Coupling a Pest and Disease Damage Module with CSM-NWheat: A Wheat Crop Simulation Model

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Highlights

- CSM-NWheat, a DSSAT wheat crop model, was coupled with a pest module named PEST.
- The coupled model can simulate the impact of pest and disease damage on wheat crops.
- Pest damage is expressed in daily steps by communication links called coupling points.
- Coupling points are linked with state variables at which pest damage can be applied.
- Field pest-scouting reports and linear interpolation are used to compute damage rates.

Abstract. *Wheat is one of the most important global staple crops and is affected by numerous pests and diseases. Depending on their intensity, pests and diseases can cause significant economic losses and even crop failures. Pest models can assist decision-making, thus helping reduce crop losses. Most wheat simulation models account for abiotic stresses such as drought and nutrients, but they do not account for biotic stresses caused by pests and diseases. Therefore, the objective of this study was to couple a dynamic pest and disease damage module to the DSSAT model CSM-NWheat. Coupling points were integrated into the CSM-NWheat model for applying daily damage to all plant components, including leaves, stems, roots, and grains, the entire plant, and to the assimilate supply. The coupled model was tested by simulating a wheat crop with virtual damage levels applied at each coupling point. Measured foliar damage caused by tan spot (*Pyrenophora tritici-repentis*) was also simulated. The modified model accurately estimated the reduction in leaf area growth and the yield loss when compared with observed data. With the incorporation of the pest module, CSM-NWheat can now predict the potential impact of pests and diseases on wheat growth and development, and ultimately economic yield.*

Keywords. *Biotic stress, Decision support, DSSAT, Model coupling, Yield loss.*

Wheat (*Triticum aestivum* L.) is one of the most important cereals in the world and is produced both as a human food and as a feed for livestock. Demand for wheat is expected to increase with the rise in the global population (Singh et al., 2016). Modern wheat cultivars developed by private and public wheat breeding programs often exhibit an extensive geographic adaptation (Braun et al., 2010). Depending on the mega-environment, wheat yield and quality are constantly at risk due to numerous pests, including insects, nematodes, and diseases (Oerke, 2006; Farook et al., 2019). The rapid evolution of wheat agrosystems in recent decades has led to a large variation and variability of crop losses due to insect pests and plant pathogens (Shewry, 2009; West et al., 2014). Damage due to biotic stresses is estimated to be responsible for 10.1% to 28.1% of the global production losses (Savary et al., 2019).

With computational advances during the past 30 years, decision support systems have been used in agriculture to help evaluate farm management and to assist with complex decision-making (Boogaard et al., 1998; Keating et al., 2003; Hoogenboom et al., 2019a; Tsuji et al., 1998). The Decision Support System for Agrotechnology Transfer (DSSAT) computes the soil-plant-atmosphere dynamics to predict crop development and can help decision makers with identifying improved management responses (Jones et al., 2003;

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Hoogenboom et al., 2019b). The Cropping System Model (CSM), which is the main modeling engine of DSSAT, simulates yield for more than 42 crops and has three different modules for simulating wheat growth and development: CROPSIM-Wheat (Hunt and Pararajasingham, 1995), CERES-Wheat (Ritchie et al., 1998), and NWheat, the latest wheat crop growth and development module that has been incorporated in CSM (Kassie et al., 2016).

Crop growth simulators have the potential to quantify and predict the effects of pests and pathogens on crop growth (Tsuji et al., 1998; Boote et al., 2010; Boote, 2019). However, the impacts of plant pests and pathogens are usually ignored in crop simulation models (Donatelli et al., 2017). In the early 1980s, attempts to evaluate pest impact on crop growth started with the development of a system that coupled pest management strategies with crop models (Wilkerson et al., 1983a, 1983b; Jones et al., 1985). At the same time, Boote et al. (1983) classified and categorized the impacts of insect pests and diseases on the type of damage they cause in plants. Boote et al. (1983) identified seven pest damage mechanisms: stand reducer, photosynthetic rate reducer, leaf senescence accelerator, light stealer, assimilate sapper, tissue eater or consumer, and turgor reducer, as a general method to incorporate the impact of pests and diseases into crop models.

In the early 1990s, Batchelor et al. (1993) developed a general framework for applying pest damage coupled with the crop models SOYGRO and PNUTGRO for soybean and peanut, respectively (Boote et al., 1989; Hoogenboom et al., 1992), through pest linkages, called coupling points, associated with rate and state variables for which pest damage can be expressed. This framework uses field pest-scouting data to interpolate damage between scouting dates, thus predicting crop losses due to pests and pathogens. Pinnschmidt et al. (1995) estimated pest and disease effects on rice crops using the CERES-Rice module and a similar pest framework, although it was never included in the official CSM source code. These attempts to couple crop models with pests and diseases would later become a generic pest framework named PEST as part of the CSM model of DSSAT (Hoogenboom et al., 2010). In a recent effort, Magarey et al. (2005) created a simple generic infection model to predict infection periods of fungal foliar pathogens based on weather conditions. Pavan and Fernandes (2009) developed a generic disease model that can be parameterized to simulate the disease cycles of several crop diseases. This model was dynamically linked to CSM through the PEST subroutines inside the CROPGRO-Soybean crop module to estimate the effects of a fungal disease on soybean (Fernandes et al., 2019). Batchelor et al. (2020) simulated the impact of leaf necrosis on maize yield due to lethal maize necrosis (MLN) using the PEST module coupled with CERES-Maize, a maize crop growth module of CSM.

Despite the current advances in coupling crop and pest modules, most dynamic wheat simulation models do not account for pest and disease damage. Willocquet et al. (2008) developed a model named WHEATPEST for estimating the effects of specific pests and diseases on wheat yield. Their model used mean temperature and solar radiation, and an array of driving functions and parameters to simulate production and daily injuries caused by pest to simulate the effects on yield loss. Whish et al. (2015) estimated the impact of wheat rust on the green leaf area of wheat crops by coupling the Agricultural Production Systems Simulator (APSIM) with a rust model developed in the DYMEX population-modeling platform. Bregaglio et al. (2021) incorporated a pest damage mechanism into five different wheat models to simulate four major wheat diseases (brown and yellow rust, *Septoria tritici* blotch and powdery mildew). Their approach used injury drivers (Willocquet et al., 2008, 2018) that represented the time course of multiple injuries through a disease progress curve (DPC) of disease severity on a 0-1 scale. Bregaglio et al. (2021) also outlined the rationale for implementing more dynamic pest damage mechanisms into crop models, as their approach was very static. Therefore, simulating the interaction between pest damage and wheat growth should be further explored to add more flexibility to pest damage mechanisms to create case-specific simulation scenarios not bound to a static DPC that shapes the simulated crop losses. In fact, the requirement for disease drivers as input is currently a severe limitation of most pest and disease models that can be solved through the use of dynamic pest modules.

Other common wheat diseases, such as rusts, blotches, and scab (Figueroa, 2018), currently contribute to yield losses, yet wheat-specific crop modules have not been dynamically coupled with a generic pest and disease framework. Understanding of the biotic impacts of pests and disease on wheat yield and development is a fundamental step toward predictive agriculture and can provide useful predictions for real farm conditions (Donatelli et al., 2017). Therefore, the objectives of this study were to: (1) create and implement pest and disease coupling points in a dynamic wheat module and couple the wheat module PEST, which is a pest and disease dynamics framework of CSM; (2) conduct a sensitivity analysis of the dynamic coupled model to evaluate its response to virtual damage levels applied for each coupling point; and (3) evaluate the performance of the new module in a real-world case study.

