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Review

25 years of the WOFOST cropping systems model

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ABSTRACT

The WOFOST cropping systems model has been applied operationally over the last 25 years as part of the MARS crop yield forecasting system. In this paper we provide an updated description of the model and reflect on the lessons learned over the last 25 years. The latter includes issues like system performance, model sensitivity, spatial model setup, parameterization and calibration approaches as well as software implementation and version management. Particularly for spatial model calibrations we provide experience and guidelines on how to execute calibrations and how to evaluate WOFOST model simulation results, particularly under conditions of limited field data availability.

As an open source model WOFOST has been a success with at least 10 different implementations of the same concept. An overview is provided for those implementations which are managed by MARS or Wageningen groups. However, the proliferation of WOFOST implementations has also led to questions on the reproducibility of results from different implementations as is demonstrated with an example from MARS. In order to certify that the different WOFOST implementations and versions available can reproduce basic sets of inputs and outputs we make available a large set of test cases as appendix to this publication.

Finally, new methodological extensions have been added to WOFOST in simulating the impact of nutrients limitations, extreme events and climate variability. Also, a difference is made in the operational and scientific versions of WOFOST with different licensing models and possible revenue generation. Capitalizing both on academic development as well as model testing in real-world situations will help to enable new applications of the WOFOST model in precision agriculture and smart farming.

1. Introduction

Cropping systems modelling has been recognised as mature technology derived from scientific research (Holzworth et al., 2015), that is currently applied in societal relevant applications, such as crop yield forecasting (this issue), climate change (Ewert et al., 2015), understanding crop responses in field trials and circumstances (Asseng et al., 2013), while new applications are expected with the use of such models for precision farming applications and smart farming. Many of such models have been developed over the past decades (Holzworth et al., 2015) and prominent examples are DSSAT (Jones et al., 2003), EPIC (Wang et al., 2012), STICS (Brisson et al., 2003) and APSIM (Holzworth et al., 2014), and new ones are constantly being added for different crops and purposes. There are calls for more standardization across all these models to lower the barriers to application across geographies, crops and purposes. For example, Kersebaum et al. (2015) describe standards for input data used in the models, so that these become better shareable. In another example, Porter et al. (2014) describe exchange mechanisms for data across models, so that these can be run in parallel on the same data set.

The WOrld FOod STudies (WOFOST) model has already been applied for 25 years as part of operational crop yield forecasting systems, and is thus one of the longest running operational models. With the developments of standardization, new crop model applications and developments in modelling capabilities, it is timely to reflect on the lessons learned over the last 25 years and to think ahead for new developments and requirements, with respect to this model. Lessons learned include issues like system performance, model sensitivity, spatial model setup, parameterization and calibration as well as software implementation and version management.

In this paper we provide first of all an overview of the WOFOST model providing an updated system description thereby focusing on the

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parts that have been updated in the course of the development of the European MARS crop yield forecasting system. Moreover, we share our experience with spatial model calibration and evaluation, often for cases with limited availability of ground data. Next, we discuss model proliferation issues that arise from the implications of an open source model. Finally, we discuss ongoing development and future development of WOFOST.

2. Background and system description

The WOFOST crop simulation model as implemented in the MARS system has been one of the key components for crop monitoring and yield prediction in Europe. Originally WOFOST was developed to estimate production potential and impact of meteorological and hydrological conditions on annual crops in the tropics (Diepen et al., 1989). Nevertheless, the biophysical core of the model is generally applicable and therefore the model could be easily applied to annual crops in Europe.

From a biophysical perspective, the WOFOST model shares many of its algorithms and approaches with the SUCROS model (Simple Universal CROp Simulator; (Laar et al., 1997)) and both were developed within the Wageningen 'School of De Wit' models (Bouman et al., 1996; De Wit and Van Keulen, 1987). Besides the solid biophysical basis, a large advantage of this approach was that WOFOST could readily use many of the model parametrizations for various crops that had been derived for SUCROS.

Nevertheless, there are some clear differences between the WOFOST and SUCROS models. The SUCROS model was mainly a research tool and was used, modified and applied by researchers as required for particular research objectives leading to a myriad of SUCROS versions differing slightly in approach and output (van Ittersum et al., 2003). Instead, WOFOST was developed in a more rigorous way, having clear version control and proper documentation. As a result, in the early nineties WOFOST was already a fully developed simulation model with a mature, open source code base. Another advantage over the SUCROS implementations was that WOFOST was designed to simulate a large range of crop types with a single code base by only changing parameter values which were external to the model itself. This made the model more suitable for implementation in an operational system like MARS.

In WOFOST, crop growth is simulated on the basis of eco-physiological processes such as growth and phenological development with a fixed time step of 1 day. The model follows the classical distinction between production levels:

1. Potential production only limited by radiation, temperature, atmospheric CO2 concentration and crop features;
2. Water and nutrient-limited production where growth limitations due to water and/or nutrient shortage play a role;
3. Actual production where growth reducing factors like weeds, pest and disease or pollutants reduce the production level further to the actual yield at field level.

The major processes simulated by WOFOST are phenological development, leaf development and light interception, CO_2-assimilation, root growth, transpiration, respiration, partitioning of assimilates to the various organs, and dry matter formation. The implementation of the soil processes (except for root growth) is not regarded to be part of WOFOST as there are multiple implementations of WOFOST using different water balance approaches with different levels of detail. Fig. 1 provides a schematic overview of the linkages between model components in WOFOST.

Table 1 provides an overview of the number of parameters used by WOFOST to simulate different processes grouped by process or plant organ. A distinction is made between scalar (single value) parameters and tabular parameter where the value of the parameter depends on another state, usually development stage or temperature. It clearly demonstrates that the most complex parts of the model deal with phenological development and leaf related processes such as growth and ageing of leaves, and CO_2-assimilation (or photosynthesis). Respiration and root development are intermediate while stems and storage organs are mere containers for biomass with relatively simple biophysical processes involved. Although phenological development entails the largest number of parameters involved, it should be noted that the actual number of parameters involved depends on the settings used for the particular crop (temperature only, including photoperiod, including vernalisation). For leaves and photosynthesis all parameters are always required.

Below we provide a narrative overview of the important processes without going into the mathematical details of the model. The latter have been fully described by Supit et al. (1994) and can be looked up in the model source code as well, given that the full source code is available to any interested reader.[2,3]

2.1. Phenological development

Phenological development is implemented as an independent process and serves as a controlling and steering mechanism for plant growth. It is therefore possible to run the phenological development module as a simulation model on its own, while this is generally not possible with the other components of WOFOST.

Phenological development is expressed using a dimensionless variable "DVS - Development Stage" which starts at −0.1 or 0.0 depending on whether the model starts at sowing or crop emergence. DVS reaches 1.0 at flowering and finally reaches 2.0 at physiological maturity. For calculating the time between sowing and emergence, WOFOST uses a temperature sum with specific cardinal temperatures for seedling emergence.

This approach for phenological development is typical for a cereal crop and all other crops are forced into this pattern. This also implies that DVS = 1 not necessarily corresponds to a flowering phase, but rather indicates the start of the formation of the reproductive organs. For example, for the simulation of potato or root crops the DVS = 1 represents the moment of tuber or root initiation rather than flowering.

The development stage is incremented by the daily development rate which is computed using:

$$DVR = F_v \cdot F_P \cdot {T_{eff}}/{TSUM_{req}}$$

Here, T_{eff} is the effective temperature, $TSUM_{req}$ is the temperature sum that is required to go to the next phase of phenological development. The effective temperature (T_{eff}) is calculated as the difference between the daily average temperature and a base temperature below which no development occurs. Above a certain maximum temperature T_{eff} remains constant. Between the maximum and base temperature, the daily increase in thermal time is obtained by linear interpolation.

