM}_{\text{leaf}} \), \( \text{DM}_{\text{stem}} \), \( \text{DM}_{\text{cob}} \), \( \text{SLA}_{\text{leaf}} \), \( \text{SLA}_{\text{stem}} \), GAI and crop height over the whole data set of experiment 1, and for the soil water content in the soil layer 0 – 60 cm over the whole data set and separated between years of experiment 3. Additionally, 1:1-plots (measured vs. simulated values) of the water content in the soil layer 0 – 60 cm and of the \( \text{DM}_{\text{shoot}} \) separated between ‘irrigated’ and ‘rain fed’ and between cultivars (experiment 3) are given.

To discuss the progress of model parameterisation in detail a comparison between the different simplifications (‘fixed \( \text{DM}_{\text{shoot}} \)’, ‘fitted GAI’ and ‘complete model’) used for parameterisation was done. Therefore the relative root mean square error (\( \text{rRMSE} \)) was calculated for the different crop variables and state variables. This measure allows the
comparison of the goodness of model accuracy among different variables and state variables.

\[ rRMSE = \frac{RMSE}{\bar{x}} \]  

(Eq. 51)

where \( \bar{x} \) is the mean of the measured data.

To characterise the predictive force of the model against the validation data set, also \( r^2 \) as well as slope and intercept including their SEs, RMSE, CD and EF were calculated for the plant parameters \( \text{DM}_{\text{shoot}} \) and \( \text{DM}_{\text{cob}} \). 1:1 plots (measured vs. simulated \( \text{DM}_{\text{shoot}} \)) are provided, assigning cultivars, sites and years separately, for analysing model predictive force towards these factors as well as to exclude possible systematically model errors, which would be a critical fact for conducting the simulation study.

3. Results

3.1. Results of parameterisation and sensitivity analyses

The parameterisation approach and the resulting parameter values are described in detail in this section. To provide a better overview, the numbers of sequence, comparable to Tab. 5, are given in the beginning of each paragraph. Tab. 3, 4 and 5 provide values for all parameters used in the model. Tab. 3 shows values of cultivar specific parameters, while Tab. 4 provides values of site specific, and Tab. 5 focuses on values of unspecific parameters, respectively. For a better understanding of model robustness the results of the sensitivity analyses are given here for some main parameters too. Additionally, the site and cultivar specific parameter values for the validation data set are given in Tab. 3 and 4.

1.1. \( T_1 \) is the base temperature for all temperature dependent development and growth processes. So, it is the first parameter to be parameterised. Following the idea of cultivar adaptation to colder North Western European climate conditions and according to some literature references, \( T_1 \) was set to this value of 6 °C. Verheul et al., 1996; Brisson et al., 1998 and Bonhomme et al., 1994 estimated a base temperature of 6 °C for plant development processes of maize. Andrade et al., 1993 found a LUE of 0 g MJ PAR\(^{-1} \) at a temperature of 6.7 °C and Pages and Pellerin, 1994 assumed a base temperature of 6 °C for processes of root growth.

1.2. Timing of whole crop growth and growth of the different organs is driven by plant development. Our maize development algorithms are mainly based on the HYBRID-Maize model (Yang et al., 2004b). Since, however, we used a different base temperature, values of
thermal time dependent parameters ($GDD_{S3}$) had to be modified. A new value for the parameter $phy$ was estimated from the linear regression between leaf number and temperature sum, using the data of experiment 1. The parameter $pla$ was derived from $phy$, considering the ratio between phyllochron and plastochron given in HYBRID-Maize. Based on this initial values of $phy$ and $pla$, both parameters were finally optimised by Meth 3 using data of leaf number and especially for $pla$ using the observed maximum number of leaves. It was necessary to use the optimisation method of the HUME framework for this purpose, because the phyllochron is in our model not computed to be constant but increases for the first leaves ($No_{lf\_first}$). Parameter value of $No_{lf\_first}$ was set to 5 according to Yang et al., 2004b.

Values of cultivar specific parameters of plant development ($GDD_{emer}$, $GDD_{silk}$, $GDD_{total}$) were generally calculated as average values over the years by the monitored data of cardinal stages of development and are given in Tab. 3 (Meth 2). Caused by a lack of data, for experiment 2 a cultivar specific estimation of $GDD_{emer}$ and $GDD_{total}$ was not possible. The cultivars PR36K67 and Mikado (experiment 3) often did not reach the target dry matter content of 32%, which indicates silage maturity. Therefore $GDD_{total}$ of both cultivars was calculated by the ratio between $GDD_{silk}$ and $GDD_{total}$ from Flavi, following Yang et al., 2004a, who found a strong correlation between $GDD_{silk}$ and $GDD_{total}$ using data of 107 maize cultivars. In the field trials of the validation data set no cultivar specific sowing or harvesting was conducted, so $GDD_{total}$ was, caused by a lack of data, assumed to be cultivar unspecific. Also no differences of emergence time were observed for the cultivars, so parameter values of $GDD_{emer}$ is equal for the cultivars. $GDD_{silk}$ instead differs between cultivars. A simple variation of the main cultivar specific parameters $GDD_{silk}$ and $GDD_{total}$, by increasing $GDD_{silk}$ in 50 °C d steps and adjusting $GDD_{total}$ via the relation found between $GDD_{total}$ and $GDD_{silk}$ of Flavi (1.95), effects dry matter production and partitioning into root and shoot. The range of $GDD_{silk}$ and $GDD_{total}$ chosen for this sensitivity analysis was done with respect to the cultivars of experiment 3 and to a cultivar range given by the AGPM, 2000. This sensitivity analysis conducted for experiment 3, 2005, irrigated and rain fed (Fig.1) shows that the dry matter production ($DM_{tot}$) increased as long as full maturity for silage maize was reached. As soon as $GDD_{total}$ was no longe achieved due to a too short vegetation period (see $Harvestdate_{latest}$), $DM_{tot}$ but especially $DM_{shoot}$ decreased, whereas $DM_{root}$ increased proportionally to $GDD_{silk}$ and $GDD_{total}$. The reactions of irrigated and rain fed treatments towards increasing $GDD_{silk}$ and $GDD_{total}$ did not differ in general, only the absolute level of the produced dry matter differed.
Tab. 3: Cultivar specific parameter values for $GDD_{\text{emer}}$, $GDD_{\text{silk}}$ and $GDD_{\text{total}}$.

<table>
<thead>
<tr>
<th>Number of experiment / Application</th>
<th>Site</th>
<th>Cultivar</th>
<th>$GDD_{\text{emer}}$ [° C d]</th>
<th>$GDD_{\text{silk}}$ [° C d]</th>
<th>$GDD_{\text{total}}$ [° C d]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>HS, KD</td>
<td>Ronaldino</td>
<td>78</td>
<td>797</td>
<td>1509</td>
</tr>
<tr>
<td>2</td>
<td>HO</td>
<td>Alize</td>
<td>118</td>
<td>734</td>
<td>1520</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Brummi</td>
<td></td>
<td>851</td>
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Fig. 1: Sensitivity analysis concerning the influence of the parameters $GDD_{\text{silk}}$ and $GDD_{\text{total}}$ on $DM_{\text{shoot}}$, $DM_{\text{root}}$ and $DM_{\text{tot}}$ and on the amount of days needed till harvest. Harvestdate was set to 294 d. Given $DM_{\text{shoot}}$, $DM_{\text{root}}$ and $DM_{\text{tot}}$ are final values at harvest date. Model parameterisations and calculations were conducted according to BS 2005, irrigated and rain fed treatments. Different symbol shapes represent different dry matter fractions. Closed symbols represent irrigated, open symbols rain fed treatments. Dashed line represents the amount of days needed till harvesting.
2. In a next step parameterisation of dry matter partitioning was conducted. To avoid any feedback reactions towards $D_{M_{\text{tot}}}$, the methods and the range of parameterisation was chosen conscientiously.

2.1. The concept of dry matter allocation into the roots was adopted from HYBRID-Maize (Yang et al., 2004b). Also the parameter value of $D_{S_{\text{stop}}}$ (1.15), which indicates a stop of dry matter allocation into the root short after silking, was taken from HYBRID-Maize, whereas the parameter value of $ACE_{\text{root}}$ was assumed to be higher compared to the 0.35 used in HYBRID-Maize (see Tab. 5). This was done because otherwise the model overestimated the early $D_{M_{\text{shoot}}}$ values.

Variation of parameter $ACE_{\text{root}}$ led to effects on $D_{M_{\text{tot}}}$, on $D_{M_{\text{root}}}$ as well on $D_{M_{\text{shoot}}}$. Averaged over 35 years (Fig. 2), $D_{M_{\text{root}}}$ increased with increasing $ACE_{\text{root}}$, but the increase was less pronounced for higher values of $ACE_{\text{root}}$. $D_{M_{\text{tot}}}$, in contrast, decreased with increasing $ACE_{\text{root}}$. This decrease of $D_{M_{\text{tot}}}$ increased with increasing $ACE_{\text{root}}$, whereas $D_{M_{\text{shoot}}}$ decreased nearly linearly with increasing $ACE_{\text{root}}$. Considering the impact of environmental conditions, exemplified by three years (1976 a dry year, 1980 a wet year, and 2003 a high yielding year) showed different $ACE_{\text{root}}$-effects on $D_{M_{\text{shoot}}}$. Generally, $D_{M_{\text{shoot}}}$ decreased in all years with increasing $ACE_{\text{root}}$ but with different intensity. In 1980 and 2003 the decrease of $D_{M_{\text{shoot}}}$ was linear or even became a bit stronger with increasing $ACE_{\text{root}}$. However, in 1976 the decrease of $D_{M_{\text{shoot}}}$ flattened with increasing $ACE_{\text{root}}$. 
Fig. 2: Sensitivity analysis concerning the influence of the parameter $ACE_{\text{root}}$ on $DM_{\text{tot}}$, $DM_{\text{root}}$ and $DM_{\text{shoot}}$. Provided are mean values over 35 years and for $DM_{\text{shoot}}$ additionally results from three exemplary years: 1976, 1980 and 2008. Different symbol shapes represent different dry matter fractions. Closed symbols represent mean values. Open symbols represent single year values. Differentiation between years was done by different characters of dashed lines.

2.2. All parameters involved in dry matter partitioning between the different shoot organs (leaf, stem and cob) were estimated using data of experiment 1 by Meth 2. Allometric parameters were estimated by linear regression between the logarithms of the sum of $DM_{\text{stem}}$ and $DM_{\text{cob}}$ and logarithms of $DM_{\text{leaf}}$ data. For this estimation only data of the leaf growth time span were used. As cob growth is described by a development dependent ratio ($f_{\text{cob}}$) between the increase of $DM_{\text{cob}}$ and the increase of $DM_{\text{cob}}$ and $DM_{\text{stem}}$, parameter estimation was done by a linear regression between $f_{\text{cob}}$ and $X_{\text{Stage}}$ (Fig. 3). Certainly, the use of, dry matter data for this purpose, included the calculation of a dry matter increases from the difference between two sampling dates and aside from that the modelled $X_{\text{Stages}}$ had to be averaged between the particular two sampling dates. Resulting parameter values indicated a starting point of cob growth shortly after tassel initiation ($X_{\text{Stage}} = 2.14$). This parameterisation led to $f_{\text{cob}}$ values $> 1$, which indicates a dry matter translocation from the stem to the cob. This translocation is limited by a minimum $DM_{\text{stem}}$ proportion of $DM_{\text{shoot}}$. This parameter was estimated by deriving the average of this stem proportion at harvest from the dry matter data.
2.3. Parameterisation of the dry matter partitioning procedures was followed by the parameterisation of functional components like GAI, crop height and RLD. For GAI and crop height data out of experiment 1 and for rooting processes data out of experiment 2 were used. Optimisation of the parameters for calculating SLA\textsubscript{leaf} and SLA\textsubscript{stem} was conducted for SLA\textsubscript{leaf} and SLA\textsubscript{stem} respectively for SLA\textsubscript{a}\textsubscript{stem} and SLA\textsubscript{b}\textsubscript{stem} by Meth 3 using calculated SLA-data. For this optimisation expo-linear curves were fitted separately to the observed DM\textsubscript{shoot} data for each year and site combination and derivatives of the obtained functions were used to calculate dry matter growth rates. This procedure avoids feedback loops. For the curve fitting the last two data points of each year site combination were excluded, because beginning senescence processes may have obscured the parameter estimates of the SLA parameters. SLA\textsubscript{ini}\textsubscript{lea} and SLA\textsubscript{ini}\textsubscript{stem}, the parameters which are limiting the negative exponential function to a maximum, had been directly taken out of the data (maximum values). Fig. 4 shows the optimised function and the measured data of SLA\textsubscript{leaf}. A sensitivity analysis was conducted in order to test the influence of SLA\textsubscript{a}\textsubscript{leaf} towards DM\textsubscript{shoot} (Fig. 5). Variation of the parameter SLA\textsubscript{a}\textsubscript{leaf} mainly led to a shifting of the level of SLA\textsubscript{leaf}. Average over 35 years, DM\textsubscript{shoot} first increased with increasing SLA\textsubscript{a}\textsubscript{leaf} and decreased for SLA\textsubscript{a}\textsubscript{leaf} exceeding 0.018. In the high yielding year 2003 similar effects were observed on a higher DM\textsubscript{shoot} level. In the dry year 1976 an increase of SLA\textsubscript{a}\textsubscript{leaf} always led to a decrease in DM\textsubscript{shoot}, whereas in the wet year 1980 an increase of SLA\textsubscript{a}\textsubscript{leaf} led always to an increase in DM\textsubscript{shoot}. 

Fig. 3: \( f_{cob} \), the ratio between the increase of cob and the increase of cob and stem, as a function of XStage, \( f_{cob} = f_{cob\text{slope}} \cdot X\text{Stage} - f_{cob0} \) with \( f_{cob\text{slope}} = 0.508 \pm 0.50 \) and \( f_{cob0} = 1.09 \pm 0.19 \), \( r^2=0.89^{**} \). Different symbols represent different site year combinations of experiment 1.
Fig. 4: SLA_{leaf} as a function of GAI_{leaf}. SLA_{leaf} = \min (SLA_{ini,leaf}, SLA_{a,leaf} \cdot GAI_{leaf}^{-SLA_{bleaf}}) with SLA_{ini,leaf} = 0.0361, SLA_{a,leaf} = 0.02298 (±0.0004) and SLA_{bleaf} = 0.1469 (± 0.0107), r^2=0.84***. Different symbols represent different site year combinations of experiment 1.

Fig. 5: Sensitivity analysis concerning the influence of the parameter SLA_{a,leaf} on DM_{shoot}. Provided are mean values over 35 years and additionally results from three exemplary years: 1976, 1980 and 2008. Closed symbols represent mean values. Open symbols represent single year values. Differentiation between years is done by different characters of dashed lines.
2.4. Senescence parameters were also optimised by Meth 3 using GAI data.

2.5. Parameter $f_{\text{crop height}}$ was estimated as the slope of the linear regression between crop height and GAI (Meth 2) by assuming a zero intercept.

2.6. Meth 3 was mainly used to optimise parameters for root depth and distribution of RLD. As in experiment 2 root dry matter was not determined, but the calculations and parameter values for root DM allocation were mainly taken from literature (see paragraph 2.1.), SRL and the parameter ‘duration’ were estimated using expo-linear curve fits of $DM_{\text{shoot}}$. The parameterisation was conducted while optimising $RL_{\text{tot eff}}$ to $RL_{\text{tot}}$-data. Afterwards, $z_{r0}$ was set to sowing depth and $z_{r max}$ was estimated site specific, taking soil conditions into account (Meth 2). Parameter $k_{zr}$ was optimised using root depth data. The parameter $k_a$ was parameterised while optimizing $RLD_{\text{eff}}$ to RLD-data.

3. The next parameterisation step was done for the parameters describing the site specific soil properties using the available information for each site (Meth 2) and filling data gaps or doing simplifications by using BGR, 2005 and Ad-hoc-AG Boden, 1999 (Meth 1). Parameter values for the Van-Genuchten-parameters considering the Mualem parameterisation ($\alpha$, $\theta_s$, $\theta_r$ and $n$), saturated soil conductivity (KS) and soil textures subdivided in the different soil horizons are given in Tab 4. Van-Genuchten-parameters and saturated conductivity assigned by * are derived from the soil texture according to BGR, 2005. Van-Genuchten-parameters, which are not assigned, were derived by the measured matrix potential dependent water contents using RETC, Version 6.0 (van Genuchten, 1991). Not assigned KS-values were taken directly out of the data sets. Since no calculation of soil water balance was necessary for the parameterisation of rooting parameters, which was done using the data set of experiment 2, for this site (HO) parameter values are not given in Tab 4. For none of the validation sites a decided soil profile classification was available, therefore parameterisation of soil properties was based on the general description of the sites. Texture classes of the soil horizons of one site have not been distinguished.
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4. After parameterization of the soil properties, values were assigned to the remaining parameters involved in the calculations of the soil water balance.

4.1. As a first step the values of parameters involved in calculations of the potential evapotranspiration were estimated. The estimation of parameters concerning crop properties (GAI and crop height) is already described in paragraph 2.3. – 2.5., only rc0 and the extinction coefficient for global radiation had to be determined in this step. For rc0 we used an average from different publications (Sinclair et al., 1975; Irmak et al., 2008; Rochette et al., 1991). The extinction coefficient for global radiation ($k_{glob}$) is calculated as a fixed ratio to the extinction coefficient for PAR radiation ($f_{PAR,glob}$), which was parameterised by Meth 1 according to Green, 1987. The parameterisation of the extinction coefficient for PAR radiation parameters was done by Meth 2 using data sets from experiment 1. Thereby light
extinction coefficient values had been calculated following Dingkuhn et al., 1999 from the GAI data and DIFN data measured by the LAI2000. As in our model the extinction coefficient for PAR radiation was assumed to be GAI dependent, the resulting values were plotted against GAI data and a linear-plateau-function with the parameters $\text{Slope}_{\text{PAR}}$, $0_{\text{PAR}}$ and $\text{GAI}_{\text{critExtPAR}}$ was fitted (Fig. 6).

Fig. 6: $k_{\text{PAR}}$ as a function of GAI, $k_{\text{PAR}} = 0_{\text{PAR}}$ if GAI > $\text{GAI}_{\text{critExtPAR}}$, $k_{\text{PAR}} = \text{Slope}_{\text{PAR}} \cdot (\text{GAI} - \text{GAI}_{\text{critExtPAR}}) + 0_{\text{PAR}}$ if GAI ≤ $\text{GAI}_{\text{critExtPAR}}$ with $0_{\text{PAR}} = 0.654 (±0.002)$, $\text{GAI}_{\text{critExtPAR}} = 1.93 (±0.156)$ and $\text{Slope}_{\text{PAR}} = -0.053 (±0.0095)$, $r^2=0.31^{**}$. Different symbols represent different site year combinations of experiment 1.

4.2. Some of the parameters required for calculating the actual evapotranspiration had been set to values deduced from general considerations. Exemplary, $\text{psi}_{\text{ini}}$ was set to water tension of field capacity, assuming that at model start (beginning of January) soil water content was 100% of plant available soil water. $\text{psi}_0$, was set to water tension at permanent wilting point, while $\text{psi}_{\text{critevap}}$ had been taken from Beese, 1978. For running the following steps of parameterisation, it was also necessary to estimate at least an interim value of $\text{psi}_{\text{crit}}$. However, $\text{psi}_{\text{crit}}$ and the LUE parameter are highly correlated. Therefore, commonly the parameterisation of the LUE should be done using data sets were drought stress could be excluded. As this demand could not be met by the data of the irrigation treatments of experiment 3 (irrigation criteria was >50% of the plant available water holding capacity) and as only final $\text{DM}_{\text{shoot}}$ data were available in this experiment, we decided to use this data set only for parameterisation of $\text{psi}_{\text{crit}}$. The LUE parameterisation was instead conducted using the data set of experiment 1, where $\text{DM}_{\text{shoot}}$ and GAI data were available for the growing
season. Still for the data set of experiment 1 drought stress impact could also not be excluded. So, it was necessary to narrow the range of possible psi\textsubscript{crit} and LUE combinations to a range of possible best model fits towards DM\textsubscript{shoot}. Therefore, the LUE parameter was optimised with varied psi\textsubscript{crit} values and the DM\textsubscript{shoot}, resulting out of these parameter combinations, was determined. The range of psi\textsubscript{crit} (400 – 1000 hPa), in which the model performance towards DM\textsubscript{shoot} was stable, was determined by a change of DM\textsubscript{shoot} RMSE less than 2 g m\textsuperscript{-2}. All psi\textsubscript{crit} and LUE combinations outside this range (psi\textsubscript{crit} = 400 – 1000 hPa) resulted in worse model performances. psi\textsubscript{crit} was set in this step of parameterisation to the interim value of 500 hPa.

In order to calculate not only the actual cumulative amount of water in the whole soil, which is influenced by soil properties, ET\textsubscript{pot} and ET\textsubscript{act}, but also in order to calculate the actual water uptake by plant roots for the single soil layers, the parameterisation of CompF had to be done. This was conducted by Meth 3 using the TDR-data of the different measurement depth from experiment 1. To reduce a feedback of CompF towards GAI a log-decay curve fit for GAI was used.

5. Last main step of parameterisation was done for the parameters concerning dry matter production, including parameters of dry matter initiation, temperature function, light use efficiency and soil water deficit function. Estimation of parameters concerning PAR radiation uptake was already described in paragraph 4.1.

5.1. Parameters for dry matter initiation have been mainly estimated by Meth 2 using data of experiment 1 and by some additional assumptions. DM\textsubscript{seed} was simply set to the weight of sown seeds per square meter. f\textsubscript{hypo} was estimated from an average value of hypocotyl dry matter data for the first sampling date in 2007 for HS and KD. Parameterisation of f\textsubscript{trans} was done by the assumption, that 30 % of the weight of planted seeds is lost during translocation and conversion processes. k\textsubscript{DMini} was fitted using Meth 3 to the DM\textsubscript{shoot} and GAI data available for the first three weeks after emergence, assuming that after this time seed reserves are fully translocated.

5.2. Remaining parameter values for calculating f\_T were taken from Yang et al., 2004b and were modified (- 2°C) for North Western European conditions following the parameterisation of T\textsubscript{1}. Only T\textsubscript{4} was directly taken out of HYBRID-Maize, caused by the assumption that this cardinal temperature is not influenced by a cultivar specific adaptation to North Western European conditions. In Fig. 7 the influence of different parameter values for T\textsubscript{1} and T\textsubscript{2} is shown. As expected, in both cases a separated increase of T\textsubscript{1} or T\textsubscript{2} led to a decrease of DM\textsubscript{shoot}. No year specific reaction could be observed (results not shown). Notably, a 1 °C increase of T\textsubscript{2} has a stronger impact on DM\textsubscript{shoot} than a 1 °C increase of T\textsubscript{1},
Fig. 7: Sensitivity analyses concerning the influence of the parameters $T_1$ and $T_2$ on $D_{\text{M}_{\text{shoot}}}$. Given are mean values over 35 years. $T_1$ and $T_2$ had been varied separately.

5.3. The remaining parameters concerning dry matter production, LUE and $\text{psi}_{\text{crit}}$, which is highly influencing SWDF had been estimated in the very last step of parameterisation. LUE was optimised by Meth 3 based on the $D_{\text{M}_{\text{shoot}}}$ data of experiment 1 and by assuming a log-decay function for GAI in order to avoid feedback reactions towards leaf and stem area expansion. $\text{psi}_{\text{crit}}$ was set to a interim value of 500 hPa, as mentioned in paragraph 4.2. After optimising LUE, $\text{psi}_{\text{crit}}$ was finally parameterised by Meth 3 using the $D_{\text{M}_{\text{shoot}}}$ data from experiment 3 with a log-decay curve fit for GAI. $\text{psi}_{\text{crit}}$ was the only parameter, which had been parameterised by using the data set from experiment 3. The sensitivity analysis towards the influence of the parameter value of LUE on $D_{\text{M}_{\text{shoot}}}$ showed in average over 35 years an increase of $D_{\text{M}_{\text{shoot}}}$ by an increased LUE. Again no year specific reaction could be observed (results not shown).
Fig. 8: Sensitivity analysis concerning the influence of the parameter LUE on $\text{DM}_{\text{shoot}}$. Provided are mean values over 35 years.

Tab. 5: Sequence (No) and method of parameterisation. Values and dimensions itemised for each parameter except of parameters assumed to be cultivar and site specific (see Tab. 3 and 4).

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<th>Value</th>
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<th>Use</th>
<th>Method</th>
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<td>$^\circ\text{C}$</td>
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### Chapter 2

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<td>d</td>
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<td>z&lt;sub&gt;r_max&lt;/sub&gt;</td>
<td>100, 120, 60</td>
<td>cm</td>
<td>Rooting depth and RLD</td>
<td>Meth 2</td>
<td>Experiment 1, Experiment 2, Experiment 3</td>
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<td>See Tab. 4</td>
<td>Soil properties</td>
<td>Meth 1, Meth 2</td>
<td>Experiment 1, 2, 3</td>
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<td>s m⁻¹</td>
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<td>Meth 1</td>
<td>Sinclair et al., 1975; Irmak et al., 2008; Rochette et al., 1991</td>
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<td>f&lt;sub&gt;PAR_glob&lt;/sub&gt;</td>
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<td>-</td>
<td>Potential Evapo-transpiration</td>
<td>Meth 1</td>
<td>Green, 1987</td>
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<td>Slope&lt;sub&gt;PAR&lt;/sub&gt;</td>
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<td>-</td>
<td>Dry matter production, Potential Evapo-</td>
<td>Meth 2</td>
<td>Experiment 1</td>
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### Chapter 2

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<td>hPa</td>
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<td>Soil water balance</td>
<td>Meth 3</td>
<td>Experiment 1</td>
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<td>g m$^{-2}$</td>
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<td>Experiment 1</td>
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<td>Assumption</td>
</tr>
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<td>g m$^{-2}$ d$^{-1}$ °C$^{-1}$</td>
<td>Dry matter initiation</td>
<td>Meth 3</td>
<td>Experiment 1</td>
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<td>°C</td>
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<td>Yang et al., 2004b modified</td>
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<td>Yang et al., 2004b modified</td>
</tr>
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<td>°C</td>
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<td>Yang et al., 2004b</td>
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<td>4.43</td>
<td>g MJ PAR$^{-1}$</td>
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<td>Meth 3</td>
<td>Experiment 1</td>
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<tr>
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<td>439</td>
<td>hPa</td>
<td>Dry matter production</td>
<td>Meth 3</td>
<td>Experiment 3</td>
</tr>
</tbody>
</table>

### 3.2. Model performance

The parameterisation data sets have been used for analysing the accuracy of the model. Therefore the data collected in experiment 1 were used to show the performance of modelled aboveground processes, mainly dry matter production and partitioning (Tab. 6 and Tab. 7). As only $\text{psi}_{\text{crit}}$ was parameterised using the data out of experiment 3 and because this experiment was an irrigation field trial, it is well suited to show model performance concerning soil water processes and drought stress impact on dry matter production (Fig. 9, Tab. 8 and Fig. 10).

To show the progress of parameterisation concerning model performance rRMSE for DM$_{\text{shoot}},$ DM$_{\text{leaf}},$ DM$_{\text{stem}},$ DM$_{\text{cob}},$ SLA$_{\text{leaf}},$ SLA$_{\text{stem}},$ GAI and crop height is provided separately for the different model simplifications (Tab. 6). For the simplification ‘Fixed DM$_{\text{shoot}}’$ rRMSE is additionally provided for the DM$_{\text{shoot}}$ curve fit and for ‘Fitted GAI’ the rRMSE for the GAI curve fit is presented. None of the model simplifications achieved rRMSE values < 10 %, but rRMSE values for fitted DM$_{\text{shoot}}$ and fitted GAI were quite high as indicated by values ranging
between 11 and 13 %, therefore rRMSE values for the ‘Complete model’ were only slightly higher with 0.21 and 0.20 for calculated DM\textsubscript{shoot} and GAI. Model performance for DM\textsubscript{leaf}, DM\textsubscript{stem} and SLA\textsubscript{leaf} did not change among the different simplification stages and the ‘Complete model’. This applied also to DM\textsubscript{cob}, which, however, had a very high rRMSE ≥ 28 %.

Tab. 6: Goodness of model parameterisation, as indicated by rRMSE for selected aboveground variables and state variables calculated for experiment 1. rRMSE is separately given for two different stages of model simplification and for the complete model, according to the approach of parameterization.

<table>
<thead>
<tr>
<th>Variable / state variable</th>
<th>Fixed DM\textsubscript{shoot}</th>
<th>Fitted GAI</th>
<th>Complete model</th>
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<tr>
<td>Fitted DM\textsubscript{shoot}</td>
<td>0.13</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Fitted GAI</td>
<td>-</td>
<td>0.11</td>
<td>-</td>
</tr>
<tr>
<td>DM\textsubscript{shoot}</td>
<td>-</td>
<td>0.20</td>
<td>0.21</td>
</tr>
<tr>
<td>DM\textsubscript{leaf}</td>
<td>0.15</td>
<td>0.16</td>
<td>0.18</td>
</tr>
<tr>
<td>DM\textsubscript{stem}</td>
<td>0.17</td>
<td>0.16</td>
<td>0.17</td>
</tr>
<tr>
<td>DM\textsubscript{cob}</td>
<td>0.28</td>
<td>0.28</td>
<td>0.29</td>
</tr>
<tr>
<td>SLA\textsubscript{leaf}</td>
<td>0.10</td>
<td>0.12</td>
<td>0.14</td>
</tr>
<tr>
<td>SLA\textsubscript{stem}</td>
<td>0.16</td>
<td>0.27</td>
<td>0.29</td>
</tr>
<tr>
<td>GAI</td>
<td>-</td>
<td>-</td>
<td>0.20</td>
</tr>
<tr>
<td>Crop height</td>
<td>-</td>
<td>-</td>
<td>0.22</td>
</tr>
</tbody>
</table>

A detailed overview of the model performance considering the ‘Complete model’ version is given in Tab. 7, again for the variables and state variables presented already in Tab. 6. The achieved $r^2$ for DM\textsubscript{shoot}, DM\textsubscript{leaf} and DM\textsubscript{stem} are satisfactory, with values above 0.94. The satisfactory model fit is confirmed by modelling efficiency (EF), varying between 0.93 and 0.95 for for DM\textsubscript{shoot}, DM\textsubscript{leaf} and DM\textsubscript{stem}. For DM\textsubscript{cob} the model generally shows the lowest agreement between measured and simulated values. It is noticeable that the RMSE of 223 g m\textsuperscript{-2} is higher than the RMSE for DM\textsubscript{shoot}. For both, SLA\textsubscript{leaf} and SLA\textsubscript{stem}, $r^2$ values are < 0.90. Simulation of SLA\textsubscript{leaf} shows with CD = 2.21 a high underestimation of the variance of observed data. Both calculations of GAI and crop height yield an $r^2 = 0.93$. 


Tab. 7: Model performance for different aboveground variables and state variables calculated for experiment 1. Provided statistical parameters are slope, intercept and belonging SEs as well as $r^2$ of the linear regression between the measured and simulated results, RMSE, EF, CD and n.

<table>
<thead>
<tr>
<th>Variable / state variable</th>
<th>Slope (SE)</th>
<th>Intercept (SE)</th>
<th>$r^2$</th>
<th>RMSE</th>
<th>EF</th>
<th>CD</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>DM$_{\text{shoot}}$ [g m$^{-2}$]</td>
<td>1.00 (±0.041)</td>
<td>23 (±49)</td>
<td>0.95</td>
<td>190</td>
<td>0.95</td>
<td>1.05</td>
<td>32</td>
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<tr>
<td>DM$_{\text{leaf}}$ [g m$^{-2}$]</td>
<td>0.92 (±0.043)</td>
<td>8 (±9)</td>
<td>0.94</td>
<td>30</td>
<td>0.93</td>
<td>0.91</td>
<td>32</td>
</tr>
<tr>
<td>DM$_{\text{stem}}$ [g m$^{-2}$]</td>
<td>1.00 (±0.036)</td>
<td>5 (±15)</td>
<td>0.96</td>
<td>57</td>
<td>0.96</td>
<td>1.04</td>
<td>32</td>
</tr>
<tr>
<td>DM$_{\text{cob}}$ [g m$^{-2}$]</td>
<td>0.96 (±0.122)</td>
<td>73 (±105)</td>
<td>0.82</td>
<td>223</td>
<td>0.81</td>
<td>1.13</td>
<td>16</td>
</tr>
<tr>
<td>SLA$_{\text{leaf}}$ [m$^2$ g$^{-1}$]</td>
<td>1.30 (±0.167)</td>
<td>-0.0053 (±0.0035)</td>
<td>0.71</td>
<td>0.0032</td>
<td>0.64</td>
<td>2.21</td>
<td>27</td>
</tr>
<tr>
<td>SLA$_{\text{stem}}$ [m$^2$ g$^{-1}$]</td>
<td>0.87 (±0.068)</td>
<td>0.0002 (±0.0001)</td>
<td>0.87</td>
<td>0.0005</td>
<td>0.85</td>
<td>0.87</td>
<td>27</td>
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<tr>
<td>GAI [-]</td>
<td>0.89 (±0.031)</td>
<td>0.15 (±0.13)</td>
<td>0.93</td>
<td>0.64</td>
<td>0.90</td>
<td>0.83</td>
<td>59</td>
</tr>
<tr>
<td>Crop height [m]</td>
<td>0.87 (±0.042)</td>
<td>0.09 (±0.08)</td>
<td>0.93</td>
<td>0.32</td>
<td>0.89</td>
<td>0.79</td>
<td>32</td>
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</table>

The goodness of model performance concerning soil water contents is presented in Fig. 9 and Tab. 8 exemplarily for experiment 3. In Fig. 9 an example is given (Mikado, 2006) for simulating the time course of soil water contents (0 – 60 cm) for an irrigated and a rain fed treatment. Measured water contents in the irrigated treatment ranged from 0.086 to 0.190 and in the rain fed treatments from 0.065 to 0.184. The simulated minima and maxima values fitted well to the measured ones. For the rain fed treatment the time course of the soil water content was reflected well by the model, whereas for the irrigated treatment the simulated soil water contents decreased, especially in the time span of intensive irrigation, not as much as the measured water contents.
The overall model performance of the soil water content (0-60 cm) (Tab. 8) shows good results concerning slope and intercept. Also a RMSE of 0.025 is acceptable. However, the EF value of 0.54 and CD value of 1.81 indicates large portions of unexplained variation. Dividing the data set of experiment 3 into the different years provides for 2005 and 2006 similar results compared to the consideration of all data. The estimations for 2007 are with an EF and an r² value of 0.30 less good. The model clearly underestimates the variance of water contents in this year (CD = 3.53).
Table 8: Model performance for soil water contents in the soil layer from 0 – 60 cm calculated for all data of experiment 3 and separated into different years, respectively different water supply levels. Provided statistical parameters are slope, intercept and belonging SEs as well as $r^2$ of the linear regression between the measured and simulated results, RMSE, EF, CD and n.

