S2. Supplementary Information on SALUS simple model calibration

# Systems Approach to Land-Use Sustainability (SALUS) model overview

SALUS (Basso and Ritchie, 2015) is a cropping systems simulation platform that allows estimating the impact of diverse agricultural management strategies on various processes within the soil–plant–atmosphere continuum. The platform contains a suite of interconnected processed-based models derived from the well-validated CERES (Crop Estimation through Resource and Environment Synthesis) model, providing simulation of crop growth and development, and carbon, water, nitrogen, and phosphorus cycling dynamics on a daily time step. The model uses as input daily values of incoming solar radiation (MJ m−2), maximum and minimum air temperature (°C), and rainfall (mm), as well as information on soil characteristics and management. SALUS has been tested extensively for its ability to simulate various soil-crop processes including: soil carbon dynamics (Basso et al., 2018; Senthilkumar et al., 2009), crop yield (Basso et al., 2007), plant N uptake and phenology (Albarenque et al., 2016; Basso et al., 2011, 2010), nitrate leaching (Basso et al., 2016; Giola et al., 2012; Syswerda et al., 2012), water use efficiency (Ritchie and Basso, 2008) and transpiration efficiency (Basso and Ritchie, 2012). A general description on SALUS is provided by Basso and Ritchie (2015).

In SALUS, crop growth can be simulated following a *complex* or a *simple* modeling approach. In this study, we used the simple modeling approach. The *simple* crop model (SALUS-Simple henceforth) represents a ‘generic’ crop model with 20-25 predefined crop parameters, which can be easily adapted to characterize growth of many annual crops. SALUS-Simple follows the same approach used by ALMANAC (Agricultural Land Management Alternatives with Numerical Assessment Criteria, Kiniry et al., 1992). Briefly, the model uses crop parameters to calculate potential leaf area index (LAI) and radiation use efficiency (RUE) curves as function of thermal time, which in turn are used to estimate daily crop resource acquisition and potential crop growth. When run with water and nutrient limitations, the model calculates water and nutrient stress factors based on a daily supply-demand balance, which then are applied to reduce the rate of potential biomass growth. For a detailed description of the SALUS-Simple crop model, we refer the reader to Dzotsi et al. (2013).

# Data sources and model set up

We assembled a dataset of published literature studies conducted within the Corn Belt to set up and calibrate the SALUS-simple model. All of these studies reported measurements of winter rye cover crop biomass at termination, as well as cover crop planting and termination dates. This dataset contains observations from 12 studies, 6 of which also were included in our original meta-analysis dataset and the rest were available from a literature search from a previous study (Martinez-Feria et al., 2016). In total, the dataset included observations from 15 sites, amounting to 52 site-year combinations (Figure S2.1). We used 60% of the data for model training and 40% for model testing. The assembled dataset is shown in Table S2.1.

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|  | ***Figure S2.1.*** *Geographical location of the experiments used for model calibration.* |

For each of the 15 sites, we retrieved daily weather data from the North American Land Data Assimilation System project phase 2 (NLDAS-2) dataset (Xia et al., 2012) using the single-pixel (0.125° resolution) extraction tool and formatter for SALUS (<https://salusmodel.ees.msu.edu/NLDAS/>). Soil information for each site was retrieved from the Soil SURvey GeOgraphic database (SSURGO; Soil Survey Staff), from which we selected data for the predominant soil series (map unit key) at each location. Soils in the region are deep, fertile and poorly to moderately-well drained.

Simulation for each experiment were run independently, from Jan-1 to June-30 of the following year, meaning that each simulation comprised a period of 18 months. We assumed both water- and N-limited rye cover crop growth. To provide for realistic initial conditions for soil water at cover crop planting, we simulated a maize crop, prior to cover crop planting. In the model, maize was planted in early May, fertilized with 150 kg N ha-1 at planting and harvested 10 days before cover crop planting (usually September or October). Planting density for rye cover crop was assumed at 300 plants m-2, 1.0 cm depth and 20 cm row spacing. No fertilizer to rye was applied in the model.