F_V and F_P are reduction factors in the development rate due to vernalisation and photoperiod. Currently, the impact of vernalisation and photoperiod can be enabled only during the pre-anthesis period. Phenological development after anthesis is always simulated using temperature only.

The photoperiod reduction factor can be enabled for crops which are sensitive to day length. Such crops accelerate their development when day length increases (long day crops) or decreases (short day crops). F_P is computed by taking the day length for the current day and linearly interpolating between the critical day length and the optimum day length.

The approach for vernalisation is based on the work of Wang and Engel (1998) and of van Bussel et al. (2015). The algorithm works by

[2] https://github.com/ajwdewit/wofost
[3] https://github.com/ajwdewit/pcse

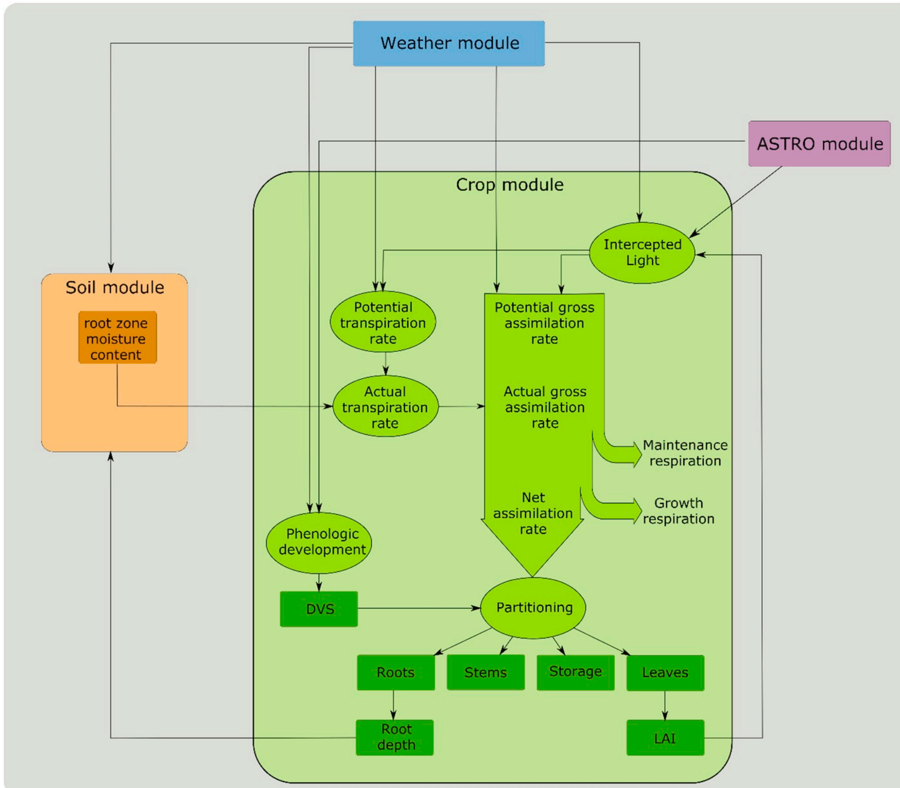

Fig. 1. Schematic overview of the major processes implemented in WOFOST and their linkages.

Table 1
Number of parameters used in WOFOST to describe different processes.

Process	Scalar	Tabular	Total
Phenological development	13	2	15
Leaf growth, senescence and assimilation	9	3	12
Root formation	4	2	6
Respiration	5	1	6
Transpiration	5	0	5
Storage organ formation	2	1	3
Stem formation	2	2	4

calculating the number of effective days for vernalisation where the vernalisation effectiveness for a day is defined by a temperature function. Accumulation of the vernalisation days yields the reduction factor which is linearly interpolated between a base vernalisation (complete reduction) and a saturated vernalisation (no reduction). The reduction factor for vernalisation was recently added to allow proper simulation of phenological development for winter crops in the MARS system (see Ceglar et al. (2018)).

2.2. CO_2 assimilation

The daily gross CO_2-assimilation rate of a crop is calculated from the absorbed radiation and the photosynthesis-light response curve of individual leaves. This response is dependent on average daytime (not average daily) temperature and leaf age. The absorbed radiation is calculated from the total incoming radiation and the leaf area. Because photosynthesis responds to light intensity in a non-linear way, variation in radiation level has been taken into account.

The first kind of variation occurs in the canopy along the vertical plane, because upper leaves receive more light than lower leaves. This is accounted for by separately calculating the adsorption of sunlight when going from the top to the lower parts of the canopy assuming a spherical leaf angle distribution. On the basis of the photosynthesis-light response curve for individual leaves, the assimilation of leaves across the relative canopy depth is calculated. The variation in the horizontal plane, e.g. the effect of plant rows, is not accounted for. The second kind of variation is temporal, caused by the daily cycle of the sun and the effect of variation in solar angle and day length over the year. WOFOST uses the total amount of daily radiation which is distributed over the day and makes a distinction between direct and diffuse radiation.

The daily gross CO_2 assimilation rate is obtained by integrating the assimilation rates through the crop canopy and over the day. For the integration over the day, a sinusoidal course of incoming radiation over the day is assumed. Both the integration through the crop canopy and the integration over the day is carried out using a three-point Gaussian integration method leading to nine iterations as described by Goudriaan (1986).

Finally, the daily gross CO_2 assimilation rate can be reduced as a function of daily minimum temperature. The background of this reduction is that during night-time the assimilates, produced during daytime, are transformed into structural biomass. This process is hampered by low temperature. If these low temperatures prevail for several days, the assimilates accumulate in the plant and the assimilation rate diminishes and ultimately halts.

2.3. Respiration

WOFOST takes into account two types of respiration losses. First of all, part of the formed assimilates is used for maintenance respiration. Maintenance respiration is estimated on basis of the dry weight of the different organs and their chemical composition. Maintenance respiration is dependent on the ambient temperature and its magnitude doubles with each 10 degrees increase in ambient temperature (Q10 = 2). The model assumes that the maintenance respiration rate cannot exceed the actual gross CO_2 assimilation rate. It is thus assumed that the vegetation will not be 'self-consuming' in terms of carbohydrates.

Second, growth respiration is the loss that occurs when carbohydrates have to be converted into structural plant material which takes a certain amount of energy. WOFOST does not compute growth respiration separately but uses a conversion efficiency factor. The efficiency of the conversion depends on the type of plant product involved. This is particularly evident for the storage organs where conversions from carbohydrates to sugar or starch have high conversion efficiencies (sugar beet: 0.82, potato: 0.85), while conversion to substances with high levels of protein or lipids have low conversion efficiencies (sunflower and rapeseed: 0.45).

2.4. Partitioning

Partitioning in WOFOST is not regarded as a separate process but is directly attached to the development stage of the crop. Static partitioning tables describe the fraction of assimilates that will be sent to the different plant organs depending on the development stage of the crop. The mechanism is simple and fairly robust but during implementation of WOFOST in different geographical regions within MARS it has been noticed that it strongly depends on having a correct description of the crop phenological development and cropping calendar.

An improper phenological development or misplaced cropping calendar can easily lead to very high or very low leaf area index. A further drawback of the static partitioning tables is that they do not take into account the ability of the plant organs to store or process the assimilates (e.g. sink limitations), moreover there is no impact of environmental conditions on partitioning. Therefore, an improved partitioning mechanism could be introduced that takes sink limitations and root-shoot functional balance into account when partitioning to the various organs. Such approach is currently used in GECROS (Xinyou and Van Laar, 2005).