Materials and Methods

Applying Pest and Disease Damage in Crop Modules

Estimation of the impacts of pests and pathogens in CSM requires communication between a crop module and another module that handles pest and disease damage, here referred to as the PEST module. The communication links are called coupling points and can reduce the daily state and rate variables, such as leaf, stem, root, seed growth, and several others, according to the source type of potential damage (Boote et al., 1983). In CSM, pest damage can be applied using several methods (Batchelor et al., 1993; Boote et al., 1983; Teng et al., 1998). In this study, two damage methods were selected to simulate the effects of pests and diseases on wheat:

1. Absolute damage (daily rate as amount per day), i.e., the exact damage based on the recorded pest population and the pest feeding rate.
2. Relative observed damage (daily rate as % per day), i.e., the removal of a certain amount of mass or area as a percentage.

The coupling points were implemented in the CSM-NWheat model using both the absolute and relative observed damage methods. The incorporated coupling points can apply daily damage for the simulated leaf area index (LAI), leaf mass, stem mass, root mass, seed mass, necrotic LAI, assimilates, and the whole plant (fig. 1). Changes in LAI, leaf, stem, root, seed mass, assimilates, and the entire plant are the coupling points based on the CERES-Maize model (Hoogenboom et al., 2010) to affect the respective CSM-NWheat state variables. The necrotic LAI was implemented based on the CROPGRO model (Boote et al., 1998).

The pest and disease coefficient file (FileP) defines the coupling points with the crop module for each individual pest and disease and the associated damage pattern (Batchelor et al., 1993). The actual observed pest or disease incidence observed through scouting reports can be defined in a time series data file (FileT), which is read and converted into daily damage using linear interpolation. This file also contains observed data for comparison with the simulation results (Hoogenboom et al., 2010). Alternatively, dynamic information about the actual pest or disease population or incidence can be provided by linking the crop model with a dynamic pest model or by incorporating dynamic pest modules into the crop model (Fernandes et al. 2019).

The equations within the coupling points were adapted from the CERES-Maize and CROPGRO models (Boote et al., 1998; Hoogenboom et al., 2010) and incorporated into the CSM-NWheat model to affect the corresponding plant growth traits. When a pest or a pathogen causes daily damage to a specific plant component, the state variable corresponding to the mass of that plant component is reduced:

$$P\left(x\right)_t = P\left(x\right)_t^* - \left(\frac{Dam_t}{Pop_t}\right) \tag{1}$$

where

$P(x)_t$ = state variable of plant component x on day t after damage has been applied

$P(x)_t^*$ = state variable of plant component x on day t before damage has been applied

Dam_t = total amount of damage applied to the state variable on day t

Pop_t = plant population on day t.

The nitrogen associated with the specific plant component is reduced according to the damage applied:

$$N\left(x\right)_t = N\left(x\right)_t^* - \left(\frac{N\left(x\right)_t^* \times \left(Dam_t \div Pop_t\right)}{P\left(x\right)_t}\right) \tag{2}$$

where

$N(x)_t$ = nitrogen available for plant component x on day t after damage has been applied

$N(x)_t^*$ = nitrogen available for plant component x on day t before damage has been applied.

The coupling points for leaf mass, stem mass, root mass, and seed mass use these equations to apply pest damage to a respective plant component with the corresponding damage variable. The coupling point for LAI computes the daily leaf area damage (*LAIDOT*) caused by pests, which is subtracted from the daily LAI state variable (*LAI*):

$$LAI_t = LAI_t^* - \left(\frac{LAIDOT}{10000}\right) \tag{3}$$

where

LAI_t = LAI on day t after damage has been applied ($m^2\ m^{-2}$)

LAI_t^* = LAI on day t before damage has been applied ($m^2\ m^{-2}$)

$LAIDOT$ = leaf area consumed by pests ($cm^2\ m^{-2}\ d^{-1}$).

When a pest damages the developing wheat grains, in addition to reducing the grain mass, the grain number per plant (GPP) is adjusted in proportion to the seed mass loss:

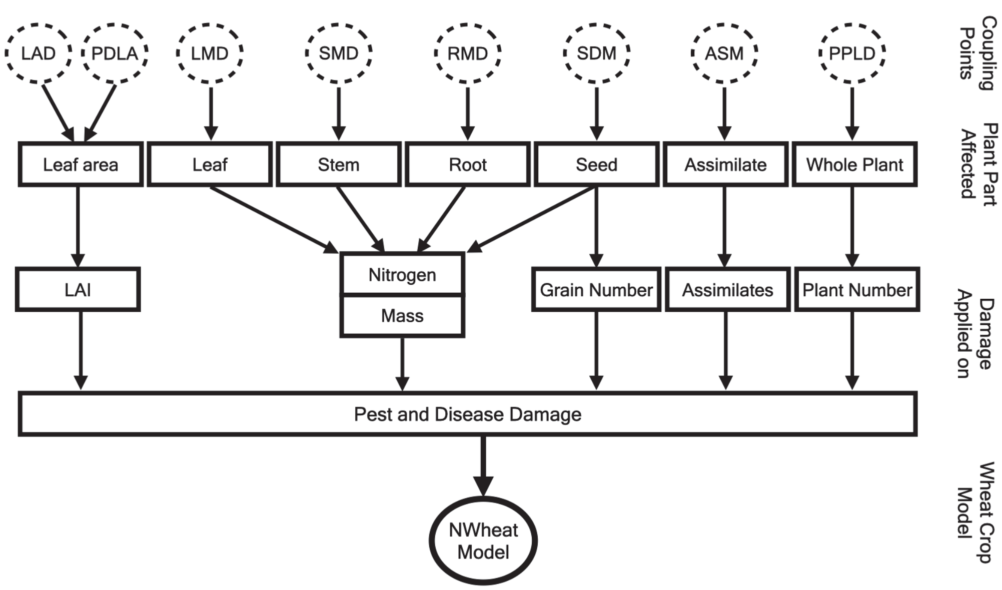

Figure 1. Implemented coupling points in CSM-NWheat and interaction with the state variables of the model. Each coupling point has a unique identification code: leaf area destroyed (LAD), plant diseased leaf area (PDLA), leaf mass destroyed (LMD), stem mass destroyed (SMD), root mass destroyed (RMD), seed mass destroyed (SDM), reduction in photosynthesis (ASM), and plants destroyed (PPLD).

$$GPP_t = GPP_t^* \times \left(\frac{SWIDOT \div PLTPOP}{SDWT_t} \right) \quad (4)$$

where

GPP_t = grain number (plant^{-1}) on day t after damage has been applied

GPP_t^* = grain number (plant^{-1}) on day t before damage has been applied

$SWIDOT$ = seed loss due to pests (g m^{-2} d^{-1})

$PLTPOP$ = plant population (plants m^{-2})

$SDWT_t$ = seed mass on day t after damage has been applied (g plant^{-1}).

Plant necrosis due to diseases affects the canopy photosynthesis potential on day t by reducing the healthy LAI:

$$AREAH_t = \left(LAI_t^* \times 10000 \right) - DISLA \quad (5)$$

where

$AREAH_t$ = area of healthy leaves on day t after damage has been applied (cm^2 m^{-2})

$DISLA$ = diseased leaf area (cm^2 m^{-2} d^{-1}).

Sap-sucking pests slow plant growth by removing soluble assimilates from the host cells (Boote et al., 1983). The simulation of such effects in CSM-NWheat is done by reducing the potential daily dry matter production:

$$PCARBO_t = PCARBO_t^* - ASMDOT \quad (6)$$

where

$PCARBO_t$ = potential dry matter production on day t after damage has been applied (g plant^{-1} d^{-1})

$PCARBO_t^*$ = potential dry matter production on day t before damage has been applied (g plant^{-1} d^{-1})

$ASMDOT$ = reduction in photosynthesis due to pests (g m^{-2} d^{-1}).

If pest or disease damage affects all plant components, the plant number is reduced according to the percentage of plants destroyed on day t:

$$PLTPOP_t = PLTPOP_t^* - \left(\frac{PLTPOP_t^* \times PPLTD}{100} \right) \quad (7)$$

where

$PLTPOP_t$ = plant population on day t after damage has been applied (plants m^{-2})

$PLTPOP_t^*$ = plant population on day t before damage has been applied (plants m^{-2})

$PPLTD$ = percentage of plants destroyed (% m^{-2} d^{-1}).