<table>
<thead>
<tr>
<th>Data set (soil water content 0 - 60 cm)</th>
<th>Slope (SE)</th>
<th>Intercept (SE)</th>
<th>$r^2$</th>
<th>RMSE</th>
<th>EF</th>
<th>CD</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS 2005 - 2007</td>
<td>0.99 (±0.037)</td>
<td>0.003 (±0.005)</td>
<td>0.54</td>
<td>0.025</td>
<td>0.54</td>
<td>1.81</td>
<td>639</td>
</tr>
<tr>
<td>BS 2005</td>
<td>1.06 (±0.067)</td>
<td>0.000 (±0.009)</td>
<td>0.61</td>
<td>0.023</td>
<td>0.55</td>
<td>1.67</td>
<td>161</td>
</tr>
<tr>
<td>BS 2006</td>
<td>0.98 (±0.058)</td>
<td>0.003 (±0.008)</td>
<td>0.60</td>
<td>0.027</td>
<td>0.60</td>
<td>1.60</td>
<td>190</td>
</tr>
<tr>
<td>BS 2007</td>
<td>1.03 (±0.093)</td>
<td>-0.003 (±0.015)</td>
<td>0.30</td>
<td>0.027</td>
<td>0.30</td>
<td>3.53</td>
<td>288</td>
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</tbody>
</table>

Model performance (Fig. 10) of DM$_{shoot}$, given for all treatments of experiment 3, shows the overall outcome of the model, especially, because these data only had been used for parameterisation of one parameter ($psi_{crit}$). The slope (0.95) and intercept (90 g m$^{-2}$) are not significantly different from 1 respectively 0. The low $r^2 = 0.58$ results mainly from 4 differing year cultivar-water-treatment combinations. These combinations are Mikado 2005, irrigated as well as rain fed and rain fed Flavi and PR36K67 in 2006 (years are not assigned in Fig. 10). However, no structural problems in simulating either rain fed or irrigated treatments concerning DM$_{shoot}$ could be observed.
3.3. Model validation

The validation data set, an orthogonal data set including \( \text{DM}_{\text{shoot}} \) and \( \text{DM}_{\text{cob}} \) measurements of 6 maize cultivars grown on 3 sites, in 3 years, was used to test the predictive power of the maize growth model. Statistical parameters showed large differences in the predictive power of the model concerning \( \text{DM}_{\text{shoot}} \) and \( \text{DM}_{\text{cob}} \). For \( \text{DM}_{\text{cob}} \) the model yielded insufficient results for all statistical parameters considered. Generally, the model overestimated \( \text{DM}_{\text{cob}} \), as well as its observed variation. Model predictive power for \( \text{DM}_{\text{shoot}} \) was much better as indicated by \( r^2 \) of 0.85, a slope of the 1:1 plot of 0.82 (Fig. 11), and EF and CD values of 0.77. RMSE (324 g m\(^{-2}\)), however, was still high. For a better understanding of these results Fig. 11 provides the 1:1 plot of the simulated and measured \( \text{DM}_{\text{shoot}} \) values, assigned separately for different cultivars (Fig. 11a), sites (Fig. 11b) and years (Fig. 11c), respectively. Fig. 11a showed in general no systematic over- or underestimation of a specific cultivar and the differences between cultivars were generally reflected by the model. The mean relative deviation and associated standard deviation calculated for each cultivar separately (not shown) revealed that all cultivars were overestimated by the model, but the simulation was still within the standard deviations of the measured values.
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![Diagram](image)

(a) Simulated $DM_{\text{shoot}}$ [g m$^{-2}$] vs. measured $DM_{\text{shoot}}$ [g m$^{-2}$] for different samples:
- Arsenal, S210
- Oldham, S220
- Probat, S230
- Symphony, S220
- Attribut, S240
- Fuego, S250

(b) Simulated $DM_{\text{shoot}}$ [g m$^{-2}$] vs. measured $DM_{\text{shoot}}$ [g m$^{-2}$] for different locations:
- Paulinenau
- Kleve
- Steinach
As for cultivars, no general systematic over- or underestimation was observed for sites too (Fig 11b and 11c). For years, some evidence was given, that in 2002 a slightly higher overestimation was detected compared to the other years. Furthermore, the simulation of specific site year combinations, like Steinach 2001, deviated from observed values to a larger extent, by overestimation. Likewise, first and second sampling dates of Kleve 2002 and 2003 were characterised by higher overestimations of DM$_{\text{shoot}}$. However, all over site year combinations were simulated adequately by the model.

### 3.4. Resulting water and radiation use efficiencies (WUE, TUE, LUE)

A simple approach for analysing dry matter production and its restrictions due to limitations of environmental factors is considering the use efficiency of these factors, such as water or radiation. Tab. 9 provides simulated DM$_{\text{shoot}}$, transpiration (cum TI$_{\text{act}}$) and potential transpiration (TI$_{\text{pot}}$) including interception as well as resulting values of water use efficiency (WUE), transpiration use efficiency (TUE) and light use efficiency (LUE) for the two mid early cultivars Ronaldino and Flavi of experiment 1 and 3, respectively. WUE, TUE and LUE are calculated considering the simulated aboveground dry matter (DM$_{\text{shoot}}$) at harvest. WUE is computed by the amount of water transpired by the crop including interception plus the water evaporated by the soil, whereas TUE is obtained...
by the amount of water that was transpired by the crop, including interception. LUE is calculated considering PAR radiation uptake. All values apply for entire years.

For a better comparison between sites, only values for Flavi, a cultivar comparable to Ronaldinio considering the maturity group, are given for experiment 3. This seems reasonable, since no interactions between cultivar and year were detected.

The simulated DM$_{\text{shoot}}$ values ranged between 1835 and 2564 g m$^{-2}$ (see Tab. 9). Generally, all sites achieved, without irrigation, a comparable DM$_{\text{shoot}}$ level. Irrigation (BS) leaded, to higher DM$_{\text{shoot}}$ values, especially in the dryer years 2005 and 2006. Consequently, the ranking of the years concerning DM$_{\text{shoot}}$ differed between irrigated and rain fed treatments in BS. Cum. Tl$_{\text{pot}}$, which can be strongly influenced by the site specific amount of global radiation, wind speed and saturation deficit, ranged between 299 and 440 mm. The most obvious site effect was obtained for KD, characterised by relatively low cum. Tl$_{\text{pot}}$ values, whereas cum. Tl$_{\text{pot}}$ values in HS and BS were on a comparable level (rain fed treatments). Irrigation had again in 2005 and 2006 an impact on cum. Tl$_{\text{pot}}$, with slightly higher cum. Tl$_{\text{pot}}$ values for the irrigated treatments. The simulated cum. Tl$_{\text{act}}$ values ranged on a lower level compared to the cum. Tl$_{\text{pot}}$ values. Cum. Tl$_{\text{act}}$ reacted similar to cum. Tl$_{\text{pot}}$ according to site effects, but it differed more between years and the increase caused by irrigation was stronger. The site effect was also recovered in the resulting TUE values. The TUE values were with $> 8.0$ g L$^{-1}$ very high at KD. HS and BS ranged in between TUE values of 5.7 and 7.1 g L$^{-1}$. Concerning the WUE, HS showed lowest values ($< 5.0$ g L$^{-1}$). All other treatments, including KD, ranged between 5.5 and 5.9 g L$^{-1}$. WUE values were not proportional to the TUE values, for example in 2007 the ratio between TUE and WUE was 1.5 in KD and HS, whereas in BS 2007 it was 1.2. The effect of irrigation on WUE and TUE was dependent of the year. The WUE decreased in 2005 with irrigation, whereas in 2006 and 2007 the WUE stayed constant with irrigation. The TUE decreased in 2005 and 2006, but stayed constant in 2007. For LUE a minimum value of 2.3 g MJ PAR$^{-1}$ and a maximum value of 3.2 g MJ PAR$^{-1}$ was found. In HS and KD the LUE was substantially higher in 2007 compared to 2008. Irrigation in BS leaded to higher LUE values compared to the rain fed treatments, with the highest increase in 2006.
Tab. 9: Simulated $\text{DM}_{\text{shoot}}$, cumulative $\text{TI}_{\text{pot}}$ and $\text{TI}_{\text{act}}$ values and resulting WUE, TUE and LUE for the data sets of experiment 1 and 3. Average values over years and cultivars, but differentiated for sites and water supply levels.

<table>
<thead>
<tr>
<th>Number of experiment</th>
<th>Data set</th>
<th>Cultivar</th>
<th>Irrigation</th>
<th>$\text{DM}_{\text{shoot}}$ [g m$^{-2}$]</th>
<th>cum. $\text{TI}_{\text{pot}}$ [mm]</th>
<th>cum. $\text{TI}_{\text{act}}$ [mm]</th>
<th>WUE [g L$^{-1}$]</th>
<th>TUE [g L$^{-1}$]</th>
<th>LUE [g MJ PAR$^{-1}$]</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>HS 2007</td>
<td>Ronaldino</td>
<td>Rain fed</td>
<td>2513</td>
<td>398</td>
<td>379</td>
<td>4.4</td>
<td>6.6</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>HS 2008</td>
<td></td>
<td></td>
<td>1968</td>
<td>437</td>
<td>342</td>
<td>4.0</td>
<td>5.7</td>
<td>2.4</td>
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<tr>
<td></td>
<td>KD 2007</td>
<td></td>
<td></td>
<td>2506</td>
<td>302</td>
<td>295</td>
<td>5.8</td>
<td>8.5</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>KD 2008</td>
<td></td>
<td></td>
<td>2059</td>
<td>299</td>
<td>257</td>
<td>5.5</td>
<td>8.0</td>
<td>2.5</td>
</tr>
<tr>
<td>3</td>
<td>BS 2005</td>
<td>Flavi</td>
<td>Rain fed</td>
<td>2005</td>
<td>375</td>
<td>274</td>
<td>5.9</td>
<td>7.3</td>
<td>2.5</td>
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<tr>
<td></td>
<td>BS 2006</td>
<td></td>
<td></td>
<td>1853</td>
<td>407</td>
<td>263</td>
<td>5.7</td>
<td>7.0</td>
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<td></td>
<td>BS 2007</td>
<td></td>
<td></td>
<td>2447</td>
<td>386</td>
<td>347</td>
<td>5.7</td>
<td>7.1</td>
<td>3.0</td>
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<tr>
<td></td>
<td>BS 2005</td>
<td></td>
<td>Irrigated</td>
<td>2360</td>
<td>403</td>
<td>339</td>
<td>5.7</td>
<td>7.0</td>
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<td></td>
<td>BS 2006</td>
<td></td>
<td></td>
<td>2515</td>
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<td>369</td>
<td>5.8</td>
<td>6.8</td>
<td>3.1</td>
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<tr>
<td></td>
<td>BS 2007</td>
<td></td>
<td></td>
<td>2564</td>
<td>387</td>
<td>362</td>
<td>5.7</td>
<td>7.1</td>
<td>3.2</td>
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</tbody>
</table>

4. Discussion
The aim of this study was to develop, parameterise and validate a dynamic growth model for silage maize, suitable for North Western European conditions, so considering low temperature regions. The model was supposed to take water limitation on maize yield potential into account and it should be sensitive for cultivar differences, at least concerning thermal time needed till silking and maturity respectively. Furthermore, the model should provide all requirements for conducting scenario analyses. Among others, the model approaches were chosen in order to develop a model, which can be parameterised using commonly available data and therefore, should be applicable at various sites and can be adapted to different cultivars.

The presented maize growth model features some well known modelling approaches. It calculates dry matter production and partitioning, as well as leaf area expansion and vertical root distribution. As the model was developed in a framework of studies concerning biomass production for the use in biogas plants, the primary target was to reliably simulate shoot DM. Therefore, a satisfactory model performance and validation for this variable is necessary. However, dry matter production depends on various processes and is often dynamically affected by different feedbacks. For example, the expansion of leaf area can influence dry matter production and dry matter production as well as the proportional dry matter allocation into $\text{DM}_{\text{leaf}}$ in turn affects leaf area expansion. Therefore, a correct simulation of variables, which are linked in feedbacks to dry matter production, is required. In the first section of the discussion, the focus will be on model performance and validation results especially for $\text{DM}_{\text{shoot}}$. In the following sections some efforts to analyse the presented results in detail, including the sequence of parameterisation and the results of the sensitivity analyses will be given, highlighting model formulations or parameters which involve feedback effects on $\text{DM}_{\text{shoot}}$ or which are influencing dry matter production in a non linear way. At the end of this
chapter the results concerning WUE, TUE and LUE will be discussed, focusing their dimension and variation.

4.1. General model performance and validation

In general the model performance of $\text{DM}_{\text{shoot}}$ is acceptable for all parameterisation data sets (experiment 1 and 3). For experiment 1 the parameters of linear regression between measured and simulated $\text{DM}_{\text{shoot}}$ values and also EF (Tab. 7) neither indicate an over- nor underestimation of $\text{DM}_{\text{shoot}}$. This implicates, that the model is able to adequately reflect the time course of $\text{DM}_{\text{shoot}}$ production for this data sets. However, a RMSE value of 190 g m\(^{-2}\) and a rRMSE value of 0.21 (Tab. 6) for $\text{DM}_{\text{shoot}}$ of experiment 1 might be, depending on the purpose, insufficient. The already relatively high rRMSE value (0.13) yielded by the expo-linear curve fits of the measured $\text{DM}_{\text{shoot}}$ values of the early and linear growth phase, indicates a high deviation from an idealised curve shape. This might mainly be due to a high variability in the measured data (relative mean standard deviation of 0.25). Consequently, this high heterogeneity raises the chance that the averaged $\text{DM}_{\text{shoot}}$ values differ from the expected mean values. Reasons for such variability in the data sets might be various, for example a high heterogeneity in soil patches, which is for example very likely for HS. On the other hand a deviation from an idealised curve shape has not inevitably to be caused by a heterogeneity in the data set, for example limitations on dry matter production, like drought stress, can be the reason too. Both, variability in soil and drought impact on dry matter production have not been taken into account in the ‘fixed $\text{DM}_{\text{shoot}}$’ model simplification. However, the ‘complete model’ version at least includes drought impact on dry matter production. Modelling horizontal soil variability was never aimed to be implemented in the presented model, because the objective of an easy model parameterisation by commonly available data would not be reached. 

The data set of experiment 3 includes three different maize cultivars, grown over three years under two different water regimes on a site, where the climate is supposed to be more continentally influenced compared to the sites of experiment 1. Additionally, these data were only used to parameterise $\text{psi}_{\text{crit}}$. So, the model performance of $\text{DM}_{\text{shoot}}$ calculations concerning experiment 3, gives a first impression of the ability of the model to calculate at least crop growth under different water availabilities and for different sites and cultivars. The yielded slope (0.95) and intercept (90 g m\(^{-2}\)) of linear regression between measured and simulated $\text{DM}_{\text{shoot}}$ values (Fig. 10) is acceptable, in particular since only $\text{DM}_{\text{shoot}}$ values from the final harvest are included. Also an RMSE value of 215 g m\(^{-2}\) seems appropriate at least considering the model performance for data of experiment 1. No systematic over- or underestimation of the two different water regimes concerning $\text{DM}_{\text{shoot}}$ can be identified and rRMSE values of 0.07 and 0.13 for the irrigated and rain fed treatments respectively support
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an acceptable model fit for the dry matter production resulting from different water regimes. Analysing the presented soil water (0 – 60 cm) time course (Fig. 9) shows that the soil water content measured under the rain fed treatment (Mikado, 2006) was simulated satisfactory by the model. For the irrigated treatment the soil water content was overestimated, especially in the main irrigation period. This might be due to an imprecise soil parameterisation. Among others, the soil in BS is characterised by a stony layer in the 50-55 cm horizon, which for several reasons was not easy to model. Possibly, some amounts of water supplied by irrigation (up to 25 mm d\(^{-1}\)) were in reality drained faster to lower soil horizons than calculated by the model.

Concerning cultivar differences Fig. 10 indicates that no systematically over- or underestimation of DM\(_{\text{shoot}}\) occurred. However, the \(r^2\) yielded by the linear regression between measured and simulated DM\(_{\text{shoot}}\) data of experiment 3 is with 0.58 quite low. This is mainly due to 4 differing year cultivar water treatment combinations. These combinations are rain fed Flavi and PR36K67 in 2006 and Mikado rain fed and irrigated in 2005. At least the overestimation of rain fed Flavi and PR36K67 in 2006 can be explained by various environmental impacts in the highly sensitive development stage around silking (Saseendran et al., 2008; Boyer and Westgate, 2004), which is not considered in the current model. Due to higher mean air temperatures the number of days needed for the duration of Xstage 2.8 - Xstage 3.2 was reduced for Flavi (54 %) and PR36K67 (59 %) in 2006 compared to 2005. For Mikado the length of flowering was not reduced, caused by a general later timing of silking attended with lower mean air temperatures. In addition, maximum air temperature for Flavi and PR36K67, averaged between Xstage 2.8 and Xstage 3.2, were very high in 2006 amounting to 32.4 °C respectively 27.6 °C. For Mikado maximum air temperatures only reached 22.5 °C, which is in the range of all other year cultivar combinations (19.9 – 23.4 °C). Moreover, Flavi and PR36K67 received more drought stress in this period than Mikado. However, all factors, shorter duration of flowering, heat stress as well as drought stress in this period, can reduce dry matter yield. A study conducted by Zinselmeier, 1995, for instance, found a brief drought stress between silking and pollination to inhibit ovary dry matter accumulation and to decrease kernel number per ear by 60%. As kernel set is highly affecting sink capacity (Setter et al., 2001), drought stress around flowering can substantially reduce DM\(_{\text{cob}}\) and therefore DM\(_{\text{shoot}}\).

To evaluate the predictive power of the presented model a validation with independent data sets is required. This was conducted with data from 3 different sites and years including 6 different maize cultivars. The linear regression between measured and simulated DM\(_{\text{shoot}}\) values yielded a slope of 0.82, an intercept of 122 g m\(^{-2}\) and a \(r^2\) of 0.85. For totally independent data these results might be acceptable, but the results indicated an average overestimation by the model and a RMSE of 324 g m\(^{-2}\) is comparably high. This might be
caused by different reasons. As no strong systematically deviations concerning cultivars, sites or years are evident, the discussion has to focus on specific site year combinations. For example, KL showed a clear overestimation for the first and second sampling dates in 2002 and 2003. As already mentioned above the soil warming in spring can be quite slow at this site. As our model dose not take into account the effect of soil temperature on seedling emergence, this might be one reason for the low model fit. This explanation can be supported by the fact that in 2002 and 2003 the average amount of days to reach GDD$_{emerg}$ was 50 % higher compared to 2001. Another site year combination, for which the model obviously failed, is ST 2001 (see Fig. 11b and c). By excluding ST 2001 from the validation data set, a clear improvement of statistical parameters concerning DM$_{shoot}$ could be achieved (RMSE 251 g m$^{-2}$, slope 0.88, intercept 79 g m$^{-2}$, $r^2$ 0.88). Identifying reasons for the disagreement concerning ST 2001 seems difficult. In this context it should be mentioned, that a strong decrease in DM$_{shoot}$ for the two last sampling dates was detected. This reduction of biomass could be caused by respiration exceeding assimilate gain by photosynthesis, but the separation between photosynthesis and respiration is not included in a simple LUE based modelling concept (Lizaso et al., 2005b), we used in the current model. However, no noticeable combination of low maximum and high minimum temperatures for the time span of interest was observed. Another reason for the biomass reduction could also be too late chosen harvest dates, which could result in dry matter reduction by e.g. losses of senescent leaves. Indeed yielded dry matter contents at harvest were clearly > 32 %, but this applied for nearly all year cultivar site combination of the validation data set. Therefore this might be an explanation for the overestimation of the DM$_{shoot}$ values of the validation data set in general, but not explicitly for ST 2001. However, most important for further use of the model is, that by this validation it could be demonstrated that the model dose not tend to systematic errors with respect to cultivars, sites or years. Moreover, model performance concerning experiment 3 indicated that different water regimes are reflected satisfactorily by the model.

4.2. Analyses of used model approaches and parameterisations on model quality

In this paragraph an analysis of the influence of used modelling approaches and the sequence of parameterisation on the model quality will be given. Especially the influence of model formulations or parameters, which involve feedback effects on DM$_{shoot}$ or which are influencing dry matter production in a non linear way, will be discussed.
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4.2.1. Development

Plant development is driving plant growth and especially partitioning processes. Therefore, the choice of model approaches and the sequence of parameterisation may substantially influence dry matter production and model fit concerning $\text{DM}_{\text{shoot}}$.

The used model approaches concerning development processes are mainly based on the HYBRID-Maize model (Yang et al., 2004b), with only some minor adaptations. In order to adapt the model to North Western European conditions we made two main modifications. Since low temperatures delay maturation and may hamper achieving physiological maturity within the vegetation period, silage maize instead of grain maize is commonly grown in North Western Europe. Additionally, for biogas production silage maize is the common cropping system. Therefore, a redefinition of maturity (XStage 5) providing maturity for silage maize maturity (early dough stage to dough stage) was done. Apart from that, cultivar adaptations to low temperature had led to a significant lower base temperature for development and growth processes compared to e.g. Northern America, where base temperatures between 8 and 10 °C are discussed (Yang et al., 2004b). In agreement to Verheul et al., 1996; Bonhomme et al., 1994 and Brisson et al., 1998, we chose a base temperature of 6 °C. Changing the base temperature caused adaptations for some temperature dependent parameters. For example the parameter phy valued in 38.9 °Cd HYBRID-Maize, while in our model phy was re-estimated, resulting in a value of 50.3 °Cd.

According to HYBRID-Maize, the environmental impact on plant development is only considered by a temperature dependency. In some cases this might be critical. For example modelling the newly introduced development rate DevRate0 simply as a function of thermal time, can imply serious model errors, because impacts on crop establishment by other factors (e.g. dynamic of soil moisture in the relevant time span or bad soil structure, resulting in infrequent contact between soil and seeds) are not considered. However, needed resolution in space and time for computing these impacts on crop establishment sufficiently, contradict the aim of an easily parameterisable maize growth model.

Maize cultivar differ beside growing and ripening types, mainly considering the duration till maturity, which is classified by maturity groups. A cultivar sensitive model, therefore, has to take into account the differences in maturation time. Following HYBRID-Maize (Yang et al., 2004b), not only GDD$\text{total}$ but also GDD$\text{silk}$ was computed cultivar specific. Additionally, GDD$\text{emer}$ is supposed to be cultivar specific in the presented model. Tab. 3 shows clear differences between the cultivars concerning these 3 parameters. As these parameter values were directly estimated from measured data, their cultivar specificity is approved. Efforts to generalise parameterisation of GDD$\text{silk}$ and GDD$\text{total}$ by finding a robust correlation between maturity groups and GDD$\text{total}$ or GDD$\text{silk}$ failed. Also model simplification by introducing the constant relationship between GDD$\text{total}$ and GDD$\text{silk}$ given by Yang et al., 2004a was not
possible, because of the different definition of XStage 5 and the different base temperature value. Still, we did not introduce a fixed relationship adopted for the North Western European conditions into our model, because, for several reasons, it was not possible to prove its existence. Only for the parameterisation of $GDD_{\text{total}}$ of PR36K67 and Mikado we used this idea of a cultivar unspecific relationship between $GDD_{\text{total}}$ and $GDD_{\text{silk}}$ using the relationship gained from Flavi. Summing up, the approach for including cultivar specificity in our model is totally empirical. However, the availability of data needed for a cultivar specific parameterisation of $GDD_{\text{emerg}}$, $GDD_{\text{silk}}$ and $GDD_{\text{total}}$ should be given, as rating the date of emergence, silking and harvesting is quite common. All other parameters of development are, according to the HYBRID-Maize model, assumed to be cultivar unspecific, this applies also for the phyllochron and the plastochron and their relationship. For the phyllochron cultivar specificity is still discussed in literature. Birch et al. (1998) reported that the phyllochron did not vary greatly among maize cultivars when grown in specific environments. Verheul et al. (1996) instead found cultivar specific differences of the phyllochron ranking between 38.9 and 52.9, taking $T_{\text{1}} = 6 \,^\circ C$ into account. However, the model calculates clear differences between cultivars. For example, concerning mean values of final leaf number (15.34 for Ronaldinio, 16.09 for Flavi, 18.78 for PR36K67 and 20.76 for Mikado) and maximal GAI (5.44 for Ronaldinio, 5.73 for Flavi, 6.83 for PR36K67 and 7.55 for Mikado). Leaf number was only recorded for Ronaldinio, but as these data had been used for parameterisation of phy, the simulated value of 15.35 fitted very well to the measured one. The range of cultivars concerning maximal GAI was found in the mean measured values too. This might give evidence, that the assumption that all other development parameters are cultivar unspecific, is sufficient.

As mentioned before, plant development is driving plant growth and especially partitioning processes. In our model the parameters $GDD_{\text{silk}}$ and $GDD_{\text{total}}$ and the relationship between plastochron and phyllochron are most potential sources to create model errors by a wrong parameterisation. The relation of plastochron and phyllochron influences for example the duration of leaf initiation and of different growth processes. However, this relation is directly transferred from HYBRID-Maize (Yang et al., 2004b), and difficult to measure. $GDD_{\text{total}}$ can have a direct impact on dry matter production by determination of the vegetation duration. $GDD_{\text{total}}$ and $GDD_{\text{silk}}$ affect the duration of vegetative to generative growth and the relation of these main phases of development. The combination of both parameters, also determine in which time span vegetative and generative growth takes place. By temporal shifting of the phases, for example the available amount of global radiation in the vegetative or generative phase can be influenced. Additionally, $GDD_{\text{total}}$ and $GDD_{\text{silk}}$ determine among others the end of leaf growth. $GDD_{\text{silk}}$ is influencing the end of root growth, the beginning of dry matter allocation into the cob and the beginning of senescence. So, the accuracy of further
parameterisation steps, such as parameterisation of partitioning, depends on a reliable fit of GDD_{silk}.

The importance to find reliable values of GDD_{total} and GDD_{silk} for each cultivar and therefore also a justification to stay totally empirical in this terms, was clearly shown by the sensitivity analysis presented in Fig. 1. The proportional increase of GDD_{total} and GDD_{silk} causes an increase of DM_{tot}, DM_{shoot} and DM_{root}, at least as long as the increase of GDD_{total} causes a real increase in vegetation time, so non-restricted by Harvestdate_{latest}. This increase is due to an increase in vegetation duration and therefore due to an increase of the amount of radiation uptake. When Harvestdate_{latest} is reached, vegetation duration does not further increase, and no noticeable change in DM_{tot} was observed, whereas DM_{root} increased and DM_{shoot} decreased. This is due to a direct effect on partitioning, as the increase of GDD_{silk} leads to a proportional extension of the time span of dry matter allocation towards the roots. It is mentionable that the rooting depth is restricted by the parameter zr_{max}, so an increase of GDD_{silk} does not lead automatically to an increase in rooting depth. This could cause an overestimation of drought stress on late cultivars, if zr_{max} is not chosen appropriately. Even though an increase of GDD_{silk} leads also to an increase of the maximum green area, DM_{tot} did not increase further, so this does not lead to an increase in radiation uptake. The critical GAI for PAR radiation uptake seems to be reached already with GDD_{silk} values < 850 °C d.

An effect of senescence, due to a reduction and a temporal shift of the time span between GDD_{silk} and GDD_{total}, which could have led to an increase of DM_{tot} for the late cultivars compared to the mid and earlier cultivars, was also not observed. This might be due to a low impact of senescence on the leaf area, caused by low effects of senescence on the GAI values measured in the parameterisation data set (experiment 1). A different reaction of the drought stress treatment compared to the irrigated treatment on DM_{tot}, DM_{shoot} or DM_{root}, caused by varying GDD_{silk} and GDD_{total}, was not observed. However, the results of the sensitivity analysis indicate clearly the importance of the site adapted choice of maize cultivars.

4.2.2. Dry matter partitioning

The way to partition total dry matter into different organs of the crop follows different approaches in the presented model. Dry matter allocation to root follows the concept of HYBRID-Maize (Yang et al., 2004b), which adopted the idea from Kropff and van Laar, 1993. The most important change we made is the parameter value for ACE_{root}, which is set to 0.68 vs. 0.35 in HYBRID-Maize. The stop of dry matter allocation into the root short after silking is not only reported by Kropff and van Laar, 1993 but by Wiesler, 1994, who conducted experiment 2.
The sensitivity analysis concerning different values of $ACE_{root}$, showed a clear impact of this parameter on $DM_{tot}$, $DM_{root}$ and $DM_{shoot}$ (Fig. 2). As already mentioned in section 4.2.1 decrease of $DM_{shoot}$, caused by increasing $DM_{root}$, is a direct effect of the partitioning, here due to an increasing $ACE_{root}$. The slight decrease in $DM_{tot}$, which might be observed by an increasing $ACE_{root}$, indicates an indirect effect of reduction of $DM_{leaf}$, the accompanied reduction of GAI under a critical GAI value for PAR radiation uptake. However, $DM_{shoot}$ reacts in average, linearly towards an increase of $ACE_{root}$, so the feedback effect is expected not to be very strong. Still, the comparison of three years, a dry year (1976, 60% $DM_{tot}$ reduction due to drought stress), a wet year (1980, no $DM_{tot}$ reduction due to drought stress) and a high yielding year (2003, < 20% $DM_{tot}$ reduction due to drought stress), showed differences in the reaction. The largest effect was observed in the wet year, where an increase of $ACE_{root}$ led to a faster reduction of $DM_{shoot}$ with increasing $ACE_{root}$. This reduction of $DM_{shoot}$ is probably caused by a reduced radiation uptake. On the contrary, in the dry year an increase of $ACE_{root}$ led to a slight reduction of the decrease in $DM_{shoot}$, possibly due to a slightly higher amount of plant available soil water by more roots. These results indicated that a correct parameterisation of $ACE_{root}$ is quite important because the value of $ACE_{root}$ can have an impact on water or radiation uptake. Therefore, our decision to set $ACE_{root}$ to such a high value might be critical, at least in some years.

Dry matter allocation among different shoot organs were realised using different model approaches. Dry matter partitioning into leaf followed an allometric concept. The general applicability of allometric relationships for biological situations is known since the 1930ies. Kage and Stützel, 1999b demonstrated that this concept is valid for the relation between $DM_{leaf}$ and $DM_{stem}$ of cauliflower and that it is suitable for crop growth modelling. Prasad et al., 1992 tested allometric vs. linear regression models for description of DM partitioning in maize. They found better $r^2$-values for allometric models describing the relationship between $DM_{leaf}$ and $DM_{shoot}$ as well as between $DM_{leaf}$ and $DM_{stem}$ than for linear regression models. The relationship between $DM_{cob}$ and $DM_{shoot}$, however, yielded better $r^2$-values using the linear regression. This result strongly supports our decision to calculate $DM_{leaf}$ and $DM_{stem}$ by an allometric approach and $DM_{cob}$ by a development dependent linear regression.

Yet, for both, parameterisation data set of experiment 1 (Tab. 6 and 7) and validation data set, the obtained results for $DM_{cob}$ were less encouraging compared to leaf and stem. The used approach for calculating $DM_{cob}$ might be too simplistic and the data base for parameterisation obviously was too small. In none of the model versions (simplifications) $rRMSE$ of $DM_{cob}$ is satisfactory (Tab. 8), which indicates, that the variation measured for $DM_{cob}$ might be due to impacts not considered in our model. These impacts may include drought or heat stress around flowering, influencing sink-source relationships and therefore influencing $DM_{cob}$. Suwa et al., 2010 found a reduction in $DM_{cob}$, due to effects on sink
activity, but did not detect an effect on $\text{DM}_{\text{shoot}}$. This indicates that a poor model prediction of $\text{DM}_{\text{cob}}$ does not necessarily cause similar poor model prediction for $\text{DM}_{\text{shoot}}$. However, there is some evidence provided by literature that the estimation of parameters involved in $\text{DM}_{\text{cob}}$ modelling, so mainly the starting time of cob growth ($f_{\text{cob0}}$) and the restriction by $f_{\text{stemmin}}$, seems not to be critical. In our model cob growth starts shortly after tassel initiation at XStage 2.14, which is in accordance to Lejeune and Bernier, 1996. APSIM (Robertson et al., 2009) allows for a total retranslocation of not more than 15 and 20% of the leaf and stem biomass present at the start of grain filling, respectively. So the 26% remaining stem, which is used in our model as translocation restriction, might be right levelled, but the source of retranslocation is different. To neglect a retranslocation of dry matter from leaves can lead to an underestimation of $\text{DM}_{\text{cob}}$ for example in dryer years like 2008 (experiment 1), where leaf senescence was obvious. Considering leaf senescence directly by calculating the amount of dry matter translocated into the cob might reduce model errors concerning $\text{DM}_{\text{cob}}$. Here, available data sets probably were insufficient, as for instance in 2007 (experiment 1), where hardly any senescence was observed. With respect to biogas production, however, the yieldable biomass per ha is the key parameter, and therefore the poor model quality concerning $\text{DM}_{\text{cob}}$ is of less importance. Additionally, in the presented model no feedback reactions between cob and shoot dry matter are computed.

4.2.3. Functional components

The simulated dry matter of the plant organs was used to derive functional components such as GAI and total root length. Total GAI is the sum of GAI$_{\text{leaf}}$ and GAI$_{\text{stem}}$ which are computed following the concept of SLA. In our model SLA for leaf and stem are calculated as a negative exponential function of the corresponding GAI. This is in agreement to APSIM (Robertson et al., 2009), where SLA also declines with increasing GAI, according to the fact, that smaller, younger crops most often have larger and thinner leaves. The simulation of SLA$_{\text{stem}}$ is not satisfactory, as indicated by a rRMSE of 0.29, probably due to an underestimation in the beginning of plant growth. But since GAI$_{\text{stem}}$ is relatively small (8% of the whole GAI), it is less important for a correct calculation of $Q$ or $T_{\text{pot}}$ than GAI$_{\text{leaf}}$. With respect to SLA$_{\text{leaf}}$ the model resulted in much better prediction, as indicated by a rRMSE of 0.14. Additionally, a variation of SLA$_{\text{leaf}}$ between 0.0361 m$^2$ g$^{-1}$ (LAI = 0) and 0.0184 m$^2$ g$^{-1}$ (LAI = 4.5) is in good agreement to other studies. Verheul et al., 1996, for instance, found an average SLA$_{\text{leaf}}$ value of 0.0303 m$^2$ g$^{-1}$ in young maize plants. However, calculating GAI from SLA and dry matter of leaf, respectively stem, yields a higher rRMSE than using the simpler approach by fitting GAI (rRMSE = 0.11) (Tab.8). Yet, compared to the 'fitted GAI' model version, the slightly lower goodness of simulating GAI by the 'complete model' version dose not result in seriously inadequate calculations of $Q$ or $T_{\text{pot}}$. The differences between the two
model versions is on average with 2% for T_{pot} and 0% for Q low, but may amount to 14% (T_{pot}) and 12% (Q) for single treatments (KD 2008). The main reason for that seems to be the underestimation of DM_{leaf} in KD 2008. A CD value of 2.21 for SLA_{leaf} indicates that the model does not explain the whole variance of measured SLA_{leaf}. Fig. 4 suggests that SLA_{leaf} differs between the years at least for low GAI_{leaf} values. Additionally, the sensitivity analyses concerning SLA_{leaf} (Fig. 5) showed clear differences between years concerning the effect of SLA on DM_{shoot}. Beside year specific reactions of DM_{shoot} on a varying SLA, the effect on the averaged DM_{shoot} is mentionable too. In contrast to the expectation, that an increasing SLA_{leaf} would lead to an increasing DM_{shoot}, this only was observed for SLA_{leaf} values below 0.018. Further increase of SLA_{leaf} caused a decrease of DM_{shoot}. In the high yielding year 2003 DM_{shoot} showed a similar reaction, whereas, in the wet year 1980, also the final SLA_{leaf} increase caused a slight increase of DM_{shoot}. In 1976, the dry year, DM_{shoot} decreased with increasing SLA_{leaf} more or less linearly. Conducting this sensitivity analysis by excluding the drought stress impact on dry matter production showed, that without drought stress, DM_{shoot} reacted in all years and in average as expected, which means, that DM_{shoot} increased monomolecular with an increasing SLA_{leaf}. So, it was mainly the impact of drought stress that led to the observed decreases in DM_{shoot} in 1976, but also in 2003. Summing up, the analysis confirms the importance of a reliable model approach and parameterisation of SLA for model quality. It is well known, that the reduction of SLA is a possible adaptation of plants towards drought stress. Including this adaptation in the presented maize model could lead to an improvement of model quality in some years. However, until now this was not possible due to a lack of data.