2.5. Leaf growth and senescence

The area of green leaves is the major determinant for light absorption and photosynthesis of the crop. WOFOST therefore specifies leaf formation with a high level of detail. First of all, the initial leaf area of the crop is derived from the initial dry weight through its initial partitioning fraction at DVS = 0. Next WOFOST makes a distinction between early leaf development which is sink-limited and the remainder of the growing season where leaf development is source limited.

The background for this distinction is that during the early stages of crop growth, temperature is the overriding factor for leaf development. The rate of leaf appearance and final leaf size are constrained by temperature through its effect on cell division and extension, rather than by the supply of assimilates. Therefore, during the initial growth stage the LAI development is described by an exponential curve defined by a crop-specific relative growth rate.

During later stages, leaf area expansion is increasingly restricted by assimilate supply (i.e. source limited increase). Branching and tillering generate an increasing number of sites per plant, where leaf initiation can take place. Therefore, it is assumed that the exponential growth rate of the leaf area index is valid until the source-limited increase of the leaf area index equals the exponential growth rate.

During the entire growth cycle WOFOST keeps a fairly complex administration of leaf biomass, leaf thickness (defined by specific leaf area) and leaf age. For each day, the amount of leaf biomass formed is administered as a separate cohort with an associated specific leaf area (SLA - depending on DVS) and leaf physiological age (starting at 0). The total living leaf biomass is the sum of all individual leaf biomass cohorts. The total leaf area is computed by multiplying each cohort with the associated SLA and summing their values. Finally, for calculating the leaf area index WOFOST takes into account that stems and storage organs may absorb substantial amount of radiation and their green area is added to the leaf area through the specific stem area and specific pod area.

Leaf senescence is more complex and refers to the loss of capacity to carry out essential physiological processes and to the loss of living biomass. WOFOST includes several factors that influence leaf senescence. First of all, leaves die due to exceedance of the life span for leaves (i.e. physiologic ageing). Life span is defined as the maximum time in days a leaf can live at a constant temperature of 35 °C. Life span is crop specific.

Second, leaves can die as a result of self-shading at a high leaf area index. A relative death rate due to self-shading is defined which increases linearly from zero at a certain critical leaf area index, to its maximum value at twice this critical leaf area index. Finally, leaf senescence can be caused by water stress which is simulated through a crop-specific maximum relative death rate of leaves due to water stress. Total leaf death rate is computed by taking the maximum of the three rates (ageing, self-shading or water-stress).

To take into account the leaf death rate on total leaf area, WOFOST removes biomass from leaf cohorts starting with the oldest leaves until the leaf biomass removed equals the leaf death rate. The biomass removed from the cohorts is added to a separate pool of dead leaf dry matter in order to keep the carbon balance closed.

2.6. Stems and storage organs

Stems and storage organs have little biophysical processes attached in WOFOST and function as mere pools for storage of biomass. For stems, WOFOST does make the distinction between living and dead stem biomass by specifying a relative death rate that causes stems to die after a certain development stage. This has impact on the calculated respiration rate as dead stem biomass does not respire.

Both the storage organs and stems can contribute to the crop photosynthetic active area which is computed from the specific stem area and specific pod area (e.g. the green area per kg biomass). This additional green area is simply added to the crop leaf area and treated in the same way.

Crop height, which is often strongly related to stem biomass, is not defined in WOFOST.

2.7. Roots

Growth of roots in terms of depth is implemented in a straightforward way in WOFOST. The model assumes that at the start of the crop simulation, the crop has an initial rooting depth which is usually set to 10 cm. After initialization, the crop grows with a fixed daily increase in rooting depth until either a crop-specific maximum depth or a soil-defined maximum depth is reached. In versions of WOFOST that implement a shallow groundwater table, the increase in root depth will also cease if the roots are within 10 cm of the groundwater table and the crop cannot form airducts. WOFOST does not define a root density profile and assumes that plant roots can subtract water equally from the entire rooted layer.

Growth of roots in terms of biomass follows the same logic as other plant organs in that the roots receive a fraction of the net daily assimilates based on the partitioning fraction to roots for that day. Similar to stems, death of root material depends on the development stage through a relative death rate that causes a fraction of the roots to die after a certain development stage.

In the model there is no relationship between the amount of biomass partitioned to the roots and the increase of the depth of the roots, with the exception that the increase in root depth will cease if there is no partitioning of biomass to roots anymore. Also there is no impact of environmental conditions (such as drought) on root growth.

2.8. Transpiration

WOFOST makes a distinction between crop transpiration, soil evaporation and open water evaporation (if applicable) which are computed separately. Transpiration is computed as part of the crop simulation model, while the calculation of soil or water evaporation is delegated to the soil water balance model. The latter will not be further discussed here as this is part of the water balance for which multiple implementations are available.

Transpiration is the loss of water from a crop to the atmosphere. Water loss is caused by diffusion of water vapour from the open stomata to the atmosphere. The stomata need to be open to exchange gasses (CO_2 and O_2) with the atmosphere. To avoid desiccation, a crop must compensate for transpiration losses, by water uptake from the soil. In WOFOST, an optimum soil moisture range for plant growth is determined as function of the evaporative demand of the atmosphere (reference potential transpiration of a fixed canopy), the crop group and total soil water retention capacity. Within that range, the transpiration losses are fully compensated. Outside the optimum range, the soil can either be too dry or too wet. Both conditions lead to reduced water uptake by the roots, in a dry soil due to water shortage, in a wet soil due to oxygen shortage.

The potential transpiration rate depends on the leaf area, the evaporative demand of the atmosphere and, in recent versions of WOFOST, on the atmospheric CO_2 level through a CO_2 level dependent correction factor. Leaf area determines the fraction of global radiation intercepted while the evaporative demand is characterized by the evapotranspiration of a reference crop.

Originally, WOFOST applied the Penman approach (Penman, 1956), adapted according to (Frere and Popov, 1979) for calculating reference evaporation values for a shaded soil surface, a shaded water surface and a reference crop. More recent versions of WOFOST apply the Penman-Monteith reference evapotranspiration (Allen et al., 1998; Monteith, 1965) for estimating the transpiration rate for the reference crop. Differences between a given crop and the reference crop can be accounted for through a correction factor, having a value of 1.0 for most crops. A plausible range for this factor is 0.8 for water saving crops and 1.2 for crops spending relatively much water. Note that the reference evapotranspiration is regarded to be an external forcing which can be derived solely from meteorological inputs rather than an internally computed rate.

A crop reacts to water stress with closure of the stomata. As a consequence, the exchange of CO_2 and O_2 between the crop and the atmosphere diminishes, and hence CO_2-assimilation is reduced. This effect is quantified assuming a constant ratio of transpiration to gross assimilation. This is done according to the equation below, were the assimilation rate A is the product of the potential assimilation rate A_p (both [kg/ha d^{-1}]) and the ratio of the actual (water-limited) transpiration rate T_a and the potential transpiration rate T_p (both mm d^{-1}) (van Keulen and Wolf, 1986).

$$A = \frac{T_a}{T_p} A_p$$

The relation between root zone soil water content and the ratio T_a/T_p is shown in Fig. 2. Between the critical soil moisture content (θ_{cr}) and field capacity (θ_{fc}), the ratio is 1, allowing potential transpiration. Outside this range, the ratio is smaller than 1, leading to reduced transpiration. At the permanent wilting point, θ_{wp}, and at the saturation point θ_{st}, transpiration and hence crop growth, come to a halt. θ_{wp}, θ_{fc} and θ_{st} depend on soil type. θ_{cr} depends on crop type and weather. A combination of high evaporative demand and a drought-sensitive crop leads to high values of θ_{cr}. A crop's drought-tolerance is indicated with a soil depletion number, within the range of 1.0 for drought-sensitive crops and 5.0 for drought tolerant crops (Doorenbos and Kassam, 1979; Driessen, 1986).