The state variable for LAI is adjusted in proportion to the amount of plants that are destroyed:

$$LAI_t = LAI_t^* \times \left(\frac{PLTPOP_t}{100} \right) \quad (8)$$

Simulating Impact of Pest Defoliation on Wheat Yield

The time series file (FileT) of a wheat experiment conducted in Kansas in 1981 and included in DSSAT (KSAS8101.WHX, Treatment 2 - Dryland; 60 kg N ha^{-1}) was adapted to serve as a proof-of-concept and to study the capability of the newly incorporated coupling points to simulate the impact of diseases and insect pests on wheat. Hypothetical damage was applied for each coupling point according to the specific pest or disease in various studies (table 1) to simulate the impact on yield loss. In addition, a case of extreme damage due to leaf defoliation was incorporated to analyze the pest coupled model response.

Case Study

An on-farm experiment was conducted in 2016 in an area of approximately 1 ha in the middle of a commercial-sized agricultural field in Carazinho, Rio Grande do Sul, Brazil (28° 13′ 46″ S, 52° 54′ 32″ W, 517 m elevation). The farm had adopted a soybean-wheat crop rotation under no tillage. Tan spot (Singh et al., 2016), a fungal disease caused by *Pyrenophora tritici-repentis*, occurred naturally on the wheat in this field. The experimental design was four randomized complete blocks. The experimental plots were sufficiently large (20 m × 100 m) to accommodate regular farm machinery. Seeds were planted on June 13 at a row spacing of 17 cm, and the final plant population was 376 plants m^{-2}. The treatments were disease control with fungicide and no disease control. Opera, a combination product of Pyraclostrobin and Epoxiconazole with protective and systemic properties, was used for controlling tan spot. The fungicide rate was 1.5 L ha^{-1} sprayed at the tillering, booting, and anthesis phenological stages. The spring wheat cultivar was BRS Parrudo (Scheeren et al., 2019). Fertilizer was applied based on recommendations from soil analysis. At approximately 40 days after planting, urea was broadcast at a rate of 80 kg N ha^{-1}.

Starting on August 2, 2016, ten plants from each plot were collected at seven-day intervals. The plants were cut close to the ground, packed in plastic bags, and transported to the laboratory. Upon arrival, the leaves were separated from the stems and fixed on an A4 white paper background with transparent tape. Images of the leaves were obtained with a CCD photographic scanner.

An image processing algorithm was used to classify and measure the damage caused by tan spot on wheat leaves. The

Table 1. Observed pest and disease damage recorded in various studies. The damage rates reported in these studies were used to evaluate the functionality of the coupling points for wheat.

Coupling Point	Pest or Disease	Damage Rate	Reference
Leaf area index	Corn earworm (*Heliothis zea*)	12% to 25% (defoliation)	Batchelor et al. (1989)
Leaf area index	Leaf beetle (*Oulema melanopus* L.)	7% to 84.5% (defoliation)	Császár et al. (2021)
Leaf mass	Cotton bollworm (*Helicoverpa armigera*)	18.5% to 28% (yield)	Rogers et al. (2010)
Stem mass	Stem rust (*Puccinia graminis*)	10% to 45% (yield)	Loughman et al. (2005)
Root mass	Nematodes (*Pratylenchus thornei*)	12% to 15% (yield)	May et al. (2016)
Seed mass	Fusarium head blight (*Fusarium graminearum*)	18.6% (yield)	Reis and Carmona (2013)
Necrotic leaf area index	Tan spot (*Pyrenophora tritici-repentis*)	9% to 29% (yield)	Bhathal et al. (2003)
Assimilate	Aphids (*Sitobion avenae*)	16% (yield)	Rabbinge et al. (1984)

algorithm was interactively trained to classify pixels in three classes: healthy, necrosis, and background. From binary images, the obtained values were: image area (I), background area (BK), necrosis area (N), and healthy area (H). The leaf area (L) was calculated by subtracting the background area (BK) from the image area (I), and the proportion of necrosis (K) was obtained by K = N/L.

Environmental variables were monitored using a micrometeorological tower installed in the center of the experimental area. Sensors attached to the tower measured relative humidity (%), temperature (°C), global incident solar radiation (MJ m^{-2} d^{-1}), and rainfall (mm). All sensors were connected to a datalogger with channel multiplexers, and readings were taken every 30 s, with averages and totals stored every 15 min for the duration of the wheat growing season.

The observed yield in the control treatment with no tan spot damage was 3,915 kg ha^{-1}, compared to 3,750 kg ha^{-1} in the plots where tan spot was present. On average, there was a reduction of 4.2% in grain yield due to tan spot infection. The data that were obtained from this experiment were used as data input for the CSM-NWheat model for simulating crop growth and development, and ultimately the impact of tan spot on wheat yield.

Results and Discussion

Coupling Points Response to Hypothetical Damage

Hypothetical pest damage was applied to KSAS8101.WHX, Treatment 2, a wheat experiment that is included with the distribution version of DSSAT (Hoogenboom et al., 2019a), to primarily identify the reliability and functionality of the coupling points in CSM-NWheat. For this simulation, the attainable yield at 248 days after planting with no disease damage was 3,688 kg ha^{-1}, while leaf weight, stem weight, root weight, and total canopy weight were 1,348, 2317, 1,596, and 8,979 kg ha^{-1}, respectively. Additionally, the maximum LAI reached 2.7 m^2 m^{-2}, and the grain number was 12,413 m^{-2}. The damage rates described in table 1 were applied and expressed as part of the time series data file (FileT).

When damage equivalent to 25% defoliation was imposed on the LAI state variable during the mid-late growing season, yield decreased to 3,027 kg ha^{-1} (-17.9%) and leaf weight decreased to 1,018 kg ha^{-1} (-24.5%). In contrast, when damage equivalent to 50% defoliation was imposed during the early-mid season, yield decreased to 1,395 kg ha^{-1} (-62.1%) and leaf weight decreased to 312 kg ha^{-1} (-76.8%). For leaf weight, damage equivalent to 20% defoliation during the mid-season resulted in a yield of 2,910 kg ha^{-1} (-21.1%) and leaf weight of 889 kg ha^{-1} (-34.0%). Damage equivalent to a 17% loss in stem mass during the late season resulted in a grain yield of 3,129 kg ha^{-1} (-15.1%) and stem weight of 934 kg ha^{-1} (-59.6%). Damage equivalent to a 15% loss in the roots during the early-mid season resulted in a grain yield of 3,177 kg ha^{-1} (-13.9%) and root weight of 1,217 kg ha^{-1} (-23.7%) (fig. 2).

Leaf area damage equivalent to 20% pest necrosis was applied late during the season, resulting in a grain yield of 3,040 kg ha^{-1} (-17.6%) and canopy weight of 8,249 kg ha^{-1} (-8.1%). Assimilate damage equivalent to a 17% assimilate supply loss late in the season resulted in a grain yield of 3,093 kg ha^{-1} (-16.1%) and canopy weight of 8,079 (-10.0%). Hypothetical damage equivalent to a 18% seed mass loss during the late season resulted in a grain yield of 2,959 kg ha^{-1} (-19.8%) and total number of grains of 9,192 m^{-2} (-26.0%) (fig. 3).

The model's response when individual plants were removed due to pests and pathogens was analyzed by applying hypothetical damage levels that reduced the plant population. Damage equivalent to destruction of 5%, 8%, and 10% of the plants was applied as daily rate damage using the time series data file (FileT) during the mid-growing season. A 5% reduction in plant population reduced yield to 1,088 kg ha^{-1} (-29.5%) and maximum LAI to 2.2 m^2 m^{-2} (-18.5%). An 8% reduction in plant population reduced yield to 1,668 kg ha^{-1} (-45.2%) and maximum LAI to 2.2 m^2 m^{-2} (-18.5%). Lastly, a 10% reduction in plant population resulted in a yield loss of 1,994 kg ha^{-1} (-54.1%) and maximum LAI of 2.1 m^2 m^{-2} (-22.2%) (fig. 4).