The other important functional component is RL_{tot} and its distribution over time and space. In the presented model RL_{tot} is calculated from DM_{root} and SRL. The range of SRL found in literature is very high, varying between 800 and 10000 cm g^{-1}, even if considering only data of field experiments with comparable sampling time and method (de Willingen and van Noordwijk, 1987). A parameterisation of SRL by using Method 1 would have been insufficient. Therefore, we estimated SRL by using RL_{tot} out of experiment 2 and by DM_{root} calculated by the model. The resulting SRL value of 6879 cm g^{-1} is in the range of literature data and calculated average diameter of 0.43 mm seems to be plausible. Horse beans, for example, were reported to have an average root diameter of 0.8 mm (Kage, 1992). Compared to results by Willingen and van Noordwijk, 1987 who found an average diameter of approx. 0.2 mm, our value seems to too high, but the values given by de Willingen and van Noordwijk, 1987 result from either pot or water culture experiments. Root depth growth is computed to be linear, which is quite common and which, for example, also had been implemented in HYBRID-Maize. For calculating RLD, the parameter k_{a} is most important. k_{a} was optimised directly based on RDL-data from experiment 2. The transfer of the root
distribution parameter values from one site to another might be critical, and for simulating e.g. nitrogen uptake this parameterisation is probably insufficient, because nitrogen uptake is very sensitive to the distribution of RLD and the uptake competition of the single roots (CompF) (Kage, 1992). However, as water mobility in soils is high, the amount of sink terms needed for water exploitation in a certain soil layers can be quite low and the competitive effects are not that for the amount of water uptake. Statistical results of water content in 0 – 60 cm soil depth (BS) given in Tab. 10 indicate an adequate model performance with RMSEs of 0.023 – 0.027. However, assessing the correctness of modelling root growth is quite difficult. Water contents only can be a hint, because the soil water dynamics are also affected by terms of soil characteristics and evapotranspiration.

4.2.4. Dry matter production

Dry matter growth rate is computed using the LUE approach, thereby light absorption is calculated by the concept of extinction coefficient. Suboptimal water availability and temperatures are considered by reduction factors. Varies studies have mentioned the disadvantage of using the LUE approach for yield simulation. Loomis and Amthor, 1999 for example concluded, that due to the high variability of LUE and due to difficulties in measurement, LUE might not be suitable for modelling crop dry matter production. The most common alternative approaches are photosynthesis and respiration based models. Recently, Lizaso et al., 2005a developed a new photosynthesis-respiration submodel for maize which is closely linked to CERES-Maize. This submodel is based on a leaf-level canopy concept and it provides the ability to separate the photosynthetic gross assimilation from the associated respiratory cost, allowing the independent simulation of both processes as affected by environmental factors (Lizaso et al., 2005a). LUE based models do not allow this separation (Lizaso et al., 2005b). For different site year interactions this can be a disadvantage. For example not being able to calculate dry matter reduction by respiration might be insufficient for situations were PAR and temperature amplitude is low. However, possible influences of structural model errors should be taken in consideration using a photosynthesis-respiration-model and, compared to LUE based models, these models are still more difficult to calibrate (Kage et al., 2001). The latter was the most important reason for choosing the LUE approach, which can simply be parameterised by the use of commonly available data. LUE is assumed to be constant in the present model (4.43 g MJ PAR\(^{-1}\)). This parameter value indicates a LUE under unstressed conditions. Furthermore, it serves for the calculation of DM\(_{\text{tot}}\), i.e. it includes the shoot and root dry matter. The parameter value is slightly lower than the value (5.00 g MJ PAR\(^{-1}\)) used in CERES-Maize (Jones and Kiniry, 1986). Loomis and Amthor, 1999 calculated a LUE of 4.9 g MJ PAR\(^{-1}\) for maize. Lindquist et al., 2005 suggested a LUE value of 3.8 g MJ PAR\(^{-1}\) for predicting optimum aboveground
biomass without growth limitations. However, a LUE value of 4.43 g MJ PAR\(^{-1}\) for maize seems not to be out of range. Additionally, the perhaps critical approach of LUE parameterisation, caused by the high interaction to \(\psi_{\text{crit}}\), was at least proved to be arguable because no other parameter combination yielded better model fits concerning \(\text{DM}_{\text{shoot}}\). The sensitivity analysis, presented in Fig. 8, showed a clear positive correlation between the value of LUE and \(\text{DM}_{\text{shoot}}\), which was expected. This sensitivity analysis revealed no interaction between LUE and year on \(\text{DM}_{\text{shoot}}\). However, as mentioned before, LUE is relatively variable and many studies gained better results when assuming a negative correlation between LUE and radiation intensity. Kage et al., 2001 showed an improvement of model performance by using a linear decrease of LUE with increasing daily photosynthetic active radiation sum for cauliflower. Stöckle et al., 2008 presented results showing a negative correlation between LUE and radiation intensity for maize, at least for conditions where LUE is not limited by stress factors. We also tested a negative impact of radiation intensity on LUE, either by a linear or by a negative exponential relation. For the data sets of experiment 1 we could not find any relation between LUE and radiation intensity. However, this might be due to too less dry matter samplings in experiment 1 (7 - 9 samplings per vegetation period), which produces highly aggregated dry matter data. So, radiation intensities for calculating LUE have been average values, this causes a smoothing of the peaks of daily radiation intensity. Beside radiation intensity, other impacts on LUE are mentioned in literature. Especially, a negative influence of saturation deficit on LUE for maize has been discussed contrary (Kiniry et al., 1998, 1999 and 2004; Sinclair and Muchow, 1999). We could not find clear evidence for an impact of saturation deficit in our data, and therefore we did not consider that approach in our model. Also, cultivar differences in LUE, shown e.g. by Capristo et al., 2007 for the reproductive growth phase and by Tollenaar and Aguilera, 1992 between old and a new maize hybrid, are not included in our model.

Simulating dry matter production requires the calculation of \(Q\), the amount of absorbed photosynthetic active light. Therefore, the use of a correct light extinction coefficient is of major importance. We assumed that \(k_{\text{PAR}}\) is a negative linear plateau function of the GAI (Fig. 6). Up to a GAI value of 1.93, \(k_{\text{PAR}}\) decreases from 0.76 down to the constant value of 0.65. This function can be explain by more horizontal leaf angles at early crop development stages (low GAI) and a more erectophile leaf orientation at later development stages (high GAI), resulting in high extinction coefficients at low GAI, respectively lower ones at high GAI (Whigham, 1971 and Pepper et al., 1977, reviewed in Lizaso et al., 2003). Our findings are supported by Irmak and Mutiibwa, 2008 and Tahiri et al., 2006, who found a negative logarithmic respectively a negative linear function extinction coefficient and GAI. However, Lizaso et al., 2003 identified the extinction coefficient to be dynamic over crop development, not over GAI, with a peak of 0.66 at silking. In HYBRID-Maize (Yang et al., 2004b) the
extinction coefficient is assumed to be constant (0.55) over crop development and GAI. As
the impact of plant density on the extinction coefficient is still under discussion (Maddonni et
al., 2001 and Lizaso et al., 2003), the functional dependency of $k_{\text{PAR}}$ on GAI may present an
appropriate solution, as plant density is indirect included in GAI. Our $k_{\text{PAR}}$ values are slightly
higher than values reported by most other studies. Older studies, for example Pepper et al.,
1977, reported similar extinction coefficients up to 0.72 for planophile maize cultivars.
$f_T$, the factor describing the influence of temperature on dry matter production, is computed
as a function based on four cardinal temperatures according to HYBRID-Maize (Yang et al.,
2004b), but with an adaptation of the values of $T_1$, $T_2$ and $T_3$ to colder North Western
European conditions. As under North Western European conditions average daily
temperatures above 34°C are reached not very frequently, there was no need and no
evidence of adapting $T_4$. Additionally, Cicchino et al., 2010 found a threshold temperature of
33.9 °C for heat stress in maize, which is similar to $T_4$ (34°C) used in our model for $f_T = 0$. For
$T_1$, a base temperature of 8 °C for dry matter production is often reported, but only few
studies are available which were conducted in cool climates. Andrade et al., 1993 reported a
LUE of 0 g MJ PAR$^{-1}$ at a temperature of 6.7 °C for cooler climates. Pages and Pellerin,
1994, who conducted their studies in the middle of France, used a base temperature of 6
°C for root growth processes. Cabelguenne et al., 1999 used a base temperature of 6 °C
(parameterisation data sets had been collected in the South-West of France) for their
simulations with the EPICseth model. We therefore decided to set $T_1$, to 6 °C, according to
the base temperature used in the development submodel. Cabelguenne et al., 1999 used an
optimum temperature of 22.5 °C, which is similar to the average value of $T_2$ (16 °C) and $T_3$
(28 °C) estimated in our study. Wilson et al., 1995 found a reduction in biomass
accumulation when mean temperature was below 16 °C for maize grown in cool climates.
However, the effect of varying $T_1$ and $T_2$ on DM$_{\text{shoot}}$, as conducted in the sensitivity analysis,
was noticeable, but not very strong compared, for example, to the effect of a LUE variation.
(Fig. 7).
The impact of drought stress on plant growth is quantified by a simple stress factor in most
current crop models. Water stress is then often computed either as a ratio between actual
available soil water content and plant available soil water content at field capacity, as a ratio
between $ET_{\text{act}}$ and $ET_{\text{pot}}$, or as a ratio between daily actual water uptake (which equals $T_{\text{act}}$)
and $T_{\text{pot}}$ (Saseendran et al., 2008). In the presented model $T_{\text{act}} / T_{\text{pot}}$ is used for calculating
the stress factor SWDF, and the impact of SWDF on dry matter production is computed as a
linear function. Other models use linear-plateau functions, including one threshold value,
below which water limitation starts to impact dry matter production. Stöckle et al., 2008 and
Ferreya et al., 2003 suggested that $T_{\text{act}} / T_{\text{pot}}$ is influencing the stressed to non-stressed
growth rate ratio in a non linear way, formulated as $y = 1+a\cdot\ln(T_{\text{act}}/T_{\text{pot}})$, respectively as $y = 1-$
(1- T_{act}/T_{pot})^a. This approach is due to the greater contribution of stomatal aperture to the total pathway resistance of water vapour compared to the total pathway resistance of CO₂ (Ferreyra et al., 2003), caused by the additional mesophyll resistance for CO₂. We followed this theory and tested a non-linear function for the influence of SWDF on dry matter formulated as y = 1-(T_{act}/T_{pot})^a. Optimising the factor ‘a’ led only to a very slight sigmoid shape of the function. So our parameterisation data sets did not support the use of a non-linear function. However, Fig. 10 shows neither a systematic underestimation of the rain fed nor of the irrigated treatments.

4.2.5. Water balance

For modelling the impact of drought stress on dry matter production an appropriate simulation of the water balance (soil water balance including evapotranspiration processes) is necessary. The model thus must be able to reliably simulate root growth, GAI and crop height. Rooting depth and root distribution are important for water uptake due to the distribution of sinks. GAI is relevant for both global radiation uptake for evapotranspiration processes and photosynthetic active radiation uptake for dry matter production. Crop height is only important for the evapotranspiration processes. Beside these crop components, the correct parameterisation of soil properties, psi_{critevap}, psi_{crit} and Rc0 are important for calculating the water balance including evapotranspiration. Rc0 was estimated to be 75 m s^{-1}, by averaging some literature values (Sinclair et al., 1975; Irmak et al., 2008; Rochette et al., 1991). Rc0 should be higher for C₄ plants than for C₃ plants, caused by a higher stomatal resistance due to the higher efficiency in CO₂ fixation by the C₄ pathway. For grassland, for example, Rc0 values commonly are below 50 m s^{-1} (Kelliher et al., 1993; Schulze et al., 1994 and Russell, 1980). psi_{critevap} was parameterised by using the value provided by Beese, 1978, who investigated the water balance of a loess luvisol. It can be critical to simply transfer this value to other soil types, especially since a psi_{critevap} of 22.5 hPa is very low. However, caused by the need of high frequency soil water content measurements in the soil layer 0 – 5 cm, there is a lack of information about psi_{critevap} values for the soil types of the used experiments. psi_{crit} was the last parameter in the sequence of parameterisation, because of the large impact of psi_{crit} on dry matter production. Therefore it can possibly also highly influence the parameterisation of LUE, at least when using data sets where drought stress can not be excluded completely. psi_{crit} was parameterised using the data set of experiment 3, because of the species specific suction power, the transfer to other sites should not be too critical. To our knowledge values for psi_{crit} are rarely reported in literature. Kage, 2000 assumed psi_{crit} to be 1000 hPa while Novák and Havrila, 2006 give a range of approx. 1000 to 2000 hPa. The value gained from our parameterisation (439 hPa) is smaller than the values reported in
literature. However, it was shown that this value was still in the range (400 hPa – 1000 hPa) where the combination of psi_{crit} and LUE results in best model fits towards DM_{shoot}.

### 4.3. Model based analyses of dry matter production (WUE, TUE, LUE)

Modelling plant growth including water balance and evapotranspiration provides the opportunity to analyse the productivity of crops grown under different conditions in addition to only analysing data gained from field experiments. The complete growth dynamics can be reproduced and variables, which are not easy to measure, such as transpiration, can be derived. This provides the opportunity to analyse the processes effecting dry matter production, dynamically and in their interactions. In this paragraph a short interpretation and classification towards the recent literature of the resulting WUE, TUE and LUE values, presented in Tab. 9, will be given.

The presented LUE values in Tab. 9 are the effective averaged LUE values, considering temperature and water availability influences on dry matter production (f_T and SWDF) and therefore on the LUE. Additionally, they are calculated considering DM_{shoot}, according to most of the LUE values presented in literature. These results of the effective averaged LUE ranged from 2.3 to 3.2 g MJ PAR\(^{-1}\) and are consequently much lower compared to the parameter value (4.4 g MJ PAR\(^{-1}\)) of the LUE. It is well known that cool temperatures affect dry matter productivity negatively. In our model this is considered by the direct influence of f_T on dry matter production. Andrade et al., 1993 investigated the effect of temperature on LUE in cool climates comparable to our experimental sites (mean area temperatures 15.8 – 20.9°C during vegetative period) over 5 years. They found the same range of LUE (2.3 to 3.2 g MJ PAR\(^{-1}\)) and a positive correlation between mean temperature during the vegetation period and LUE. Negative effects of water deficit on LUE are well known (Earl and Davis, 2003), therefore a reduction of LUE in the dry year 2006 (BS) from 3.1 to 2.3 g MJ PAR\(^{-1}\) caused by drought stress is not astonishing.

For WUE and TUE, values reported in literature vary to a large extent, even if the reference base for calculating WUE and TUE, here aboveground dry matter, is similar. Kropff et al., 1984 found a TUE of 10 g L\(^{-1}\) for maize. Grassini et al., 2009 assumed a TUE for maize grown in North West Europe of > 5.4 g L\(^{-1}\), whereas the aboveground dry matter yield level of both studies was comparable. The variability of WUE and TUE has various reasons. Environmental impacts, like saturation deficit and drought stress, but also nutrient availability, here especially nitrogen availability and cultivar specificity effect WUE and TUE. Considering species, main difference occur between C_4 and C_3 plants. C_4 plants are supposed to yield higher WUE and TUE values than C_3 plants (Ehlers, 1996), due to the already mentioned higher efficiency in their CO\(_2\) fixation pathway and therefore to lower stomata conductivity values with a greater contribution of stomata aperture to the total pathway resistance of
water vapour versus CO$\textsubscript{2}$. Cultivar specific differences in maize, concerning TUE, might be due to physiological differences, too. WUE differences between cultivars may also be caused by a shift between transpiration and evaporation due to different vegetation durations of the different maturity groups of maize. However, differences between cultivars concerning the amount of actual evaporation of the cultivars of experiment 3 were negligible (values not shown), which might be due to the quite low $\psi_{\text{critvap}}$ value combined with the soil characteristics of BS. Cultivar differences in terms of TUE were directly caused by differences in GAI, but no interaction between year and cultivar could be observed, at least for BS (values not shown). Further investigations concerning interactions have to be conducted on additional sites.

A comparison of the sites, here focused on HS 2007 rain fed and BS 2007 irrigated, revealed some interesting aspects. WUE differed clearly with 5.7 g L$^{-1}$ for BS and 4.4 g L$^{-1}$ for HS. This should be mainly due to a 100 mm higher amount of evaporation in HS, possibly caused by higher amounts of rain fall in HS during the quite mild winter 2007. The calculated TUE was much higher for BS (7.1 g L$^{-1}$) than for HS (6.6 g L$^{-1}$), which is quite astonishing. Ehlers, 1996 presented for a site in Northern Germany (comparable to HS) and for a site in the middle of Germany TUE values of 9.9 g L$^{-1}$ respectively 6.7 g L$^{-1}$, so TUE values in contrary to our model calculations. Due to a larger influence of continental climate, saturation deficit should be higher in regions in the middle of Germany compared to regions in Northern Germany with a more maritime climate impact. From literature (Stöckle et al., 2008 and Ehlers, 1996) it is well known that the TUE of maize is inversely related to the saturation deficit, caused by an increasing transpiration demand. However, the calculated cum. $\mathit{T}_{\text{pot}}$ values were equal for BS and HS (Tab. 9), whereas the saturation deficit was much higher in BS than in HS (4.9 mbar vs 3.3 mbar), as expected (Tab. 1). But the effect of saturation deficit on potential transpiration was negated by the much higher wind speed in HS, which is positive correlated to transpiration demand. Wind speed also explains the differences in the TUE level between our calculations and the calculations of Ehlers, 1996, who did not include wind speed. However, the presented explanations show, why TUE values in BS are even higher for BS compared to HS. As transpiration was equal on both sites and PAR radiation uptake was just minimally higher in HS, probably the higher temperatures measured in BS, have been causing the higher TUE and additionally the higher LUE. LUE and TUE differed about 6 respectively 8 % between the sites, whereas $\mathit{DM}_{\text{shoot}}$ only was about 2 % higher in BS, which might be due to a slightly lower PAR uptake and a slightly higher drought stress (difference between $\mathit{T}_{\text{pot}}$ and $\mathit{T}_{\text{act}}$) despite irrigation. Comparison of the irrigated and the rain fed treatment of BS 2007, showed that TUE stayed constant, consequently $\mathit{DM}_{\text{shoot}}$, LUE and cum. $\mathit{T}_{\text{act}}$ increased proportionally by irrigation. It is well known, that due to the different reactions of H$_2$O and CO$_2$ concerning reduction of stomatal conductivity, TUE usually
increases with drought stress (Stöckle et al., 2008), but caused by the used model approach for calculating drought stress impact on dry matter production, which assumes a proportional reduction of transpiration and dry matter production, the calculated TUE is not sensitive to this effect. Still, in the very dry year 2006 a higher TUE of the rain fed treatment (7.0 g L\(^{-1}\)) could be observed compared to the irrigated treatment (6.8 g L\(^{-1}\)). This might be due to an early reduction of the GAI in the rain fed treatment, caused indirectly but irreversibly by drought stress, accompanied by the effect of a lower critical GAI for PAR uptake compared to the critical GAI for global radiation uptake, leading to a stronger reduction of transpiration compared to dry matter production and therefore to a higher TUE. Further comparison e.g. between years can be similar analysed. For example, the difference between HS 2007 and 2008 is caused by a higher saturation deficit in 2008, resulting in a higher transpiration demand, which in combination with less rainfall led to more pronounced drought stress. Additionally, mean temperature in 2008 have been lower. Both, drought stress and lower temperature causes reduction in DM\(_{\text{shoot}}\) and especially lower LUE values, whereas TUE is not effected as strongly as DM\(_{\text{shoot}}\) and LUE. Comparing the years 2006 and 2007 at BS, showed highest saturation deficits for 2006, which led to low TUE value. High temperatures in 2006 caused a high LUE for the irrigated treatment, but LUE was substantially reduced in the rain fed treatment by drought stress. The obviously high TUE and also WUE values for KD in comparison to HS have not been mentioned yet. This result from lower cum. T\(_{\text{pot}}\) values in KD due to lower wind speeds, whereas DM\(_{\text{shoot}}\) remained constant. As the experimental site at KD was surrounded by bushes and trees, the Penman-Monteith approach, which derives ra from crop height and wind speed, might be insufficient for this specific location and can lead to an underestimation of potential evapotranspiration.

5. Conclusions
The aim of this study was to provide a dynamic growth model for silage maize valid under North Western European conditions. The model was developed in order to generate a useful tool for analysing and evaluating the production capacity of silage maize cropping, and in special of energy maize cropping, under different environmental conditions. Therefore a simple, modular structured growth model, featuring some well known model approaches, was developed. For an easy applicability of this model to different year cultivar and site combinations only few, commonly available data are needed. The presented maize growth model has the general ability to calculate crop development, dry matter production, dry matter partitioning into different plant organs (roots, leaf, stem and cob), leaf area expansion and spatial root distribution, as well as potential evapotranspiration and soil water balance. The negligence of drought stress impacts, like on SLA or on CO\(_2\) vs. H\(_2\)O fluxes, or of
drought and heat stress impact on kernel set, are due to the high degree of simplification of the model and might be the reason for model failures in some specific year cultivar and site combinations or for the poor model accuracy concerning $\text{DM}_{\text{cob}}$. The poor accuracy concerning $\text{DM}_{\text{cob}}$ in combination with the absence of a quality sub model restricts the applicability of this model to analyse some special terms of silage maize production. However, results concerning model performance and validation showed that the presented silage maize model can simulate crop growth and resulting biomass yields appropriate for different maize cultivars grown in differing environments. The satisfactory model performance of soil water contents under water limitations and the level and range of the WUE, TUE and LUE values demonstrated the applicability of the model to simulate crop growth under different levels of water availability, including drought stress impacts. Therefore, we are confident, that this crop growth model can be a useful tool for evaluating silage maize cropping focusing biomass production under different environmental conditions and for analysing yield limitations due to different stress impacts.

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References


Chapter 2


Chapter 2


Model based assessment of silage maize yield potential in temperate climates with special reference to water use: a simulation study

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Abstract

The quantification of the production potential of silage maize becomes currently more important, since favourable economic conditions caused by the German and European energy policy, led to a strong increase of silage maize acreage. High biomass yields are important for the economical profitability, but also for the greenhouse gas reduction effect of maize based energy cropping for biomethane production. Yield gaps of silage maize, i.e. the difference between yield potentials and averaged farmers yields, are probably due to insufficient water availability or low temperatures in many regions of Germany. To evaluate and analyse the production capacity of silage maize in different regions of Germany a simulation study was conducted. An empirical, dynamic crop growth model was used to calculate yield potentials of three different regions under four different water supply levels ex-post over 35 years. Analysing the temperature and drought stress impact predictions of the maize simulation model on dry matter growth underlined the importance of optimal leaf area growth for high yields and resource use efficiencies. Comparing the yield potentials of silage maize grown under the different environmental conditions of three example regions, indicates a clearly higher production capacity for the warmer regions compared to the colder region of Northern Germany, with approx. 16 % (rain fed) and approx. 27 % (irrigated) higher averaged aboveground biomass for silage maize grown under the warmer conditions of Southern Germany and with approx. 5 % (rain fed) and approx. 20 % (irrigated ) higher averaged aboveground biomass for silage maize grown in the more drought prone region in Central Germany. Still, even under non-limiting water supply yield potentials at the two sites characterised by higher temperatures did not exceed 30 Mg dry matter ha$^{-1}$ on the long-term average.
1. Introduction
A significant increase of silage maize acreage (39%) up to approx. 1.83 Mio. ha was observed between 2004 and 2010 in Germany (DMK, 2011). Among others, German energy policy led to this increase by supporting biomass cropping for methane production in biogas plants (first amendment of the Renewable Energy Sources Act, 2004). Maize is dominating these energy cropping systems by 80% (Schütte, 2010), because its high specific methane yield (l methane per kg organic matter) and high biomass yield provide a high methane yield per hectare (Schittenhelm, 2008). The increase of silage maize acreage caused an expansion of silage maize into highly productive as well as into non-typical and less productive sites. The latter include sites, which might be less favourable for maize due to low mean temperatures or insufficient water availability. However, a high biomass yield is a key factor in silage maize cropping for methane production (Amon et al., 2007a), since it determines the profitability and the greenhouse gas reduction effect.

Plant productivity strongly depends on the interception of photosynthetic active radiation (PAR) and finally on the transformation of radiation energy into assimilates. High yields are therefore achieved by maximizing the extent and duration of radiation interception, and the efficient energy transformation (Loomis and Amthor, 1999). Both, temperature and water availability can reduce crop yields by effecting these processes. Temperature has a direct effect on the metabolic processes of plant growth and influences the leaf canopy development. In addition, the length of the crop growth period and thereby the amount of intercepted radiation is determined (Muchow et al., 1990). Water deficit, however, also can decrease crop yields by reducing canopy absorption of incident PAR due to its negative effects on leaf area expansion or by reducing the efficiency with which the absorbed PAR is used by the crop to produce dry matter (the light use efficiency (LUE)). Drought stress, in maize especially during silking, may also limit grain yield, e.g. by influencing the kernel set and thereby the sink strength (Earl and Davis, 2003).

Interactions between site and crop genotype with respect to the influence of radiation, temperature and drought stress determine the attainable crop yield, respectively the yield potential under non-limiting water availability (van Ittersum and Rabbinge, 1997). The site, as a specific combination of climatic and pedological characteristics, determines the amount of global radiation supply, the availability of water, temperature amplitude, saturation deficit and other environmental factors. The crop genotype determines the LUE under optimal conditions and the reaction on resource limitations besides many other characteristics. Plant growth is a dynamic process and the effect of limiting environmental resources may differ depending on the actual crop development stage. By the ability to calculate the site specific resource limitations dynamically, crop growth models are appropriate tools to analyse stress impacts on crop growth in detail. Analysing simulation results concerning dynamic crop
growth in combination with resulting resource efficiencies, like LUE and water or transpiration use efficiency can provide a comprehensive assessment of yield potential limitations at different sites or in different regions.

The objective of this work is to analyse and evaluate the yield potential of silage maize (referring a current maize cultivar) in three typical regions of Germany and to quantify the yield gap between attainable yield and yield potential, in order to discuss chances and limitations of possible yield increase in these regions. Therefore, we conducted a simulation study concerning the limitation of yield potential in the different regions. The crop growth model we used calculates dry matter production, dry matter partitioning into root, leaf, stem and cob, leaf area expansion and spatial root distribution and is linked to modules calculating potential evapotranspiration and soil water balance (Chapter 2). According to the capabilities of the model we focused on effects of radiation, of temperature and of water supply, origin from rainfall and soil water storage. Additionally, we analysed different water supply scenarios, in order to evaluate the effects of water availability on yield and on water, transpiration and light use efficiencies.

2. Material and Methods

2.1. The model

As a detailed description of the used maize growth model is provided in ‘Chapter 2’, therefore only a brief characterisation of the basic model algorithms and some remarks towards additional model extensions for the simulation study will be given here.

2.1.1. Model characteristics

The presented model is an empirical dynamic model for calculating growth of silage maize adapted to temperate climate. It is implemented using an object orientated component library (Kage and Stützel, 1999a), which works with the concept of visible software components of the Delphi®/C++ Builder®, Borland. The model is divided into several sub models. These sub models describe potential evapotranspiration, soil water balance, crop development, dry matter production and dry matter partitioning, including green area expansion and root growth. Principally, the model runs on daily time steps, but internal computation of the soil water balance module uses a variable length of time steps. External data inputs required for running the model include daily mean temperature [°C] \(T_{\text{mean}}\), incoming global radiation \([\text{W m}^{-2} \text{d}^{-1}]\), precipitation [mm], wind speed \([\text{m s}^{-1}]\) and air humidity [%]. The latter is used to calculate vapour pressure [mbar] and saturation deficit [mbar]. The main algorithms of the crop growth model are based on the effective daily mean temperature \(T_{\text{eff}}\) and PAR. Thereby, \(T_{\text{eff}}\) is the difference between \(T_{\text{mean}}\) and a base temperature \(T_{1}\) of 6 °C, with a defined

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minimum of 0 °C. PAR is derived from the global radiation using a factor of 0.5 (Szeicz, 1974).

Potential evapotranspiration [mm d⁻¹] (ETpot) is computed according to Penman-Monteith (Monteith, 1973). Crop parameters like green area index and crop height are delivered dynamically by the partitioning module. The extinction coefficient for global radiation [-] (kglob) is derived from the extinction coefficient for PAR by a division factor of 1.35 (Green, 1987). The soil water balance is calculated by a potential based layer module, using the water content based formulation of the Richards equation for calculating the vertical soil water movement. The retention function proposed by van Genuchten, 1980 in the formulation revised by Wöstken and van Genuchten, 1988 is used to quantifiy the coherence between water content and water potential. The van-Genuchten-parameter m is calculated according to Mualem (1976).

The description of crop development is based on the approaches used in the HYBRID-Maize model (Yang et al., 2004), which were slightly modified. Five main steps of development are distinguished: emergence (XStage 1), tassel initiation (XStage 2), silking (XStage 3), end of effective grain filling (XStage 4) and maturity (XStage 5). Since in the present study, the focus is not on grain maize production, we included silage maize maturity (dough stage) instead of physiological maturity. The temperature sums required for achieving emergence [°C d⁻¹] (GDDemer), silking [°C d⁻¹] (GDDsilk) and maturity [°C d⁻¹] (GDDtotal) are assumed to be cultivar specific, while the remaining parameters related to maize development are assumed to be cultivar unspecific.

Plant dry matter production [g m⁻²] (DMtot) is based on the LUE approach [g MJ PAR⁻¹]. More detailed, the growth rate for DMtot [g m⁻² d⁻¹] is computed as a function of absorbed photosynthetic radiation [MJ m⁻² d⁻¹] (Q) and light use efficiency [g MJ PAR⁻¹] (LUE) corrected by factors for temperature (fT) [-] and soil water deficit [-] (SWDF). Thereby, Q is calculated from PAR, the green area index (GAI) [-], and the extinction coefficient for PAR [-] (kPAR). The latter is supposed as negative linear-plateau function of the GAI, with a plateau value of kPAR is fixed by 0.654. LUE is assumed to be constant, where a value of 4.43 g MJ PAR⁻¹ was obtained by parameterization. Temperature factor fT is calculated by an optimum function using 4 cardinal temperatures (T₁ = 6 °C, T₂ = 16 °C, T₃ = 28 °C and T₄ = 34 °C). SWDF is the ratio between actual transpiration [mm d⁻¹] (Tact) and potential transpiration [mm d⁻¹] (Tpot).

The basic idea underlying the partitioning module is, that total plant dry matter is the sum of its single components. Dry matter allocation to the roots [g m⁻² d⁻¹] is assumed to be dependent of crop development and to stop shortly after silking (Yang et al., 2004). The remaining shoot dry matter [g m⁻²] (DMshoot) is partitioned to DMleaf, DMstem and DMcob. The daily changes of DMleaf are derived from an allometric relation (Kage and Stützel, 1999b) between DMleaf and (DMstem + DMcob). Leaf dry matter growth stops with the expansion of the
last appearing leaf. The cob growth rate is computed considering a development dependent proportion of shoot dry matter growth allocated to the cob. Growth rate of DM\textsubscript{stem} is simply the difference of the growth rates of DM\textsubscript{shoot} and (DM\textsubscript{leaf} + DM\textsubscript{cob}). The calculation of GAI is based on the approach of specific leaf area [m\textsuperscript{2} g\textsuperscript{-1}] (SLA\textsubscript{leaf}) and specific stem area [m\textsuperscript{2} g\textsuperscript{-1}] (SLA\textsubscript{stem}), both assumed to be dependent on GAI. A senescence factor reducing GAI is also included. Crop height is a simple function of GAI. Total root length [cm] (RL\textsubscript{tot}) is calculated by root dry matter and a constant specific root length [cm g\textsuperscript{-1}] (SRL). Descent of roots is temperature dependent and linear with soil depth, whereas root length density decreases exponentially with soil depth (Kage et al., 2000).

2.1.2. Model extensions
For the simulation study optional extensions have been implemented into the maize growth model.
(i) The first extension ensures that the crop will be harvested in autumn, even if the temperature sum does not reach GDD\textsubscript{total} by introduction the parameter harvestdate\textsubscript{latest}, which denotes the day of year when harvest will be conducted at the latest. This modification was already used for some sensitivity analyses presented in ‘Chapter 2’.
(ii) The second model adaptation allows the soil water content of the preceding crop to affect the following crop by using final soil water contents as initial values for the following calculations.
(iii) The third modification provides the opportunity to calculate crop growth without any impact of drought stress, by setting SWDF to 1 and therefore pretending that T\textsubscript{act} equals T\textsubscript{pot}.
(iv) The fourth model extension is an automatic irrigation option. Thereby, irrigation is controlled by the actual soil water content in the potential rooting zone. If soil water falls below a critical percentage of plant available field capacity (parameter Autoirri\textsubscript{inPKcrit}), irrigation is triggered. The parameter Autoirri\textsubscript{amount} [mm] allows for choosing the amount of irrigation.

2.2. Simulation study
A simulation study was conducted for three sites in Germany, which, however, differed with respect to their environmental conditions. Simulations were done \textit{ex post}, using weather data of 1970 – 2004 from meteorological stations of Deutscher Wetterdienst (DWD) in Holtenau (HA) in Northern Germany (54°22’N, 10°08’E), Magdeburg (MA) in the Mid-East (52°07’N, 11°38’E) and Regensburg (RE) in the South-East of Germany (49°01’N, 12°05’E). Weather conditions are provided in Tab. 1 as averages of the 35 year investigation period. The
Northern most site HA was characterised by low average air temperature (8.7 °C, 14.7°) and high precipitation (763 mm, 338 mm), on an annual basis as well as for the growing season (May till end of September). MA, in contrast, showed high air temperatures and low amounts of precipitation. Differences between HA and MA became evident in particular for the silage maize growing period, where MA was 1.2 °C warmer, but received 26% less rainfall. RE was characterized by strong winters, warm summers, and a relatively high amount of precipitation. In summary, the sites can be characterized as follows: HA is cold and wet (c + w), MA is warm and dry (w + d) and RE is warm and moderate wet (w + m). Important to note is also high wind speed and saturation deficit for MA (Tab.1). Saturation deficit for RE was comparable to that of MA, but wind speed was considerably lower, while HA achieved moderate levels of wind speed and lowest saturation deficit.

Tab. 1: Weather conditions averaged over the 35 years given for the three different locations (HA: Holtenau, c + w: colder and wet; MA: Magdeburg, w + d: warmer and dryer; RE: Regensburg, w + m: warmer and moderate wet). Average air temperature and sum of precipitation are provided as annual values, while air temperature, wind speed and saturation deficit values as well as sum of global radiation and precipitation refer to the main growing season of maize, from beginning of May till end of September.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>HA (c + w)</td>
<td>8.7</td>
<td>763</td>
<td>14.7</td>
<td>2515</td>
<td>338</td>
<td>2.3</td>
<td>4.4</td>
</tr>
<tr>
<td>MA (w + d)</td>
<td>9.1</td>
<td>497</td>
<td>15.9</td>
<td>2573</td>
<td>249</td>
<td>3.1</td>
<td>5.7</td>
</tr>
<tr>
<td>RE (w + m)</td>
<td>8.6</td>
<td>649</td>
<td>16.0</td>
<td>2686</td>
<td>335</td>
<td>1.9</td>
<td>5.6</td>
</tr>
</tbody>
</table>

Soil horizons were assumed similar for all sites, i.e. 0 – 30 cm, 30 – 60 cm, 60 – 90 cm, 90 – 120 cm, but at one site soil texture classes have been chosen homogenous with soil depth (Tab. 2). Van-Genuchten-parameters and saturated conductivity (KS) were from BGR, 2005. The plant available soil water [mm] (SW_{pa}) was calculated by the use of the plant available field capacity refering the effective rooting zones [cm] RZ_{eff}. SW_{pa} in RZ_{eff} [mm], and differed considerably between the three sites. Parameterisation resulted in a SW_{pa} in RZ_{eff} of 166 mm for HA and 240 mm for MA, whereas SW_{pa} for RE region was only 107 mm, latter partly due to the lower RZ_{eff}. The parameterization of soil properties was primarily motivated by choosing representative soils for the three regions, but also to provide a large variation in the water availability.