The plant transpiration rate can also be reduced when the water content in the root zone is near saturation. Root systems which have been developed in aerobic soils do not have airducts and degenerate within several days when anaerobic conditions (waterlogging) are imposed (Penning de Vries et al., 1989). Flooding quickly depletes the oxygen in the soil and root cells disintegrate when their metabolic activities are hampered by oxygen depletion. Transpiration reduction occurs when the actual soil moisture content exceeds the critical soil moisture content for aeration. The latter should be specified as a soil-specific parameter.

The maximum reduction due to oxygen stress is reached after four successive days of anaerobic conditions. In reality however, this period depends on the development stage and species, moreover the process of transpiration reduction due oxygen shortage is poorly parametrized and values for the reduction factor are rather speculative.

2.9. Soil moisture

For estimating the water-limited production WOFOST needs to be connected to a soil water balance model in order to keep track of the moisture content of the soil. However, the soil moisture balance model itself is not regarded to be part of the WOFOST model as WOFOST has been connected to many different types of soil modules for different purposes.

Examples of different soil water balances are the original simple tipping bucket soil water balance approach (Diepen et al., 1989) and which is still operationally applied within the MARS system. A more advanced soil water balance is available through the Soil-Water-Atmosphere-Plant (SWAP) system that uses WOFOST to simulate the growth of annual crops and grasslands (Kroes et al., 2017, 2000). SWAP uses a multi-layer approach to simulate the flow of water and solutes through the soil and applies a numerical solution to the Richard's equation with variable time stepping.

Within the BioMA framework several water balance approaches are available that can be connected to the WOFOST implementation inside BioMA through a modular component-based approach (Donatelli et al., 2010). Finally, WOFOST has recently been coupled to the soil water balance of the Noah land surface model as an intermediate solution (in terms of complexity) between the simple tipping-bucket approach and the SWAP approach (Eweys et al., 2017).

3. Spatial implementation for crop yield forecasting

3.1. Background

WOFOST was one of the first crop simulation models to be implemented in a spatial framework that brought together all the components for applying a crop simulation for multiple locations: observed and gridded weather variables, soil maps, agro-ecological zones with cropping calendars and crop cultivars, storage of model simulation results and finally the visualisation of the model simulation results through maps and charts as well as yield prediction.

The spatial implementation of WOFOST within the MARS system has a spatial grid at its basis which connects all other inputs that are required. The size of the grid cells is arbitrary and is often related to the size of the area, the variability within the area and the resolution of the available data sources. First of all, weather variables are interpolated or downscaled towards the grid cell centres in order to have complete and consistent time-series of daily weather variables available. Next, maps of soil properties are intersected with the grid cells in order to have unique combinations of soil type and grid cell. Finally, the cropping calendar defines the cultivar type and the sowing/harvesting time for each combination of year, grid cell and crop type. At the same time, the crop calendar also acts as a crop mask, by only implementing the calendar for the relevant grid cells where the crop is cultivated.

Simulations with WOFOST are then carried out for each individual soil type within each grid cell and for all crops available. The system

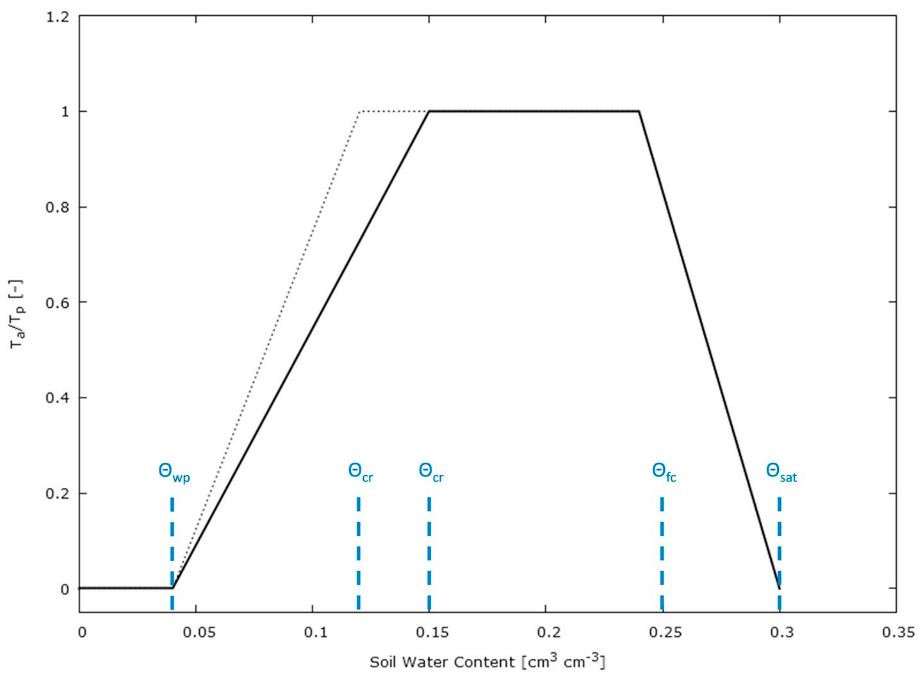

Fig. 2. The relation between soil water content, θ, and T_a/T_p for a crop/soil combination. θ_{wp}, θ_{cr}, θ_{fc} and θ_{st} represent the water content of the soil at wilting point, the critical point for potential transpiration, field capacity and saturation, respectively. The dashed line represents either a more drought resistant species under the same field conditions, or the same species under a lower evaporative demand, caused by different weather conditions (Penning de Vries et al., 1989; van Laar et al., 1992).

takes into account that certain soil types are not suitable which are skipped from simulating. For historic years, the model always simulates the entire year, while for the current year the system takes into account the availability of weather data up till today. The simulation results are stored as time-series of simulated crop variables for both potential production and water-limited production levels including phenologic development, biomass, leaf area index, water use and soil moisture.

The WOFOST simulation results at the lowest level are of little use for yield forecasting and visualisation. Therefore, aggregations are carried out to grid and regional levels. Aggregations towards grid level are performed by computing an average of the simulated variables weighted on the relative area of each soil type within the grid. The grid level products are then used to produce maps such as current season biomass, phenological development and water use, often relative to the climatology of those variables.

Aggregations towards the regional level should ideally be carried out using crop-specific area estimates for each grid. However, crop-specific area estimates are not available at the grid level and therefore the aggregations are performed in a two-step approach. The first step involves aggregation of grid level variables towards the lowest level of administrative regions. For this aggregation the weight factor for each grid is defined by the area of arable land as derived from non crop-specific land cover maps such as GlobCover (Arino et al., 2007) or CORINE land cover (Feranec et al., 2010). In the second step, the aggregation from the lowest level of administrative regions up to higher levels and finally national level, is carried out by using the reported crop area for each administrative region as the weight factor for all variables that have to be aggregated.

The aggregated variables at the regional level are used in a similar fashion as the gridded variables to generate maps and charts often relative to the climatology. Moreover, they are used as input in the statistical infrastructure of MARS. This infrastructure combines time-series of indicators from several sources including weather, crop simulation results and satellite observations with time-series of reported yields at regional level in order to develop models for crop yield forecasting. The latter are one of the inputs used for issuing the MARS bulletins together with qualitative and quantitative analysis of different types of indicators by experts.

3.2. Calibration and parameterization

Model calibration and parameterization is done through a tool called Calibration Platform - CALPLAT (Akkermans et al., 2008; Wolf et al., 2011). CALPLAT was developed because the spatial extension of the MARS system, as a result of enlargement of the European Union, led to disjoint simulation results across Europe. The latter was caused by artificial changes in the parameter values of the model rather than real agronomic differences in crop cultivars or crop calendars. CALPLAT defines a structured approach for model calibration that takes into account the model structure of WOFOST, the spatial aspects of calibrating a spatial model setup as well as the data handling that comes with calibration of complex systems.