This proof-of-concept showed the potential of the pest module coupled with a wheat module to dynamically simulate the potential impacts of different pest and disease damage scenarios. The coupled model was able to simulate the yield and leaf area losses due to damage caused by multiple pests and diseases on the different plant components of wheat based on studies reported in the literature (table 1). The damage levels were implemented in one of the crop model input files (FileT) following the reported chronological occurrence pattern of each pest, as reported crop losses in general depend on when a given pest or disease damage occurs. The advantage of using coupling points is that they are not bound to specific pests or diseases. Therefore, this approach can be used to simulate the impacts of different insect pests and diseases on wheat growth and development as long as they have the same coupling points as listed in table 1. Even cases with severe pest damage that kill the entire plant can be simulated.

Field Experiment

Tan spot is caused by the fungus *Pyrenophora tritici-repentis* and is also known as yellow leaf spot or yellow leaf blotch. The ascospores or conidia of this fungus infect the host cells and induce necrosis and chlorosis symptoms on wheat leaves (Singh et al., 2016). Infection starts as a small tan spot, destroying the living tissue, and develops into lesions with a brown spot in the center and yellow borders (Schierenbeck et al., 2019). Temperature and free moisture on the leaf surface are critical environmental factors for tan spot infection (Bouras et al., 2009). This pathogen reduces the photosynthetic area of leaves, which results in substantial losses in both yield and grain quality, including reduced grain fill, a smaller number of kernels per head, and kernel shriveling (Singh et al., 2010).

Natural infection of tan spot disease occurred in the wheat field experiment that was conducted in 2016 in Carazinho, Rio Grande do Sul, Brazil. Throughout the field experiment, the disease severity was expressed as the mean proportion of necrosis measured on each measurement date (fig. 5). The

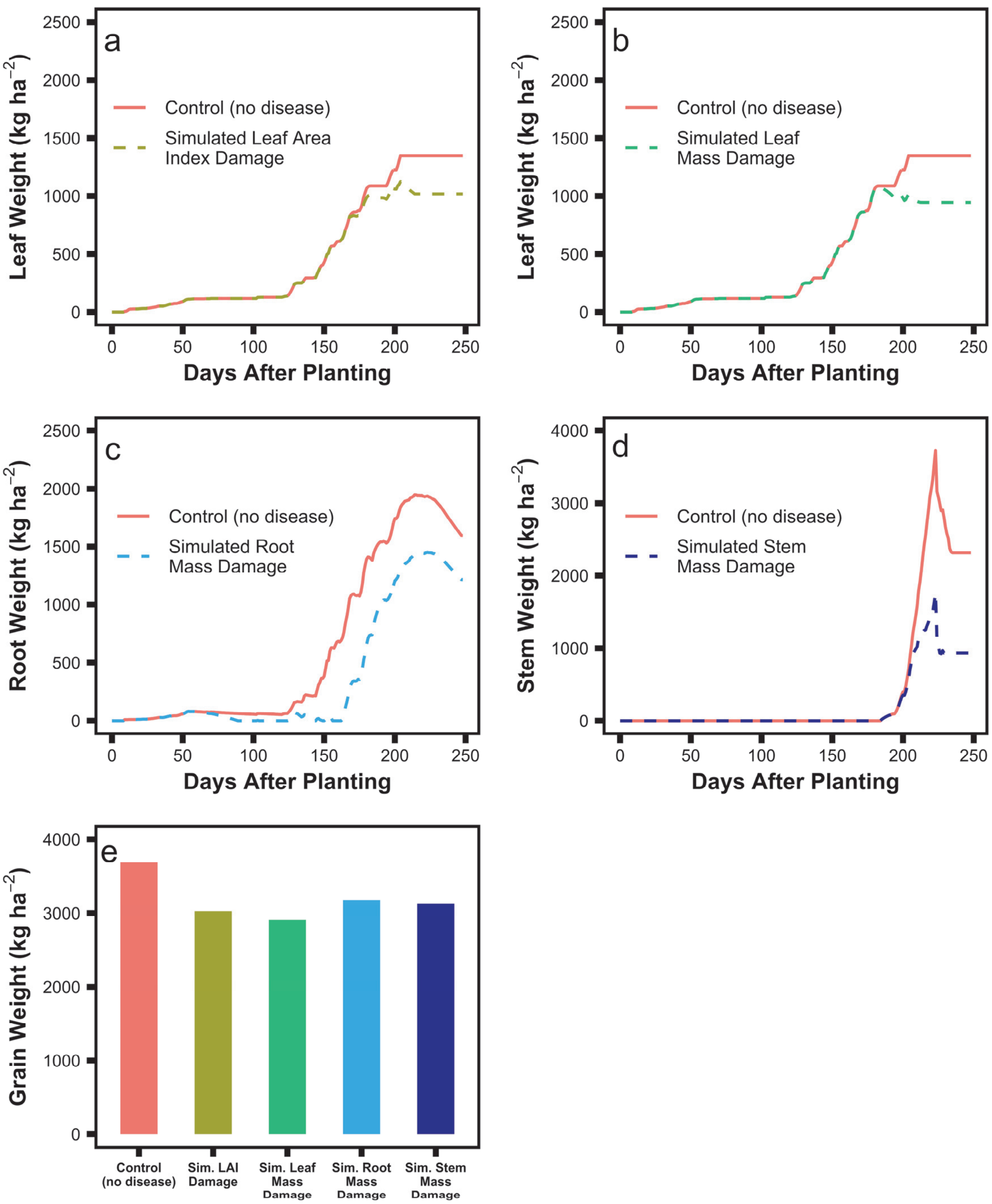

Figure 2. Response of the coupled NWheat and PEST modules to hypothetical pest and disease impacts, as presented in table 1, in comparison to control simulations: simulated leaf weight with damage applied to (a) LAI, (b) LAI with severe damage, and (c) leaf mass; (d) simulated root weight with damage applied to root mass; (e) simulated stem weight with damage applied to stem mass; and (f) simulated yield response to individual instances of damage applied to LAI, leaf mass, root mass, and stem mass.

pest data from the scouting reports were entered into the time series data file (FileT) to simulate the effect of the observed tan spot in the wheat field. The damage was applied using the observed damage method (% as a daily rate) and the necrotic LAI coupling point (table 1).

The simulated wheat yield with the new coupled NWheat and PEST modules for the treatment with no disease was 4,414 kg ha^{-1}, while the yield simulated for the treatment affected by tan spot was 4,207 kg ha^{-1} due to the reduction in leaf mass and LAI. This corresponds to a reduction in yield of 4.6% due to tan spot infection (fig. 6). Overall, the CSM-NWheat model predicted higher grain yield than the yield measured in the field experiment. However, the yield loss due to tan spot infection predicted by the pest-coupled model was similar to the percentage yield loss observed in the field experiment, with a slight overestimation of 0.4% yield loss. This indicates that the newly coupled model is capable of simulating the potential impact of disease damage during wheat growth and development.