Tab. 2: Soil texture, Van-Genuchten-parameters considering Mualem parameterization (α, θₛ, θᵣ and n) and saturated water conductivity (KS), as well as depth of effective rooting zone (RZ_{eff}) and plant available soil water (SW_{pa}) in RZ_{eff} given for soils of the three different locations respectively.

<table>
<thead>
<tr>
<th>Site</th>
<th>Soil texture</th>
<th>α [cm⁻¹]</th>
<th>θₛ [cm³ cm⁻³]</th>
<th>θᵣ [cm³ cm⁻³]</th>
<th>n [-]</th>
<th>KS [cm d⁻¹]</th>
<th>RZ_{eff} [cm]</th>
<th>SW_{pa} in RZ_{eff} [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HA</td>
<td>Sl4</td>
<td>0.043</td>
<td>0.3394</td>
<td>0</td>
<td>1.18</td>
<td>21</td>
<td>100</td>
<td>166</td>
</tr>
<tr>
<td>MA</td>
<td>Ut3</td>
<td>0.008</td>
<td>0.3998</td>
<td>0</td>
<td>1.22</td>
<td>12</td>
<td>240</td>
<td></td>
</tr>
<tr>
<td>RE</td>
<td>Ls4</td>
<td>0.050</td>
<td>0.3431</td>
<td>0</td>
<td>1.11</td>
<td>36</td>
<td>80</td>
<td>107</td>
</tr>
</tbody>
</table>
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The simulation study was conducted for a mid early cultivar in order to ensure that silage maize maturity was achieved in most years at the warmer sites (MA and RE) (see Tab. 5). Cultivar specific parameters (GDD\textsubscript{emerg}, GDD\textsubscript{silk} and GDD\textsubscript{total}) were used as obtained for hybrid Flavi (S 250) of field experiment 3 (Chapter 2). Temperature sums for emergence, silking, and silage maturity amounted to 100 ºC d, 840 ºC d, and 1641 ºC d, respectively.

The model runs for each site were conducted continuously over the 35 year period in order to consign the soil water content of the last crop to the following crop. A crop cycle was defined to start on March 1\textsuperscript{st} and to end at February 28\textsuperscript{th} in the following year. Sowing date was fixed to 18\textsuperscript{th} of April. Harvest was assumed if either GDD\textsubscript{total}, i.e. silage maturity, or harvestdate\textsubscript{latest} (20\textsuperscript{th} of October) was reached.

Four different scenario simulations concerning drought stress impact on plant growth and water supply level were conducted.

(i) Crop growth without additional irrigation (‘\textit{SWDF} = \frac{T\textsubscript{act}}{T\textsubscript{pot}}’) - providing the attainable silage maize yield at a specific site, so including drought stress impact, but without any restrictions due to sub optimal crop management.

(ii) Crop growth without drought stress (‘\textit{T}\textsubscript{act} = T\textsubscript{pot}’) - providing the yield potential without any restrictions concerning crop management and water availability.

(iii) Irrigation scenario I, with Autoirri\textsubscript{inFKcrit} 60 % (‘60 % to 80 %’), and a target of 80% of usable field capacity - providing yields without any limitation by crop management and moderate drought stress.

(iv) Irrigation scenario II, with Autoirri\textsubscript{inFKcrit} 80 % (‘80 % to 90 %’), and a target of 90% of usable field capacity - providing yields without any limitation by crop management and low drought stress.

The target amounts of irrigation and the impact of drought stress on dry matter production are given in Tab. 3.

Tab. 3: Characterisation of the four scenario simulations by their irrigation amount and impact of drought on dry matter production.

<table>
<thead>
<tr>
<th>Scenario simulation</th>
<th>Target amount of irrigation [mm]</th>
<th>Drought impact</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HA</td>
<td>MA</td>
</tr>
<tr>
<td>SWDF = \frac{T\textsubscript{act}}{T\textsubscript{pot}}</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>\textit{T}\textsubscript{act} = T\textsubscript{pot}</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>‘60 % to 80 %’</td>
<td>33</td>
<td>48</td>
</tr>
<tr>
<td>‘80 % to 90 %’</td>
<td>17</td>
<td>24</td>
</tr>
</tbody>
</table>
3. Results

In this section firstly a short characterisation of the site differences concerning water availability and temperature will be given. The main part will focus on yield performance as influenced by water supply and resulting effects on water balance, and efficiencies of water use, transpiration, and light use. Finally, leaf area dynamics and their effects on TUE and WUE are exemplified for specific years.

3.1. Site differences in water availability and temperature

The amount of water, available for crop growth at a specific site, is mainly determined by the amount of precipitation during the vegetation period and the plant available soil water in RZ_{eff} at sowing (Payero et al., 2009). HA showed on average of 35 years the highest sum of precipitation plus SW_{pa} in RZ_{eff} (Tab. 4), being approx. 90 mm higher compared to MA and RE. The main difference between the two latter sites is the proportion between SW_{pa} in RZ_{eff} and precipitation. Precipitation was approx. 100 mm lower in MA, but SW_{pa} in RZ_{eff} was 100 mm higher compared to RE. The standard deviation values (SD) of both parameters indicated that the variation over years was comparable for MA and RE, whereas at HA the variation was noticeably higher, especially for precipitation.

At MA, the average SW_{pa} in RZ_{eff} showed a depletion of 40 mm compared to the theoretically derived SW_{pa} in RZ_{eff} presented in Tab. 2. However, for none of the sites a systematic decrease of soil water storage over the years could be observed. Furthermore, no clear differences between the different simulation scenarios concerning SW_{pa} in RZ_{eff} could be found (data not presented).

Tab. 4: Mean and standard deviation (SD) values of precipitation summed from sowing till harvestdate_{latest}. Mean and standard deviation (SD) values of the amount of SW_{pa} at sowing date in RZ_{eff} calculated for SWDF = T_{act} / T_{pot} as well as the sum of precipitation and SW_{pa} in RZ_{eff}. All parameters are given separately for the three different sites.

<table>
<thead>
<tr>
<th>Site</th>
<th>Precipitation [mm]</th>
<th>SW_{pa} in RZ_{eff} [mm]</th>
<th>Sum [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HA</td>
<td>397 (84)</td>
<td>175 (16)</td>
<td>572</td>
</tr>
<tr>
<td>MA</td>
<td>280 (67)</td>
<td>202 (13)</td>
<td>482</td>
</tr>
<tr>
<td>RE</td>
<td>378 (63)</td>
<td>107 (12)</td>
<td>485</td>
</tr>
</tbody>
</table>

As already shown in Tab. 1, the sites differ with respect to water availability as well as in mean air temperature. Average daily temperatures in the maize growing season were lowest for HA (14.7 °C) and similar for MA and RE (15.9 respectively 16.0 °C). This is reflected in the mean XStage and the number of years, where silage maturity was achieved (Table 5).
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The minimum XStage values indicate that the end of effective grain filling (XStage 4) was reached in all years on all sites. Nevertheless, the mid early hybrid had a high risk of not achieving the target dry matter content of approx. 35 % at HA.

Tab. 5: Mean, minimum and maximum values of XStage at harvestdate_{latest} and number of harvestings before harvestdate_{latest} given separately for the three different sites.

<table>
<thead>
<tr>
<th>Site</th>
<th>XStage at harvestdate_{latest}</th>
<th>Number of harvests at silage maturity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean</td>
<td>min; max</td>
</tr>
<tr>
<td>HA</td>
<td>4.61</td>
<td>4.16; 5.2</td>
</tr>
<tr>
<td>MA</td>
<td>5.00</td>
<td>4.46; 5.57</td>
</tr>
<tr>
<td>RE</td>
<td>5.01</td>
<td>4.44; 5.88</td>
</tr>
</tbody>
</table>

3.2. Yield potential without irrigation

The green area duration [d] (GAD), which is the sum of GAI during the vegetation period, is a key factor determining the PAR uptake of a crop (Q). The average GAD, sum of Q, DM_{tot} (dry matter of root and shoot) and DM_{shoot} (aboveground biomass yield) realised without additional water supply ('SWDF = T_{act} / T_{pot}') was lowest for HA, moderate for MA and highest for RE (Tab. 6). However, the site differences were more distinct for sum of Q, DM_{tot} and DM_{shoot} than for GAD. The variation between years (SD) concerning GAD was highest for HA, while sum of Q varied least at this site. The highest observed variation of DM_{tot} and DM_{shoot} was found in RE. In general, no difference concerning the root / shoot ratio was observed between the sites. Approximately 20 % of DM_{tot} was translocated to the root, independent on the site. LUE, i.e. the ratio of DM_{shoot} and sum of Q, tended without any additional water supply to be higher for HA, followed by RE and MA.

Tab. 6: Mean and standard deviation (SD) values of simulated GAD, sum of Q, DM_{shoot} and DM_{tot} for the first scenario simulation, SWDF = T_{act} / T_{pot}, provided for the three sites.

<table>
<thead>
<tr>
<th>Site</th>
<th>GAD [d]</th>
<th>Sum of Q [MJ PAR m^{-2}]</th>
<th>DM_{shoot} [g m^{-2}]</th>
<th>DM_{tot} [g m^{-2}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HA</td>
<td>614 (88)</td>
<td>784 (140)</td>
<td>1930 (291)</td>
<td>2425 (326)</td>
</tr>
<tr>
<td>MA</td>
<td>632 (61)</td>
<td>866 (345)</td>
<td>2026 (296)</td>
<td>2505 (318)</td>
</tr>
<tr>
<td>RE</td>
<td>650 (67)</td>
<td>917 (320)</td>
<td>2240 (354)</td>
<td>2731 (372)</td>
</tr>
</tbody>
</table>

As GAD is the sum of GAI during the vegetation period, it is strongly determined by two factors and their interactions, firstly by the level and time course of GAI and secondly by the length of the vegetation period. Fig. 1 shows that the observed time course of the GAI at HA showed a delay and a lower exponential increase compared to MA and RE. This resulted in
approx. one unit lower GAI values from beginning of June till mid of July for HA. Additionally maximal GAI, ranging at all sites between 5.5 and 6.0, was reached later. However, due to the average longer vegetation period of HA, the time span, in which GAI was maximal or close to maximum was rather long. Just small differences occurred between the GAI time course of MA and RE, with slightly higher values observed for RE from beginning of June. However, the temporal interaction between GAI and incident PAR radiation drives the actual uptake of PAR radiation and on an aggregated level in the sum of Q. The presented average time course of the incident PAR radiation (Fig. 1), shows for all sites highest radiation values from April till July, whereas from July till harvestdate latest radiation intensity steadily decreased at all sites from approx. 9.5 to 2.0 MJ m². Differences in incident PAR among the sites were marginal, with slightly lower irradiation found for HA and slightly higher irradiation found for RE, especially in the second half of the vegetation period.

![Fig. 1: Time course of GAI and of mean incident PAR, as simulated in the first scenario (SWDF = T_{act} / T_{pot}). Different colours indicate the three different regions. For each site the dotted line indicates the GAI time course in the period between the earliest harvest date observed in the 35 years and harvestdate latest. Data represent averages of 35 years.](image)

Fig. 2 presents the factors of temperature f_τ and drought stress SWDF as well as the ratio between absorbed and incident PAR radiation (Q / incident PAR) obtained without additional water supply. The time course of Q / incident PAR observed at HA differed comparably to those found at MA and RE with a delayed increase in the early growth period, resulting in up to 0.25 lower Q / incident PAR ratios for HA. Similar site differences were already observed...
for the time course of GAI (Fig. 1). However, the small differences in GAI detected between MA and RE did not appear in the ratio of $Q$ / incident PAR.

The temperature factor $f_T$ revealed a stronger impact of low temperature in early summer for HA compared to MA and RE, while in autumn it was by trend reversed. At all sites $f_T$ increased till beginning of August, stayed on a constant level of approx. 0.9 and decreased again till harvestdate$_{latest}$. SWDF in contrast started on a high level. In the first half of May SWDF was slightly lower for HA and RE compared to MA, but stayed till middle of June on a high level ($> 0.9$) at all sites. From middle of June till end of August SWDF decreased steadily at all sites, reaching minimum values in HA of approx 0.75 and in RE and MA of approx. 0.6. The following increase of SWDF in autumn led to a SWDF above 0.9 at HA and at MA to a SWDF of approx. 0.8 and at RE to a SWDF of approx. 0.7.

![Graph showing temperature factor, SWDF, and the proportion between absorbed and incident PAR radiation.]

Fig. 2: Time courses of temperature factor ($f_T$), of drought stress factor (SWDF) and of the proportion between absorbed and incident PAR radiation given for the scenario calculation SWDF = $T_{act}$ / $T_{pot}$. Different colours indicate the three different regions. Data represent averages of 35 years.
3.3. Yield potential with irrigation and resulting water balance

Potential restrictions of crop growth by environmental conditions have already been indicated in section 3.1 and 3.2. In the following section, the yield capacity with and without additional water supply will be analysed. In Fig. 3 simulated DM$_{\text{shoot}}$ yield of both irrigation scenarios and the second scenario assuming full water supply ($T_{\text{act}} = T_{\text{pot}}$) are presented, supplemented by the first scenario (SWDF = $T_{\text{act}}/T_{\text{pot}}$), which served as reference.

Compared to the reference scenario, additional water supply, as provided in irrigation scenario I (‘60 % to 80 %’), substantially improved yield performance for all sites. Further water supply in irrigation scenario II (‘80 % to 90 %’) and full water supply resulted in small additional yield increases, resulting in potential yields ($T_{\text{act}} = T_{\text{pot}}$) of approx. 2500 g m$^{-2}$ in HA and 3000 g m$^{-2}$ in RE end MA. Highest yield improvements by additional water supply were found for MA, followed by RE. Irrigation reduced yield variation at RE while at HA an opposite trend was observed.

![Fig. 3: Box-Whisker-plots of simulated DM$_{\text{shoot}}$, provided separately for the three different sites and for all four scenario simulations. Lower and upper boundary of the box give the 25th and 75th percentile, the middle line gives the median, while lower and upper whisker indicate the 10th and 90th percentiles, dots give the 5th and 95th percentiles.](image-url)
Fig. 4 presents the mean drought stress and its variation by water supply. Drought stress units were calculated as the sum of \((1 - \text{SWDF})\). For the simulation scenario \(\text{SWDF} = \frac{T_{\text{act}}}{T_{\text{pot}}}\), the observed variation of drought stress was very high at all sites. HA showed the widest range, but apart from the upper 10% on the lowest level. MA and RE ranged on a similar level, but drought stress variation in RE was smaller compared to MA. The reduction of drought stress by additional water supply reduced both, level and variation of drought stress, at all sites. Implicitly, no drought stress was observed in the scenario \(T_{\text{act}} = T_{\text{pot}}\). Also the ‘80% to 90%’ irrigation resulted in drought stress values below 5. Whereas, the irrigation scenario 60 % to 80 % showed median values around 5 at all sites, with still the highest variation observed in HA.

![Box-Whisker-plots of calculated Drought stress units](image)

The average additional water supply, as well as the corresponding SD values, the number of irrigation events required to realize the \(\text{DM}_{\text{shoot}}\) yields and the reduction in drought stress shown for the two irrigation scenarios ‘60 % to 80 %’ and ‘80 % to 90 %’ are presented in Tab. 7. Additionally provided are the theoretical average amounts of additional water needed to reach yield potentials without any drought stress limitation. These theoretical amounts of
additional water (Diff. cum. ETI) were calculated as the difference between the cumulative amount of evapotranspiration (cum. ETI) of the $T_{act} = T_{pot}$ and the SWDF = $T_{act} / T_{pot}$ scenarios. Independent of the simulation scenario, HA required the lowest additional amounts of water followed by RE and MA. While in HA and RE the amount of irrigated water increased from ‘60 % to 80 %’ to ‘80 % to 90 %’ only by approx. 40 %, it increased in MA by approx. 80 % and exceeded even the theoretical amount of additional water needed for reaching yield potential. Latter can occur, because processes like refilling the soil water storage or leakage are considered in the irrigation calculations, but certainly not in the calculation of the Diff. cum. ETI. However, also the observed number of irrigation events indicates that in MA especially the irrigation scenario 80 % 90 % was intensive. Whereas in HA and RE the number of irrigation events needed in ‘80 % to 90 %’ was doubled compared to ‘60 % to 80 %’, it was tripled in MA.

Tab. 7: Mean number of irrigation events and mean and standard deviation (SD) values of cumulative irrigation amount for the two irrigation scenario simulations, as influenced by the site. As well as mean values of the difference between cumulative evapotranspiration including interception (Diff. cum. ETI) of $T_{act} = T_{pot}$ and of SWDF = $T_{act} / T_{pot}$.

<table>
<thead>
<tr>
<th>Site</th>
<th>Number of irrigation events [d]</th>
<th>Cumulative irrigation amount [mm]</th>
<th>Diff. cum. ETI [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>‘60 % to 80 %’</td>
<td>‘80 % to 90 %’</td>
<td>‘60 % to 80 %’</td>
</tr>
<tr>
<td>HA</td>
<td>4.7</td>
<td>10.4</td>
<td>117 (121)</td>
</tr>
<tr>
<td>MA</td>
<td>7.2</td>
<td>22.4</td>
<td>268 (176)</td>
</tr>
<tr>
<td>RE</td>
<td>8.1</td>
<td>18.8</td>
<td>141 (57)</td>
</tr>
</tbody>
</table>

Tab. 8: Mean and standard deviation (SD) of the cumulated evapotranspiration (cum. ETI) including interception from sowing till harvestdate_{latest}, provided for all four scenario simulations and different sites.

<table>
<thead>
<tr>
<th>Site</th>
<th>Cum. ETI [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SWDF = $T_{act} / T_{pot}$</td>
</tr>
<tr>
<td>HA</td>
<td>377 (39)</td>
</tr>
<tr>
<td>MA</td>
<td>417 (35)</td>
</tr>
<tr>
<td>RE</td>
<td>377 (44)</td>
</tr>
</tbody>
</table>

Tab. 8 presents the resulting cumulative amounts of ET in average over the 35 years for all sites and scenario simulations. The cum. ETI values used in the $T_{act} = T_{pot}$ scenario were cumulative potential ET values. For all other scenario simulations cumulative actual ET values have been used. The amount of transpiration (cum. TI) was generally calculated including interception and the evaporation (cum. E) values applied for the period between sowing date and harvestdate_{latest}. Independently of the site, cum. ETI increased with
decreasing drought stress. Concerning the site effects on cum. ETI, Tab. 8 shows that without additional water supply cum. ETI was similar for HA and RE and only slightly higher for RE with additional water supply. Cum. ETI observed for MA instead was noticeably higher in all scenario simulations and increased disproportionately with additional water supply compared to the two other sites. Consequently, the potential cum. ETI of the $T_{act} = T_{pot}$ scenario was in HA 150%, in RE 162% and in MA 182% and of the ET values of the SWDF = $T_{act} / T_{pot}$ scenario. The variation of cum. ETI observed in RE stayed constant, independent from the water supply level, whereas in HA and MA the SD values increased with additional water supply.

3.4. Water and light use efficiencies

For all scenarios at all sites the observed WUE values were on a lower level compared to the TUE values, with smallest differences between TUE and WUE at MA (Fig. 5). Generally, MA was characterised by lowest levels of TUE and WUE, whereas RE yielded the highest values. Especially for TUE, the site effect was much higher than the effect of water supply. However, the most obvious impact of the water supply scenario was observed for the WUE values of the $T_{act} = T_{pot}$ scenario, which were clearly lower compared to the other scenarios. For the other water supply scenarios no clear trend of median WUE values could be observed. Also, for median TUE values no clear trend of the water supply level was obvious. By trend the 5th, 10th, 25th TUE percentile of HA and MA showed a slight decrease with increasing water supply, whereas in RE no effect of increasing water supply was noticeable.

Fig. 6 shows the relationship between $D_{m_{shoot}}$ (single-year values) and the cumulative transpiration (including interception) separately for the three different sites ((a) = HA, (b) = MA and (c) = RE). The sites differ mainly in the range of cum. TI. Values observed in HA and RE ranged from approx. 180 mm to approx. 530 respectively 500 mm. Instead in MA cum. TI ranged wider from approx. 280 mm to approx. 800 mm. In HA and RE $D_{m_{shoot}}$ increased roughly proportional with cum. TI, whereas in MA the increase of $D_{m_{shoot}}$ got smaller in the high cum. TI range, which was not achieved at the other sites. Additionally, Fig. 6 gives for each site three lines, all crossing the origin and a specific data point, the slope of these lines is the TUE for the corresponding data point. The slope of the upper line is the highest TUE observed at the site in the 35 years. The two lower lines indicate the lowest TUE values separated between the SWDF = $T_{act} / T_{pot}$ scenario and all other scenarios. At all sites the highest TUE value was reached independently of the water supply level. Especially in HA and MA this high TUE was realised at a low cum. TI level. Whereas at all sites, the low TUE values were, dependent on the water supply level, obtained at low cum. TI values for the SWDF = $T_{act} / T_{pot}$ scenario and at high cum. TI values for the scenarios with additional water supply.
Chapter 3

Fig. 7 presents single-year DM\textsubscript{shoot} values plotted against the cumulative evapotranspiration (including interception) separately for the three different sites. In general, the maximum cum. ETI values were higher compared to the cum. TI values (Fig. 6) and the observed range of the cum. ETI values was also wider at all sites. The slopes of the three lines indicate the WUE. Again, the upper lines assign the data points with the highest observed WUE at the site in the 35 years and the slopes of the two lower lines indicate the lowest TUE values, but here separated between the T\textsubscript{act} = T\textsubscript{pot} scenario and all other scenarios. Latter distinction was chosen, because at all sites a parallel translation of the T\textsubscript{act} = T\textsubscript{pot} data compared to all other data was observed. This resulted in the lowest observed WUE values for the T\textsubscript{act} = T\textsubscript{pot} scenario at all sites. Excluding T\textsubscript{act} = T\textsubscript{pot}, the lowest TUE values in HA and RE were gained by a data of the SWDF = T\textsubscript{act} / T\textsubscript{pot} scenario and in MA by the ‘80 % to 90 %’ scenario. Again excluding T\textsubscript{act} = T\textsubscript{pot}, highest observed WUE values were comparable to the highest TUE values independent from the water supply level.

Fig. 5: Box-Whisker-plots of calculated TUE and WUE values, given separately for the three different sites and for all four scenario simulations. Lower and upper boundaries of the box give the 25\textsuperscript{th} and 75\textsuperscript{th} percentile, middle line gives the median, lower and upper whisker indicates 10\textsuperscript{th} and 90\textsuperscript{th} percentile, dots give the 5\textsuperscript{th} and 95\textsuperscript{th} percentile.
Fig. 6: Single-year $\text{DM}_{\text{shoot}}$ yields for all scenario simulations plotted against the corresponding cumulative transpiration including interception (cum. Tl) for (a) site HA, (b) site MA and (c) site RE. Lines crossing the origin assign specific data points, e.g. the data point with the highest TUE (upper line), the data point with the lowest TUE of the SWDF = $T_{\text{act}}$ / $T_{\text{pot}}$ simulation and the data point with the lowest TUE of all other scenarios (lower lines).
Fig. 7: Single-year DM_{shoot} yields plotted against the corresponding cumulative evapotranspiration including interception (cum. ETI) for (a) site HA, (b) site MA and (c) site RE. Lines crossing the origin assign specific data points, like the data point with the highest WUE (upper line), the data point with the lowest WUE of the T_{act} = T_{pot} simulation and the data point with the lowest WUE of all other scenarios (lower lines).
Studies comparing TUE observed for different sites, often mention the dependency of TUE on the saturation deficit (Stöckle et al., 2008 and Ehlers, 1996). However, correlating all of our simulated TUE values with the single-year saturation deficit value (averaged over each vegetation period) led to a very low $r^2$-value of 0.19 ($TUE = -1.207 \cdot \text{saturation deficit} + 9.4$).

Fig. 8 shows the single-year TUE values plotted against the potential cumulative transpiration (potential cum. TI) during vegetation period. The potential transpiration is the transpiration demand and includes beside saturation deficit also other environmental factors, like global radiation and wind speed. The obtained $r^2$-value of the correlation between TUE and potential cum. TI (0.60) was much higher compared to the correlation with the saturation deficit. However, from Fig. 8 it appears that TUE found at RE are shifted parallel, realizing higher TUE values at similar potential cum. TI levels.

Besides WUE and TUE, the PAR radiation uptake efficiency (sum of Q / cum incident PAR) and the light use efficiency (LUE) are important parameters to analyse crop growth under differing environmental conditions. Fig. 9 provides Box-Whisker-plots of the PAR radiation uptake efficiency for the different sites and scenario simulations. All median values of the different site and water supply level combinations ranged around 0.45, so no clear site nor water supply effects on the median were observed. However, concerning the 75th, 90th and 95th percentiles a site and water supply level interaction became evident. The 75th and 90th
percentiles obtained in HA were on a lower level compared to the other sites and both as well as the 95th percentile increased by trend with increasing water availability. For the 75th percentile this increase could also be observed in RE. However, no reaction of the 90th and 95th percentile in RE and in HA also of the 75th percentile on increasing water availability was noticeable at all.

Fig. 9: Box-Whisker-plots of the PAR radiation uptake efficiency calculated by sum of Q divided by the cumulative incident PAR radiation of a whole year. Box-plots are given separately for the three different sites and for all four scenario simulations. Lower and upper boundary of the box give the 25th and 75th percentile, middle line gives the median, lower and upper whisker indicates 10th and 90th percentile, dots give the 5th and 95th percentile.

The light use efficiencies, the ratios between the final DM\textsubscript{shoot} and the sum of absorbed PAR radiation obtained at the different sites under differed scenario simulations are presented in Fig. 10. Without irrigation (SWDF = T\textsubscript{act} / T\textsubscript{pot}), the calculated median LUE values were highest for HA (2.6 g MJ PAR\textsuperscript{-1}) and lowest for MA (2.3 g MJ PAR\textsuperscript{-1}). By additional water supply MA and RE yielded higher LUE values compare to HA, resulting in median values of 3.0, 3.3 and 3.4 g MJ PAR\textsuperscript{-1} for HA, MA and RE, respectively (T\textsubscript{act} = T\textsubscript{pot}).
Fig. 10: Box-Whisker-plots of the LUE given separately for the three different sites and for all four scenario simulations. Thereby, $T_{act}/T_{pot}$ indicates scenario simulation SWDF = $T_{act}/T_{pot}$. Lower and upper boundary of the box give the 25th and 75th percentile, middle line gives the median, lower and upper whisker indicates 10th and 90th percentile, dots give the 5th and 95th percentile.

Fig. 11 presents single-year $DM_{shoot}$ values plotted against the cumulative PAR radiation uptake (sum of Q) separately for the simulation scenario SWDF = $T_{act}/T_{pot}$ (a) and $T_{act} = T_{pot}$ (b). For SWDF = $T_{act}/T_{pot}$ no correlation between $DM_{shoot}$ and sum of Q could be found on the three sites. Q values were ranked according to HA < MA < RE. $DM_{shoot}$ level in RE was slightly higher than at the two other sites even if compared at similar sum of Q levels. Under full water availability ($T_{act} = T_{pot}$) at all sites a positive correlation between $DM_{shoot}$ and sum of Q could be found, which was highest in HA ($r^2 = 0.79$) and lowest in RE ($r^2 = 0.49$). As the regression lines had been forced through the origin, their slopes represent the mean LUE observed at the sites. The slope obtained for HA was comparable lower than the slope found for HA and RE.
3.5. Exemplary studies of changes in leaf area dynamics influencing TUE and WUE

Changes in leaf area dynamics due to environmental limitations, like drought stress or suboptimal temperatures, can affect the TUE and the WUE. Fig. 12 presents exemplarily for RE 2000 and for MA 2001, the drought stress factor SWDF of the scenario calculation SWDF = T_{act} / T_{pot} and the relative GAI (rel. GAI), i.e. the GAI ratio between GAI gained from the
SWDF = $\frac{T_{act}}{T_{pot}}$ and from the $T_{act} = T_{pot}$ scenario plotted against plant development (XStages). These two examples were chosen because the cumulative drought stress was on a similar level, but timing of drought stress differed. SWDF in RE 2000 fell below values of 1 clearly before XStage 3 (silking). At MA, 2001 drought stress started later, around silking. Therefore, a direct and strong reduction of GAI (rel. GAI) by drought stress was observed for RE 2000, whereas only a very small GAI reduction was observed for MA 2001.

![Graph](chart.png)

**Fig. 12:** Relative GAI (rel. GAI) between SWDF = $\frac{T_{act}}{T_{pot}}$ and 80 % 90 % and drought factor SWDF of SWDF = $\frac{T_{act}}{T_{pot}}$ plotted over XStages. Different colours indicate the exemplarily chosen region year combinations, RE 2000 and MA 2001.

The differing impact of drought stress on GAI, shown in Fig. 12, resulted in a differing reaction with respect to TUE (Tab. 9). Silage maize grown at RE 2000 revealed a clear decrease of the TUE under increasing water availability as indicated by a TUE value of 8.7 g L$^{-2}$ for the SWDF = $\frac{T_{act}}{T_{pot}}$ scenario and a TUE value of 8.2 g L$^{-2}$ for the ‘80 % to 90 %’ irrigation scenario. In MA 2001 the TUE values (5.5 and 5.4 g L$^{-2}$) showed hardly any response to irrigation. The ‘80 % to 90 %’ irrigation scenario in RE 2000 led to a strong increase of GAI, which in addition led to a higher proportional increase of global radiation (GlobRad) uptake compared to PAR radiation uptake ($Q / \text{GlobRad}$). This resulted in a decrease of TUE, as transpiration is supposed to be a function of global radiation uptake and dry matter production is a function of PAR radiation uptake. However, the observed change of the ratio between $Q$ and absorbed global radiation in RE 2000 was moderate.
Tab. 9: $D_{\text{m, shoot}}$, cum. TI, TUE, sum of $Q$, cumulative global radiation uptake (sum of GlobRad) and the ratio between sum of $Q$ and sum of GlobRad for $\text{SWDF} = T_{\text{act}} / T_{\text{pot}}$ and ‘80 % to 90 %’ given exemplarily for RE 2000 and MA 2001.

<table>
<thead>
<tr>
<th>Site</th>
<th>Year</th>
<th>Scenario simulation</th>
<th>$D_{\text{m, shoot}}$ [g m$^{-2}$]</th>
<th>Cum. TI [mm]</th>
<th>TUE [g L$^{-1}$]</th>
<th>Sum of Q [MJ PAR m$^{-2}$]</th>
<th>Sum of GlobRad [MJ m$^{-2}$]</th>
<th>$Q / \text{GlobRad}$ [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>RE</td>
<td>2000</td>
<td>$T_{\text{act}} / T_{\text{pot}}$</td>
<td>2484</td>
<td>287</td>
<td>8.7</td>
<td>958</td>
<td>1784</td>
<td>0.537</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80 % to 90 %</td>
<td>3452</td>
<td>421</td>
<td>8.2</td>
<td>977</td>
<td>1857</td>
<td>0.526</td>
</tr>
<tr>
<td>MA</td>
<td>2001</td>
<td>$T_{\text{act}} / T_{\text{pot}}$</td>
<td>2168</td>
<td>396</td>
<td>5.5</td>
<td>870</td>
<td>1642</td>
<td>0.530</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80 % to 90 %</td>
<td>2960</td>
<td>548</td>
<td>5.4</td>
<td>873</td>
<td>1654</td>
<td>0.528</td>
</tr>
</tbody>
</table>

Tab. 10 presents results out of two different years calculated for MA respectively RE, comparing the $\text{SWDF} = T_{\text{act}} / T_{\text{pot}}$ and the ‘80 % to 90 %’ scenario, chosen because the corresponding TUE did not change with water supply level. WUE instead was affected at both sites by differing water supply levels. In MA 1981 it decreased under irrigation and in RE 1994 it increased. As for both site and year combinations the change of WUE was not influenced by a change in TUE, it probably was caused by a change in the proportion of evaporation to evapotranspiration. In RE 1994, additional water supply led to a decrease of the cum. $E / \text{cum. ETI}$ ratio from 0.25 to 0.19. In MA 1981 instead the additional water supply (80 % to 90%) led to a slight increase of the cum. $E / \text{cum. ETI}$ ratio from 0.18 to 0.20.

Tab. 10: TUE, WUE, cumulative transpiration including interception (cum. TI), cumulative evaporation (cum. $E$), ratio between cum. $E$ and cum. ETI (cum. $E / \text{cum. ETI}$) for $\text{SWDF} = T_{\text{act}} / T_{\text{pot}}$ and ‘80 % to 90 %’ as well as number of irrigation events for ‘80 % to 90 %’ given exemplary for MA 1981 and RE 1994.

<table>
<thead>
<tr>
<th>Site</th>
<th>Year</th>
<th>Scenario simulation</th>
<th>TUE [g L$^{-1}$]</th>
<th>WUE [g L$^{-1}$]</th>
<th>Cum. TI [mm]</th>
<th>Cum. $E$ [mm]</th>
<th>Cum. $E / \text{Cum. ETI}$ [-]</th>
<th>Number of irrigation events</th>
</tr>
</thead>
<tbody>
<tr>
<td>MA</td>
<td>1981</td>
<td>$T_{\text{act}} / T_{\text{pot}}$</td>
<td>6.8</td>
<td>5.6</td>
<td>349</td>
<td>75</td>
<td>0.18</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80 % to 90 %</td>
<td>6.8</td>
<td>5.4</td>
<td>386</td>
<td>97</td>
<td>0.20</td>
<td>15</td>
</tr>
<tr>
<td>RE</td>
<td>1994</td>
<td>$T_{\text{act}} / T_{\text{pot}}$</td>
<td>7.4</td>
<td>5.5</td>
<td>272</td>
<td>91</td>
<td>0.25</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80 % to 90 %</td>
<td>7.4</td>
<td>6.0</td>
<td>425</td>
<td>103</td>
<td>0.19</td>
<td>24</td>
</tr>
</tbody>
</table>
4. Discussion
The objective of this work was to evaluate yield potentials and yield gaps of silage maize under different environmental conditions using a calibrated and validated mechanistic crop growth model for silage maize. Especially we aimed to analyse the effects of temperature, radiation and drought stress on yield levels and their variability. In order to quantify drought stress effects and to explore potential yield levels, we simulated four different water supply respectively irrigation scenarios on three typical, but in terms of environmental conditions different sites in Germany. The simulation results concerning attainable yields, LUE, WUE and TUE will shortly be discussed concerning plausibility in terms of their level and ranking. Afterwards, we analyse the impact of direct and indirect temperature and drought stress on yield potentials and resource use efficiencies at the different sites. However, it should be considered that the presented results are generated by a crop growth model and therefore reflect the assumptions made by the construction of the model.

4.1. Level of attainable yield, LUE, WUE and TUE
The attainable average yields (SWDF = T_{act} / T_{pot}), simulated for the three regions, ranged from 1930 g m\(^{-2}\) (HA) to 2240 g m\(^{-2}\) (RE) (Fig. 3). These values are in good accordance with results from federal variety experiments. These experimental data usually are not confounded by suboptimal crop management. For Schleswig-Holstein, the federal state in which HA is located, the measured 3 years (2008 – 2010) average yield of mid early hybrids was 1959 g m\(^{-2}\) (LK Schleswig-Holstein, 2010). Mid early cultivars grown at comparable sites to MA yielded in average (2007 – 2009) 2106 g m\(^{-2}\) (Kuhlmann, 2010). For Bavaria, the federal state where RE is located, an average long-term yield of 2149 g m\(^{-2}\) was measured for the mid early maturity group (LfL, 2010).

Also the estimated LUE values (Fig. 10) are comparable to reported values. Andrade et al., 1993 for example, found similar to our results LUE values ranging from 2.3 to 3.2 g MJ PAR\(^{-1}\) for maize crops grown under low temperature conditions, comparable to those of North Western Europe. Values of WUE and also TUE reported in literature for maize vary for several reasons to a large extent. For example, data presented by Grassini et al., 2009 indicate for North Western Europe TUE values > 5.4 g L\(^{-1}\), whereas Kropff et al., 1984 assumed a TUE of 10 g L\(^{-1}\) for silage maize grown in the Netherlands. Therefore, the TUE values, found in our simulation study (Fig. 5), are within this range of literature values. Also our simulated WUE values are on a same level to the WUE values (4.5 – 7.6 g L\(^{-2}\)) found by Schittenhelm, 2010 for a maize / sorghum intercrop under different water supplies grown on a site with comparable climatic conditions to those of MA.