***Table S2.1.*** *Dataset of published estimates of rye cover crop biomass at terminations which was used for model training and testing*

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| --- | --- | --- | --- | --- | --- | --- |
| **Obs. ID** | **Used for** | **Source** | **Location** | **Planting** | **Termination** | **Biomass** |
| **(Mg ha-1)** |
| 1 | Training | Cornelius and Bradley, 2017 | Columbia, MO | 2012-9-11 | 2013-4-25 | 2.89 |
| 2 | 2013-9-12 | 2014-5-2 | 2.19 |
| 3 | 2014-9-10 | 2015-4-23 | 1.15 |
| 4 | Moberly, MO | 2013-9-12 | 2014-5-2 | 1.39 |
| 5 | 2014-9-10 | 2015-4-23 | 3.93 |
| 6 | Davis, 2010 | Urbana, IL | 2004-10-1 | 2005-5-13 | 7.10 |
| 7 | 2005-10-1 | 2006-5-12 | 6.00 |
| 8 | 2006-10-1 | 2007-5-11 | 6.00 |
| 9 | Bruin et al., 2005 | Rosemont, MN | 2001-10-25 | 2002-5-1 | 0.49 |
| 10 | 2001-10-25 | 2002-5-8 | 0.73 |
| 11 | 2001-10-25 | 2002-5-15 | 1.03 |
| 12 | 2001-10-25 | 2002-5-22 | 1.80 |
| 13 | 2002-11-1 | 2003-5-13 | 0.15 |
| 14 | 2002-11-1 | 2003-5-23 | 0.41 |
| 15 | 2002-11-1 | 2003-6-2 | 1.42 |
| 16 | 2002-11-1 | 2003-6-17 | 2.93 |
| 17 | Waseca, MN | 2001-10-18 | 2002-5-1 | 0.38 |
| 18 | 2001-10-18 | 2002-5-8 | 0.85 |
| 19 | 2001-10-18 | 2002-5-20 | 2.19 |
| 20 | 2001-10-18 | 2002-5-28 | 3.77 |
| 21 | 2002-10-11 | 2003-5-1 | 0.15 |
| 22 | 2002-10-11 | 2003-5-7 | 0.22 |
| 23 | 2002-10-11 | 2003-5-14 | 0.52 |
| 24 | 2002-10-11 | 2003-5-20 | 0.99 |
| 25 | Feyereisen et al., 2006 | St. Paul, MN | 2000-9-18 | 2001-5-25 | 5.90 |
| 26 | Forcella, 2014 | Stevens county, MN | 2009-9-2 | 2010-6-9 | 6.00 |
| 27 | 2010-9-20 | 2011-6-14 | 6.00 |
| 28 | Kaspar et al., 2007 | Ames, IA | 2001-9-20 | 2002-4-17 | 2.43 |
| 29 | 2002-9-10 | 2003-5-6 | 2.50 |
| 30 | 2003-10-2 | 2004-4-16 | 1.48 |
| 31 | 2004-10-6 | 2005-4-25 | 2.74 |
| 32 | Testing | Kaspar et al., 2012 | Ames, IA | 2005-9-30 | 2006-4-21 | 2.44 |
| 33 | 2006-10-24 | 2007-5-10 | 0.61 |
| 34 | 2007-9-28 | 2008-4-29 | 1.26 |
| 35 | 2008-10-29 | 2009-5-21 | 0.50 |
| 36 | 2009-9-28 | 2010-4-19 | 1.73 |
| 37 | Martinez-Feria et al., 2016 | Kelley, IA | 2008-10-21 | 2009-5-6 | 0.37 |
| 38 | 2009-11-6 | 2010-5-5 | 1.18 |
| 39 | 2010-10-4 | 2011-5-10 | 1.53 |
| 40 | 2011-10-10 | 2012-4-18 | 2.50 |
| 41 | 2012-10-15 | 2013-5-11 | 0.50 |
| 42 | Ruffo and Bollero, 2003 | Brownstown, IL | 1998-10-3 | 1999-4-28 | 4.73 |
| 43 | 1999-10-2 | 2000-4-29 | 2.92 |
| 44 | Urbana, IL | 1998-10-1 | 1999-5-2 | 4.02 |
| 45 | 1999-10-5 | 2000-5-4 | 3.16 |
| 46 | Strock et al., 2004 | Lamberton, MN | 1998-10-1 | 1999-4-30 | 2.70 |
| 47 | 1999-9-29 | 2000-4-11 | 1.00 |
| 48 | 2000-10-4 | 2001-5-16 | 0.50 |
| 49 | Werle et al., 2018 | North Platte, NE | 2016-9-20 | 2017-4-18 | 4.08 |
| 50 | 2016-10-17 | 2017-4-18 | 3.77 |
| 51 | Williams et al., 1998 | Ithaca, NE | 1994-9-20 | 1995-6-6 | 6.31 |
| 52 | 1995-9-20 | 1996-5-23 | 2.89 |

# Model calibration and performance

To calibrate the SALUS-simple model for simulating rye cover crop biomass, we first compared simulated values to data from the testing dataset (Table S2.1). To quantify model fit to the observed data we computed the Nash-Sutcliffe model efficiency (NSE) and root-mean-squared error (RMSE). The RMSE is a measure of model error (the closer to zero, the better), while NSE is a measure of model precision compared to an arithmetic mean (a value of 1 indicates perfect fit). The equation for these two measures can be seen in Archontoulis and Miguez (2013). Model fit was also evaluated visually by means of plotting the observed vs. simulated values, with the regression line as measure of model bias.