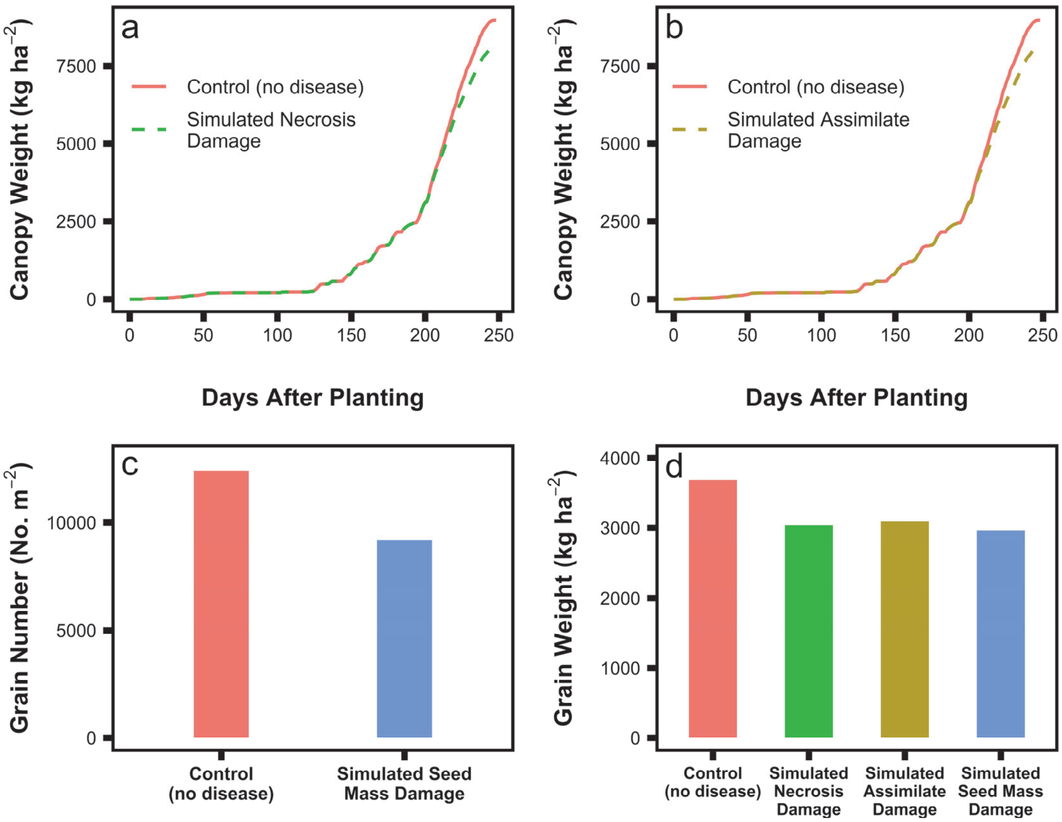

Figure 3. Response of coupled NWheat and PEST modules to hypothetical pest and disease impacts, as presented in table 1, in comparison to control simulations: (a) simulated canopy weight with necrosis damage applied to LAI, (b) simulated canopy weight with damage applied to crop assimilate supplies, (c) simulated grain number with damage applied to seed mass, and (d) simulated yield response to individual instances of damage applied to assimilate supplies, leaf area due to necrosis, and seed mass.

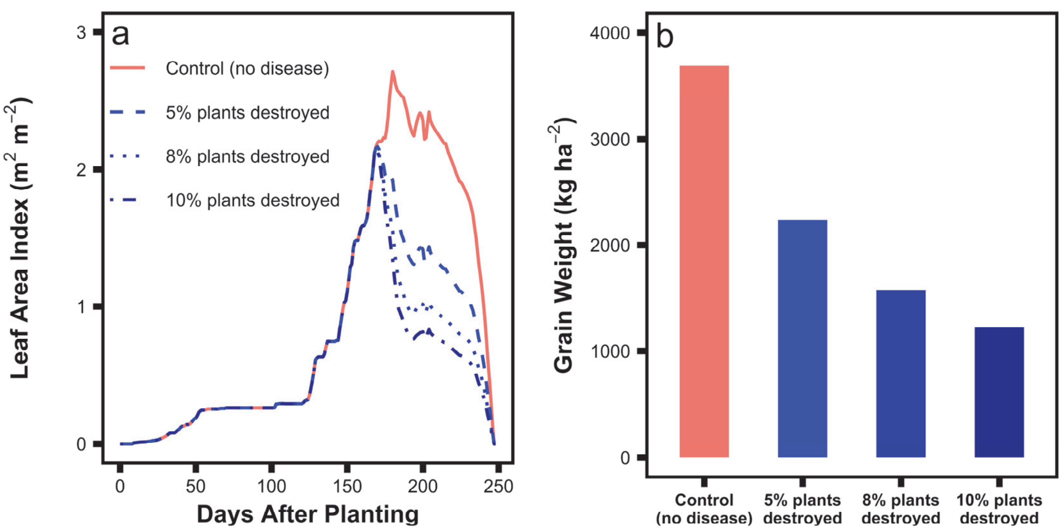

Figure 4. Sensitivity of the CSM-NWheat module coupled with the disease module to simulate the effects on (a) LAI and (b) yield when 5%, 8%, and 10% of the plants are removed.

Summary and Conclusions

The pest coupling points created to link the CSM-NWheat crop growth model to the PEST module of DSSAT allow daily pest interaction with the growth and development of leaves, stems, roots, and grains, and the photosynthesis rate of the wheat model. The damage routines simulated wheat defoliation and yield loss according to different types of pests and diseases. A case study was used to simulate tan spot (*Pyrenophora tritici-repentis*) infection on wheat, and the results were compared to those observed in a field experiment. The coupling points provide the model with flexibility to predict crop growth in combination with pest damage levels. Although the average leaf area loss due to tan spot infection observed in the study case was less than 5%, overall the model had a similar response to the measured

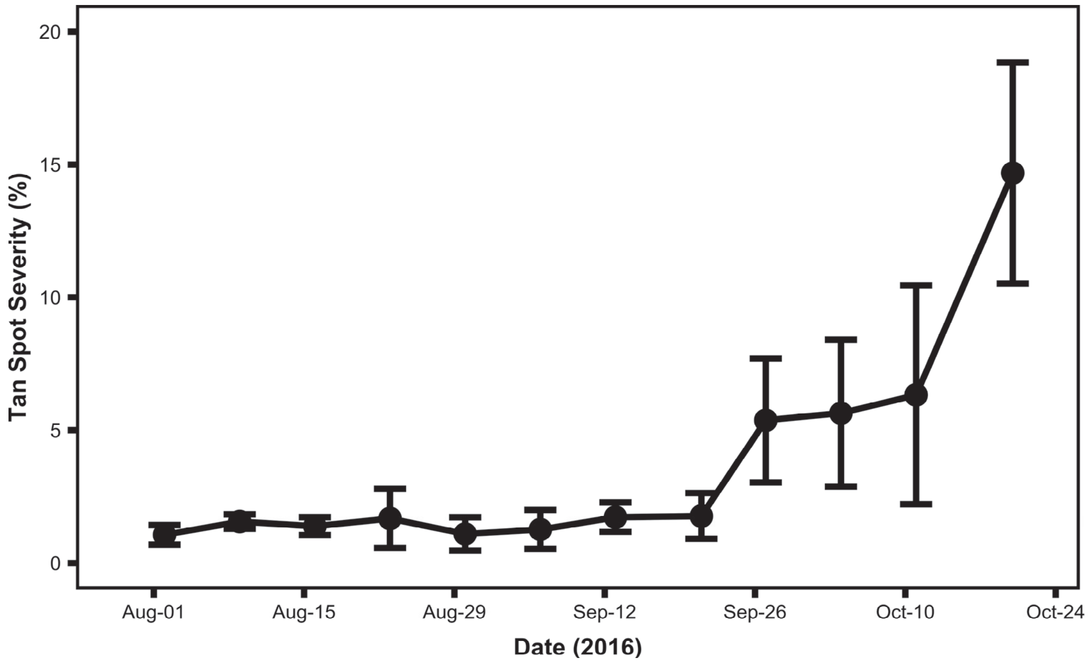

Figure 5. Naturally occurring tan spot severity measured in wheat plots without fungicide applications during an on-farm experiment conducted in 2016 in Carazinho, Rio Grande do Sul, Brazil.