These comparisons of our model results to data or values given in literature prove the ability of the model to be used as a simulation tool for studying yield potentials, LUE, TUE and
WUE of silage maize (mid early cultivar) grown under the environmental conditions of the three chosen sites in Germany. Additionally a validation of the model towards independent data sets was already given in ‘Chapter 2’.

4.2. Direct and indirect stress impacts on dry matter production and LUE

Suboptimal temperature and drought stress can have diverse effects on crop dry matter production. Both influence the metabolic processes directly negative, which results in a reduction of growth rates (Andrade et al., 1993). During the vegetative development stages (before silking) this can also result in a reduction in dry matter partitioned to the leaves and especially in a decrease of specific leaf area and therefore finally in reduced leaf area. This in turn can have a negative feedback on radiation uptake (Maddonni and Otegui, 1996; Muchow and Carberry, 1989), and therefore on dry matter production. Because temperature is the key driver of crop development, some indirect effects on dry matter production can also be caused by effects on the duration of single development stages (e.g. emergence or vegetative growth) and the duration of the whole crop growth period (Muchow et al., 1990). Additionally, some specific stress effects are mentionable, like drought or heat stress during silking, limiting grain yield by influencing the sink strength or the fertility of the ovaries (Earl and Davis, 2003), but will not discussed further on, because the used crop growth model dose not consider these mechanisms.

However, the interaction between site specific conditions, simplified weather and soil, and crop genotype determines the strength and timing of the impact of these different factors. This interaction mainly determines which effect is most important for silage maize growth on a specific site or even more in a specific region.

4.2.1. Temperature stress effects

With mean temperatures between 14.7 and 16.0 °C temperature stress is most often determined by suboptimal temperatures and occurred at all three sites, as proved by $f_T$ values being $< 1$ during the whole vegetation period (Fig. 2). The Northern most region, HA, is characterised by the lowest mean air temperature and obtained the lowest amount of global radiation during the growing season (Tab. 1). On the other hand, the total sum of available water was with 572 mm by approx. 90 mm higher compared to the two other sites (Tab. 4). Therefore in HA the average dry matter production was lowest (Fig. 3), but the gap between attainable yield (SWDF = $T_{act}$ / $T_{pot}$) and yield potential under full water availability ($T_{act} = T_{pot}$) was smallest (Fig. 3). As expected drought stress therefore is not the most important stress at this site. However, according to the cumulative drought stress units (Fig. 4), drought stress also occurred in HA, but it was with an averaged value of 20 d (SWDF = $T_{act}$ / $T_{pot}$) approx. 10 d lower compared to the two warmer sites.
The low yield potential observed at HA also was not mainly the result of a lower global radiation supply. Comparing HA and MA, global radiation supply was in HA 98% of the supply in MA (Tab. 1), whereas the yield potential \( T_{\text{act}} = T_{\text{pot}} \) obtained in HA reached only 84% of the yield potential obtained in MA (Fig. 3). Clearly, low temperatures seem to be the key stress factor in HA. This is also indicated by our calculated LUE values excluding drought stress (Fig. 10 and slopes of the regression lines of Fig. 11 (b)) which were with a median value of 3.0 g MJ PAR\(^{-1}\) lowest at the coldest site, HA, and with values of 3.3 respectively 3.4 g MJ PAR\(^{-1}\) highest at the two warmer sites, MA and RE. Because, other negative factors influencing the level of the LUE, like high radiation intensity (Kage et al., 2001; Stöckle et al., 2008), could be excluded, the low LUE observed in HA probably resulted from a direct effect of low temperatures. Analysis of Fig. 2 strongly supports this conclusion concerning the importance of temperature stress in HA. Moreover, it allows additionally an assumption towards direct and indirect stress effects. Temperature stress was, especially in the beginning of vegetation period, most obvious in HA. The time course of the ratio between absorbed and incident PAR radiation \( (Q / \text{incident PAR}) \) at HA compared with the two warmer sites (Fig. 2) shows that low early temperatures led to a strong delay in radiation uptake caused by a delay of leaf area growth (Fig. 1). A strong indirect stress effect of low temperatures on plant growth is therefore obvious in HA. Partly this is caused by a delay of mean emergence dates which were 6 days later compared to the two warmer sites.

On the other hand and at least for the chosen mid early maturing cultivar, lower temperatures may lead to an extension of averaged crop vegetation period. In HA in nearly all years the maximum duration of vegetation period was reached, whereas in MA and in RE crop was harvest before harvestdate\(_{\text{latest}}\) in half of the years (Tab. 5). A longer vegetation period, here averaged over 35 years, is expected to increase the amount of radiation uptake by a higher leaf area duration (Muchow et al., 1990). However, Tab. 6 shows, that no prolonged GAD was observed in HA compared to the other sites, so the contrasting temperature effects on leaf area development (early delay, but prolonged mean vegetation period) cancel out each other concerning the GAD. The temperature effects resulted even in a lower sum of Q (Tab. 6) in HA compared to MA and RE. In the beginning of maize growth the PAR radiation supply (Fig. 1) was in all regions much higher than in autumn. Additionally, the maximum GAI values (approx. 5-6) were in all regions on a level, where additional green area does not cause proportional increase in PAR radiation uptake (Fig. 2). Consequently, the reduced PAR uptake in HA in the beginning of growth was not counterbalanced by the prolonged leaf area duration at the end of vegetation period.
4.2.2. Drought stress effects

Under drought stressed conditions crop productivity was poorly correlated with the amount of absorbed radiation (Fig. 11a), but without drought stress a clear relationship between dry matter production and radiation uptake was obvious at every site (Fig. 11b). This indicates the strong drought stress impact at all sites, including HA. Our simulation study allows quantifying the impact of drought stress on yield production in detail, differentiating between direct and indirect drought stress effects.

Drought stress reduced yield potential ($T_{act} = T_{pot}$) in average at HA by approx. 500 g m$^{-2}$, at MA by approx. 880 g m$^{-2}$ and at RE by approx. 860 g m$^{-2}$. Accordingly, the decrease of average LUE due to drought stress was also highest for MA and RE. This stronger LUE decrease indicates the higher impact of direct drought stress at the two warmer sites. However, the indirect drought stress impact on dry matter production was in average over the 35 years negligible. For HA and RE exists in the very early beginning a period, in which SWDF was < 1 and lower compared to MA (Fig. 2). Still, the strongest drought impact occurred at all sites mainly from the end of June till the end of the vegetation period.

The mild early drought stress period, observed at HA and RE, occurred in HA because of a common spring drought in this region. In RE the amount of SW$_{pa}$ at sowing was, especially compared to MA with approx. 110 mm very low. Therefore, in RE the availability of water is relatively more based on precipitation. As availability of water from precipitation is a function of long term precipitation disposition in the specific region and actual weather conditions, it causes a higher uncertainty of water availability compared to SW$_{pa}$. This might result in some years in an early drought in RE and therefore possibly to an early reduction of green area expansion (Debeake and Aboudrare, 2004). However, comparing the GAI time course of MA and RE directly showed that RE gained on average slightly higher GAI values, starting at the beginning of July (Fig. 1). This indicates that possible reductions of GAI by early drought stress in RE were on average of the 35 years cancelled out. Other environmental factors, like the slightly higher amount of global radiation (Tab. 1) observed at RE were in terms of green area differences between MA and RE more important. Finally, the observed sum of $Q / \text{cum}$ incident PAR ratio obtained from the SWDF = $T_{act} / T_{pot}$ and $T_{act} = T_{pot}$ scenario calculations (Fig. 9) did not differ. Consequently, in terms of dry matter production, indirect drought stress effect was at none of the sites of high importance.
4.3. Site differences concerning TUE and WUE

4.3.1. Site differences concerning TUE and WUE

The level of TUE and WUE for maize varied to a large extent between sites (Fig. 5). Independently of the water supply level RE obtained the highest TUE and WUE level, followed by HA, whereas MA obtained the lowest level. As indicated by the scatter plots of (Fig. 6) MA showed a wider range of cum. TI and higher maximum cum. TI than the other two sites because of a generally higher evapotranspiration demand (Tab. 8, Fig. 8). At the high level of cum. TI at MA, DM_{shoot} increased not anymore proportionally with increasing cum. TI resulting in low TUE values (slope of the line, which connects one data point with the origin). Differences in TUE result from different environmental conditions influencing dry matter production and transpiration not proportional. For low TUE values at high cum TI levels probably high saturation deficits and wind speeds are possible reasons. Both affect the evapotranspiration demand positively (see Penman-Monteith equation in Chapter 2), without affecting the dry matter production, which results in lower LUE values. A negative affect of saturation deficit on TUE is well known and often discussed in literature (Stöckle et al., 2008; Ehlers, 1996). However, correlating all single-year TUE values with the corresponding saturation deficit led only to a poor correlation ($r^2 = 0.19$), whereat the distribution of data resulting from the different scenario simulation had been equal. The single-year TUE values, however correlated well with the corresponding potential cum. TI ($r^2 = 0.60$, Fig. 8), indicating that besides saturation deficit also wind speed may account for varying TUE values. TUE values gained at similar potential cum. TI level were most often higher at RE compared to the two other sites (Fig. 8). Higher temperatures at similar potential cum. TI levels may explain this. Mean temperatures (averaged over 35 years) in June, July and August were highest in RE (data not shown).

The differences of WUE between the regions are comparable to those already described concerning TUE (Fig. 5 and 7). But increasing water availability to $T_{act} = T_{pot}$ resulted at all sites in a noticeable decrease of WUE (Fig. 5) an effect which was not observed for TUE. Under full water supply evaporation is just restricted by energy supply to the soil surface (Suleiman and Ritchie, 2003) and not by water availability. So, unproductive evaporation increased and therefore WUE decreased.

4.3.2. Indirect drought stress impacts on TUE and WUE

Following section 4.2.2., no clear indirect drought stress effects on dry matter production or LUE were observed in average over the 35 years at all sites. However, by trend the $5^{th}$, $10^{th}$, $25^{th}$ percentile of TUE decreased at HA and MA with increasing water supply, whereas in RE no effect of increasing water supply was noticeable (Fig. 5). This indicates at least by trend
an interaction of water supply level and site concerning TUE and WUE values, which was probably more distinct in single years. Therefore, we analysed this effect exemplary by single-year analyses of the two warmer sites RE and MA, showing that different effects can occur parallel at one site and might cancel each other out (Fig. 12, Tab. 9 and 10).

Again, leaf area played a key role in these complex interactions of stress impacts. Fig. 12 showed strong drought stress clearly before XStage 3 (silking) at RE 2000, resulting in an obvious reduction of green area, whereas in MA 2001 a comparable strong but later drought stress was observed, which did not affect leaf expansion. This time dependent differing impact of drought stress on GAI resulted in a differing reaction of TUE (Tab. 9), with a clear decrease of the TUE under increasing water availability in RE 2000, whereas in MA 2001 TUE stayed constant independent of water availability. This indicates that the increased DM\textsubscript{shoot$_{growth}$} growth due to additional water supply in RE 2000 was under-proportional compared to the transpiration increase, whereas for MA in average a proportional increase of dry matter and transpiration could be assumed. The ‘80 % to 90 %’ irrigation scenario led in RE 2000 to a strong increase of GAI up to a high level (7.1), which again led to a higher proportional increase of global radiation uptake compared to PAR radiation uptake, resulting in a TUE decrease. This is due to the fact that the absorption efficiency of global radiation as a function of GAI differs from that of PAR radiation (Bonhomme, 2000). Ritchie and Basso, 2008 also discussed similar effects of differing threshold GAI values for maximum transpiration and maximum light interception for photosynthesis. However, the increase of absorption efficiency of PAR radiation with increasing GAI is higher compared to the increase of absorption efficiency of global radiation when GAI levels are low, resulting in an increasing TUE by increasing GAI. When GAI levels are high the increase of absorption efficiency of PAR radiation with increasing GAI is lower compared to global radiation, resulting in a decrease of TUE with increasing GAI. Latter, caused the decrease of TUE in RE 2000.

Tab. 10 presents with RE 1994 an example for a TUE in a drought stress year (significant increase of cum. TI), which stayed constant even if GAI increased strongly (approx. 20 %) with increasing water availability. The GAI (4.9) reached in the SWDF = $T_{\text{act}} / T_{\text{pot}}$ scenario was on a level where an increase of GAI results in an increasing TUE, but the GAI gained under the irrigation scenario (6.2) was probably already on a level, where GAI increase results in a decrease of TUE. So, the additional water supply and therefore the increases of green area led more or less incidentally to the same TUE observed in the SWDF = $T_{\text{act}} / T_{\text{pot}}$ scenario. However, the observed change of the ratio between $Q$ and absorbed global radiation in RE 2000 (Tab. 9) was not very high and this therefore not explains the strong response of the TUE value entirely. But a second effect of increasing GAI is mentionable. The increasing GAI leads to a reduction of whole canopy resistance (see Penman-Monteith equation in Chapter 2; Steduto and Hsiao, 1998). This results in an increasing transpiration,
but not consequently to a proportional increase in PAR radiation uptake. In literature another positive effect of drought stress on TUE was reported (Stöckle et al., 2008), which is due to a non-linear effect of stomata closure towards the reduction of CO$_2$ and H$_2$O fluxes, caused by the additional mesophyll resistance for CO$_2$ (Ferreyra et al., 2003; Sinclaire et al., 1975). However, according to the simple LUE base approach the used silage maize growth model is neglecting these circumstances.

Besides this, drought stress effects on TUE, WUE can additionally be affected by a changing GAI due to a change in the proportion of evaporation to evapotranspiration (Gregory et al., 2000). In MA 1981 WUE decreased under irrigation and in RE 1994 it increased (Tab. 10). As the change of WUE in both region year combinations was not influenced by a change in TUE, it possibly was a result of a change in the proportion of evaporation to evapotranspiration. In RE 1994, additional water supply led to an increase in leaf area, reducing the available energy for evaporation and the cum. E / cum. ETI ratio decreases from 0.25 to 0.19. A comparable reduction of the evaporation proportion of evapotranspiration going down from 0.19 (SWDF = T$_{act}$ / T$_{pot}$) to 0.16 (‘80 % to 90 %’), under irrigation was also observed in RE 2000 (data not shown). This might affect the WUE positively because it reduces the amount of unproductive evaporation, by reducing the amount of energy supplied to the soil surface, leaving the water for productive transpiration and so resulting in an increase of WUE (Suleiman and Ritchie, 2003; Gregory et al., 2000; Debeake and Aboudrare, 2004). In RE 1994 this positive effect on WUE was obvious, whereas in RE 2000 the decreasing TUE levelled this effect out and WUE stayed constant (data not shown). In MA 1981 instead the additional water supply (80 % to 90%) led to a slight increase of the cum. E / cum. ETI ratio from 0.18 to 0.20, caused by a combination of unchanged leaf area and the increase of soil water content in the upper soil layer as a consequence of every irrigation event.

In this context the differing physical soil properties of the two regions are also mentionable. As evaporation only takes place from the most upper soil layer (Suleiman and Ritchie, 2003), the infiltration rate of water is a key soil property. In MA the saturated water conductivity (Tab. 2) was comparably low. Therefore, the additional water infiltrated slowly and together with a comparable high amount of water supplied per irrigation event (Tab. 9) led to a high water loss by surface runoff. Thus, the real amount of water, which was available for increasing soil water content from ‘80 % to 90 %’ plant available soil water, was quite low and caused an increase in irrigation events in the SWDF = T$_{act}$ / T$_{pot}$ scenario (Tab. 9), even if drought stress was not very strong. Consequently, the proportion of evaporation to evapotranspiration was shifted towards evaporation and the WUE decreases. In RE instead, the amount of water supplied per irrigation event was indeed low, but the high saturated
water conductivity led to a fast infiltration and consequently the additional water was than available for transpiration, but not anymore for evaporation.

4.4. Regional assessment of yield potentials

Summing up the analyses of direct and indirect stress effects indicates that, comparing the most northern site HA with the other sites, low temperature is at HA the most important factor influencing directly and indirectly yield potential and LUE. Here, low temperatures led in average over the 35 years to a clearly delayed leaf area expansion, causing the lower yield potential level compared to MA and RE. At all sites, but to a larger extent at the two warmer sites, drought stress is directly limiting dry matter production by reducing LUE. The indirect effects of drought stress on dry matter production and LUE were marginal. Still, the exemplary analyses underlined the importance of leaf area for the various effects of indirect drought stress respectively of additional water supply on the WUE and TUE. The single year site combination studies showed, that indeed indirect drought stress effects can be observed at all sites, but that the different effects often cancel out each other with in a single year or that averaging over 35 years conceal these effects.

However, the differences in yield, LUE, WUE and TUE between the sites are obvious. Due to higher temperatures combined with higher global radiation supply, RE, the most southern site, gained, with 3098 g m\(^{-2}\) (averaged over 35 years), the highest yield potential (\(T_{act} = T_{pot}\)). Drought stress did not reduce dry matter that strong, resulting in an average attainable yield (2240 g m\(^{-2}\)) well above the one obtained for HA (1930 g m\(^{-2}\)). However, the yield gap (yield potential – attainable yield) observed for RE (860 g m\(^{-2}\)) was considerably higher compared to HA (approx. 500 g m\(^{-2}\)). Due to favourable high temperatures, maize crops grown at MA reached also a high yield potential (2902 g m\(^{-2}\)). But this was, caused by slightly lower global radiation supply, still lower compared to RE. Yield reduction due to drought stress was also higher (approx. 880 g m\(^{-2}\)) in MA. Moreover, the use of water, rain fed or additionally applied, was most inefficient at MA, due to a generally high evapotranspiration demand, caused by a combination of high saturation deficit and wind speed. In terms of WUE a second, but smaller effect, was noticeable, which was due to the lower saturated water conductivity leading to a stronger increase in evaporation by increasing water availability. The northern most region, HA, achieved the lowest yield potential (2435 g m\(^{-2}\)), caused by direct and indirect temperature limitations. Also the attainable yield was lowest, even if the LUE found under rain fed conditions was slightly higher compared to the two other sites, indicating, that the direct drought stress impact at these two warmer sites tended to be stronger than the direct temperature effect at HA. However, the presented results support strongly the assumption that silage maize production was most valuable at the two warmer more southern sites.
The simulated DM$_{shoot}$ values under full water supply indicate the average potential yield for the chosen maize cultivar, representing the mid early maturity group, at the three sites. Assuming crop management to be optimal within the simulation study, only irrigation remained a possible tool for closing the yield gap between attainable yield and yield potential. The presented results indicate that additional water supply is to a different extent effective at the different sites. Since at HA the observed yield gap and the reachable yield potential were lowest, HA is not the most favourable irrigation site. But HA tends towards early drought stress, which can, besides effecting crop growth directly, limit green area expansion in some years, leading to a reduction in dry matter productivity, or at least to a reduction in water use efficiency. However, additional water supply at the two warmer sites MA and RE seem more efficient, as the reachable yield potential was higher compared to HA. Due to the described differences in water and transpiration use efficiency and due to the slightly higher yield potential, RE is probably the site at which additional water supply is most efficient. For MA the irrigation method tend to be very important, as discussed by comparing the results between the different water supply levels, showing ‘60 % to 80 ‰ to be the most efficient, and most realistic scenario.

Other strategies for improving yields lead to a shift in yield potential. A commonly discussed strategy, especially in terms of silage maize production for using in biogas plants, is to choose cultivars out of a higher maturity group, because late ripening cultivars can produce higher yields (Amon et al., 2007b). Even if we did not include late cultivars in our study, the presented results indicate that the success of this strategy might be limited at the chosen sites. The choice of a late cultivar would lead at all sites to an expansion of the vegetation period into late autumn, been soon restricted by temperatures below base temperature or even by frost events. As in HA the mid early cultivar did not reached full maturity in most of the years, quality e.g. dry matter content might also be a limiting factor at this site. Anyway, our results concerning the temperature impact on green area growth showed clearly, that an extended vegetation period would neither lead to an increase in PAR radiation uptake nor to an increase in dry matter production at HA. Concerning the two warmer sites, MA and RE, the strategy of later maturity might fail because of low water availability. In general, our simulation study showed that yields up to approx. 30 Mg ha$^{-1}$ are achievable with irrigation, but the amount of additional water supply would be comparably high, especially at a site like MA. However, without breeding efforts towards higher water use efficiency and chilling tolerance of maize cultivars yield potentials will probably not exceed 30 Mg ha$^{-1}$, at least in the three studied maize production regions.
5. Conclusions
The simulation study shows, that crop growth modelling is an appropriate tool to evaluate biomass yield potentials of silage maize grown under differing environmental conditions. The used model provides by dynamic simulation of crop growth processes and water balance, the ability to analyse stress impacts, like temperature or drought stress, which limit yield potential and influence resource use efficiencies. The presented results indicate that stress factors, like temperature limitations or drought stress led to a direct reduction of dry matter growth and caused, depending on the intensity and timing of the stress impact, a reduction of leaf area growth reducing biomass yield potential by feedback reactions concerning PAR radiation uptake. A stress induced impact on leaf area influenced both, the ratio of evaporation and evapotranspiration and the level of transpiration use efficiency. Therefore, depending on the year site combination, different water supply levels resulted either in increasing, decreasing or constant water use efficiency. Consequently, if above ground biomass is the production target, crop management issues, like irrigation, have to ensure an optimal leaf area growth and have to be adapted to the cropping region. Anyway, even with full water availability in our simulation study yield potentials did not exceed 30 t ha\(^{-1}\). Strategies to increase yield potential levels seem more valuable by trying to improve chilling tolerance and water use efficiency, than by simply trying to increase green area duration and therefore PAR radiation uptake.
Evaluating the yield potentials and resource use efficiencies of silage maize grown in the three considered regions of this simulation study, indicates that due to higher yield potentials production capacity of silage maize is higher in the warmer regions of Germany. For the colder regions with sufficient water supply it could be worth to discuss and investigate alternatives to silage maize grown in monoculture for biomass production, like intensive energy crop rotations mixing C\(_3\)- and C\(_4\)-plants.

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References


Evaluation of productivity, light and water use efficiency of different bioenergy cropping systems: a combined experimental-modelling approach

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Keywords: crop rotation, silage maize, bioenergy, aboveground biomass, LUE, WUE, TUE, biogas

Abstract
In terms of economical profitability, but also for the greenhouse gas reduction effect, energy cropping systems for producing biomethane have to realise high biomass yields. Bioenergy cropping is most often based on maize cultivated in monocultures due to its high yield potential. In order to reduce environmental problems arising from maize monocultures alternative cropping systems attract notice to agronomy. This study evaluates light and water use efficiencies of different bioenergy cropping systems, by a combined experimental-modelling approach. At two field sites in Northern Germany perennial ryegrass and intensive crop rotations including winter intercrops and combining C₄- and C₃-crops were compared with maize monocultures with respect to their productivity and nitrogen use efficiency. Comparison of these cropping systems showed that intensive crop rotations can reach, due to prolonged leaf area duration a biomass yield level similar to maize monocultures under northern German climatic conditions (low annual air temperatures and high annual amounts of precipitation). Still, the needed nitrogen supply was higher for these crop rotations and the yield performance of maize grown within rotations was highly dependent on the proceeding crop. Perennial ryegrass was on the chosen experimental site clearly less productive than maize grown in monoculture. Groundwater recharge was mainly site dependent, but on both sites higher for maize than for crop rotations.
1. Introduction

The energy policy of the European Union and Germany strongly promote renewable energy production. Germany has recently become the most important producer of biogas (biomethane) worldwide (Weiland, 2010). The key substrate for the biogas plants is, with over 90% (DMK, 2006), whole-crop maize silage (Schittenhelm, 2008). This causes a strong increase of acreage cultivated with maize in monoculture (Schittenhelm, 2010), also on less productive sites. In order to reduce problems arising from maize monoculture, like reduction of crop species diversity, increase of pest pressure or possible increase of nutrient losses, investigations on alternative cropping systems attract notice in agronomy (Schittenhelm, 2010). Biomass cropping for energy production can only be sustainable, if high biomass yields per unit acreage and high resource use efficiencies are achieved.

Different alternative biomass production systems, such as double- and inter-cropping or crop rotation systems, have been proposed in literature (Karpenstein-Machan and Stuelpnagel, 2000; Heggenstaller et al., 2009; Schittenhelm, 2010; Vetter et al., 2010). However, as high biomass yields can only be obtained, if environmental resources, such as radiation and water, are used in a most efficient way, a site adapted choice of the cropping system using the most suitable crops for a specific region is necessary.

Under the climatic conditions of Northern Germany, which are characterised by low air temperatures (annual and summertime) and relatively high amounts of precipitation uniformly distributed over the year, for example intensive crop rotations including winter intercrops and combining \( C_4 \)- and \( C_3 \)-crops might provide an adequate alternative to maize monoculture. This is because relatively low temperatures at least during the early growth period are comparatively more unfavourable for the thermopile \( C_4 \)-plant maize (Andrade et al., 1992).

Secondly, in this region the water availability is high, so that the prolonged leaf area duration of crop rotations and therefore their higher water demand might not cause suffering from strong drought stress. Instead, the prolonged leaf area duration may cause a high cumulative uptake of photosynthetic active radiation (PAR) which leads, depending on the light use efficiency (LUE), to a high biomass production (Dohleman and Long, 2009; Heggenstaller et al., 2009).

To investigate dry matter productivity and resource use efficiency of energy cropping systems for the Northern part of Germany, a two year field experiment was conducted on two differing sites (tillage area vs. forage production area). Thereby we established on a site with loamy sand soil texture three contrasting cropping systems, including a maize monoculture, an intensive biomass crop rotation (silage maize – silage wheat - grass winter intercrop) and a mixed crop rotation (silage maize – grain wheat – mustard winter intercrop) and on a sandy soil site a maize monoculture and a four-cutting perennial grassland. All cropping systems were cultivated under four different N-supply-levels.
The objective of the presented study was to analyse resource use efficiencies of different cropping systems for biomass production including effects of environmental factors (radiation, temperature and water) and the nitrogen supply level. For that purpose data gained by a field experiment, and a simple semi descriptive mode were used. The model includes soil water and evapotranspiration processes.

2. Material and Methods

2.1. Experimental data

A multi-factorial (site, cropping system, nitrogen-amount) field experiment was conducted during the main experimental years 2007 and 2008 at two different sites, Hohenschulen (HS) (54° 18'N, 9° 58'E) and Karkendamm (KD) (53° 55'N, 9° 56'E) in Northern Germany. HS is located in a typical tillage area, whereas KD is located in a forage production area. So, the sites mainly differed concerning soil types, with a sandy loam soil (Luvisol) in HS and with a sandy soil (Gleyic Podzol) in KD. Assuming an effective rooting depth of 100 cm plant available soil water would be approx. 166 mm in HS and approx. 125 mm in KD. However, KD is a groundwater affected site, with groundwater tables going up to 80 cm in winter and decreasing down to 240 cm in summer. Additional, in KD an incipient orterde was found in the soil layer 30 – 40 cm. Further information about the soil texture, Van-Genuchten-parameter ($\alpha$, $\theta_s$, $\theta_r$ and n) and saturated water conductivity (KS) are given in Tab. 3. Both sites are characterised by an average annual precipitation of approx. 750 – 800 mm with a uniform allocation over the year and a relatively low mean air temperature of approx. 8.5 °C. Weather data given in Tab. 1 separately for the experimental years indicate that at HS and KD the sum of precipitation was in 2007 with 903 mm respectively 1040 mm significantly higher compared to the long term average. Also the averaged air temperature was on both sites with approx. 1.7 °C above the long term mean value. Whereas, 2008 was just a bit warmer (approx. + 1.1 °C), but not more wet compared to the long term average. The two sites differ mainly by approx. 1.0 m s$^{-1}$ higher wind speed in both years in HS compared to KD. Both sites tend to a drought period during spring. In 2007, April was with summed rainfall values of 2 mm for HS and 9 mm for KD very dry. In 2008 a dry period occurred in May with 17 mm HS and 12 mm for KD, respectively. The weather data were recorded directly on the field sites.
Tab. 1: Weather conditions for the two experimental sites Hohenschulen (HS) and Karkendamm (KD). Average air temperature, wind speed and saturation deficit values as well as sum of global radiation and precipitation are given for a whole year, from beginning of January till end of December.

<table>
<thead>
<tr>
<th>Site</th>
<th>Year</th>
<th>Air temperature [°C]</th>
<th>Global radiation [MJ m⁻²]</th>
<th>Precipitation [mm]</th>
<th>Wind speed [m s⁻¹]</th>
<th>Saturation deficit [mbar]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HS</td>
<td>2007</td>
<td>10.1</td>
<td>3525</td>
<td>903</td>
<td>3.0</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>2008</td>
<td>9.5</td>
<td>3560</td>
<td>706</td>
<td>3.1</td>
<td>2.4</td>
</tr>
<tr>
<td>KD</td>
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<td>3490</td>
<td>1040</td>
<td>2.1</td>
<td>2.1</td>
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<tr>
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<td>9.7</td>
<td>3619</td>
<td>724</td>
<td>2.1</td>
<td>2.4</td>
</tr>
</tbody>
</table>

The experiment was established in mid of September 2006. The experimental design was a randomized block design with four replications for each treatment. Plot size was 12 x 12 m. The established cropping systems (FF) differ between HS and KD. In KD maize grown in monoculture (FF1) and a four-cutting perennial grassland (FF4) was cultivated. In HS again maize grown in monoculture (FF1) and two crop rotations were observed. One was with silage maize, silage wheat and a two-cutting grass winter intercrop an absolute biomass rotation (FF2). The other was a mixed food-biomass rotation with silage maize and grain wheat followed by a mustard catch crop (FF3). The two crop rotations (FF2 and FF3) were each one established two times, differing by the starting crop in autumn 2006. For a short overview of the established cropping systems see Fig. 1. The used maize hybrid in FF1 and FF3 was a mid early cultivar (S 240, Ronaldino, KWS), whereas the hybrid used for FF2 was an early cultivar (S 200, Salgado, KWS); with the maturity index (BSA, 2008); name of cultivar and breeder given in brackets. All maize crops were established with a plant density of 10 plants m⁻² and a row-spacing of 0.75 m. FF4 was established with a Perennial ryegrass mixture (Fennema and Edda, NPZ) at a sowing density of 30 kg ha⁻¹ and a row-spacing of 0.1 m. The wheat (Biscay, C-type-wheat, KWS) used for both grain and silage production was sown with 240 seeds per m² and a row-spacing of 0.1 m. The winter intercrop of FF2 was an Italian ryegrass (Gisel, NPZ), which was established with a sowing density of 40 kg ha⁻¹ and a row-spacing of 0.1 m. The in FF3 used catch crop was a mustard, sown with 15 kg ha⁻¹ and a row-spacing of 0.1 m. Fig. 1 shows harvest respectively sowing dates (thin lines) of each particular crop. If the interval between harvesting and sowing of the following crop was < 14 d sowing date was not extra signed. Nitrogen fertilizer was graded in four levels N1, N2, N3 and N4. For maize and wheat this was 0, 120, 180 and 360 kg N ha⁻¹, split, respectively, for maize in two and for wheat in three applications of equal N rates. For the perennial ryegrass the amount of N given per N level was with 0, 160, 320, 480 kg N ha⁻¹ higher compared to maize and wheat. Nitrogen supply for the perennial ryegrass was split into four slightly decreasing applications, given in the early beginning of each growth. For the Italian ryegrass only two nitrogen supply levels were distinguished, N1 with 0 kg N ha⁻¹ and N2, N3 and N4 with 160 kg N ha⁻¹. Here, again the nitrogen fertilisation was split (two equal rates) and given in the early beginning of each growth. The catch crop of FF3 was not
fertilised. Nitrogen fertilizer was applied as calcium ammonium nitrate. Otherwise, plants were treated according to local best practice recommendations.

Fig. 1: Cropping systems of the field trial in HS and KD. Thin vertical lines indicate sowing or harvest (or cutting) dates, if the interval between harvesting and sowing of the following crop was < 14 d sowing date was not extra signed. Arrows indicate the freezing off date of the catch crop, used as harvest date. Thick vertical lines with dots show start and end of the quantification periods by modelling (24 months). ‘Initiation’ indicates the model calculation period conducted in advanced to level off some output variables, e.g. soil water contents.

Description of plant sampling and measurement methods are focusing only on the data, which were actually used in the presented study, so mainly on aboveground dry matter [g m⁻²] (DM yield), crop height [cm] and green area index [m² m⁻²] (GAI) and N content [kg N ha⁻¹]. The DM yield data were obtained from mechanical harvest. Crop height and GAI were measured during the vegetation period in general fortnightly, resulting in approx. 13 -17 measurements per year in the maize and wheat crops and in ≥ 4 measurements per cut in the grass crops. But, in the catch crop only in 2008 five measurements were conducted. Crop height was measured with a folding rule in all crops in N1 and N4, but not in the maize crops grown in FF3. For early determination of GAI, pictures have been taken with a standard digital camera. Using a digital image analysis technique (Böttcher, personal communication), canopy closure was determined. Out of these canopy closure values the GAI was calculated by a transformation of the Lambert-Beer law. For higher GAI values (GAI > 1), GAI was determined using the LAI-2000 (LI-COR LAI-2000 meter; LI-COR, Inc., Lincoln, NE). For maize and wheat attended to every second GAI measurement conducted by digital pictures or LAI-2000, also a ‘destructive’ GAI measurement was done. Here, plant samples of 0.25 m² or of 10 plants (maize) per plot were taken. Plants were fractionated and leaf and stem area were measured using the LAI-3100 (LI-COR, Inc., Lincoln, NE). N uptake of the winter intercrops was calculated by multiplying DM yield and N content. N content was determined by near-infrared-spectroscopy (FOSS NIR Systems Modell 5000).

The weather data were recorded directly on the field sites. Soil water content was measured approx. fortnightly with time domain reflectometry (TDR) technique (Dobson et al., 1985) in
30 cm thick layers down to 120 cm. Soil samplings for gravimetric water content measurements have been generally conducted at every sowing and harvest date and at the beginning and end of vegetation period. These soil samplings have been also taken in 30 cm thick layers but only down to 90 cm. Furthermore, a soil profile classification was done at three soil pit dug for each site. Soil analyses included, for each soil horizon, a determination of soil texture, soil bulk density, matrix potential dependent water contents and of saturated soil conductivity.

2.2. The model

2.2.1. General concept
For conducting the presented simulation study a simple cropping system model, which links single crops to a crop rotation, was used. This model calculates potential evapotranspiration and soil water balance dynamically, including an empiric dynamic modelling approach for root growth. Aboveground crop growth, instead, is described by linear interpolation of the data gained from the field experiments. Integrating these different modelling approaches is possible due to the sub model based structure. For a better handling of the up-scaling from the single crop to the cropping system level an additional sub module, which aggregates selected results, is implemented. Furthermore, the soil water content of the last crop is consigned to the following crop. Latter was done in order to assure, that a possible depletion of soil water content is considered in the model calculations.

The model is implemented using an object orientated component library (Kage and Stützel, 1999), which works with the concept of visible software components of the Delphi®/C++ Builder®, Borland. Principally it runs on daily time steps, just internal processes of the soil water balance module are calculated by a variable length of time steps. External data inputs required for running the model are daily mean temperature [°C] (T\textsubscript{mean}), incoming global radiation [W m\textsuperscript{-2} d\textsuperscript{-1}], precipitation [mm], wind speed [m s\textsuperscript{-1}] and air humidity [%]. The latter is used to calculate vapour pressure [mbar] and saturation deficit [mbar].