We used as a starting point the rye crop species parameters available in the ALMANAC model (Kiniry and Spanel, 2009; Table S2.2). Using this parameterization, however, the model tended to overestimate fall growth, which resulted in premature senescence in the spring. Therefore, we evaluated increasing the length of the growth cycle (TTtoMatr from 1200 to 1800 °C-day) and adjusting phenology (relTT\_P1, relTT\_Sn) and LAI curve parameters (relLAI\_P2). Additionally, because the model tended to overpredict biomass growth in the spring, we decreased maximum potential radiation use efficiency (RUEmax) from 3.0 to 2.0 g MJ (PAR)-1. A list of parameter values derived from the model training step are included in Table S2.2, and an model fit to the training data set is shown in Figures S2.2 and S2.3.

***Table S2.2.*** *Calibrated SALUS-simple parameters used to simulate winter rye cover crop growth.*

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| --- | --- | --- | --- | --- |
| **Parameter** | **Description** | **Units** | **Value** | |
| **ALMANAC (original)** | **Calibrated\*** |
| relTT\_P1 | Relative development thermal time at point 1 | °C-day °C-day-1 | 0.3 | 0.25 (0.05-0.45) |
| relLAI\_P1 | Relative LAI at point 1 | m2 m-2 | 0.01 | - |
| relTT\_P2 | Relative development thermal time at point 2 | °C-day °C-day-1 | 0.5 | - |
| relLAI\_P2 | Relative LAI at point 2 | m2 m-2 | 0.95 | 0.9 (0.9-0.99) |
| LAImax | Maximum leaf area index | m2 m-2 | 3 | - |
| RUEmax | Maximum potential radiation use efficiency | g MJ (PAR)-1 | 3 | 2 (1-3.5) |
| relTT\_Sn | Relative development thermal time at senescence | °C-day °C-day-1 | 0.8 | 0.5 (0.5-0.85) |
| SnParLAI | Parameter for RUE decline after senescence | unitless | 1 | - |
| SnParRUE | Parameter for RUE decline after senescence | unitless | 1 | - |
| TbaseDev | Base temperature for development | °C | 0 | - |
| ToptDev | Optimal temperature for development | °C | 15 | - |
| TTtoGerm | Development thermal time to germinate | °C-day | 20 | - |
| TTtoMatr | Development thermal time to mature | °C-day | 1200 | 1800 (1200-2500) |
| EmgInter | Intercept of emergence time calculation | leaf eq. | 15 | - |
| EmgSlope | Slope of emergence time calculation | leaf eq. cm-1 | 6 | - |
| HrvIndex | Harvest index | Mg Mg-1 | 0.42 | - |
| PlntN\_Em | Optimal N in plant at emergence | g g-1 | 0.0226 | - |
| PlntN\_Hf | Optimal N in plant halfway to maturity | g g-1 | 0.018 | - |
| PlntN\_Mt | Optimal N in plant at maturity | g g-1 | 0.014 | - |
| GrnN\_Mt | Optimal N in grain at maturity | g g-1 | 0.023 | - |
| CHeight | Approximate height of crop | m | 1.0 | - |
| \*Values within parenthesis show the range explored in the calibration | | | | |

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| ***Figure S2.2.*** *Example of rye cover crop spring growth as simulated by the SALUS-simple crop model. The data for the experiments shown here were obtained from Bruin et al. (2005).* |

Having calibrated the SALUS-Simple crop model to simulate rye growth, the next step was to compare the simulated values to the independent measurement in the testing dataset. Considering that set-up and model training was largely based on limited (i.e. publicly available) data and literature values, the SALUS-simple model was able to satisfactorily reproduce the measured cover crop biomass at termination in the testing dataset. Biomass across all sites in the testing dataset were simulated with a RMSE of 1.2 Mg ha-1. This was about the same than for the training dataset (1.1 Mg ha-1), which suggest no overfitting of the training data. The model did tend to overpredict more the rye biomass in the testing dataset, especially that of high yielding environments. This translated to lower NSE compared to the training data (0.74 vs. 0.39), although it was still within acceptable ranges. Based on these results we deemed this model calibration appropriate for estimating rye biomass growth as a function of weather, soils and management across the US Corn Belt.

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|  | ***Figure S2.3.***  *SALUS simple model fit to the training and testing datasets. NSE = Nash-Sutcliffe model efficiency; RMSE = root mean squared error.* |

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