Within CALPLAT a hierarchy in model calibration is defined that links to the hierarchy in production levels as used by WOFOST. First of all the phenological parameters of the model need to be calibrated in order to correctly reproduce the crop phenological cycle. Second the crop parameters defining the potential production parameters should be calibrated based on experimental observations that were carried out under optimal conditions. Finally, the crop parameters related to water-limited production should be calibrated based on experimental observations under water-stressed conditions. Based on this hierarchy, a calibration engine was developed that minimizes the differences between simulated and observed variables using an optimization algorithm. Moreover CALPLAT defines an explicit link between model parameters and the specific observations that are needed to calibrate that parameter.

Further, CALPLAT combines the calibration engine with a database with agronomic observations that provides input for the engine in order to compare simulation results with observed values. The database is flexible to allow different kind of observations: 1) observed values from true crop experiments at experimental stations; 2) regional crop calendars such as provided by FAO or other sources; 3) Expert estimates that could be added if no other observations were available. Moreover, all observations are linked to a particular grid cell within the CGMS grid definition and can be assigned different weights.

Finally, with CALPLAT a strategy was developed to deal with the spatial aspects of the WOFOST implementation in CGMS. CALPLAT provided functionality to define or import an agro-ecological zonation for the model spatial domain. Each agro-ecological zone is calibrated separately and for starting the calibration all observations available for that zone are retrieved from the database. The engine then performs the calibration by jointly minimizing the differences between simulations and observations over all available observations in that zone.

Although the CALPLAT approach was successfully implemented and applied to calibrate the WOFOST model for different crops and regions (Djaby et al., 2013; Huang et al., 2011; Wolf et al., 2011), it was found that the available observations were often so scarce that the calibration rarely proceeded beyond the first level (phenology). To evaluate the crop simulation results of WOFOST at potential and water-limited level in the absence of observed data a procedure was developed that allowed to check the plausibility and consistency of the WOFOST simulation results. The procedure that we developed has similarity with the model calibration protocol that was developed for the Global Yield Gap Atlas (GYGA) as described by (Grassini et al., 2015) and available online.[4] However, our procedure is more targeting WOFOST specifically taking into account the spatial aspects of the simulation and calibration as well.

First of all, the observed vs simulated variables must be analyzed for example by generating maps of error statistics (RMSE, MAE) by agro-ecological zone. Large deviations in the error statistics should be analyzed to search for problems with the input data in the agrophenological database. Next, maps of the calibrated parameter values must be created in order to judge their spatial coherence. For example, calibrated temperature sums for phenological development often reflect climatic gradients. Agro-ecological zones with strongly deviating values that do not correspond to the climatic gradient are suspicious and should be checked for problems with the agronomic data as well.

Second, the WOFOST simulation results themselves must be analyzed taking into account the logic of the calibration: first the phenology, next the potential production level and finally the water-limited production level. For this analysis it is needed to implement the new crop parameters in the system and use WOFOST to simulate a considerable time-series (say 25 years) with the new parameter values.

We find the following analyses and maps based on WOFOST simulation output crucial in judging if a CGMS/WOFOST implementation is appropriate:

1. Phenology:
   - For crops that are supposed to reach physiological maturity it should be checked that maturity is actually reached by the model. Maps displaying the number of years where maturity is reached (meaning DVS $\geq$ 2) are highly useful in identifying areas with problematic parameter values.
   - Maps showing the variability in the flowering and maturity date over time help in finding areas with unstable phenological development. The latter can be caused by inappropriate values for critical day length or vernalisation.
2. Potential production level:
   - Mid-season leaf area index: Average maximum leaf area index during the growing season and its variability over time. Crop simulations in areas with low maximum leaf area index (< 4) will not reach their full growth potential due to incomplete light interception. A large variability in maximum leaf area index between years (say a coefficient of variation > 20%) is often caused by instability in the partitioning and phenological development.
   - End of season leaf area index: For crops that are supposed to have a fully senesced canopy, the remaining LAI at the end of the simulation should be checked. High LAI values at the end of the cycle are often caused by a too high life span of leaves (SPAN).
   - End of season biomass: Maps of average total above-ground biomass at the end of the growth cycle. These maps should indicate realistic values for potential production situation. Low total above-ground biomass is often linked to low maximum leaf area index and low light interception.
   - Harvest Index: Maps of the average harvest index at the end of the growth cycle. In WOFOST, the harvest index is not an input but is a model result and computed from the different biomass pools. Checking maps of the harvest index is often useful because unrealistic low or high values of the harvest index often indicate problems with the assimilate partitioning.
3. Water-limited production level:

- Except for phenology, all analysis described for the potential production level are relevant also for the water-limited production level in the sense that differences with the potential production situation should be explainable from the perspective of water-limited growth conditions.
- Initial soil water: The initial amount of soil water should preferably have little or no influence on the simulation results of WOFOST. In general the best strategy here is to start with a relatively low amount of initial water in the soil and increase the lead time (simulation days before crop sowing or emergence) until the simulation results do not change anymore. It has been demonstrated in practice that a proper initialization of the water balance can have a large positive impact on the simulation results (de Wit et al., 2013).

A final step in the evaluation of a CGMS/WOFOST parameterization for a given area is to make a comparison with an independent reference dataset for example regional reported yield or production levels as provided by national or regional statistical offices. Simulated yields provided by WOFOST or often considerably higher than reported yields at regional level or at individual farmer fields (De Wit et al., 2010). Nevertheless, a correlation in the yield variability is often present in time and space that can be used as an independent validation of the results.

3.3. Performance considerations on spatial model simulations

Spatial crop simulations are computationally heavy given the various inputs (weather, crop and soil parameters, agromanagement), complex calculations and the large number of output variables that have to be stored. Given the strong non-linearity in crop models, the spatial version of WOFOST implemented in MARS strongly adheres to the principle of simulation at the lowest level first, then perform aggregation in time and space.

Developments within MARS have steadily increased the computational requirements that are needed to operate the system. Initially, the system implementation only covered the EU12 which was covered by around 2200 50 × 50 km grid cells. Extension of the system to include the EU27, Ukraine, parts of Russia, Turkey, Morocco, Algeria and Tunisia extended the number of grid cells to 5600. Finally, the decrease in grid cell size to 25 × 25 km quadrupled the number of grids to around 22,000.

Decreasing the cell size is not the only factor involving the increase of the computation load. Since 2010 the MARS system not only includes observed weather but also stores ECWMF reanalysis and weather forecasts ensembles (10-day, 1-month and 6-months). The use of ensemble forecasts provided another increase in the computational load of the MARS system as now not a single (deterministic) run of WOFOST is sufficient, instead an ensemble of models has to be simulated. For the 10-day forecasts, the added computational load is limited because only the last 10 days of the simulation have to be run in ensemble mode. However, for the monthly and particularly the 6 monthly forecast the additional computational load is large because of the length of the period where the model has to run in ensemble mode.

Finally, the number of individual simulation units increases nearly linearly with the number of crops that have to be simulated although not all crops are simulated over the entire domain. Originally the

[4] http://www.yieldgap.org/web/guest/methods-model-calibration

Table 2
Number of WOFOST simulations carried out within a year to operate MARS for Europe. Total number of simulations is found by multiplying the runs/year and members with the number of individual simulations in the spatial schema (as defined by number of crop types, grid cells and soil type per grid cell).