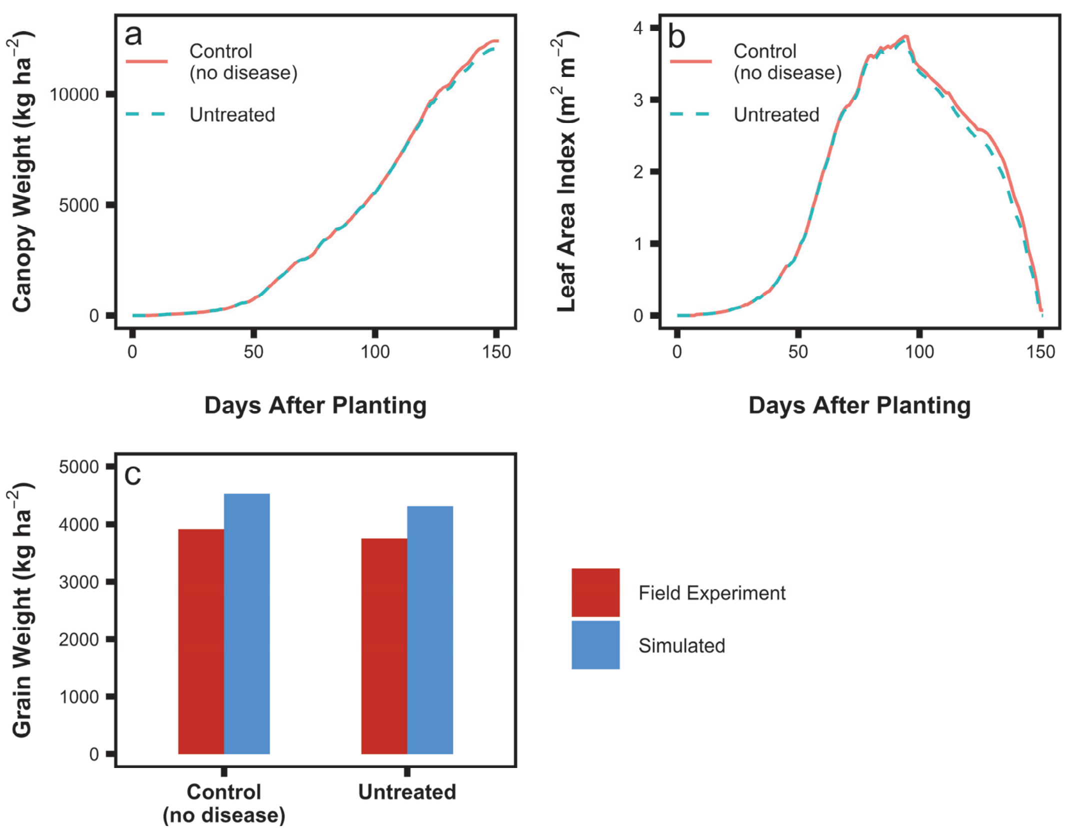

Figure 6. Response of simulated (a) wheat canopy weight, (b) leaf area, and (c) yield loss due to tan spot damage applied according to the disease severity measured in the field experiment conducted in 2016 in Carazinho, Rio Grande do Sul, Brazil.

data. The sensitivity analysis indicated the capability of the model coupled with the PEST module to predict damage similar to that observed in the field.

The newly coupled model can be applied for simulating the potential impacts of insect pest and disease damage. It is not limited to a specific pest or crop condition. This allows simulation of different pest scenarios for wheat, following the chronological occurrence pattern of a given pest or disease to estimate the effects of pest damage on crop development and predict yield loss. Future research should include more field data from a range of environments to evaluate the model's ability to estimate disease and pest effects on wheat for different management practices and environmental conditions. This research extends the functionalities of the CSM-NWheat crop model and expands its potential applications to address pest and disease-related issues occurring in real-world scenarios. This is the first wheat model in the DSSAT crop modeling ecosystem (Hoogenboom et al., 2019b) that has been coupled with the DSSAT pest module and is capable of estimating pest damage for all plant parts of wheat. It will allow dynamic simulation of combinations of abiotic and abiotic stresses on wheat growth and development and ultimately predict yield more accurately.

The Appendix to this article contains the CSM-NWheat source code used to estimate the effects of pest and disease damage on crop growth.

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References

Batchelor, W. D., Jones, J. W., Boote, K. J., & Pinnschmidt, H. O. (1993). Extending the use of crop models to study pest damage. *Trans. ASAE, 36*(2), 551-558. https://doi.org/10.13031/2013.28372

Batchelor, W. D., McClendon, R. W., Jones, J. W., & Adams, D. B. (1989). An expert simulation system for soybean insect pest management. *Trans. ASAE, 32*(1), 335-342. https://doi.org/10.13031/2013.31006

Batchelor, W. D., Suresh, L. M., Zhen, X., Beyene, Y., Wilson, M., Kruseman, G., & Prasanna, B. (2020). Simulation of maize lethal necrosis (MLN) damage using the CERES-maize model. *Agronomy, 10*(5), article 710. https://doi.org/10.3390/agronomy10050710

Bhathal, J. S., Loughman, R., & Speijers, J. (2003). Yield reduction in wheat in relation to leaf disease from yellow (tan) spot and *Septoria nodorum* blotch. *European J. Plant Pathol., 109*(5), 435-443. https://doi.org/10.1023/A:1024277420773

Boogaard, H. L., Van Diepen, C. A., Rötter, R. P., Cabrera, J. M., & Van Laar, H. H. (1998). WOFOST 7.1: User's guide for the WOFOST 7.1 crop growth simulation model and WOFOST Control Center 1.5. Wageningen, Netherlands: DLO Winand Staring Center for Integrated Land, Soil, and Water Research.

Boote, K. J. (2019). *Advances in crop modelling for a sustainable agriculture.* Cambridge, UK: Burleigh Dodds Science. https://doi.org/10.1201/9780429266591

Boote, K. J., Jones, J. W., Hoogenboom, G., & Pickering, N. B. (1998). The CROPGRO model for grain legumes. In G. Y. Tsuji, G. Hoogenboom, & P. K. Thornton (Eds.), *Understanding options for agricultural production* (pp. 99-128). Dordrecht, Netherlands: Springer. https://doi.org/10.1007/978-94-017-3624-4_6

Boote, K. J., Jones, J. W., Hoogenboom, G., & White, J. W. (2010). The role of crop systems simulation in agriculture and environment. *Intl. J. Agric. Environ. Info. Syst., 1*(1), 41-54. https://doi.org/10.4018/jaeis.2010101303

Boote, K. J., Jones, J. W., Hoogenboom, G., Wilkerson G., G., & Jagtap, S. S. (1989). PNUTGRO V1.02 Peanut crop growth simulation model: User's guide. Florida Agricultural Experiment Station Journal No. 8420. Gainesville, FL: University of Florida, Department of Agricultural Engineering and Department of Agronomy.