2.2.2. Evapotranspiration module
For the calculation of potential evapotranspiration [mm d\textsuperscript{-1}] (ET\textsubscript{pot}) the Penman-Monteith equation (Monteith, 1973) is implemented in the model. The used variables concerning environmental conditions, such as global radiation, wind speed, saturation deficit and daily mean temperature, are derived from the input weather data. The crop variables GAI and crop height, which are necessary for calculation of canopy resistance [s m\textsuperscript{-1}] (rc) and aerodynamic resistance [s m\textsuperscript{-1}] (ra) are provided by the crop growth modules. Important parameters of the model component are rc0 [s m\textsuperscript{-1}], describing the canopy resistance at water saturation and
Chapter 4

$k_{\text{glob}} \ [-]$, the extinction coefficient for global radiation. Latter is derived out of the extinction coefficient for PAR (see section 2.2.4.) by a division factor of 1.35 (Green, 1987).

2.2.3. Soil water module

The soil water balance is calculated by a potential based layer module, using the water content based formulation of the Richards equation for calculating the vertical soil water movement. The retention function proposed by van Genuchten, 1980 in the formulation revised by Wösten and van Genuchten, 1988 is used to describe the coherence between water content and water potential. The Van-Genuchten-parameter $m$ is calculated according to Mualem, 1976. Potential transpiration is distributed between the soil layers depending on root length densities. Groundwater is considered by the measured values of the groundwater table, which represent then the lower boundary condition. The actual water uptake by the plant roots in each layer is calculated by a reduction factor, if the species specific critical soil water potential $[\text{hPa}] \ (\psi_{\text{crit}})$ is reached. Actual evaporation $[\text{mm d}^{-1}] \ (E_{\text{act}})$ is calculated by a reduction factor, which corrects $E_{\text{pot}}$ by the influence of low soil water content in the top soil layer, according to a critical soil water potential $[\text{hPa}] \ (\psi_{\text{crivevap}})$. A more detailed description of the model is given in Kage et al., 2003.

2.2.4. Crop growth modules

Aboveground crop data are linearly interpolated by the model. Linear interpolation was possible because plant samplings were taken in a high temporal resolution (see section 2.1.). As only the calculation of potential evapotranspiration needs plant variables (GAI and crop height), implementation of these variables was sufficient. Linear interpolation starts with an initial value of zero at emergence. Emergence is calculated by a species dependent temperature sum $\text{GDD}_{\text{emem}}$, taking a base temperature ($T_{\text{1}}$) into account. Root growth starts with sowing and is calculated by an empirical dynamic approach. Root depth growth is computed to be linear over the root depth $z_r \ [\text{cm}]$ with $k_{sr} \ [\text{cm} \ (\degree \text{C} \ \text{d})^{-1}]$ denoting the increase of rooting depth per growing degree day $[\degree \text{C} \ \text{d}]$. $z_r$ is initiated with $z_{r_0} \ [\text{cm}]$, which defines sowing depth. Root depth growth ends, if the maximal rooting depth $z_{r_{\text{max}}} \ [\text{cm}]$, a site and species specific parameter, is reached. Root length $RL \ [\text{cm cm}^{-2}]$, is computed to be a logistic temperature dependent function, using the parameters $RL_0 \ [\text{cm cm}^{-2}]$, $RL_{\text{max}} \ [\text{cm cm}^{-2}]$, and $k_{RL} \ [\text{cm cm}^{-2} \ (\degree \text{C} \ \text{d})^{-1}]$. $k_{RL}$ denotes the increase of rooting depth per growing degree day, $RL_0$ and $RL_{\text{max}}$ are the initial and maximal root length per unit soil. The total root length $[\text{cm}] \ (RL_{\text{tot}})$ is simply the sum of $RL$ in all soil layers. The vertical root distribution is calculated according to Kage et al., 2000. Thereby, root length density $RLD \ [\text{cm cm}^{-3}]$, starting with $RLD_0$, decreases exponentially with soil depth ($z$) $[\text{cm}]$ and $kr$, which indicate the fractional decrease in RLD per unit increase of soil depth. $kr$ is calculated as the
negative logarithm of a fit parameter $k_\alpha$ divided by $zr$. $RLD_0$ is the root length density at $z = 0$ cm and is calculated from $RL_{tot}$, which is inserted in the transformed equation used for calculating RLD.

For further analyses the crop modules also calculate the amount of PAR radiation uptake ($Q$) by incident PAR, GAI and the extinction coefficient for PAR [-] ($k_{PAR}$). Thereby $k_{PAR}$ is assumed to be constant and species dependent.

$$Q = PAR \cdot (1 - e^{-k_{PAR}GAI})$$  \hspace{1cm} (Eq. 1)

Furthermore, a temperature factor [-] $f_T$ is calculated taking 4 cardinal temperatures [°C] ($T_1$, $T_2$, $T_3$ and $T_4$) for crop growth into account, which are also assumed to be species specific. $f_T$ is zero, if $T_{mean}$ is below the base temperature $T_1$ or exceeds the upper threshold $T_4$. Temperatures equal or higher $T_1$ lead to a linear increase of $f_T$ until $T_2$ is reached. Between $T_2$ and $T_3$ a temperature optimum is reached and $f_T$ is one. Higher temperatures than $T_3$ lead to a linear decrease of $f_T$ until $T_4$ is reached. Additionally, a drought stress factor [-] ($SWDF$), again ranking between zero and one, is calculated by the ratio between $T_{act}$ and $T_{pot}$.

For a more detailed description of the model approaches, concerning calculations of potential evapotranspiration, soil water balance, root depth growth and vertical distribution of root length density and also for PAR radiation uptake, $f_T$ and SWDF see ‘Chapter 2’.

2.2.5. Parameter values

Values for the used plant parameters are given separately for the different crops in Tab. 2. Thereby, certainly no distinction between wheat grown for silage or grain production or maize grown in a monoculture respectively in a crop rotation was done. Latter includes the assumption that the two maize cultivars (Ronaldino and Salgado) did not differ concerning plant parameters. The parameter values for the two grass species have also assumed to be equal, except of $k_{PAR}$ (*Italian and **Perennial ryegrass). Parameter values of $zr_0$ and $RL_0$ for grass, assigned in Tab. 2 with *, are only used for crop establishment. After cutting, the remaining values of $zr$ and $RL$ of the earlier cut are transferred to the following one as $zr_0$ and $RL_0$. 
Tab. 2: Crop parameters, their units and their values, for different crops used in the model analysis. * indicates Italian ryegrass, ** Perennial ryegrass. # indicates parameter values, which were used for crop establishment and not for the following cuts.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dimension</th>
<th>Maize</th>
<th>Wheat</th>
<th>Grass</th>
<th>Catch Crop</th>
</tr>
</thead>
<tbody>
<tr>
<td>rc0</td>
<td>s m⁻¹</td>
<td>75</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>T1</td>
<td>°C</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>T2</td>
<td>°C</td>
<td>16</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>T3</td>
<td>°C</td>
<td>28</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>T4</td>
<td>°C</td>
<td>34</td>
<td>34</td>
<td>34</td>
<td>34</td>
</tr>
<tr>
<td>GDDₜₚₑᵣₚ</td>
<td>°C d</td>
<td>77.5</td>
<td>168</td>
<td>124</td>
<td>150</td>
</tr>
<tr>
<td>kₚₐᵣ</td>
<td>-</td>
<td>0.661</td>
<td>0.5</td>
<td>0.63*</td>
<td>0.55**</td>
</tr>
<tr>
<td>zₙ₀</td>
<td>Cm</td>
<td>6</td>
<td>2</td>
<td>1#</td>
<td>2</td>
</tr>
<tr>
<td>zₙₘₐₓ</td>
<td>Cm</td>
<td>100</td>
<td>120</td>
<td>70</td>
<td>120</td>
</tr>
<tr>
<td>kₛ</td>
<td>cm (°C d⁻¹)</td>
<td>0.156</td>
<td>0.09</td>
<td>0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>RL₀₀</td>
<td>cm cm⁻²</td>
<td>3.7</td>
<td>1</td>
<td>1#</td>
<td>1</td>
</tr>
<tr>
<td>RLₙₘₙₓ</td>
<td>cm cm⁻²</td>
<td>252</td>
<td>300</td>
<td>300</td>
<td>80</td>
</tr>
<tr>
<td>kₛₙ</td>
<td>cm cm⁻² (°C d⁻¹)</td>
<td>0.0087</td>
<td>0.0045</td>
<td>0.0045</td>
<td>0.0045</td>
</tr>
<tr>
<td>kₐ</td>
<td>[-]</td>
<td>0.009</td>
<td>0.042</td>
<td>0.042</td>
<td>0.042</td>
</tr>
<tr>
<td>ψₛᵣᵢᵗᵳᵳₑᵥᵃᵖ</td>
<td>hPa</td>
<td>439</td>
<td>200</td>
<td>500</td>
<td>500</td>
</tr>
</tbody>
</table>

Tab. 3 gives the soil parameters (Van-Genuchten-parameters and saturated soil conductivity) for the two sites, separately for each soil horizon. ψₛᵣᵢᵗᵳᵳₑᵥᵃᵖ was assumed to be with a value of 22.5 hPa equal for both sites.

Tab. 3: Soil texture, Van-Genuchten-parameter considering Mualem parameterisation (α, θₛ, θᵣ and n) and saturated water conductivity (KS) for HS and KD subdivided in the different soil horizons [cm]. Parameter values assigned by * are derived out of BGR, 2005. All other parameters result from direct measurements at the sites.

<table>
<thead>
<tr>
<th>Site</th>
<th>Soil horizon</th>
<th>Soil texture</th>
<th>α [cm⁻¹]</th>
<th>θₛ [cm³ cm⁻³]</th>
<th>θᵣ [cm³ cm⁻³]</th>
<th>n [-]</th>
<th>KS [cm d⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HS</td>
<td>0-30</td>
<td>S14</td>
<td>0.043*</td>
<td>0.3394*</td>
<td>0*</td>
<td>1.18*</td>
<td>42*</td>
</tr>
<tr>
<td></td>
<td>30-60</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>21*</td>
</tr>
<tr>
<td></td>
<td>60-90</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>90-200</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0-30</td>
<td>mSgs</td>
<td>0.038</td>
<td>0.4276</td>
<td>0.1187</td>
<td>1.66</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td>30-40</td>
<td>mSfs</td>
<td>0.035</td>
<td>0.3661</td>
<td>0.0783</td>
<td>2.48</td>
<td>91</td>
</tr>
<tr>
<td></td>
<td>40-50</td>
<td>mSgs</td>
<td>0.042</td>
<td>0.4008</td>
<td>0.1375</td>
<td>1.62</td>
<td>157</td>
</tr>
<tr>
<td></td>
<td>50-200</td>
<td>SS</td>
<td>0.087*</td>
<td>0.3707*</td>
<td>0.0430*</td>
<td>1.57*</td>
<td>67*</td>
</tr>
</tbody>
</table>
2.3. Data processing

The input data used for the model had been the weather data (see section 2.2.1.) as well as the crop height and GAI data (see section 2.1.). Additionally, for the here presented study also aboveground dry matter data were used. For an appropriate use of these data some preparations had to be done.

Gaps within the weather data sets were filled for HS with data from a weather station in approx. 500 m distance, whereas for KD the alternate weather stations were in a distance of at least 15 km to the field site. The LAI-3100 data had been used to adjust the GAI values measured with the LAI-2000. Therefore, multiplication factors were determined by linear regression between LAI-3100 and LAI-2000 data. The multiplication factor gained for maize was 1.22, whereas the factor gained for wheat was with 1.14 lower. The latter was also used to adjust the LAI-2000 data obtained in the grass crops and in the catch crop. Missing crop height values (for all crops in N2 and N3 and for maize in FF3 additionally in N1 and N4) were deduced from best fit regression correlations between measured GAI and crop height values. Therefore, for wheat regressions were generated separately for years and N-levels (N1 vs. N2 – N4), for grass years and cuts were distinguished and for maize and the catch crop just one regression was used for all crop height calculations. For all cultivars, it was assumed that crop height stayed constant with decreasing GAI.

As denoted before, for the catch crop (mustard) some data were missing. As the catch crop freezes off over winter, aboveground dry matter data at harvest (here, freezing off date) have not been available. Additionally, GAI and crop height values are missing for the catch crop grown in winter 2006 / 2007 and for the catch crop grown in winter 2007 / 2008 values of these crop parameters are missing after the end of vegetation period. In order to deduce the missing values a simple dynamic oil seed rape model (Müller, 2009) was used. For a mustard specific parameterisation of the most important crop parameters, a data set gained from a field trial conducted in autumn of 1998 at a site located near Hannover, Germany “Ruthe”, was used. Here, data concerning the time course of GAI, aboveground, leaf and stem dry matter had been available. The parameter values of the specific leaf area and the allometric relationship between leaf dry matter and stem dry matter were directly calculated out of this data set. By using a simplified model version the light extinction coefficient (LUE) parameter value was optimised. The model simplification was an expo-linear curve fit of the GAI time course, which was used in order to avoid feedback reactions towards green area while optimising LUE. LUE was optimised by fitting the simulated dry matter value against the measured dry matter data. The optimised growth model for mustard was validated against aboveground dry matter data gained within the described field trail at HS in 2006, 2007, 2008 at the end of vegetation period. The reached RMSE (see section 2.5.1.) was with 34 g m$^{-2}$ sufficient. Validation of the model performance concerning GAI was conducted.
using the GAI time courses observed during the autumn of 2007 and 2008 in HS. Here model performance was with a RMSE value of 0.92 m² m⁻² sufficient too. Finally, this model was used to calculate the missing DM yield values at day of freezing off and the missing GAI values, which again were taken to calculate the crop height, according to the description given above.

### 2.4. Analysed periods

The duration of the field experiment (first sowing and latest harvest date given in Fig. 1), the chosen period for model simulation (the entire time span presented in Fig. 1) and the period to which the presented values concerning e.g. evaporation, transpiration and drainage refer (start and end indicated by the vertical lines with dots in Fig. 1), differ due to several reasons slightly. In order to level off some model output variables, especially soil water contents, model run started for each cropping system with an initialisation period (‘Initiation’ in Fig. 1) on the 1st of January 2006. The period which was chosen for the quantitative evaluation of the cropping systems, was exactly 2 years long. This was done in order to assure the comparability of the resulting variables, e.g. cumulative E_{act}, T_{act} or PAR radiation uptake, between the cropping systems. Thereby, the harvest date of the last crop yielded in 2008 was the reference date for each cropping system. Based on this reference date the starting dates of the quantification periods differ slightly for the single cropping systems. Additionally, for the cropping systems FF4, FF2 and FF3 (starting crop = wheat) this caused an exclusion of the results of the model calculations concerning the very early beginning of these cropping systems in autumn 2006 (see Fig. 1). For FF3, starting with the catch crop, in turn a short fallow period had to be added in autumn 2006 to the calculations. Both, cutting off and adding, was due to the fact, that all winter annual crops had been sown in the middle of September 2006 and not adequate to their ranking in the cropping systems. The short fallow shown in Fig. 1 for FF2 (starting crop = wheat) between silage wheat and grass was due to a late establishment of the grass crop.

### 2.5. Statistics

For both, aboveground dry matter accumulated over a whole cropping system and aboveground dry matter of single crops, single block values averaged over the two years were used for the statistic analyses. Data were subjected to an analysis of variance using the SAS procedure PROC MIX, with block set as random (SAS version 8.2, SAS Institute Inc., Cary, NC, USA). Comparison of means was performed by the Tukey-test. Model results, like amount of transpiration or sum of absorbed PAR radiation or derived crop characteristics, like LUE were not statistical analysed, because no replications were available.
Model simulations were compared with measured data in order to characterise model performance. This was done using soil water content data of the field experiment. Coefficient of correlation ($r^2$) as well as slope and intercept including their standard errors (SE) of the linear regression ($y = a + bx$) between the measured and simulated results, root mean square error (RMSE), coefficient of determination (CD) and modelling efficiency (EF) (Loague and Green, 1991) have been determined.

3. Results

3.1. Model performance

As model uncertainties concerning aboveground plant parameters (GAI and crop height) are minimized by linear interpolation of the data, the goodness of simulating soil water balance is most important for an adequate model performance. Therefore, measured soil water contents were used to prove the general ability of the model to simulate the water balance. The overall model performance for all soil water content data available for the soil layer 0 – 90 cm (mean values) at both sites was with an $r^2$ of 0.75 and an RMSE of 0.025 satisfactory (Tab. 4). Especially, an EF value of 0.72 and a CD value of 0.94 indicated in general a good model fit concerning dynamic and variation of soil water contents. Focusing on model performance separated between the two sites, showed with 0.026 and 0.022 for HS respectively KD convincing RMSE values. However, $r^2$ values of both sites have been with 0.62 and 0.51 lower compared to the $r^2$ value gained by the overall consideration of all data. EF and CD values were with 0.47 and 0.75 low in HS, but EF (0.08) and CD (0.58) values gained in KD have been even lower.

<table>
<thead>
<tr>
<th>Site</th>
<th>Slope (SE)</th>
<th>Intercept (SE)</th>
<th>$r^2$</th>
<th>RMSE</th>
<th>EF</th>
<th>CD</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>HS + KD</td>
<td>0.84 (±0.035)</td>
<td>0.037 (±0.009)</td>
<td>0.75</td>
<td>0.025</td>
<td>0.72</td>
<td>0.94</td>
<td>187</td>
</tr>
<tr>
<td>HS</td>
<td>0.68 (±0.047)</td>
<td>0.085 (±0.013)</td>
<td>0.62</td>
<td>0.026</td>
<td>0.47</td>
<td>0.75</td>
<td>131</td>
</tr>
<tr>
<td>KD</td>
<td>0.56 (±0.076)</td>
<td>0.080 (±0.015)</td>
<td>0.51</td>
<td>0.022</td>
<td>0.08</td>
<td>0.58</td>
<td>56</td>
</tr>
</tbody>
</table>

Fig. 2 presents, exemplary, simulated and measured time courses of soil water contents (0 – 90 cm) of one cropping system for each site, in HS FF3, N4, 2008 and in KD FF1, N4, 2008. This time courses show for HS a lower variability within the single plot data at one measurement date, but therefore a higher variability within the dynamic over time of the
averaged soil water contents, which is indicated by a minimum value of approx. 0.15 and a maximum value of approx. 0.35. In KD the opposite was considered, a generally high variability in the single plot measurements at one measurement date, but a lower variability in the averaged measurements over the time course. This might explain the lower model performance at KD. However, Fig. 2 shows that the aberrations of the simulated from the measured soil water contents are in an acceptable range.

Fig. 2: Measured and simulated soil water contents in the soil layer from 0 – 90 cm over time, provided exemplary for FF3, N4 in HS, 2008 and FF1, N4 in KD, 2008. Lines represent simulation values, symbols measured data. Crosses represent single measured data points, closed symbols represent the average of the measurements.
3.2. Dry matter yield

For a better comparability, the used DM data refer to the total aboveground dry matter, so including for the FF3 in HS also the dry matter biomass of the catch crop and the wheat straw.

Comparing the cropping systems grown in HS and grown in KD separately, the averaged DM yields per year of the whole cropping systems, given by the total height of the bars in Fig. 3, had been significant ($P$-value < 0.05) affected by the cropping system (FF), the N-supply-level (N) and their interaction FF*N (Tab. 5). Comparison of the two maize monocultures (FF1) cultivated in HS and KD, showed a significant effect of the site. Certainly, also the effect of N-level was significant, whereas the interaction site*N had no significant effect on DM yield (Tab. 5).

Tab. 5: P-values of the main effects and interactions on the whole cropping system DM yields. Tested separately, including all cropping systems in HS, including all cropping systems in KD and including FF1 on both sites.

<table>
<thead>
<tr>
<th>Site</th>
<th>Cropping system</th>
<th>Factors</th>
<th>$P$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>HS</td>
<td>FF1</td>
<td>N</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td></td>
<td>FF2</td>
<td>FF</td>
<td>&lt;.0001</td>
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<td></td>
<td>FF3</td>
<td>FF*N</td>
<td>0.0024</td>
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<td>KD</td>
<td>FF1</td>
<td>N</td>
<td>&lt;.0001</td>
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<td></td>
<td>FF4</td>
<td>FF</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FF*N</td>
<td>0.0309</td>
</tr>
<tr>
<td>HS</td>
<td></td>
<td>N</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>KD</td>
<td></td>
<td>site</td>
<td>0.0008</td>
</tr>
<tr>
<td></td>
<td></td>
<td>site*N</td>
<td>0.3235</td>
</tr>
</tbody>
</table>

Focusing the cropping system effects, necessary leads to a comparison of the DM yields gained by the cropping systems at the same N-level. In detail this will be done for N-level 3 in section 3.3. As for the other N-levels no separate statistical analysis concerning the cropping system differences of DM yields had been conducted, here just some short consideration will be given. With N supply (N2, N3 and N4), FF1 (HS and KD), FF2 and FF3 reached a DM yield level ranging between approx. 1500 g m$^{-2}$ and approx. 1900 g m$^{-2}$ (Fig. 3). FF4 whereas gained by N-supply only DM yields between approx. 900 g m$^{-2}$ and 1300 g m$^{-2}$. Also without any N fertilisation (N1) lay the DM yield obtained for FF4 with approx. 300 g m$^{-2}$ obviously below the DM yields observed for the other cropping systems. However, without any N fertilisation the DM yields gained by FF1 (HS and KD), FF2 and FF3 varied with approx. 850 g m$^{-2}$ and approx. 1350 g m$^{-2}$ stronger between the cropping systems as the observed DM yields with N fertilization. Comparison of the DM yields reached by the two maize monocultures (FF1), showed at least by trend for all N levels higher DM yields for FF1 grown in HS.
Focusing on N-level effects, (Fig. 3, letters (‘a’ to ‘c’)), the most obvious effect for all cropping systems were the, compared to N2, N3 and N4, significant lower DM yields obtained without any N-supply (N1). However, the response of DM production to an increased N-level from N1 to N2 differed between the cropping systems. FF1 (HS and KD) and FF3 showed no further effect on DM yield by increasing N-level from N2 over N3 to N4. FF2 instead reacted on an increase of the N-supply from N2 to N3 still with an increasing DM yield, but increasing N-supply from N3 to N4 led not anymore to a DM increase, moreover actually dry matter decreased. The perennial ryegrass (FF4) obtained a significant increase of DM yield between N2 and N3, but no increase between N3 and N4.

Beside DM yields of the whole cropping system, Fig. 3 also provides information about the yield proportions of the single crops within a cropping system (differing symbols) and about the ratio of DM yield gained in the two main cropping years (differing colours) by a single crop. However, no statistical analysis was conducted concerning single crop differences or year differences, consequently presented differences can only be discussed by trend.

Comparison of the yield proportions of the single crops within the two crop rotations cultivated in HS (FF2 and FF3) led to the following range: maize > wheat > winter intercrops, whereat grass > mustard (catch crop). A clear ranking of the years could not be observed. Maize grown in FF1 (HS and KD) and in FF3 yielded showed only for the lower N levels by trend higher yields in 2007, whereas for all other N-levels no year specific differences occurred. Maize grown in FF2 instead yielded in all N-levels lower in 2007. Wheat reached, at least for N2, N3 and N4 higher DM yields in 2008. The perennial ryegrass grown in KD, instead, gained at all N-levels higher DM yields in 2007.
3.3. Resource use efficiencies of the cropping systems under appropriate N supply

In order to focus the differences between the cropping systems and between the two sites, the following section provides only results out of N-level 3 (N3), assuming an appropriate N-supply in all cropping systems. The fact that an increase of the N-supply from N3 to N4 led in none of the cropping systems to a significant increase of the DM yield indicated, that N3 supply level was sufficient to reach attainable yields within the site year cropping system combinations. However, FF2 showed by trend a decreasing DM yield by increasing the N-supply from N3 to N4, which could be refer to too high N-supply in this cropping system. Analysis of the single plot values instead indicated that this slight decrease was possibly an artefact of average determination. DM yields of entire cropping systems are the sum of DM yields gained by the single crops within a system. Due to outliers of Italian ryegrass and wheat, incidentally two single plot values of the whole cropping system, which included the highest maize DM yields, were not considered for calculating average DM yield. This resulted
in the too low average DM yield of N4 observed in FF2 and therefore underlined the decision for choosing N3 for analysing cropping system and site differences.

The period, in which radiation was taken up by a sufficient high green crop area, started for maize cultivated in monoculture at HS (FF1) in both years in the beginning of May, then incident PAR radiation was maximal, and ended in the beginning of October, then incident PAR radiation already decreased down to values lower than 4 MJ m\(^2\) (Fig. 4). \( \frac{Q}{\text{incident PAR}} \), the ratio between absorbed and incident PAR radiation, increased for FF1 rapidly gained from the beginning of July values > 0.80 in both years. Compared to the other cropping systems (FF2 and FF3), which absorbed radiation also during winter, the period of radiation uptake for FF1 was quite short. By the two wheat crops of FF2 and FF3 approx. 40 – 50 % of the low incident PAR radiation was absorbed, but \( \frac{Q}{\text{incident PAR}} \) reached in summer also values of approx. 0.8. The increase of proportional radiation uptake was for both winter intercrops very rapidly and reached also during winter values > 0.8. Anyway, the to crop rotations, differed mainly concerning radiation uptake, by the much shorter radiation uptake period of the catch crop, ending by freezing off, compared to the Italian ryegrass, which is ones cut in autumn and then only in spring (April).

FF1 grown in KD was by trend concerning radiation uptake comparable to FF1 cultivated in HS, because the time course of daily incident PAR radiation averaged over 35 years and the vegetation period of the two maize monocultures did not differ mentionable between the two sites. FF4 instead reached the longest radiation uptake period, without any disruption during the two years (time courses for KD not shown).
The dynamic of Q / incident PAR and the corresponding time course of daily averaged incident PAR radiation affect the total sum of absorbed PAR radiation (sum of Q). Consequently, Tab. 6 shows that FF4 gained the highest sum of Q, followed by FF2 and again followed by FF3. For FF1 (HS and KD), instead, the lowest sum of Q was observed. Between the two sites FF1 did not differ concerning sum of Q. Tab. 6 also shows that the ranking of the cropping systems concerning sum of Q was not similar to the ranking concerning DM yield gained in N-level 3. In HS all cropping systems reached comparable DM yields at N-level 3. However, by trend FF1 (HS) yielded higher DM yields, while taking up the lowest amount of PAR radiation. In KD, FF1 obtained a significant higher DM yield, but again accumulated a clearly lower amount of PAR., with approx. half of the sum of Q reached by FF4. This high efficiency of PAR radiation use observed in the two maize monocultures was reflected with 2.5 (HS) and 2.2 g MJ PAR$^{-1}$ (KD) by the highest observed LUE values. FF3 cultivated in HS gained a LUE value of 1.9 g MJ PAR$^{-1}$, followed by FF2.
with 1.7 g MJ PAR\(^{-1}\), whereas FF4 reached the lowest LUE with 0.9 g MJ PAR\(^{-1}\). The impact of temperature and drought stress on cropping systems productivity is presented in Tab. 6 by the stress factors \(f_T\) and SWDF. Both, \(f_T\) and SWDF have been calculated by the used model according to the description given in section 2.2.4 and have additionally been weighted by the daily PAR radiation uptake before calculating mean values for each cropping system. The difference of the obtained averaged SWDF was in HS with values between 0.90 and 0.86 relatively low. Within this range FF1 was exposed to the lowest drought stress impact, followed by FF2 and again followed by FF3. In KD SWDF values ranged between 0.90 and 0.80, indicating the highest drought stress impact for FF4. The impact of low temperatures differed in HS with values between 0.90 and 0.86, comparably to SWDF, little. However, here FF3 showed the lowest temperature stress impact followed by FF1 and again followed by FF2. In KD even no differences at all occurred between FF1 and FF4 with \(f_T\) values of 0.89 and 0.90 respectively.

Comparing the two sites, by comparing FF1 at HS and KD, indicated no differences of sum of Q. By trend FF1 at HS yielded higher DM values than FF1 at HS. However, no differences concerning the averaged values of the drought stress and temperature factor occurred, but the observed LUE was higher in HS compared to KD.

Tab. 6: Averaged measured dry matter yield per year (DM yield), corresponding simulated sum of Q, calculated LUE, \(f_T\) and SWDF given for the N-level 3 of all cropping systems in HS and KD. \(f_T\) and SWDF were, before averaging, weighted by the daily PAR absorption. Significant differences concerning DM yield between the different cropping systems within one site are indicated by different letters (‘a’ to ‘c’). FF1 differed only by trend between the two sites HS and KD.

<table>
<thead>
<tr>
<th>Site</th>
<th>Cropping system</th>
<th>DM yield [g m(^{-2})]</th>
<th>Sum of Q [MJ PAR m(^{-2})]</th>
<th>LUE [g MJ PAR(^{-1})]</th>
<th>(f_T) [-]</th>
<th>SWDF [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HS</td>
<td>FF1</td>
<td>1838 a</td>
<td>747</td>
<td>2.5</td>
<td>0.88</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>FF2</td>
<td>1789 a</td>
<td>1046</td>
<td>1.7</td>
<td>0.86</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td>FF3</td>
<td>1750 a</td>
<td>905</td>
<td>1.9</td>
<td>0.90</td>
<td>0.86</td>
</tr>
<tr>
<td>KD</td>
<td>FF1</td>
<td>1676 a</td>
<td>761</td>
<td>2.2</td>
<td>0.89</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>FF4</td>
<td>1333 b</td>
<td>1434</td>
<td>0.9</td>
<td>0.90</td>
<td>0.80</td>
</tr>
</tbody>
</table>

As not only the averaged strength of stress impact is important for crop growth, but also the dynamic and interactions of temperature and drought stress, Fig. 5 presents exemplary for the year 2008 time courses of PAR radiation uptake (Q) weighted via multiplication by \(f_T\) respectively SWDF observed for FF1 (N3) at HS and at KD. Generally, stress factor \(f_T\) * Q increased from May to August and decreased during August rapidly leading to an already low level in mid of August, which again decreases till end of October. Direct comparison between the sites shows that the dynamic and the level of \(f_T\) * Q did not differ. SWDF * Q instead obtained especially in the beginning of crop growth lower values compared to HS, indicating a stronger drought stress in KD between (between mid of June and mid of July). Therefore, HS received mainly, beside on short period at the end of July, stronger drought stress in the late vegetation period. Especially the stronger drought stress impact in the beginning of the
vegetation period at KD was also observed in 2007, differing not that clear from HS (data not shown).

Fig. 5: Simulated time courses (7 days moving averages) of the stress factors $f_T$ and SWDF multiplied by PAR radiation uptake (Q) presented separately for FF1 (N3) at HS and KD, exemplary for 2008.

Tab. 7 provides for all cropping systems (N3) the cumulative amount of drainage, the actual cumulative transpiration including interception (cum. T$_{act}$) and the actual cumulative evaporation (cum. E$_{act}$), all average over the two years. Additionally, resulting transpiration use efficiency (TUE) and water use efficiency (WUE) values are presented. Comparison of the cropping systems at KD showed a lower drainage and a lower evaporation for the perennial ryegrass compared to FF1 in KD. Therefore, cum. T$_{act}$ was with approx. 100 mm higher for FF4. The resulting TUE and WUE values instead were with 3.5 g L$^{-1}$ respectively 2.9 g L$^{-1}$ lower for FF4 compared to FF1 (5.8 g L$^{-1}$ respectively 4.1 g L$^{-1}$). In HS the amount of drainage was comparable for FF3 and FF1, but lower for FF2. Again the ranking of cum. E$_{act}$ corresponded to the observed ranking of the drainage, whereas cum. T$_{act}$ was highest for FF2 followed by FF3 and lowest for FF1. Therefore, yielded FF1 the highest TUE and WUE values (5.5 and 3.5 g L$^{-1}$) in HS, followed by FF3 (4.9 and 3.2 g L$^{-1}$). FF2 reached with 4.6 g L$^{-1}$ a slightly lower TUE compared to FF3, but with 3.2 g L$^{-1}$ a comparable WUE. The site differences concerning drainage observed for FF1 at HS and KD were with a clearly higher value obtained at KD obvious. The level of the cum. T$_{act}$ and cum. E$_{act}$ also differed
between the sites, but here with higher values observed at HS. The resulting TUE and WUE values were lower in HS.

Tab. 7: Simulated cumulative drainage, \( \text{Tl}_{\text{act}} \), and \( \text{E}_{\text{act}} \), calculated TUE and WUE given for the N-level 3 of all cropping systems in HS and KD.

<table>
<thead>
<tr>
<th>Site</th>
<th>Cropping system</th>
<th>Drainage [mm a(^{-1})]</th>
<th>cum. ( \text{Tl}_{\text{act}} ) [mm a(^{-1})]</th>
<th>cum. ( \text{E}_{\text{act}} ) [mm a(^{-1})]</th>
<th>TUE [g L(^{-1})]</th>
<th>WUE [g L(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HS</td>
<td>FF1</td>
<td>337</td>
<td>333</td>
<td>187</td>
<td>5.5</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>FF2</td>
<td>288</td>
<td>392</td>
<td>166</td>
<td>4.6</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>FF3</td>
<td>328</td>
<td>355</td>
<td>192</td>
<td>4.9</td>
<td>3.2</td>
</tr>
<tr>
<td>KD</td>
<td>FF1</td>
<td>513</td>
<td>288</td>
<td>123</td>
<td>5.8</td>
<td>4.1</td>
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<tr>
<td></td>
<td>FF4</td>
<td>457</td>
<td>382</td>
<td>76</td>
<td>3.5</td>
<td>2.9</td>
</tr>
</tbody>
</table>

3.4. Resource use efficiencies of cropping systems under different N supply

As presented in Tab. 5, an interaction between cropping system and N-level on DM yield was determined at both sites, therefore Fig. 6 shows the sum of Q values and the LUE values separately for the four N-levels for all cropping systems. Fig. 7 presents the corresponding TUE and WUE values. Certainly, results concerning N3 have already been shown in Tab. 6 and 7 and are here only repeated to provide a better overview.

Generally, the reaction of sum of Q on an increasing N supply was less distinct, than the reaction of the resource use efficiencies. By trend, the effect of increasing N supply on all resource use efficiencies was in all cropping systems comparable to the already described effect on DM yield. This means for FF1 at HS, that according to the observed DM yields a mentionable increase of all resource use efficiencies from N1 to N2 was considerable, sum of Q instead showed only a small increase. Generally, N level increase from N2 to N3 and to N4 in FF1 (HS) led for all recourse use efficiencies and for DM by trend also to a slight increase, whereas no effect on sum of Q was observed. FF1 grown in KD react according to all parameters similar to FF1 cultivated in HS, but as already observed for the DM yields, even though the sites * N interaction had not been significant (Tab. 5), the reached level at N1 was lower and the effect of an increasing N supply was more distinct concerning the resource use efficiencies. FF4 grown in KD even showed the strongest reaction on an increasing N supply compared to all other cropping systems. In HS generally lowest reactions of all parameters on increasing N levels were observed for FF3 followed by FF1 and highest reaction was observed for FF2.
Fig. 6: Simulated sum of Q and calculated LUE, given for all four N-levels of all cropping systems in HS and KD.

Fig. 7: Calculated TUE and WUE, given for all four N-levels of all cropping systems in HS and KD.
3.5. Dry matter production and resource use efficiencies of the three maize crops cultivated at HS

Focusing on results from different system levels might be helpful for analysing the dry matter production, resource use efficiencies and the mechanisms of the interactions between cropping system and N-supply-level. For example, crop species can react differently on different levels of N-supply. Additionally, in a cropping system also the impact of a previous crop on the following crop might be noticeable in terms of the effects of a changing N-supply. Maize is the crop species, which dominates the cropping systems for producing biomass for biogas plants (DMK, 2006; Schittenhelm, 2008). Therefore, the following section will focus on yield performance and resource use efficiencies observed for the three maize crops cultivated in HS, differing by preceding crop and in terms of FF2 by the cultivar and sowing date.