Model	Simulations based on	Runs/year	Members	Total
Obs	Observed weather	36	1	7.87E + 07
Ope	Observed weather extended with 14 day deterministic forecast	36	1	7.87E + 07
obs + ope	As ope but extended to next dekad boundary	5	1	1.09E + 07
10-day	Observed weather extended with 10-day ensemble forecast	36	51	1.78E + 09
30-day	Observed weather extended with 30-day ensemble forecast	5	51	2.47E + 08
180-day	Observed weather extended with 180-day ensemble forecast	3	51	1.48E + 08
			Total	2.34E + 09

system included 7 crops, currently 15 crops are simulated with in some cases multiple versions of the same crop using another parameter set. In total, we estimate that the deterministic runs involve $2.1{\cdot}10^6$ simulation units, while the ensemble runs are carried out for less crop types and involve around $0.9{\cdot}10^6$ simulation units. When we express this in the number of WOFOST simulations that are typically carried out over a year to operate MARS, we see that this adds up to around $2.34{\cdot}10^9$ individual simulations (Table 2).

Expressing this in the total amount of processing time or run-time per simulation is difficult because this varies through the season as the number of days to simulate increases and so does the processing time. However, for a complete seasonal run, including data retrieval from the database, we estimate that a single WOFOST simulation takes about 120 ms on a 2.3 Ghz CPU. Individual WOFOST simulations are independent as there are no spatial or temporal relationships between individual simulations in the system. Therefore, the workload can be easily distributed across multiple CPU cores or multiple computers in a cluster.

4. Software implementations

4.1. Available implementations

Traditionally, crop simulation models developed in Wageningen have been distributed including the full source code of the model (van Ittersum et al., 2003). WOFOST is no exception and it is one of the few widely known crop models whose source code has been publicly available already since the late eighties. Originally these were in hardcopy form, see for example (van Diepen et al., 1988), but nowadays through public code repositories.[5]

The public availability of source code helped tremendously in spreading the scientific background of the model and it helped take up of the model in the application domain. Nevertheless, it also spurred the proliferation of model implementations as illustrated by the many implementations of WOFOST that exist today (Table 3). It is evident that implementations of WOFOST have been created in a wide variety of programming languages ranging from interpreted languages (R, python) dedicated to science and education, to high performance implementations dedicated at operational implementation (F90, C, C#, Java).

Nevertheless, the list of different model implementations in Table 3 is also exemplary of the problematic status of software development in agricultural modelling today. A recent review by (Janssen et al., 2017) raised issues such as redundancy, poor re-use of model components and difficult coupling of models and model components. All of this applies to WOFOST as well, given that (even within Wageningen University & Research) different modelling groups have created implementations of WOFOST. Some recoding of model implementations is probably unavoidable if the model has to be implemented in very different modelling frameworks or embedded in existing systems. Nevertheless, Table 3 does illustrate the need for better reuse of model components in order to avoid re-implementing models over and over again.

The list of WOFOST implementations also raises questions from a numerical perspective as it is often unclear which parts of the WOFOST model are implemented in the different implementations of WOFOST. Neither is it known how well the different implementations are reproducing the results of the original model and under what conditions tests have been carried out. Particularly if different modelling studies are carried out with different model implementations the results may not be reproducible.

The difficulties in creating different model implementations that produce exactly the same results is illustrated in Fig. 3. Here two WOFOST implementations that are used for MARS related activities differ considerably in the water-limited simulation results with over 2000 kg/ha difference in the final biomass which is caused by a difference in the root zone soil moisture content. Initial inspection of the code demonstrated that both implementations used *exactly* the same equations. Only after careful debugging and comparing state variables at each time-step it was found that implementation 2 had a state update at a wrong location in the water balance leading to this discrepancy.

It is somewhat remarkable that such small differences in the model code can lead to such large differences in the model simulation results. It is therefore highly unlikely that all WOFOST implementations listed in Table 3 will exactly reproduce the original model.

4.2. Implementations supported by MARS or Wageningen modelling groups

4.2.1. WCC/SWAP WOFOST

The original implementation of the WOFOST model was developed in FORTRAN and this version has been distributed as part of the WOFOST Control Centre (WCC) package (Boogaard et al., 2014) and as part of the SWAP (Soil Water Plant Atmosphere) model (Kroes et al., 2017, 2000). The FORTRAN implementation of WOFOST will continue to be supported as part of the SWAP model. Its stand-alone use as part of WCC will be discouraged as limited maintenance has been carried out in favour of developing new implementations.

4.2.2. PCSE/WOFOST

PCSE/WOFOST provides an implementation of WOFOST in pure python and is developed within a framework called Python Crop Simulation Environment (PCSE). The PCSE implementation grew out of a desire for more flexibility particularly for scientific studies where simulation results are combined with observations through data assimilation techniques (de Wit et al., 2012b; de Wit and van Diepen, 2007; Combe et al., 2017). PCSE/WOFOST is actively developed and due to its flexibility functions as a test-bed for testing new ideas or implementations.

The model is provided with full source code and documentation through public repositories under a permissive license (EUPL). The use of python ensures that PCSE/WOFOST integrates very well with tools in the scientific software stack. For example, PCSE/WOFOST has been used extensively in combination with Jupyter notebooks that allow researchers to publish code, results and explanations that are both

[5] http://github.com/ajwdewit/

Table 3
Overview of available WOFOST implementations known to the authors.

WOFOST implementation	Language	license	Created	Maintained by	Reference	URL
WCC/WOFOST	F77	EUPL	1988	WUR	Diepen et al. (1989), Boogaard et al. (2014)	http://wageningenur.nl/wofost
SWAP/WOFOST	F90	GPLv3	2000	WUR	Kroes et al. (2000), Kroes et al. (2017)	http://www.swap.alterra.nl/
PCSE/WOFOST	Python	EUPL	2014	WUR	(Wit, 2018)	http://wageningenur.nl/wofost
WISS/WOFOST	Java	Unpublished	2017	WUR	N/A	http://wageningenur.nl/wofost
BioMA/WOFOST	.Net C#	CC By-SA 4.0	2010	EU/JRC	(Donatelli et al., 2010)	http://bioma.jrc.ec.europa.eu/models.htm
CGMS/WOFOST	C++	proprietary	1998	EU/JRC	(Supit and Van der Goot, 2003)	http://supit.net
IDL/WOFOST	IDL	GPLv3	2015	RADI-CAS	(Cheng et al., 2016)	https://github.com/ajwdewit/IDL_WOFOST_7.1
RWOFOST	R	GPLv3	2016	University of California, Davis	N/A	https://github.com/cropmodels/Rwofost
WOFOST-SLEEK	C	proprietary	2015	SLEEK consortium	N/A	http://www.sleek.environment.go.ke/

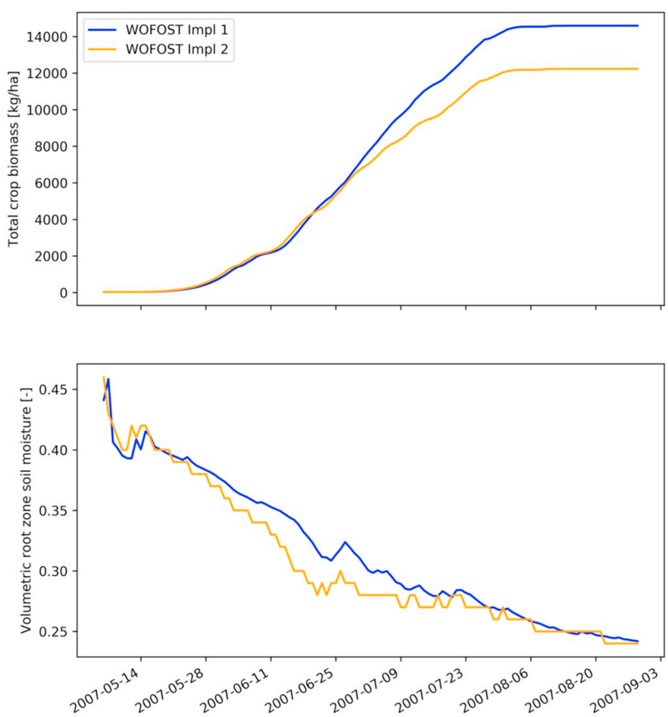

Fig. 3. Simulation results of the total crop biomass (top) and volumetric soil moisture (bottom) for two different WOFOST implementations used in the MARS system. The jagged appearance of the soil moisture curve of implementation 2 is caused by the limited number of decimals that are stored in the database from which the results were retrieved.

readable and executable (Kluyver et al., 2016).