Boote, K. J., Jones, J. W., Mishoe, J. W., & Berger, R. D. (1983). Coupling pests to crop growth simulators to predict yield reductions. *Phytopathology, 73*(11), 1581-1587. https://doi.org/10.1094/Phyto-73-1581

Bouras, N., Kim, Y. M., & Strelkov, S. E. (2009). Influence of water activity and temperature on growth and mycotoxin production by isolates of *Pyrenophora tritici-repentis* from wheat. *Intl. J. Food Microbiol., 131*(2), 251-255. https://doi.org/10.1016/j.ijfoodmicro.2009.02.001

Braun, H. J., Atlin, G., & Payne, T. (2010). Multi-location testing as a tool to identify plant response to global climate change. In *Climate change and crop production* (pp. 115-138). Wallingford, UK: CABI. https://doi.org/10.1079/9781845936334.0115

Bregaglio, S., Willocquet, L., Kersebaum, K. C., Ferrise, R., Stella, T., Ferreira, T. B., ... Savary, S. (2021). Comparing process-based wheat growth models in their simulation of yield losses caused by plant diseases. *Field Crops Res., 265*, article 108108. https://doi.org/10.1016/j.fcr.2021.108108

Császár, O., Tóth, F., & Lajos, K. (2021). Estimation of the expected maximal defoliation and yield loss caused by cereal leaf beetle (*Oulema melanopus* L.) larvae in winter wheat (*Triticum aestivum* L.). *Crop Prot., 145*, article 105644. https://doi.org/10.1016/j.cropro.2021.105644

Donatelli, M., Magarey, R. D., Bregaglio, S., Willocquet, L., Whish, J. P., & Savary, S. (2017). Modelling the impacts of pests and diseases on agricultural systems. *Agric. Syst., 155*, 213-224. https://doi.org/10.1016/j.agsy.2017.01.019

Farook, U. B., Khan, Z. H., Ahad, I., Maqbool, S., Yaqoob, M., Rafieq, I., ... Sultan, N. (2019). A review on insect pest complex of wheat (*Triticum aestivum* L.). *J. Entomol. Zool. Studies, 7*(1), 1292-1298.

Fernandes, J., Pavan, W., Pequeno, D., Wiest, R., Holbig, C., Oliveira, F., & Hoogenboom, G. (2019). Improving crop pest/disease modeling. In K. J. Boote (Ed.), *Advances in crop modelling for a sustainable agriculture* (pp. 127-147). Cambridge, UK: Burleigh Dodds Science. https://doi.org/10.19103/AS.2019.0061.07

Figueroa, M., Hammond-Kosack, K. E., & Solomon, P. S. (2018). A review of wheat diseasee: A field perspective. *Molec. Plant Pathol., 19*(6), 1523-1536. https://doi.org/10.1111/mpp.12618

Hoogenboom, G., Jones, J. W., & Boote, K. J. (1992). Modeling growth, development, and yield of grain legumes using SOYGRO, PNUTGRO, and BEANGRO: A review. *Trans. ASAE, 35*(6), 2043-2056. https://doi.org/10.13031/2013.28833

Hoogenboom, G., Jones, J. W., Porter, C. H., Wilkens, P. W., Boote, K. J., Hunt, L. A., & Tsuj, G. Y. (2010). Decision Support System for Agrotechnology Transfer Ver. 4.5. Volume 1: Overview. Honolulu, HI: University of Hawaii.

Hoogenboom, G., Porter, C. H., Boote, K. J., Shelia, V., Wilkens, P. W., Singh, U., ... Jones, J. W. (2019b). The DSSAT crop modeling ecosystem. In K. J. Boote (Ed.), *Advances in crop modeling for a sustainable agriculture* (pp. 173-216).

Cambridge, UK: Burleigh Dodds Science. https://doi.org/10.19103/AS.2019.0061.10
Hoogenboom, G., Porter, C. H., Shelia, V., Boote, K. J., Singh, U., White, J. W., ... Jones, J. W. (2019a). Decision Support System for Agrotechnology Transfer (DSSAT) Ver. 4.7.5. Gainesville, FL: DSSAT Foundation. Retrieved from https://DSSAT.net
Hunt, L. A., & Pararajasingham, S. (1995). CROPSIM-Wheat: A model describing the growth and development of wheat. *Canadian J. Plant. Sci., 75*(3), 619-632. https://doi.org/10.4141/cjps95-107
Jones, J. W., Hoogenboom, G., Porter, C. H., Boote, K. J., Batchelor, W. D., Hunt, L. A., ... Ritchie, J. T. (2003). The DSSAT cropping system model. *European J. Agron., 18*(3-4), 235-265. https://doi.org/10.1016/S1161-0301(02)00107-7
Jones, J. W., Mishoe, J. W., Wilkerson, G. G., Stimac, J. L., & Boggess, W. G. (1985). Integration of soybean crop and pest models. In R. E. Frisbie & P. L. Adkisson (Eds.), *Integrated pest management on major agricultural systems.* College Station, TX: Texas A&M University.
Kassie, B. T., Asseng, S., Porter, C. H., & Royce, F. S. (2016). Performance of DSSAT-NWheat across a wide range of current and future growing conditions. *European J. Agron., 81*, 27-36. https://doi.org/10.1016/j.eja.2016.08.012
Keating, B. A., Carberry, P. S., Hammer, G. L., Probert, M. E., Robertson, M. J., Holzworth, D., ... Smith, C. J. (2003). An overview of APSIM, a model designed for farming systems simulation. *European J. Agron., 18*(3), 267-288. https://doi.org/10.1016/S1161-0301(02)00108-9
Loughman, R., Jayasena, K., & Majewski, J. (2005). Yield loss and fungicide control of stem rust of wheat. *Australian J. Agric. Res., 56*(1), 91-96. https://doi.org/10.1071/AR04126
Magarey, R. D., Sutton, T. B., & Thayer, C. L. (2005). A simple generic infection model for foliar fungal plant pathogens. *Phytopathology, 95*(1), 92-100. https://doi.org/10.1094/phyto-95-0092
May, D. B., Johnson, W. A., Zuck, P. C., Chen, C. C., & Dyer, A. T. (2016). Assessment and management of root lesion nematodes in Montana wheat production. *Plant Disease, 100*(10), 2069-2079. https://doi.org/10.1094/pdis-02-16-0176-re
Oerke, E. C. (2006). Crop losses to pests. *J. Agric. Sci., 144*(1), 31-43. https://doi.org/10.1017/S0021859605005708
Pavan, W., & Fernandes, J. M. (2009). Uso de orientação a objetos no desenvolvimento de modelos de simulação de doenças de plantas genéricos. *Revista Brasileira de Agroinformatica, 9*(1), 12-27. https://doi.org/10.5335/rbca.2009.003
Pinnschmidt, H. O., Batchelor, W. D., & Teng, P. S. (1995). Simulation of multiple species pest damage in rice using CERES-rice. *Agric. Syst., 48*(2), 193-222. https://doi.org/10.1016/0308-521X(94)00012-G
Rabbinge, R., Sinke, C., & Mantel, W. P. (1984). Yield loss due to cereal aphids and powdery mildew in winter wheat. *Mededelingen-Universiteit Gent, Faculteit Landbouwkundige en Toegepaste Biologische Wetenschappen, 48*(4), 1159-1168.
Reis, E. M., & Carmona, M. A. (2013). Integrated disease management of *Fusarium* head blight. In M. T. Alconada & S. Chulze (Eds.), *Fusarium head blight in Latin America* (pp. 159-173). Dordrecht, Netherlands: Springer. https://doi.org/10.1007/978-94-007-7091-1_10
Ritchie, J. T., Singh, U., Godwin, D. C., & Bowen, W. T. (1998). Cereal growth, development, and yield. In G. Y. Tsuji, G. Hoogenboom, & P. K. Thornton (Eds.), *Understanding options for agricultural production* (pp. 79-98). Dordrecht, Netherlands: Springer.
Rogers, D. J., & Brier, H. B. (2010). Pest-damage relationships for *Helicoverpa armigera* (Hubner) (Lepidoptera: Noctuidae) on soybean (*Glycine max*) and dry bean (*Phaseolus vulgaris*) during pod-fill. *Crop Prot., 29*(1), 47-57. https://doi.org/10.1016/j.cropro.2009.08.015
Savary, S., Willocquet, L., Pethybridge, S. J., Esker, P., McRoberts, N., & Nelson, A. (2019). The global burden of pathogens and pests on major food crops. *Nature Ecol. Evol., 3*(3), 430-439. https://doi.org/10.1038/s41559-018-0793-y
Scheeren, P., Caetano, V. D., Caieirão, E., Só E. Silva, M., Eichelberger, L., de Miranda, M. Z., ... Chaves, M. (2019). BRS Parrudo: Wheat cultivar from Embrapa. *Annual wheat newsletter, 65*, 7-10.
Schierenbeck, M., Fleitas, M. C., Gerard, G. S., Dietz, J. I., & Simón, M. R. (2019). Combinations of fungicide molecules and nitrogen fertilization revert nitrogen yield reductions generated by *Pyrenophora tritici-repentis* infections in bread wheat. *Crop Prot., 121*, 173-181. https://doi.org/10.1016/j.cropro.2019.04.004
Shewry, P. R. (2009). Wheat. *J. Exp. Bot., 60*(6), 1537-1553. https://doi.org/10.1093/jxb/erp058
Singh, P. K., Singh, R. P., Duveiller, E., Mergoum, M., Adhikari, T. B., & Elias, E. M. (2010). Genetics of wheat-*Pyrenophora tritici-repentis* interactions. *Euphytica, 171*(1), 1-13. https://doi.org/10.1007/s10681-009-0074-6
Singh, R. P., Singh, P. K., Rutkoski, J., Hodson, D. P., He, X., Jørgensen, L. N., ... Huerta-Espino, J. (2016). Disease impact on wheat yield potential and prospects of genetic control. *Ann. Rev. Phytopathol., 54*(1), 303-322. https://doi.org/10.1146/annurev-phyto-080615-095835
Teng, P. S., Batchelor, W. D., Pinnschmidt, H. O., & Wilkerson, G. G. (1998). Simulation of pest effects on crops using coupled pest-crop models: The potential for decision support. In G. Y. Tsuji, G. Hoogenboom, & P. K. Thornton (Eds.), *Understanding options for agricultural production* (pp. 221-266). Dordrecht, Netherlands: Springer. https://doi.org/10.1007/978-94-017-3624-4_12
Tsuji, G. Y., Hoogenboom, G., & Thornton, P. K. (1998). *Understanding options for agricultural production* (Vol. 7). Dordrecht, Netherlands: Springer Science & Business Media. https://doi.org/10.1007/978-94-017-3624-4
West, P. C., Gerber, J. S., Engstrom, P. M., Mueller, N. D., Brauman, K. A., Carlson, K. M., ... Siebert, S. (2014). Leverage points for improving global food security and the environment. *Science, 345*(6194), 325-328. https://doi.org/10.1126/science.1246067
Whish, J. P., Herrmann, N. I., White, N. A., Moore, A. D., & Kriticos, D. J. (2015). Integrating pest population models with biophysical crop models to better represent the farming system. *Environ. Model. Software, 72*, 418-425. https://doi.org/10.1016/j.envsoft.2014.10.010
Wilkerson, G. G., Jones, J. W., Boote, K. J., Ingram, K. T., & Mishoe, J. W. (1983b). Modeling soybean growth for crop management. *Trans. ASAE, 26*(1), 63-73. https://doi.org/10.13031/2013.33877
Wilkerson, G. G., Mishoe J., W., Jones J., W., Stimac J., L., Swaney D., P., & Boggess. W., G. (1983a). SICM: Florida soybean integrated crop management model. Model description and user's guide. Ver. 4.2. Report AGE 83-1. Gainesville, FL: University of Florida, Institute of Food Sciences.
Willocquet, L., Aubertot, J. N., Lebard, S., Robert, C., Lannou, C., & Savary, S. (2008). Simulating multiple pest damage in varying winter wheat production situations. *Field Crops Res., 107*(1), 12-28. https://doi.org/10.1016/j.fcr.2007.12.013
Willocquet, L., Félix, I., de Vallavieille-Pope, C., & Savary, S. (2018). Reverse modelling to estimate yield losses caused by crop diseases. *Plant Pathol., 67*(8), 1669-1679. https://doi.org/10.1111/ppa.12873