For the three maize crops the single effects of cropping system and N supply as well as their interaction FF * N were significant concerning DM yield. Reached DM yield level without N fertilisation (N1) was clearly lowest for the maize crop grown in FF2, followed by the maize of FF1 and again followed by the maize of FF3 (Tab. 8). At N-level 3, instead, no significant differences between the DM yields of the three maize crops were observed. Maize grown in FF3 reached already without N supply a yield level comparable to all other N-levels (N2, N3, N4). For maize of FF1 DM yield increases by an N supply increase from N1 to N2 and stayed constant by a further N increase (N3, N4). DM yield of maize cultivated in FF2 increased always with increasing N supply level, but increasing N supply from N3 to N4 resulted in a decrease. However, this DM yield decrease was already discussed in section 3.3 to be due to an artefact, excluding incidentally the two highest DM yields gained by the maize crop in N4. If all four single plot values of the maize grown in FF2 would be considered, resulting averaged DM yield for N4 would be 1453 g m\(^{-2}\) and would not be anymore statistically significant different from the DM yield obtained in N3. Additionally, the significance of the single effects of cropping system and N-level as well as their interaction while comparing the different maize crops would still be given. Consequently, the observed decreases of DM yield, but also of the resulting resource use efficiencies will not be discussed furthermore.

PAR radiation uptake (sum of Q) was highest for maize grown in FF1 and FF3, but lower for FF2. An effect of N-supply on sum of Q was only given for the increase from N1 to N2 in FF2, all other maize crop N-level combinations showed no reaction. The observed impact of N supply on the LUE values was for all three maize crops qualitatively comparable to the impact observed on DM yield. At N1 maize of FF3 with 2.3 g MJ PAR\(^{-1}\) the highest LUE followed by maize of FF1 (1.9 g MJ PAR\(^{-1}\)) and again followed by maize of FF2 (1.3 g MJ PAR\(^{-1}\)), whereas at N3 the three maize crop obtained comparable LUE values. Also the TUE and WUE values showed differences comparable to the reaction observed for DM yield on
changing N supply. Concerning the TUE and the WUE again the level reached under N1 differed between the three maize crops (FF3 > FF1 > FF2), but under N3 it was comparable. The observed drought stress impact (weighted SWDF) ranked for all N-level cropping system combinations between 1.00 and 0.90, so was not very strong. Maize crops grown without N supply (N1) showed slightly higher SWDF values compared to maize of N2, N3 and N4 and drought stress impact observed in FF2 was a bit lower compared to FF1 and FF3.

Tab. 8: Averaged measured dry matter yield per year (DM yield), corresponding simulated sum of Q, calculated LUE, TUE and WUE given for all four N-levels of the three maize crops cultivated in FF1, FF2 and FF3 in HS. Significant differences concerning DM yield between the different N-application-levels within a crop are indicated by different letters (‘a’ to ‘c’). SWDF was, before averaging, weighted by the daily PAR absorption.

<table>
<thead>
<tr>
<th>Site</th>
<th>Cropping system / crop</th>
<th>N-level</th>
<th>DM yield [g m⁻²]</th>
<th>Sum of Q [MJ Par m⁻²]</th>
<th>LUE [g MJ PAR⁻¹]</th>
<th>TUE [g L⁻¹]</th>
<th>WUE [g L⁻¹]</th>
<th>SWDF [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>FF1</td>
<td>Maize</td>
<td>N1</td>
<td>1343 a</td>
<td>713</td>
<td>1.9</td>
<td>4.4</td>
<td>3.3</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N2</td>
<td>1780 b</td>
<td>741</td>
<td>2.4</td>
<td>5.4</td>
<td>4.3</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N3</td>
<td>1838 b</td>
<td>747</td>
<td>2.5</td>
<td>5.5</td>
<td>4.4</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N4</td>
<td>1904 b</td>
<td>748</td>
<td>2.5</td>
<td>5.7</td>
<td>4.5</td>
<td>0.91</td>
</tr>
<tr>
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<td>FF2 / Maize</td>
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<td>513</td>
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<td>1362 b</td>
<td>639</td>
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<td>5.1</td>
<td>3.8</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N3</td>
<td>1618 c</td>
<td>660</td>
<td>2.5</td>
<td>5.7</td>
<td>4.4</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N4</td>
<td>1380 b</td>
<td>644</td>
<td>2.2</td>
<td>5.0</td>
<td>3.8</td>
<td>0.96</td>
</tr>
<tr>
<td>FF3</td>
<td>Maize</td>
<td>N1</td>
<td>1712 a</td>
<td>734</td>
<td>2.3</td>
<td>5.3</td>
<td>4.1</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N2</td>
<td>1826 a</td>
<td>750</td>
<td>2.4</td>
<td>5.5</td>
<td>4.4</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N3</td>
<td>1815 a</td>
<td>749</td>
<td>2.4</td>
<td>5.4</td>
<td>4.3</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N4</td>
<td>1724 a</td>
<td>713</td>
<td>2.4</td>
<td>5.5</td>
<td>4.2</td>
<td>0.92</td>
</tr>
</tbody>
</table>

Maize cultivated in FF1 was sown in spring after a fallow, whereas maize of FF2 after an Italian ryegrass and maize of FF3 after a winter catch crop (mustard). The fallow respectively the two winter intercrops consigned different amounts of mineral soil nitrogen (Nₘᵢₙ) for the maize crops. In March 2007 highest Nₘᵢₙ values were observed after the catch crop, followed by the Nₘᵢₙ determined for the Italian ryegrass. After the fallow lowest Nₘᵢₙ values were measured. A distinction between the N-levels was in 2006 /2007 not necessary, as no differential fertiliser application was conducted within the entire experiment before March 2007. In May 2008, short before maize sowing, separated samplings concerning the N-levels had been conducted, again resulting in highest Nₘᵢₙ values determined after the catch crop, followed by the Italian ryegrass and again followed by the fallow. In 2008 after Italian ryegrass a differentiation of the N-levels concerning remaining Nₘᵢₙ could be observed, with lowest values in N1, followed by N2, again followed by N3 and with highest values in N4. After the catch crop for the N-levels N2, N3 and N4 Nₘᵢₙ did not differ, but Nₘᵢₙ in N1 was comparable lower. After the fallow no differentiation of Nₘᵢₙ between the N-levels was observed. In both years, even in 2007, the N uptake observed for the Italian ryegrass was
lowest in N1 and highest for all other N-levels. N uptake by the mustard did not differ clearly between the N-levels.

Tab. 9: Averaged mineral N ($N_{\text{min}}$) values measured in the soil layer 0 – 90 cm before maize sowing and N uptake of the winter inter crops. $N_{\text{min}}$-measurements were in spring 2007 (2006 / 2007) conducted in the beginning of March before any N supply was conducted. Therefore, $N_{\text{min}}$ was not distinguished between the N-levels. In spring 2008 (2007 / 2008) $N_{\text{min}}$-measurements were conducted in the beginning of May right after harvesting Italian ryegrass. N uptake of the winter intercrops was determined for Italian ryegrass in both years at the harvest date of the spring cut and for the catch crop calculated from N contents determined in November and the simulated DM yields at date of freezing off.

<table>
<thead>
<tr>
<th>Site</th>
<th>Cropping system / crop</th>
<th>Year</th>
<th>N-level</th>
<th>$N_{\text{min}}$ (0 - 90cm) [kg N ha$^{-1}$]</th>
<th>N uptake of the winter intercrop [kg N ha$^{-1}$]</th>
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</thead>
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<tr>
<td>FF1 / Maize</td>
<td>2006 / 2007</td>
<td>N1</td>
<td>39</td>
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<td></td>
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<td>N2</td>
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4. Discussion

The aim of this study was to evaluate different cropping systems for biomass production concerning their productivity and their light and water use efficiencies. Therefore, two intensive crop rotations including winter intercrops and combining C₄- and C₃-crops, a perennial ryegrass and silage maize cultivate in monoculture were grown under differing N supply levels in a 2-year field experiment conducted at two representative sites of Northern Germany. Productivity, resource use efficiencies and possible effects of the preceding crops on the performance of the following crop were analyses using a combined experimental-modelling approach, which takes mainly data of DM yield, GAI and crop height and simulated water balance variables into account. In the following sections firstly the model performance concerning level and dynamics of soil water contents will be discussed. After that an analysis focusing on the single effects of cropping systems and sites on DM production and resource use efficiencies will be given. In a second step, the effects of the interaction between cropping system and N-supply level, including effects of preceding crops on the performance of the following crops will be analysed.

4.1. Model performance

As model uncertainties concerning aboveground plant parameters, GAI and crop height, have been via linear interpolation of frequently measured data minimized, satisfactory simulation of the water balance and correct estimates of radiation uptake remain the most important requirements for adequate model calculations. The comparison between simulated and measured soil water contents (section 3.1) gives some evidence about an appropriate simulation of the water balance. The obtained RMSE value with 0.025 and the EF value with 0.72 and the CD value with 0.94 (Tab. 4, HS+KD) indicate that the model simulates the level, the dynamic and the range of variability of the soil water contents (0 - 90 cm) satisfactory. However, the results given separately for the two sites (Tab. 4) indicate that model performance for KD was comparable lower to this gained in HS. Reasons for this might be various, but one main aspect seems to be the higher variability in the measured soil water contents at one measurement date in KD combined with a low dynamic of the measured mean soil water contents during the vegetation period, and less measurement events compared to HS. The variability within one measurement date can be explained by a high spatial variability of the incipient ortherde. Its spatial differences in succession result in a high spatial variability of the soil water conductivity, which could not be considered in the model. Another aspect concerning the lower model performance gained for KD is surely the dynamic of groundwater and of its plant availability. Even though the model is taking the dynamics of the groundwater table into account, this might still cause some uncertainties and might lead to a lower model performance. However, Fig. 2 proved not only the ability of the model to
simulate adequate soil water contents under two differing cropping systems (FF3, HS and FF1, KD), it also proved exemplary the ability of the model to simulate soil water contents in KD at least on a sufficient level. Still, simulating the level and dynamic of soil water contents satisfactory, only indicates that water in- and outcome is simulated adequate, it does not prove if the proportion of single variables, e.g. evaporation, transpiration or drainage is calculated absolute correct. Estimates of radiation uptake could not be compared with data, as radiation uptake of the crops was not measured. Anyway, as mentioned before, Q is calculated from incident PAR radiation, GAI and \( k_{\text{PAR}} \). Incident PAR radiation, a direct model input variable, was derived from the global radiation, which was directly measured at the field sites, using a factor of 0.5 according Szeicz, 1974. Due to the short measurement intervals of GAI, the linear interpolation should provide a good estimate of this variable. \( k_{\text{PAR}} \) values were assumed to be crop specific (Tab. 2). The \( k_{\text{PAR}} \) value for maize had been calculated following Dingkuhn et al., 1999 from the GAI data and DIFN data measured by the LAI2000. The derived \( k_{\text{PAR}} \) value for maize is at the head of values given in literature (Lizaso et al., 2003). \( k_{\text{PAR}} \) value for wheat was taken from Thorne et al., 1988. For the catch crop (mustard) a \( k_{\text{PAR}} \) value provided by Müller, 2009 respectively Andersen et al., 1996 for oil seed rape was chosen. Monsi and Saeki, 2005 assumed an extinction coefficient for mustard of 1. The \( k_{\text{PAR}} \) values for Italian ryegrass were taken from Sheehy and Peacock, 1975 and for perennial ryegrass from Sheehy and Peacock, 1975 and Lantinga et al., 1999. As the used \( k_{\text{PAR}} \) values are either derived directly from the literature or fit within values given by literature, we are certain that our model calculates PAR radiation uptake appropriate.

### 4.2. Cropping system and site effects without nitrogen limitation

Comparing DM yields and resource use efficiencies on one N-level without N-limitation (N3) allows focusing on the single cropping system and site effects affecting DM yields and resource use efficiencies.

#### 4.2.1. DM yield and LUE of the cropping systems

The observed cropping systems mainly differ by the cultivated species (e.g. maize, wheat, grass) and by the number of different crops grown on the same field per year, resulting in different sums of absorbed PAR radiation and light use efficiencies (Tab. 6). As expected, cropping systems with a prolonged leaf area duration gained higher amounts of absorbed PAR radiation, FF4 > FF2 > FF3 > FF1 (HS and KD). Literature indicate that high PAR radiation uptake, due to prolonged leaf area duration can led to a higher biomass production. Heggenstaller et al., 2009 found 25 % higher DM yields in a triticale-corn double-cropping system compared to a sole grown corn and reasoned this to higher leaf area...
durations and therefore to higher amounts of PAR radiation uptake. Dohleman and Long, 2009 showed that the higher yields observed in miscanthus compared to corn were primarily reached by higher leaf area duration of miscanthus, offsetting the impact of the biochemical differences. However, the higher sums of Q observed in our study for FF4, FF2 and FF3 was not converted into higher DM yields. This resulted in comparable lower LUE values (Tab. 6), obtained for the two crop rotations in HS and for the perennial ryegrass in KD. Heggenstaller et al., 2009 concluded that a prolong leaf area duration only can be successful in terms of increasing biomass productivity, if the reduction in growth efficiencies is minimal.

However, the LUE, a main indicator for growth efficiency, is determined by several factors. The potential LUE is defined by the crop species itself or for a cropping system by the mixture of crop species. Due to environmental stress factors and due to the reaction of the crop species on the stress, potential LUE is reduced to an actual LUE value. Main environmental stress factors affecting the LUE negatively are low temperatures (Andrade et al., 1993; Louarn et al., 2008) or water deficit (Earl and Davis, 2003). In HS the cropping systems with the highest prolong leaf area (FF2, FF3) showed the lowest weighted averaged SWDF value (Tab.6). Still, the drought stress differences between the cropping systems were not very distinct and their ranking were not one to one comparable with the observed ranking of the LUE values, so drought only partly explains the lower LUE values gained by the two crop rotations. Averaging the two stress factors, SWDF and f_T, results, with 0.89 for FF1, 0.88 for FF3 and 0.87 for FF2, in the same ranking of cropping system observed for the LUE. But again, differences were too low to explain the LUE differences entirely. In KD instead the perennial ryegrass obtained a clearly lower SWDF value compared to the maize grown as a single crop (Tab.6). Here, drought stress was obviously an important factor limiting the actual LUE of FF4. As f_T was comparable between F4 and FF1 (KD), it was for LUE differences between the cropping systems in KD from no importance.

As mentioned before, the actual LUE value results from an interaction of environmental conditions and crop species. Concerning crop specific LUE differences Bleken et al., 2009 considered, beside differences in the canopy architecture, differences between C_3 and C_4 physiology to be most important. Measured and calculated LUE values for C_4 crops generally exceed those of C_3 crops (Loomis and Amthor, 1999; Sun et al., 2009). With highest LUE values obtained in the two sole C_4 cropping systems FF1 (HS and KD), middle LUE values observed for the cropping systems mixing C_4 and C_3 crops (FF2 and FF3) and the lowest LUE value found in the C_3 perennial grass system, our results underline this conclusion. Moreover, our LUE values obtained for the single crops grown in the cropping systems fit well into the range of LUE values given in literature for these crops. Averaged single crop LUE values determined in our study for maize were 2.2 g MJ^{-1} in KD and 2.4 respectively 2.5 g MJ^{-1} in HS, 1.5 and 1.7 g MJ^{-1} for grain wheat respectively silage wheat, 0.9 and 1.0 g MJ^{-1}
for perennial respectively Italian ryegrass and 1.9 g MJ$^{-1}$ for the catch crop mustard. Experiments conducted by Dohlman and Long, 2009 in the U.S. Corn Belt obtained an average LUE value for maize of 2.2 g MJ$^{-1}$. Earl and Davis, 2003 found in their experiments conducted in Georgia an average LUE for maize of 2.9 g MJ$^{-1}$. Andrade et al., 1993 determined LUE values for maize between 2.3 and 3.2 g MJ$^{-1}$. For wheat given LUE values in literature are comparable lower to those observed in maize. Mishra et al, 2009 found average values of 1.6 and 1.7 g MJ$^{-1}$ for two different wheat varieties. O’Connell et al, 2004 estimated a LUE value for wheat of 1.8 g MJ$^{-1}$, but the averaged LUE value determined by Calderini et al., 1997 for wheat was with 1.1 g MJ$^{-1}$ even lower. For mustard O’Connell et al, 2004 estimated a LUE value of 1.9 g MJ$^{-1}$. Available LUE values in literature for grass often apply for total dry matter, so including root dry matter. Therefore, these values are comparable higher to the values we found. Gower et al., 1999 presented LUE values, considering total dry matter, for differing short or mixed grasslands in a wide range between 0.5 and 2.0 g MJ$^{-1}$. Akmal and Janssens, 2004 instead found for perennial ryegrass cultivated without any limitation to water or nitrogen LUE values, referring total dry matter, which were with 3.2 and 4.2 g MJ$^{-1}$ comparable high. However, they explained these high LUE values by the high impact of grass roots on the level of LUE mainly due to high root to shoot ratios in the early growth and root regeneration during growth. This in reverse explains in comparison to their results the much lower LUE level (referring to aboveground dry matter) we found for grass. Additionally, the periodic defoliation and the differences in plant physiology (vegetative vs. generative) between the different growths might explain the lower LUE observed in grass compared for example to wheat.

4.2.2. Water balance, TUE and WUE of the cropping systems

The investigated cropping systems also differ by the presented values of the water balance (TI$_{act}$, E$_{act}$, drainage) and by the resulting WUE and TUE values. The water balances we obtained are unfortunately not exactly comparable between the cropping systems due to the slightly differing periods of quantitative evaluation of the cropping systems (Fig. 1). This was most obvious comparing FF2 and FF3, resulting in average in a lower (by approx. 30 mm) sum of cum E$_{act}$, cum TI$_{act}$ and drainage for FF2, assuming cumulative no change in the soil water storage.

However, the presented results indicated that cum. E$_{act}$ is reduced and cum. TI$_{act}$ is increased by a prolonged leaf area duration (Tab. 7). This is most obvious for FF4 compared to FF1 in KD, but also for FF2 compared to FF1 and FF3 grown in HS. These differences between the cropping systems observed in HS were, however, not high. This is probably because evapotranspiration is not only a function of the total height of leaf area duration, but also of the environmental conditions dominating the period where green area is present. For
example, in the period between late autumn and spring, so the time span in which FF1 possesses a bare soil due to the fallow and in which FF2 possesses green area due to the Italian ryegrass or winter wheat, the evapotranspiration demand is comparably low. This leads in this period to comparably low evaporation rates for FF1 and for FF2 to comparably low transpiration rates. Additionally, the quite low GAI values observed for wheat during winter time (FF2 and FF3) caused by the late sowing date of the wheat crops after maize, increases the ratio between evaporation and transpiration for these cropping systems. However, concerning drainage the negative effect of prolonged leaf area was obvious for FF2 in HS and FF4 in KD. Compared to this cropping systems showed FF1 in HS and KD approx. 50 mm respectively 55 mm higher drainage values. A higher drainage can have positive and negative environmental effects. On one hand it can cause higher discharges of inorganic chemicals into the ground water (Böhlke, 2002). On the other hand it causes a higher recharge of the ground water storage. Latter might gain also in temperate climates importance, considering climate change, which is predicted to cause dry and hot summers in Germany FNR, 2010.

The observed differences of the TUE values (Tab. 7) between the cropping systems are due to several reasons. Section 4.2.3 provides a discussion about differences of TUE and also of WUE due to site effects, comparing FF1 grown at HS and at KD. Here the crop species effect should be shortly discussed. Maize grown as a single crop received with 5.5 g L\(^{-1}\) (HS) and 5.8 g L\(^{-1}\) (KD) the highest TUE values. This values fit well in the range of TUE values reported in literature for maize of 4.1 g L\(^{-1}\) - 8.3 g L\(^{-1}\), summarised by Kremer et al., 2008. Main species differences concerning TUE occur between C\(_4\) and C\(_3\) plants and therefore explain the higher TUE values observed for FF1 in comparison to the other cropping systems. C\(_4\) plants are supposed to gain higher TUE values than C\(_3\) plants (Ehlers, 1996; Long, 1983), due to a higher efficiency in their CO\(_2\) fixation pathway and therefore due to lower stomata conductivity values (see higher rc0 parameter value given in Tab. 2) with a greater contribution of stomata aperture to the total pathway resistance of water vapour versus CO\(_2\). This means, that C\(_4\) crops can produce with comparable radiation uptake higher DM yields accompanied with lower amounts of transpiration, leading to a higher TUE compared to C\(_3\) crops. However, another species specific difference is the difference concerning the value of base temperature (Tab. 2), which is clearly higher for maize. This in contrary affects the ratio between DM yield and transpiration of the C\(_4\) crop negatively. The effect of temperature is highest on DM production, middle on transpiration and again lowest on radiation uptake. So, LUE and TUE are correlated with each other but differ in the mentioned points. However, the big differences concerning TUE between FF4 and FF1 grown in KD is reasoned by a clear difference in light use efficiency. Comparison of the crop rotations FF2 and FF3, combining maize and C\(_3\) crops in the same proportion, indicated by
trend a lower TUE for FF2. This might also be due to the low LUE observed for the Italian rye grass in FF2 (Tab. 6).

WUE is a function of TUE and of the proportion between evaporation and evapotranspiration (Gregory et al., 2000). As mentioned before, the cropping systems with prolonged leaf area duration, obtain a smaller ratio between evaporation and evapotranspiration. This is most obvious comparing FF4 (0.17) and FF1 (0.30) in KD. Therefore the reduction in water use efficiency due to evaporation is lower for the perennial ryegrass. Still, the reached WUE value for FF4 is, due to the low TUE, lowest for FF4. The ranking of the WUE values found within this study were comparable to those found in Literature. Mueller et al., 2005 found for sites located in the mid East of Germany WUE values > 4 for maize, for wheat values around 3 and for grassland values between 1.8 and 2.7. The WUE values obtained in HS and KD indicate that the higher TUE values reached for the maize crops was not cancelled out by higher amounts of evaporation, resulting in a still higher WUE observed in FF1 compared to the other cropping systems.

However, the estimated evaporation amounts are astonishingly high for all cropping systems, but especially for the ones which cover soil surface by green area nearly during the whole year (FF2 and FF4). This might be caused by the used model approach for calculating water balance. Actual evaporation is in our model calculated by a reduction factor, which corrects the potential evaporation, by the influence of low soil water content in the top soil layer. This dependency on the thickness of the top soil layer (10 cm) might result in an overestimation of actual evaporation, especially in the stage of evaporation where vaporization is limited not only by energy supply but also by water availability. This possible overestimation of evaporation consequently leads to an underestimation of WUE. The use of, so called, two-stage models like presented by Ritchie, 1972 might be an appropriate solution for reducing this uncertainty, because evaporation simulation by these models is independent on the thickness of soil layer. Gavin and Agnew, 2004 also pointed that the Penman-Monteith equation leads in grasslands to an overestimation of evaporation during periods of non-saturated soil water content. They suggested the Priestley-Taylor method as a better alternative. Additionally, the high evaporation values observed in FF2, are possible also a result of the suboptimal long period between silage wheat harvest and sowing of Italian ryegrass which occurred in summer 2007 (approx. 80 mm evaporation).

4.2.3. Site differences

Because the cropping systems used differed between the sites, site effects will only be discussed for FF1.

The DM yield gained by the maize crop cultivated with appropriated N supply (N3) in HS was with approx. 160 g m⁻² by trend higher compared to the DM yield obtained by the maize crop
grown in KD (Tab. 6). As the sum of absorbed PAR radiation was equal at both sites, the DM yield differences had to be due to the higher LUE value (2.5 g MJ PAR$^{-1}$) observed in HS. Reasons for the lower LUE value (2.2 g MJ PAR$^{-1}$) observed in KD can be narrowed down to environmental stress factors, as effects of e.g. differing maize cultivars or limitations due to deficient N supply can be excluded. As mentioned before, most important environmental stress factors in the two regions are low temperature and drought. However, the averaged and weighted (by the daily PAR uptake) stress factors, $f_T$ and SWDF (Tab. 6), showed no differences between the two maize crops grown in HS and KD. The dynamic of the stress factors, instead, differed between the sites (Fig. 5). Assuming that the dynamic of PAR radiation uptake was comparable between the two sites, Fig. 5 indicates that the impact of drought stress was, compared to HS, in KD clearly stronger in spring and early summer. In autumn instead drought stress was higher in HS. Stress due to low temperatures did not differ mentionable between the two sites and was for both strongest in autumn. So, the maize grown in KD revised over the whole growing season either drought or temperature stress, which reduced crop productivity. In HS instead the two stress factors occurred to their stronger extent parallel. So the higher drought stress impact, observed in HS in autumn, occurred during a period where growth rates were anyway limited by low temperatures. Consequently, the limitation of DM yield due to drought stress was lower compared to KD.

Maize grown in HS or KD also differed concerning their water balance and their WUE and TUE. Under the maize cultivated in KD the averaged drainage per year was approx. 180 mm higher compared to HS (Tab. 7). This was mainly an effect of higher saturated water conductivity of the sandy soil of KD (Tab. 2) and of a higher amount of annual precipitation, which was especially distinct in 2007 (Tab. 1). The observed annual averaged values form cum. $T_{I_{act}}$ and $E_{act}$ had been lower and the TUE and WUE values had been higher at KD (Tab. 7). TUE and WUE values often differ between sites. In literature this is often refer to a negative effect of saturation deficit on TUE (Stöckle et al., 2008; Ehlers, 1996). However, saturation deficit was only by trend and just in 2007 higher for HS. Consequently, the higher level of wind speed observed in HS led to a higher evapotraspiration demand and therefore to lower TUE and WUE values in HS (see Chapter 3).

**4.3. Effects of interactions between cropping systems and nitrogen supply level and impact of proceeding crops**

Concerning DM yield at both sites a statistical significant interaction between the cropping systems and the N-supply was observed (Tab. 5). The cropping systems mainly differ in the level of the averaged DM yield reached without additional N supply and additionally by a different pronounced increase of DM yield with N fertilisation (Fig. 3).
In all cropping systems, except of grass, an increasing N supply led to a stronger reaction of LUE than of sum of Q (Fig. 6). So, the positive N supply effect on dry matter productivity was, at least in the cropping systems including maize, due to an increasing LUE, which results from an increase in the leaf N content per unit leaf area (Muchow and Sinclair, 1994), whereas the effect of sum of Q, due to changes in leaf area by changes in GAI (Colmenne et al., 2002) or specific leaf area, on dry matter production was not so obvious for these cropping systems. Our observed results concerning the cropping systems are directly linked to the response of maize to N limitations, which is described by maintaining leaf area at the expense of resource use efficiency (Lemaire et al., 2008). For FF4 both effects of increasing N supply on dry matter production were observed, the LUE as well as the sum of Q increased (Fig. 6). Akmal and Janssens, 2004, found in their experiments also reduction of LUE and a reduction of leaf area, latter was due to a reduction in leaf dry matter and number of tiller.

The reaction of TUE on nitrogen limitation was comparable to the reaction of LUE in all observed cropping systems. Also the WUE reacted at least by trend proportional to the TUE. This showed that no strong change between evaporation and evapotranspiration was observable and supports the assumption that nitrogen effects on leaf area were not very strong.

As a C$_4$ crop, maize has a higher nitrogen use efficiency due to an elevated CO$_2$ concentration at the site of Rubisco carboxylation (Massad et al., 2007). This higher nitrogen use efficiency implicaes that only a comparable low nitrogen level lead to a reaction to nitrogen limitation, like reducing LUE. Therefore, the amount of nitrogen needed for reaching maximal yields under certain environmental conditions is comparable lower to C$_3$ crops. The lower N optimum for maize within this experiment was especially obvious comparing FF1 and FF4 in KD (Fig. 3). FF1 (KD) showed an optimal N level of 135 kg N ha$^{-1}$ a$^{-1}$, whereas the N optimum for perennial ryegrass was with 300 kg N ha$^{-1}$ a$^{-1}$ much higher (Sieling et al., unpublished). This differing N optimum values explain the significant DM yield increases up to N3 (320 kg N ha$^{-1}$ a$^{-1}$) in FF4 and up to N2 (120 kg N ha$^{-1}$ a$^{-1}$) in FF1, considering the differing amounts of nitrogen applied to maize and perennial ryegrass at the same N level (see section 2.1.). Comparing the DM yields of the cropping systems cultivated in HS, also indicates the same low nitrogen level (N2) needed in FF1 for reaching highest observed yields (Fig. 3). However, also FF3 reached highest yields at N level 2, but FF2 just at N3. The difference between these tow cropping systems in terms of N fertilisation management was an additionally N supply (160 kg N ha$^{-1}$ a$^{-1}$) applied to the Italian ryegrass at N2, N3, and N4, but not supplied to the catch crop. Anyway, these differences do not explain the lower DM yields observed for FF2 at N2 compared to FF3. Consequently, this is not the reason for the higher N fertilisation level needed in FF2 to reach highest observed DM yields. The main
single crops within the crop rotations react on an N supply increase from N2 to N3 different. Whereas wheat showed at least by trend an increase of DM yield in both rotations (Fig. 3), DM yield of maize only increased significantly in FF2 (Tab. 8). Consequently, the different reaction of FF2 and FF3 on an increase of N supply from N2 to N3 is a result out of the different reaction observed for the maize crops. Comparison of the maize grown in FF2 with the other maize crops grown in HS indicate that the lower DM yield observed at N2 for FF2/Maize was due to a lower LUE. The observed sum of Q was, probably due to a shorter vegetation period (Fig. 1, late sowing), indeed lower compared to FF1/Maize and FF3/Maize, but as the maize grown in FF2 reached in N3 compared to N2 a significant higher DM yield with a nearly similar amount of absorbed PAR radiation, LUE remain the most important factor. Reasons for differences in terms of LUE can be various. As in all cropping systems maize obtained under high N supply (N3) a LUE of 2.5 MJ PAR$^{-1}$ differences concerning the different maize cultivars (see section 2.1.) can be excluded. The different preceding crops respectively the fallow can cause different conditions especially in the beginning of maize growth which might affect the LUE of maize. Winter intercrops can affect the following crop by influences on the disease suppression, soil structure, on the water dynamic and on the availability of soil N (Miguez and Bollero, 2005; Gabriel and Quemada, 2011). In this study no differences by effects of disease suppression should be occurred, because crops were treated in terms of crop protection according to local best practice recommendations. As we did not investigated soil structure issues this factor can only be discussed concerning indirect effects, like increased infiltration rates or reduced run offs, on soil water dynamics. Anyway, due to the water consumption by the winter intercrop also differences concerning the water availability for the following crop can occur. The weighted average SWDF values (Tab.8) indicate that the drought stress impact on the maize grown in FF2 was lowest compared to the two other maize crops. Also, the soil water content at sowing date in the upper 30 cm was comparable between all maize crops, whereas the plant available soil water observed in the entire rooting zone (100 cm) at sowing date was with 25 mm lower for FF2/Maize. Latter might indicate that for other years a drought stress impact on maize crops after Italian ryegrass can not be excluded. However, large differences between the maize crops occurred concerning the mineral soil nitrogen short before maize sowing (Tab. 9). In average over all N levels and years the $N_{min}$ was with approx. 20 kg N ha$^{-1}$ lowest after Italian ryegrass, followed by FF1 with approx. 40 kg N ha$^{-1}$ and highest after the catch crop with approx. 80 kg N ha$^{-1}$. These differing levels of mineral soil nitrogen, especially by considering the even lower $N_{min}$ levels observed before maize for N1 in 2007 / 2008, explain the clear differences between the biomass yields observed for the maize crops, but also for the whole cropping systems without any additional N fertilisation (N1). For both, maize crops and entire cropping systems highest yields were observed in FF3, followed by FF1 and lowest yields were
obtained by FF2. Additionally, the differing $N_{\text{min}}$ levels might also explain the higher nitrogen fertilisation amounts needed for reaching highest DM yields in FF2, respectively the significant DM increase between N2 and N3. Definitely, these results showed that the catch crop is most efficient in terms of transferring nitrogen to the following maize crop, by retaining the nitrogen in their plant biomass and making it available after mineralisation in the next vegetation season (Kulig et al., 2010; Hartwig and Ammon, 2002). Kulig et al., 2010 assumed, by their experimental results, mustard crops to be not only valuable in terms of protecting environment by reducing nitrogen leaching but also by increasing the yield of the following crop (spring wheat) significantly. For the Italian ryegrass instead the presented low $N_{\text{min}}$ values indicated, especially in comparison to the higher $N_{\text{min}}$ values observed after the fallow in FF1, an immobilisation of nitrogen. In terms of immobilisation the following maize crop would be provided with this nitrogen later in the vegetation period. Still, nitrogen loss by leaching can not be excluded, especially as the maximal rooting depth of comparable grass species is assumed to be between 60 – 80 cm (De Willigen and van Noordwijk, 1987; Garwood, 1979). However, drainage was in comparison to the fallow reduced under both crops, Italian ryegrass and under the catch crop.

Summing up, the interaction between cropping system and N supply level concerning DM yield was mainly due to a differing LUE reaction of the cropping systems observed under differing nitrogen supply levels. In the cropping systems including maize, obviously, the differences in the reaction of the maize crops reasoned the interaction observed for the whole cropping systems. In turn the differences concerning the productivity, LUE, TUE and WUE of the maize crops under differing N supply levels had been due to differences in the N-dynamic, namely in the $N_{\text{min}}$ level, provided by the proceeding crop respectively by the fallow. However, especially concerning the fate of the nitrogen within the fallow, catch crop but primary within the Italian ryegrass no clear evidence can be presented.

Generally, it should be considered that all results refer to only two year field experiments, which might be in terms of investigating crop rotations, especially analysing the impact of the proceeding crop on the following crop, not sufficient. Also, the results concerning DM yields reflect only an aperture of possible site year combinations influencing the cropping system productivity. Finally, some uncertainties are given by the used model approaches. However, we are certain that this study still provides a valuable contribution in terms of evaluating the productivity, light and water use efficiencies of different bioenergy cropping systems on different sites and N supply levels. Still, a mechanistic dynamic growth model for energy cropping systems would be helpful in terms of generalising the obtained results.
5. Conclusions
This study shows that intensive crop rotations, including winter intercrops and combining C₄- and C₃-crops, can reach similar biomass yields in comparison to maize monocultures under Northern German conditions (high water availability by precipitation), by higher leaf area duration and therefore PAR radiation uptake. However, most efficient in terms of resource use efficiency was maize. The generally higher LUE of the C₄ crop, maize, was just slightly reduced by environmental conditions, like low temperatures. LUE values therefore were still higher compared to the crop rotations or the perennial ryegrass. Furthermore, the advantage of a high TUE observed for maize was only partly cancelled out by high amounts of evaporation, and WUE values for both single grown maize crops were higher. Groundwater recharge was mainly site dependent, but on both sites higher for maize than for crop rotations respectively perennial ryegrass. Finally, the two maize monocultures were highly efficient in terms of nitrogen use. Also the mixed crop rotation (FF3) needed, in comparison to the complete bioenergy rotation (FF2), a lower N supply level for reaching highest observed biomass yields. The strong interaction observed between cropping system and N supply level was, at the tillage site, mainly due to the impact of the proceeding crops on the productivity of the following maize crops. The catch crop, mustard, was most efficient in providing the following maize crop with high amounts of nitrogen, explaining the comparable low N fertilisation level needed in this crop rotation for reaching highest observed DM yields. Whereas the amount of mineral soil nitrogen provided at maize sowing by the Italian ryegrass was due to either immobilisation or nitrogen leaching. However, the by trend lower yield level observed also in N3 for the maize crop grown in FF2 was mainly due to an shorter vegetation period, caused by the late cutting date of Italian ryegrass. The perennial ryegrass grown at the site, typical for forage production, was, mainly due to a very low light and nitrogen use efficiency, clearly less productive in terms of biomass compared to the other cropping systems. However, the evaluation of bioenergy cropping systems has to consider environmental impacts, like nutrient losses or status of carbon soil content. Doing that, may result in a better performance of the perennial ryegrass.

This study underlines how valuable a combined experimental-modelling approach can be, using only simple model approaches. However, developing a dynamic mechanistic growth model for energy cropping systems would allow a more generalised investigation of these cropping systems, also in other regions.