However, versatility comes at a price and the PCSE/WOFOST implementation is relatively slow in executing model simulations. Although comparisons are difficult to make due to differences in I/O, PCSE/WOFOST can be a factor 100 slower than the equivalent implementation in Fortran. Nevertheless, large simulation studies have been carried out with PCSE/WOFOST because the model is easy to parallelize and distribute across a compute cluster (Müller et al., 2017). Moreover, the model is used within CALPLAT to run model calibrations which also requires a large number of simulations to be executed (Ceglar et al., 2018).

4.2.3. BioMA/WOFOST

The BioMA/WOFOST implementation was created by (Donatelli et al., 2010), with the idea of creating a modular and computationally performing version of WOFOST. BioMA (Biophysical Models Applications) is a modular software framework designed and developed for parameterizing and running modelling solutions based on biophysical models (Donatelli and Rizzoli, 2008).

In an agronomical model like WOFOST, each component deals with the different aspects of a crop simulation: WOFOST contains a component to simulate the crop growth, a component to simulate the soil water balance, a component to calculate heat stress, and so on. Not all components are mandatory. For the operational simulations used within the MARS system, the only components used are the crop grow model (encapsulated in library EC.JRC.MARS.Crop.CropML) and the “CGMS water balance component” (encapsulated in library EC.JRC.MARS·CGMSWaterBalanceComponent).

The modular architecture allows the re-usability and interchangeability of the discrete units of software. For example it is relatively easy to replace the “CGMS water balance component” with another component that calculates the soil water balance in a different way (some examples are present within the available Bioma components library) without modifying the other components of the modelling solution. In the same way, it would be easy to reuse the “CGMS water balance component” together with a different crop growth model implemented in the Bioma framework. An example of such reuse is the substitution of the WOFOST model by the WARM model, a dedicated rice simulation model (Confalonieri et al., 2009), applied for monitoring rice growth in specific regions in Europe.

The following components are part of the WOFOST model implementation used in the MARS operational context:

- WOFOST potential component: this component performs the crop growth simulation by simulating the crop in potential conditions (no water stress or any other stress)
- WOFOST water-limited component: this component performs the crop growth simulation by considering the water limited crop growth. Its code is a copy of the WOFOST potential component, but its state variables take into account the limitation due to water scarcity, which is calculated by the Water balance component. Therefore, a single simulation can calculate simultaneously both the potential and the limited results.
- Water balance component: this component calculates the soil water balance and communicates to the WOFOST limited component the water content available in the soil for the plant (necessary for calculating the water limited crop growth).
- Agromanagement component: this component manages the agromanagement practices. It reads the agromanagement configuration and, during the simulation, checks if some agromanagement rule is satisfied. When a rule is satisfied, the corresponding impact event is triggered. In the operational version of the modelling solution, the only practices managed are sowing and harvest.
- Weather provider component: this component provides the weather

data to the other components.

- Soil data provider: this component provides the soil data to the other components.

To combine a good simulation performance and the use of a user-friendly language, the Bioma development team coded the platform using the C# programming language, under the Microsoft .NET Framework environment. Starting from 2015, the BioMA implementation replaced the CGMS implementation for running the operational MARS simulations. To make it possible, several adaptations were done on the Bioma applications to increase the simulation performances to cope with the high scheduling requirements of the operational runs, particularly with regard to simulations driven by ensemble weather forecasts.

Support for the BioMA framework and its model implementations will be provided through MARS as BioMA/WOFOST is foreseen to be applied operationally in the coming years. The BioMA framework itself has reached a high level of maturity over the last few years and no major modifications are foreseen to the framework itself. Developments currently focus on two aspects: First of all, on building an improved user interface called 'BioMA Studio' that facilitates configuring and running the simulation of models through a wizard-like interface. Second, on experimenting with porting BioMA to the .NET Core framework that will allow BioMA to run on any operating system (Windows, macOS, Linux) and provides support for distributed computing environments.

4.2.4. WISS/WOFOST

The WISS (Wageningen Integrated Systems Simulator) framework is under active development in order to fulfil the requirements of operational application of simulation models. WISS is written in the Java programming language and provides high numerical performance and robustness of the model implementations. To achieve these objectives, all simulation models in WISS are split into components that are essentially stateless and whose states and rates are managed by a dedicated state exchange object. States in this object are registered such that other model components can only read the value and cannot accidentally change the value. This is done by returning a 'token' on registration of a state variable. This token contains the privilege whether the holder can change the state value (by providing a rate value), or can only read the state value. This token also enables fast storage and retrieval of data as it contains the direct location of the data, i.e. searching for the data is not necessary. Furthermore, WISS provides facilities for runtime checking of states bounds as well as automatic unit conversion allowing components that calculate in different physical units to seamlessly interact.

The WOFOST implementation within the WISS framework has been tested against the existing implementations and is able to reproduce those results. Moreover, we are striving to compatibility between WISS and PCSE in terms of databases and parameter formats for soil types, crop parameters and agro-management. This will allow easy reuse of calibrated parameter sets between the two frameworks. For crop parameters sets this has already been realized through a common storage format and which are available through a github repository.[6]

As of October 2017, WISS is still under active development and has not been published so far. WISS/WOFOST will be made available to the modelling community in the near future as part of a new version of the WOFOST Control Centre (WCC), replacing the compiled FORTRAN executable that currently is packaged with WCC. However, the model will not be distributed under a permissive license and it will not include the full source code. The reluctance for releasing WISS is due to the difficulties we face in sustained funding of model maintenance and development. Since WISS targets operational applications, we argue that WISS/WOFOST can be licensed to serve commercial interests. Income generated through such licensing can be used to support maintenance and development of the entire model ecosystem (WISS, PCSE and supporting tools and datasets) which can serve the broader community as well.

[6] https://github.com/ajwdewit/WOFOST_crop_parameters

5. Ongoing developments and discussion

5.1. Thematic extensions

From a thematic point of view several model extensions have been realized that deal with crop nutrient dynamics, crop responses to critical temperature (both cold and heat) and the response of crop assimilation to changes in ambient CO2 level. Some of these enhancements are mostly based on existing approaches that have been tested in other models such as NWHEAT or LINTUL, while others are based on recent developments also within the internationally coordinated activities such as the agricultural model intercomparison project (AgMIP; (Rosenzweig et al., 2013)) and the European MACSUR initiative (Modelling European Agriculture with Climate Change for Food Security).

5.1.1. Dynamic simulation of nutrient limited crop growth

A clear limitation of the WOFOST model is that it does not include a component for nutrient-limited growth. The nutrient-limited production scenario included within the WOFOST Control Centre package is based on the QUEFTS approach (Janssen et al., 1990; Sattari et al., 2014). The QUEFTS approach has been successfully applied for estimating the requirements and impact of fertilizers on crop yield. However, the approach is basically a post-processing step on the WOFOST simulated water-limited production which does not allow dynamic feedbacks between model and nutrient availability. Therefore, WOFOST has now been extended with a dynamic treatment of nutrient (N/P/K) uptake and demand by the crop and soil.