APPENDIX

CSM-NWHEAT SOURCE CODE FOR PEST DAMAGE SIMULATION

```
LAIDOT = 0
IF (PLTPOP .GT. 0.0 .AND. plantwt(leaf_part) .GT. 0.0 .AND. WLIDOT .GT. 0.0) THEN
   LAIDOT = WLIDOT * ((pl_la - sen_la) /100) / (plantwt(leaf_part))
ENDIF

IF(PLTPOP.GT.0.0) THEN
    pl_nit(leaf_part) = pl_nit (leaf_part) -
&   pl_nit(leaf_part) * (WLIDOT/PLTPOP) / plantwt(leaf_part)
    plantwt(leaf_part) = plantwt(leaf_part) - WLIDOT/PLTPOP
    plantwt(leaf_part) = MAX(plantwt(leaf_part),0.0)
ENDIF
    pl_la = pl_la - (LAIDOT * 100/PLTPOP)
    LAI = LAI - LAIDOT/10000
    LAI = MAX(LAI, 0.0)
```

Figure A1. Source code to apply daily pest and disease damage to LAI and leaf mass.

```
IF(PLTPOP.GT.0.0 .AND. plantwt(stem_part) .GT. 0.0 .AND. WSIDOT .GT. 0.0) THEN
    pl_nit(stem_part)=pl_nit(stem_part) - pl_nit(stem_part)*(WSIDOT/PLTPOP)/plantwt(stem_part)
    plantwt(stem_part) = plantwt(stem_part) - WSIDOT/PLTPOP
    plantwt(stem_part) = MAX(plantwt(stem_part), 0.0)
ENDIF
```

Figure A2. Source code to apply daily pest and disease damage to stem mass.

```
IF(PLTPOP.GT.0.0 .AND. plantwt(root_part) .GT. 0.0 .AND. WRIDOT .GT. 0.0) THEN
    pl_nit(root_part)= pl_nit(root_part) - pl_nit(root_part)*(WRIDOT/PLTPOP)/plantwt(root_part)
    plantwt(root_part) = plantwt(root_part) - WRIDOT/PLTPOP
    plantwt(root_part) = MAX(plantwt(root_part), 0.0)
ENDIF
```

Figure A3. Source code to apply daily pest and disease damage to root mass.

```
IF (PLTPOP.GT. 0.0 .AND. plantwt(grain_part) .GT. 0.0 .AND.
&  SWIDOT .GT. 0.0) THEN
    pl_nit(grain_part) = pl_nit(grain_part) - pl_nit(grain_part)*
&  (SWIDOT/PLTPOP)/plantwt(grain_part)
    gpp = gpp - gpp *(SWIDOT/PLTPOP)/plantwt(grain_part)
ENDIF

IF(PLTPOP.GT.0.0 .AND. SWIDOT .GT. 0.0) THEN
    plantwt(grain_part) = plantwt(grain_part) - SWIDOT/PLTPOP
    plantwt(grain_part) = MAX(plantwt(grain_part), 0.0)
    plantwt(seed_part) = plantwt(seed_part) - SWIDOT/PLTPOP
    plantwt(seed_part) = MAX(plantwt(seed_part), 0.0)
ENDIF
```

Figure A4. Source code to apply daily pest and disease damage to seed mass.

```
LAI = (pl_la - sen_la)
AREALF = LAI * 10000
AREAH  = AREALF - DISLA
AREAH  = MAX(0.,AREAH)
XHLAI = AREAH/10000
radfr = 1.0 - exp (-nwheats_kvalue * XHLAI)
```

Figure A5. Source code to simulate leaf area necrosis and apply daily damage to the healthy leaf area.

```
pcarbo = pcarbo - ASMDOT
pcarbo = MAX(pcarbo, 0.0)
```

Figure A6. Source code to apply daily pest and disease damage and reduce the potential dry matter production.

```
IF(PLTPOP.GT. 0.0 .AND. PPLTD.GT.0) THEN
   PLTPOP = PLTPOP - PLTPOP * PPLTD/100
   PLTPOP = MAX(PLTPOP, 0.0)
   LAI = LAI - LAI*(PPLTD/100)
   LAI = MAX(LAI, 0.0)
ENDIF
```

Figure A7. Source code to apply daily pest and disease damage that affects all plant parts.