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References


Chapter 4


General discussion

1. Introduction

German and European energy policy is driven by energy security and climate change (BMELV and BMU, 2009). Global energy demand is increasing rapidly, while fossil energy sources are limited. Coincidentally, the use of fossil energy contributes highly to the increase of the atmospheric greenhouse gas concentrations (Weiland, 2010), leading to the climate change. Latest since the ratification of the Kyoto-protocol (1997), which target the reduction of the common greenhouse gas emissions by 5% (reference year: 1990), German energy policy focused on the increase of renewable energy sources. A cornerstone in supporting renewable energy was the adoption of the Renewable Energy Sources Act (EEG) in 2000. The first amendment of the EEG in 2004 underlined the importance of biomass for reaching the climate protection targets by the introduction of an extra financial support (biomass bonus). A big proportion of biomass for energy production is provided by agricultural crops, mainly oilseed rape (940000 ha) for biodiesel or vegetable oil fuel production, followed by crops grown for biogas production (650000 ha) and sugar and starch producing crops for bioethanol (240000 ha) (FNR, 2011).

Food, feed and biofuel production compete for the narrow resource of agricultural land (Zegada-Lizarazu, 2010; Bauer et al., 2010; Cassman, 2010; Sheehan, 2010). The critical challenge will be to cover the increasing food, feed and bioenergy demand in an environmental friendly way (Cassman and Liska, 2007; Bauer et al., 2010) and strong research efforts have to be undertaken to explore yield potentials and strategies to close the yield gaps between potential and actual yields (Cassman, 2010). The requirements for sustainable bioenergy cropping systems are high, referring climatic, environmental and socio-economic subjects (Lewandowski and Faaij, 2006; de Vries et al. 2010; Bauer et al., 2010). Following de Vries et al., 2010 indicators for an integrated assessment investigating the sustainability of bioenergy cropping systems in terms of productivity and ecological aspects have to focus on energy yield, on the potential of saving greenhouse gas emissions, and on the agro-environment, including soil erosion, soil organic matter, risk of soil borne diseases, eutrophication, pesticide usage and water use. So, the assessment of cropping systems for bioenergy production is complex, caused by the plurality of the evaluation criteria and by the need of quantitative weighting.

Compared to other agricultural bioenergy production lines, biogas production is generally supposed to be one of the energy-efficient and environmental friendliest technologies (Fehrenbach et al., 2008). It has high potentials to reduce greenhouse gas emissions
(Weiland, 2010), which is clearly linked to the biomass production capacity (Herrmann and Taube, 2006). Additionally, the digestion residues are commonly used as improved fertilisers substituting mineral fertiliser, so biogas production has a high potential for a closed nutrient cycle (Weiland, 2010; Bauer et al., 2010). Furthermore, the wide range of usable substrates for biogas production allows a high flexibility, adapted to locally available resources (Weiland, 2010; Bauer et al., 2010). However, silage maize is currently dominating bioenergy cropping systems (Bauer, et al. 2010; Schittenhelm, 2008; Amon et al., 2007) with 80 % (Schütte, 2010), due to its high yield potential and high specific methane yield [l methane per kg organic matter] (Murphy and Power, 2009; Amon et al., 2007; Weiland, 2010). Maize, especially grown in monocultures, can cause several environmental problems, like reduction of crop species diversity, increase of pest pressure or possible increase of nutrient losses and soil erosion (Schittenhelm, 2010; Frede, 2010). Consequently, sustainable bioenergy cropping needs site-adapted cropping systems (FNR, 2010) with high resource use efficiencies (including high land use efficiency) (Zegada-Lizarazu, 2010), for ensuring both high yield and reduced environmental effects.

2. Summarised discussion of the methods and results

Against the above described background the objectives of this study were firstly, the development, parameterisation and validation of an empirical dynamic growth crop model for silage maize, applicable for North Western European conditions, in order to provide an appropriate tool for analysing dynamically the impact of resource limitation on dry matter productivity and resource use efficiencies of silage maize grown for bioenergy production (Chapter 2); secondly, the application of this crop growth model by conducting simulation studies for evaluating the yield potentials of silage maize grown in three different regions of Germany, in order to discuss limitations but also chances to close the yield gap between potential yields and farmers respectively attainable yields (Chapter 3) and thirdly, an investigation of alternative cropping systems compared to maize monocultures, by using an experimental-modelling approach, in order to assess dry matter productivity and resource use efficiencies including nitrogen use efficiency of different biogas cropping systems at two sites in Northern Germany (Chapter 4).
2.1. Summarised discussion of the silage maize crop growth model and the simulation study

2.1.1. Choice of method

Agricultural science comes with a large pool of methods for evaluating bioenergy production systems. Since 1990 numerous agro-environmental indicators and indicator-based methods have been developed to assess the adverse effects of cropping and farming systems (Bockstaller et al., 2009). The most common indicator method, especially in terms of evaluating bioenergy production systems, is the life-cycle-assessment, or likewise multicriteria analysis of process chains (Hanegraaff et al., 1998). Indicator based methods provide a global evaluation of production systems, being easily expendable by introduction of indicators evaluating climatic, environmental and socio-economic subjects and allow an aggregated and generic assessment of the compared production systems. Therefore, they are currently most favoured as supporting decision tools e.g. in policy or for developing certification systems (Hanegraaf et al., 1998; Lewandowski and Faaij, 2006). However, these methods are surely just as good as the choice of indicators, the underlying quantitative assumptions and an adequate quantitative weighing of the indicators.

The potential of system-orientated crop growth models for examining components and interactions of natural systems, estimating the changes and uncertainties on outcomes, is widely acknowledged (Bellocchi et al., 2010). These models provide the ability to analyse dynamic crop growth processes and their interactions with environmental factors and can provide important parameters, like transpiration, which are hardly measurable, but which are important in terms of water balance and resource use efficiencies. Understanding species respectively cropping system site interactions and quantifying dry matter productivity and resource use efficiencies is valuable in evaluating and choosing site-adapted bioenergy cropping systems and provides a more analytical tool compared to indicator based methods. Additionally, crop growth simulation models allow the quantification of yield potentials at different sites and, by controlled simulation experiments the evaluation of yield gains possible with specific management changes (Lobell et al., 2009). However, crop growth models linked with evapotranspiration and soil water modules, like the presented silage maize model (Chapter 2), consider the system level of a crop. In principle the upgrade of system-orientated models to a higher system level is possible, shown by models focusing on farming- or agro-ecosystems, like DSSAT (Jones et al., 2003), EPICphase (Cabelguenne et al., 1999), APSIM (Robertson et al., 2009), CropSyst (Stöckle et al., 2003), DAISY (Abrahamsen and Hansen, 2000), WOFOST (Boogard et al., 1998) or STICS (Brisson et al., 1998). But, the development of system-orientated models is labour and time consuming and limits an easy and fast introduction of other levels of consideration. The experimental-
modelling method (Chapter 4), linking single crops to crop rotations is an appropriate first step to amplify the model approach.

2.1.2. Evaluation of the crop growth model for silage maize

The developed crop growth model for silage maize is a simple, modular structured growth model, featuring some well known model approaches. It calculates dry matter production, dry matter partitioning into root, leaf, stem and cob, green area expansion and spatial root distribution, and is linked to modules calculating potential evapotranspiration and soil water balance. Crop development is, with slight adaptations, calculated according to Yang et al., 2004.

The predictive power of the crop growth model is with an RMSE of 324 g m\(^{-2}\), an \(r^2\) value of 0.85 and a slope of 0.82 (1:1 plot) acceptable for calculating dry matter yields at harvest of different cultivars at different sites (Chapter 1).

However, in some terms the developed crop growth model for silage maize needs further improvements. The direct impact of drought stress on dry matter production was simply considered by the stress factor \(T_{\text{act}}/T_{\text{pot}}\), which implicate a proportional reduction of transpiration and dry matter production. Stöckle et al., 2008 and Ferreyra et al., 2003 suggested that \(T_{\text{act}}/T_{\text{pot}}\) is influencing the stressed to non-stressed growth rate ratio in a non-linear way. Still, a non-linear impact of \(T_{\text{act}}/T_{\text{pot}}\) was not in agreement with the used parameterisation data sets and therefore might be just a hint, which could be followed if the model fails in simulating dry matter yields under water limited conditions at other sites. The negligence of specific drought stress impacts, like an effect on specific leaf area (SLA), are due to the high degree of simplification of the model (Chapter 1). It is known, that the reduction of SLA is a possible adaptation of plants towards drought stress. Including this adaptation in the presented maize model could lead to an improvement of model quality for some site year combinations. The sensitivity analysis presented in Chapter 2 showed under different weather conditions (dry, wet, favourable) differing reactions of DM\(_{\text{shoot}}\) on changes of the SLA. Anyway, integrating a drought stress impact on the SLA led not to a higher model accuracy for the parameterisation data sets. Also the negligence of drought and heat stress impacts on the kernel set (Zinselmeier, 1995; Setter et al., 2001; Saseendran et al., 2008; Boyer and Westgate, 2004), might lead to model failures, here especially to the often observed overestimations of DM\(_{\text{cob}}\). Modelling these stress impacts requires the consideration of sink limitation and probably the integration of a flowering model. Approaches for that are presented by Lizaso et al., 2007. A simple empirical approach is not conceivable, because an appropriate parameterisation of e.g. simple stress factors reducing the kernel set would probably be difficult. However, the poor accuracy concerning DM\(_{\text{cob}}\) in combination with the absence of a quality sub model restricts the applicability of the crop growth model to
analyse some special terms of silage maize production. At least a quantification of dry matter content would be needed for predicting optimal harvest time. At dry matter contents between 30 and 35 % maize can easily be silaged and gives according to Amon et al., 2007 the maximum biomass yields. Herrmann et al., 2005 assumed in their model for predicting harvest time in silage maize that the dry matter content increased with higher temperatures, higher radiation intensity and under drought conditions. Other quality parameters, like starch or crude protein content effect the specific methane yield of a substrate, but as the influence of dry matter yield per hectare on the methane yield per unit land is comparably high (Amon et al. 2007), the negligence of a quality sub model considering substance of content might be arguable. However, another critical point within the model is the absence of the impact of daily temperature amplitudes (minimum vs. maximum temperatures) on respiration losses. Modelling these processes is with a simple LUE based model not achievable (Lizaso et al., 2005b) and would require a photosynthesis-respiration-model. Photosynthesis-respiration-models allow the independent simulation of both processes as affected by environmental factors (Lizaso et al., 2005a). However, possible influences of structural model errors should be taken in consideration using a photosynthesis-respiration-model and, compared to LUE based models, these models are still more difficult to calibrate (Kage et al., 2001). Finally, as described in Chapter 4, the model might tend to overestimate evaporation especially in dryer situations. Two-stage models like presented by Ritchie, 1972 might be an appropriate solution for reducing this uncertainty. However, the most important expansion of the model is probably the introduction of a sub module describing the nitrogen uptake and the impact of insufficient nitrogen availability dynamically. Therefore, the concept of the critical N concentration, firstly formulated by Ulrich, 1952, could be a sufficient approach. A nitrogen uptake module would allow, in combination with an introduction of soil nitrogen dynamics within the soil water module, the calculation of nitrogen losses, like nitrogen leaching. However, the validation results and the comparison of the averaged 35 years dry matter yields, calculated with full drought stress impact for the three different sites within the simulation study (Chapter 2), with averaged yields obtained at federal variety experiments (LK Schleswig-Holstein, 2010; Kuhlmann, 2010; LfL, 2010), showed by good fits in level and site ranking the adequate ability of the model to calculate dry matter production under different environmental conditions. Furthermore, the calculated LUE values obtained in all three chapters (full drought stress, no nitrogen limitation) were with a range of approx. 2 – 3 g MJ PAR\(^{-1}\) comparable to LUE values observed by different authors for maize (Andrade et al., 1993; Dohleman and Long, 2009; Earl and Davis, 2003). Also, the wide range of TUE values (approx. 4.5 – 9.0 g L\(^{-1}\)) was within the range given in literature for maize (Grassini et al., 2009; Kropff et al., 1984; Kremer et al., 2008). Comparison of TUE values gained for HS using the simulated DM_{\text{shoot}} values in Chapter 2 with the TUE values gained by the
experimental $D_{\text{shoot}}$ data (Chapter 4) fit well, whereas for KD a slight overestimation of $D_{\text{shoot}}$ (Chapter 2) led to an overestimation of TUE. WUE values of both chapters are not comparable, as in Chapter 2 evapotranspiration referred to the vegetation period and in Chapter 4 to a whole year. Anyway, in general the calculated WUE values were in agreement with WUE values found by Schittenhelm, 2010 and Mueller et al., 2005 at German sites. The satisfactory model performance of $D_{\text{shoot}}$, soil water contents under water limitations and the level and range of the WUE, TUE and LUE (Chapter 2 and 3) values demonstrated the applicability of the model to simulate crop growth under different levels of water availability, including drought stress impacts. Moreover, it could be assumed that the model is in terms of $D_{\text{shoot}}$ valid for silage maize growth under North Western European conditions, considering low temperature regions. Furthermore, the model provides all requirements for conducting scenario analyses, not at least because it can be easily parameterised using commonly available data and therefore, it should be applicable at various sites and can be adapted to different cultivars.

2.1.3. Summarised discussion of the silage maize simulation study

The results of the simulation study showed clearly the differences between the regions concerning their environmental impact on the crop growth of silage maize. Observed yield potentials were highest at the warmer sites and clearly lower at the site located in Northern Germany. At this site yield potential was mainly limited by low temperatures, which affected crop growth directly, by a direct negative influence on the metabolic processes (Andrade et al., 1993) and therefore by reducing the LUE. Additionally, low temperatures led to a clearly delayed green area expansion, which reduced the yield potential due to a feedback reaction on radiation uptake (Maddonni and Otegui, 1996; Muchow et al., 1990). The analyses towards water limitations showed that at all sites a direct drought stress impact could be considered, being lowest at the Northern site and highest at the site in Mid-East Germany, due to a high evapotranspiration demand. Consequently, in terms of reaching yield potentials, irrigation would be most valuable at the warmer sites, but the amount of additional water supply would be comparably high, especially at sites with comparable weather and soil conditions to the site in Mid-East Germany, resulting into low water use efficiencies. Considering the restrictions in water availability at many sites in Germany, TUE and WUE of bioenergy cropping systems are of special interest (Schittenhelm and Kruse, 2010). However, the simulation study showed that also with sufficient water supply yield potentials were limited to 30 Mg ha$^{-1}$.

A commonly discussed strategy, for increasing yield potentials in terms of silage maize production for using in biogas plants, is the choice of late ripening cultivars (Herrmann and Taube, 2006). According to Amon et al., 2007 these cultivars can produce higher methane
yields per hectare. Even if in the presented simulation study no late cultivars were investigated, the study indicates that this strategy might be limited at least at the simulation sites. The choice of a late cultivar would probably lead at all sites to an expansion of the vegetation period into late autumn, soon restricted by temperatures below base temperature or even by frost events. As at the most Northern site the mid early cultivar did not reached full maturity in most of the years, quality e.g. dry matter content might also be a limiting factor at this site. Anyway, the presented results concerning temperature impacts on green area growth showed clearly, that an extended vegetation period would neither lead to an appreciable increase in PAR radiation uptake nor to an increase in dry matter production at the most Northern site. Additionally, Amon et al., 2007 assumed that late cultivars should be harvested towards full ripeness, whereas earlier cultivars can already be harvested at the end of wax ripeness. Concerning the two warmer sites, the strategy of later maturity might fail because of low water availability. However, within this study, some investigations concerning the water demand of the cultivars grown in experiment 3 (Chapter 2) were conducted, using a simple growth curve based model linked with modules concerning evapotranspiration and soil water dynamics. Schittenhelm and Kruse, 2010 published these results combined with own calculations showing, that the amount of water transpired by the late cultivars was higher, but that the WUE was similar or even lower compared to a mid early cultivar. Anyway, without breeding efforts towards higher water use efficiency and chilling tolerance of maize cultivars, yield potentials will probably not exceed this 30 Mg ha$^{-1}$, at least in the investigated regions.

Besides trying to increase the yield potential itself, another strategy in order to increased actual yield levels is the closing of the yield gaps. Surely, yield gaps can not be closed to 100 % (Cassman, 2010). According to Lobell et al., 2009; Cassman, 2010; Grassini and Cassman, 2010 for none of the major crops, like rice, wheat or maize, yields passing beyond 70 – 80 % of the yield potentials were observed. Lobell et al., 2009 suggested that the economic optimum for the farmers might level at approx. 80 % of the yield potential. Therefore, the global need of increasing yields per hectare may be partly restricted by the target of profit maximization. As the conducted simulation study focused on closing the yield gap between attainable yield (not restricted by suboptimal crop management but by drought stress) and yield potential (not restricted by suboptimal crop management and drought stress; definitions according to Loomis and Connor, 1998), it has to be discussed if irrigation of maize grown for biogas production is a realistic and profitable strategy for farmers. The prices for biomass for biogas production, especially for maize, were during the last years increasing in Germany (Schüsseler, 2011). Irrigation in silage maize became more and more common, whereas before bioenergy farming silage maize was in hardly any region worthy to be irrigated. For the two cultivars Flavi and Mikado grown in the field experiment 3 (Chapter
1) at a site in Central Germany, an increase in economical benefit of approx. 250 respectively 580 € ha\(^{-1}\) in the very dry year 2006 was calculated and it was assumed that with the effects of climate change (hot dry summers) the importance of irrigation for biomass production will increase substantially (FNR, 2010).

However, as this study did not investigate the yield gap between farmers yield and attainable yield, various of crop management strategies, like optimisation of nutrient supply or crop protection, have not been discussed. As, last years federal state averaged DM yields, (deduced from DMK, 2010 by averaging fresh matter values of 2002 - 2009 and assuming a dry matter content of 30 %) were with approx. 15 Mg ha\(^{-1}\) in Bavaria (RE) and 11 Mg ha\(^{-1}\) in Saxony-Anhalt (MA) and Schleswig-Holstein (HA) much lower compared to the attainable yields calculated in the simulation study, there seems to be potential for improvements by crop management, even if the average farm yield for the maize cultivar grown at the three sites of the simulation study is not exactly known.

2.2. Summarised discussion of cropping systems assessment

2.2.1. Dry matter yields and land use efficiencies

The presented simulation study showed that, due to higher yield potentials, production capacity of silage maize is higher in the warmer regions of Germany. For the colder more wet regions for example intensive energy crop rotations mixing C\(_3\)- and C\(_4\)-plants might be valuable alternatives for biomass production. The calculated ratios between the simulated attainable yields of the maize crops and federal state average yields of grain wheat (Statistisches Bundesamt, 2007 – 2010), show that at the two warmer sites, MA and RE, theoretically 2.7 respectively 3.2 times more silage maize biomass compared to wheat grain dry matter could be produced, whereas in HA only 2.2 times more silage maize could be produced. Assuming a harvest index of 0.5 for wheat, dry matter yield of silage wheat has the potential to reach in Northern German regions nearly comparable yield levels like silage maize. Consequently the combination of silage maize, silage wheat and Italian ryegrass, like FF2 of the conducted field experiment within the BIOGAS-EXPERT project, should lead, at Northern German tillage sites, to comparable or even higher dry matter yields compared to the yield level of silage maize grown in monoculture. The results of the combined experimental-modelling assessment of cropping systems showed that, at least statistically, it is possible to produce comparable dry matter yields by intensive crop rotations, including winter intercrops and combining C\(_4\) and C\(_3\)-crops, grown with sufficient nitrogen supply under Northern German conditions (Chapter 4). High biomass yields observed in these crop rotations were due to an increased leaf area duration and therefore an increased radiation uptake, whereas the maize grown in monoculture realized high dry matter yields by an high
LUE, even under the cold conditions of Northern Germany. The latter and the fact that the presented results have been derived by only 2 experimental years, maybe in some terms not highly representative, might cause, that the observed crop rotations did not exceed the dry matter yields gained by the maize monoculture. Manning et al., 2006 for example showed by field experiments, conducted on a site with a loamy sand soil texture, located in a distance of approx. 30 km respectively 45 km from HS and KD, that cropping systems including maize and Italian ryegrass can achieve with appropriate N supply higher yields compared to maize grown in monoculture. Also, Quakernack et al., 2011 found by trend higher dry matter yields for a similar crop rotation to FF2 at a site in the most Northern part in Germany, approx. 80 Km from HS. At this site even perennial ryegrass yielded on a comparable level as the silage maize grown in monoculture, which is mainly caused by a very heavy soil (Fluvimollic Gleysol) with low soil temperatures in spring, often directly followed by spring drought.

However, the low dry matter yields gained by the wheat crops within the crop rotations of the BIOGAS-EXPERT field experiments were clearly one reason for the by trend lower dry matter yield at least observed for FF2. The biomass yield of grain and silage wheat was with approx. 10 Mg ha\(^{-1}\) in 2007 and 15 Mg ha\(^{-1}\) in 2008 low. Wheat grown in 2007 at the BIOGAS-EXPERT field trail was the third wheat cultivated at this field site in a row. Maximal yield depression in the third or fourth wheat of monocultures have been observed by many researches (Sieling et al., 2005; Gerlagh, 1968; Shipton, 1975; Sieling and Hanus, 1990) and are discussed to be due to allelochemical effects or soil born diseases, like take-all. Additionally, 2007 and 2008 differed by the growing conditions for wheat, with unfavourable high rainfalls during grain filling and harvest in June and July in 2007 (> 120 mm per month). The wheat crops grown in 2008 were, typically for the crop rotations, sown late in autumn (middle of October) after the silage maize harvest and reached possibly therefore not maximum yields. However, a field experiment conducted by Seidel, 2011 showed that in average over the years (2008 – 2010) silage wheat grown in HS (normal sowing date) gained dry matter yields of approx. 20 Mg ha\(^{-1}\), indicating that higher dry matter yields of wheat are generally possible at this site. On the other hand, results of this field experiment also indicate that other cereals like barley or rye grown for biomass production, both yielding approx. between 20 - 25 Mg ha\(^{-1}\), are even more favourable compared to wheat. Experiments conducted within the EVA project, a Germany wide project for analysing site adapted cropping systems for biomass production, showed that the yield performance for a cropping system with early cut silage rye intercrop and silage maize was at least at sites with sufficient water supply comparably high (FNR, 2010). For the BIOGAS-EXPERT crop rotation with Italian ryegrass as winter intercrop not only poor wheat yields but also the, by trend, lower silage maize yields might limit higher dry matter yields for the whole crop rotation. With sufficient N supply, the lower yield level observed for this maize crop was due to lower PAR
radiation uptake caused by a later sowing date compared to the two other maize crops. Experiments comparing double-crop systems and rotations with intercrops showed that in terms of dry matter yields optimal sown main crops are more efficient (FNR, 2010). Also, Fletcher et al., 2011 reported that late sowing dates due to a long duration of the preceding crop, have a negative impact on yield performance of the following crop. The effect of intercrops on the dry matter yield of the maize crops and therefore of the whole cropping system and the observed high interaction of cropping system and N-supply level due to effects of the intercrops respectively the fallow observed within the BIOGAS-EXPERT indicate, that an adequate choice of the winter intercrop is very important.

Summing up, in the BIOGAS-EXPERT field trial the crop rotations, grown at the tillage site, were not more successful in terms of biomass production per hectare compared to the maize monocultures. Still, by an adapted choice (e.g. silage wheat vs. silage rye) respectively an adequate crop management of the second main crop within the rotation and by a choice of winter intercrops, which support the main crop in terms of optimal sowing conditions, but also concerning the availability of soil mineral nitrogen (catch crop vs. Italian ryegrass) probably a higher land use efficiency in terms of biomass production per unit land and certainly a reduction of maize percentage within production regions (with sufficient water supply) can be reached.

2.2.2. Resource use efficiencies and other indicators
Within the BIOGAS-EXPERT experiment the maize monocultures achieved the highest TUE and WUE values. Additionally, the two maize monocultures were highly efficient in terms of nitrogen use, whereas the intensive cropping systems differ strongly concerning nitrogen use efficiency. The perennial ryegrass, grown at the site typical for forage production, gained not only the lowest dry matter yields, but also lowest values in terms of water and nitrogen use efficiencies. However, it was not due to find comparable resource use efficiencies for the different crops respectively cropping system. The impact of C$_3$ vs. C$_4$ plant types on e.g. the level of the potential LUE was already discussed in Chapter 4. Additionally, the resource use efficiencies of crops grown only in summertime, like maize in monoculture or crops grown over the whole year, like perennial ryegrass might generally not comparable. For example, under Northern German conditions, so at sites with comparably high water availability, maize grown during the warmest season (summer) gained per se higher LUE values compared to a crop which is also grown during colder seasons (winter). Furthermore, certainly the amount of evaporation for the fallow of a maize monoculture is lower compared to the evapotranspiration of a crop during wintertime, leading to a stronger limitation of the water use efficiency (per year) for the winter crop. On the other hand, the meaning of a low water
use efficiency during the wintertime might be limited at sites with a generally high water availability in spring.

Still, water and nitrogen use efficiency are important indicators for evaluating sustainability of cropping systems (de Vries et al., 2010; Spiertz, 2010). However, a generic assessment of bioenergy cropping systems needs to consider not only single indicators, but rather needs to evaluate the indicators parallel and to weight them in terms of importance. For example very extensive cropping systems for biomass production are proposed as alternative systems compared to high input systems. In terms of energy use efficiency, here energy input / energy output, these systems show often good results, especially because mineral fertiliser, mainly nitrogen, is the highest energy input in agricultural production (Boehmle et. al, 2008). But, in turn these low input systems normally gain very low land use efficiencies (dry matter or bioenergy per unit land). Against the background that high yields are important for both economic and ecologic sustainability, land use efficiency might be more important for evaluating cropping systems for biogas production. Anyway, a various number of other indicators for assessing biomass cropping systems can and has to be appointed (de Vries et al., 2010; Bockstaller, 2009; Lewandowski and Faaij, 2006). However, as the presented study was restricted to land use, water use and nitrogen use efficiency only some assumptions can be given. Comparing the maize monoculture and the perennial ryegrass grown in KD within the BIOGAS-EXPERT field experiment, maize showed for all, land, water and nitrogen, the highest use efficiencies and was therefore more favourable. Including considerations towards e.g. habitat function, soil erosion or soil-organic matter would partly cancel of the negative evaluation of perennial ryegrass. Compared to grasslands agro-ecosystem functions such as habitats for wild plants and animal species can be potentially be limited in maize monocultures. A literature survey by Neumann et al., 2009 showed for example that especially the breeding success for birds is limited in maize crops grown for biomass production. A possible negative effect of maize grown in monoculture on soil erosion and run off is well known, mainly due to the long period of bare soil. The prolonged leaf area duration of perennial ryegrass, but also of crop rotations including winter crops are clearly less prone to soil erosion (Laloy and Bidders et al., 2010). Möller et al., 2011 investigated soil humus budgets of farms setting up a biogas plant and assumed that due to an increase of silage maize acreage a clear negative effect on the soil humus budget could be observed. Grasslands potentially store high amounts of carbon and therefore release high amounts of CO₂ by their transformation into arable land (Gitz and Ciais, 2004). However, especially in some regions of Northern Germany grassland used for bioenergy production is often cultivated on obligatory grassland sites and therefore silage maize is no alternative crop. Consequently, considering the mentioned points and comparing the maize monoculture with crop rotations considering the risk of disease, the overall appearance of the landscape
or other factors would in turn partly cancel off the positive evaluation of maize monocultures. However, all of the mentioned processes are highly complex, depending on many impact factors and are not easily to quantify. Therefore, also these processes have to be considered site and region specific in their environmental impacts.

Important topics concerning the evaluation of cropping systems have not been executed by the presented study. For example, the whole complex of organic fertiliser supply by digestion residues was excluded even if this is commonly practiced and data concerning yield performance and environmental impacts are available by the BIOGAS-EXPERT experiment. Still, Krauter and Claupein defined 2004 in terms of energy cropping systems for biogas production the following open working fields: requirements of biomass quality in terms of specific methane yield; biomass yield potentials considering the given limits in water availability and thermal time; as well as integration of energy maize in sustainable cropping systems to minimise negative effects on environment and to maximise net energy yield. The presented study could, using model based and combined experimental-modelling approaches at least contribute to the two latter working fields.

3. Conclusions
Silage maize is, due to high biomass yields, currently the most important bioenergy crop grown for biogas production. Exploring yield potentials and strategies to close the yield gaps between potential and actual yields is necessary in order to face the global increase in food, feed and bioenergy demand. Therefore, crop growth models are appropriate tools, providing by dynamic simulation of crop growth processes and water balance the ability to analyse temperature or drought stress impacts on resource use efficiencies and yield potentials. By irrigation, which gains actually more importance in silage maize cropping, aboveground dry matter yields up to 30 Mg ha\(^{-1}\) are reachable at warmer sites of Germany. Under the climatic conditions of Northern Germany, intensive crop rotations can provide in terms of biomass yield an adequate alternative to maize monoculture, but on a more intensified water and nitrogen level. Site adapted cropping systems should, in terms of high biomass yields, generally pursue to support the main crops by an adequate choice of intercrops and main crop combinations. The combined experimental-modelling analysis conducted for the cropping systems within the BIOGAS-EXPERT field experiments provided an interim, but helpful tool towards the assessment of bioenergy cropping systems for biogas production.
4. Outlook
Against the background that a flattening of the ‘biogas-boom’ is not likely, further efforts have to be executed in order to provide appropriate tools helping to refine the optimisation of bioenergy cropping systems for biogas production.

The need of linking dynamic and system oriented crop growth models to whole bioenergy cropping system models is directly deducible from the presented study. Therefore, additional dynamic crop growth models for other relevant crops for biogas production will be needed. Linked bioenergy cropping system models would assure the possibility of generalising and regionalising research efforts gained by field experiments, like BIOGAS-EXPERT and additionally could achieve benefit by analyses towards scenario calculations. The integration of nitrogen uptake processes of the crops and of soil nitrogen dynamics is a clear requirement for evaluating the fertiliser and environmental effects of digestion residues within different cropping systems and for focusing on nitrogen and later also on carbon flows within the whole production chain ‘soil-plant-fermenter’. To achieve a high degree of nutrient cycle closure for biogas production systems, the tracing and quantification of potential losing pathways, like nitrogen leaching, ammonia volatilisation at fertiliser application, and greenhouse gas emission (N₂O, but also CH₄), is highly important. Data concerning all mentioned processes gained from the BIOGAS-EXPERT field experiment are available, and first model approaches towards ammonia volatilisation (Gericke, 2009) and soil nitrogen dynamics exist. The model implementation using an object orientated component library (Kage and Stützel, 1999) allows a modular structure of the model and will therefore allow easier model amplifications. By choosing model approaches, which can be parameterised using commonly available data, the model should be applicable to various sites, cropping systems and digestion residues conditions.

References


Summary / Zusammenfassung

1. Summary
A strong promotion of renewable energy production by the European and German energy policy led to a substantial increase of crops grown for biogas (methane) production in Germany. Maize is, due to its high yield potential, dominating energy cropping systems for biogas production, tending to maize monocultures or rotations with very high percentage of maize. The quantification of the production potential and the analyses towards resource use efficiencies of bioenergy cropping systems are highly important because the economical profitability, but also the greenhouse gas reduction effects depend on high biomass yields.

In order to quantify the yield potentials of silage maize grown under different environmental conditions and to analyse the impacts of stress factors, like temperature and drought stress, on dry matter productivity and resource use efficiencies, a new dynamic crop growth model for silage maize was developed. This crop growth model calculates dry matter production, dry matter partitioning into root, leaf, stem and cob, leaf area expansion and spatial root distribution, and was linked to modules simulating potential evapotranspiration and soil water balance. The model is featuring well known model approaches working on a high level of simplification. However, the predictive power of the crop growth model concerning aboveground dry matter production (RMSE 324 g m\(^{-2}\)), the satisfactory model performance of soil water contents, WUE, TUE and LUE also under water limited conditions and the fact that this model can easily be parameterised using commonly available data underlined its applicability for executing scenario simulations.

The ex-post simulation study (35 years) conducted for three typical regions of Germany, differing mainly by temperatures and water availability, showed that at the most Northern site dry matter production was limited by low temperature directly, affecting the LUE negatively, and indirectly, reducing leaf area expansion. The observed yield gaps (between attainable and potential yield) at the two warmer sites were mainly caused by direct drought stress impacts, but yield potentials observed without water limitations were higher compared to the colder site. Still, even at the warm sites long-term average yield potentials of silage maize did not exceed 30 Mg ha\(^{-1}\).

The assessment of different bioenergy cropping systems was conducted by a combined experimental-modelling approach with special respect to dry matter productivity, light, water and nitrogen use efficiency. Perennial ryegrass and intensive crop rotations including winter intercrops and combining \(\mathrm{C}_4\)- and \(\mathrm{C}_3\)-crops were compared with maize monocultures using...
data from a two year field experiment conducted at two sites in Northern Germany within the BIOGAS-EXPERT project. The comparison of these cropping systems showed that, under Northern German conditions with low annual air temperatures and high annual amounts of precipitation, intensive crop rotations can reach, due to prolonged leaf area duration a biomass yield level similar to maize monocultures. Indeed, the needed amount of water and nitrogen was higher for these crop rotations and the yield performance of the maize grown within the rotations was highly dependent on the proceeding crop. Perennial ryegrass was on the chosen experimental site clearly less productive than maize grown in monoculture. However, an extensive assessment of bioenergy cropping systems has to consider also indicators, like nutrient losses, soil erosion or soil-organic matter, which would partly cancel off the negative evaluation of perennial ryegrass. The combined experimental-modelling approach provides an interim, but helpful tool towards the assessment of bioenergy cropping systems for biogas production.

The presented studies underlined the importance of a site adapted choice of bioenergy cropping systems, the importance of supporting the main crops within crop rotations by an adequate choice of intercrops or main crop combinations and the importance of leaf area expansion in terms of dry matter production. The presented results of this thesis contribute to the quantification of biomass yield potentials considering the given limits in water availability and thermal time, and secondly to the integration of energy maize in sustainable cropping systems to minimise negative effects on environment and to maximise net energy yield.
2. Zusammenfassung


Um das Ertragspotential von Silomais unter verschiedenen Umweltbedingungen zu quantifizieren und die Wirkung von Stressfaktoren, wie Temperatur- oder Trockenstress, auf die Trockenmasseproduktivität und die Ressourcennutzungseffizienzen zu analysieren, wurde ein dynamisches Pflanzenwachstumsmodell für Silomais entwickelt. Das entwickelte Pflanzenwachstumsmodell berechnet die Trockenmasseproduktion, die Aufteilung der Trockenmasse auf Blatt, Stängel und Kolben, das Blattflächenwachstum und die räumliche Wurzelverteilung und ist an ein Evapotranspirationsmodell sowie an ein Bodenwasserhaushaltsmodell gekoppelt. Bei der Entwicklung des Modells wurde auf einfache und bekannte Modellansätze zurückgegriffen. Dennoch, die ausreichend hohe Genauigkeit, die bei der Modellvalidierung bezüglich der Trockenmasseerträge erzielt werden konnte (RMSE 324 g m⁻²), die zufriedenstellenden Ergebnisse bezüglich der modellierten Bodenwassergehalte, Wasser-, Transpirations- und Lichtnutzungseffizienzen sowie die einfache Parametrisierbarkeit des Modells unterstreichen dessen Eignung zur Durchführung von Szenarienberechnungen.


Die vorgelegte Arbeit unterstreicht die Bedeutung der standortangepassten Wahl von Energiepflanzenanbausystemen, der Betonung der Hauptkultur innerhalb der Fruchtfolgen durch die Wahl adäquater Winterzwischenfrüchte und Fruchtartenkombinationen und der Blattflächenbildung für die Trockenmasseproduktion. Die präsentierten Ergebnisse tragen, erstens zur Quantifizierung von Ertragspotentialen unter Berücksichtigung der limitierten Wasserverfügbarkeit und der temperaturlimitierten Vegetationsdauer und zweitens zur Integration von Silomais in nachhaltige Anbausysteme, die negative Umwelteffekte minimieren und Energieerträge maximieren, bei.
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