The implementation of nutrient dynamics is based on the method as described by Groot and De Willigen (1991) and Shibu et al. (2010). The approach uses the concept of nutrient deficiency which is defined as the ratio of actual nutrient concentration and critical nutrient concentration in the crop. The actual nutrient concentration in the crop depends on the nutrient amounts that are available in the soil, either through fertilizer applications or through mineralisation. Uptake of these nutrients is driven by demand, which on its turn is defined as the difference between the maximum nutrient concentration in the crop and the actual nutrient concentration. Nutrient translocation, i.e. nutrient transport to the storage organs from the other plant parts is accounted for. Note that nutrient uptake and translocation stop at a certain development stage, which is crop dependent. WOFOST assumes that nutrient stress affects the assimilation rate, the dry matter partitioning as well as the leaf extension. In case also drought stress occurs, the strongest of these factors is selected as the overall stress factor.

5.1.2. Impact of ambient CO_2 concentration

The impact of changes in atmospheric CO_2 level was initially not taken into account in the WOFOST model. However, recent WOFOST implementations correct for the effect of atmospheric CO_2 concentrations on assimilation rate by using a CO_2 dependent factor that modifies the leaf-level maximum assimilation rate (AMAX) and initial light use efficiency (EFF) (Vanuytrecht and Thorburn, 2017; Wolf et al., 2010, 2012). Similarly, the transpiration rate is adjusted through a factor that depends on the CO_2 concentration.

For C3 crops, WOFOST assumes that with increasing CO_2 concentration from the base level (360 ppm) up to 720 ppm, EFF increases with 11%, AMAX increases with 60% while the transpiration rate decreases with 10%. For C4 crops the photosynthetic response to CO_2 is only very steep for atmospheric CO_2 concentrations well below the current level. Therefore, increasing CO_2 concentrations from 360 to

720 ppm does not change the EFF and AMAX parameters. However, the transpiration rate is assumed to decrease with 26%. For atmospheric CO_2 concentrations that are intermediate between 360 and 720 ppm, the correction factors are found by linear interpolation. While for atmospheric CO_2 levels above 720 ppm the correction factor is limited to the value at 720 ppm.

5.1.3. Cold stress and winter-kill

The impact of cold stress so far is limited to the winter crops that can experience frost conditions during the dormancy period in winter. A module for winter-kill has been implemented based on the FROSTOL model of (Bergjord et al., 2008). FROSTOL simulates the hardiness (frost tolerance) of plants as a function of snow depth, temperature and vernalisation stage. It has been connected to a kill function that estimates the fraction of plants dying as a results of the daily minimum crown temperature. This provides a feedback to WOFOST as a reduction factor on standing leaf biomass. Tests of the model for Russian and Scandinavian conditions demonstrated that the model can predict frost kill events fairly well, but that in practice the survival of winter crops also depends on many other factors (fungal diseases, asphyxiation, etc.). The latter make the results sometimes difficult to validate or apply since the causal relationships are not clear (Bergjord Olsen et al., 2018; de Wit et al., 2012a).

5.1.4. Heat stress

To estimate the impact of heat stress around flowering of cereal crops an approach has been implemented in WOFOST which is comparable to that used by Teixeira et al. (2013) for GAEZ and by Challinor et al. (2005) for the GLAM model. They use a threshold temperature above which grain formation and fertilization are reduced and the number of infertile and aborted grains increases. WOFOST assumes a linear reduction of the grain formation with no reduction as the average daytime temperature in a particular period around anthesis is below the threshold temperature, and full reduction when the average daytime temperature around anthesis is 10° (or more) above the threshold temperature. The maximum growth rate of an individual grain therefore limits the total grain growth rate (i.e. sink limitation).

Further, in the context of the ModExtreme project (Bellocchi et al., 2014), the BioMA version of WOFOST was upgraded by creating a new component to simulate extreme heat stress events and their influence on the final yield in terms of harvest index. The component is currently under improvement: in particular, the aim of the new ongoing developments is to calculate better the canopy temperature, which has a significant role in this process, by considering the plant height and the latent heat.

5.2. Consolidating software implementations

Crop simulation models developed in Wageningen have been predominantly developed using the Fortran language or FST: the Fortran Simulation Translator (Van Kraalingen et al., 2003). Although these software tools have been valuable in the past, it has become increasingly clear that they represent a dead end for sustained model development. On the one hand, the academic and educational world is predominantly moving to high level interpreted languages (python, R, Julia) that allows focussing on the science and the problem at hand rather than the details of computer programming. On the other hand, operational application of models requires a level of software engineering (performance, interfacing, robustness) that interpreted languages and FST cannot provide. The BioMA framework and its WOFOST implementation that has been co-developed within MARS and is currently operationally applied, is a good example of the need for robust frameworks for operational applications.

New implementations of WOFOST have been created recently in order to serve both academic and operational users which is required to keep the model relevant for both science and applications. Moreover, this allows to capitalize both on academic development as well as model testing in real-world situations.

First of all, the WOFOST implementation in PCSE has its main application domain in science and education. A large effort has been dedicated to provide an understandable and readable model implementation that users should be able to modify easily as is often needed to test ideas in an academic environment. Nevertheless, many software design principles have been taken into account such as loose coupling of components, removal of all I/O from model components and the use of a simulation engine that drives the model simulation process.

Next to PCSE, there are three operational implementations under maintenance of the EC JRC MARS and Wageningen UR groups: SWAP WOFOST, BIOMA/WOFOST and WISS/WOFOST. All three implementations can reproduce the results of the original WOFOST version 7.1. Nevertheless, some WOFOST implementations can have features that are specific for a certain implementation as a result of distributed development and specific needs. Despite differences in implemented features, care will be taken that the common denominator in terms of processes implemented should yield identical results across different implementations.

Further, the large number of implementations of WOFOST that have been created call for an effort to consolidate the simulation results across the various implementations (Table 3). In practice, this is difficult given the various programming languages, ownership and availability of source code. Therefore, the only feasible way we see in consolidating WOFOST is to make it easy to perform rigorous testing on the individual model components as well as the model as a whole. This should urge developers of a WOFOST implementation to properly test their implementation before calling it "WOFOST" and use it as such in studies and applications. For this purpose we make available a large set of test cases as supplementary material with this paper. These test cases provide all inputs required to run (components of) the model and the outputs that should be reproduced by the particular implementation. Appendix 1 provides information on the structure of the test cases and an explanation of the different components.

6. Conclusions

WOFOST as a model has matured with its application in an operational crop yield forecasting system, and many methodological and software implementation improvements have been introduced due to requirements in the operational system. Methodological improvements include approaches to large scale calibration, improvements in robustness and representation of winter crops (incl. winterkill and vernalisation). In terms of software implementations, WOFOST has been a success as an open source model, with many different implementations of the same concept. For operational applications many improvements in source code and model set up were made, that allow fast large scale spatially explicit applications.

For the future, next to methodological extensions in modelling nutrients, extreme events and climate variability, we need to certify that the different WOFOST implementations and versions available can reproduce basic sets of inputs and outputs as attached to this publication in an appendix. Also, a difference is made in the operational and scientific versions of WOFOST, and improvements in the setup of both will help to enable new applications of the WOFOST model in precision agriculture and smart farming.

Appendix A. WOFOST test cases

This manuscript includes a set of test cases that can be used to verify that any implementation of WOFOST can reproduce the results of the original model. The reference set has been generated by compiling model inputs and outputs for 11 locations across Europe covering a climatic gradient ranging from Morocco to Finland and from Turkey to N-Russia. The test set covers 7 different crops: potato, sugar-beet, sunflower, grain maize, winter-wheat, field beans and spring-barley. This leads to 44 unique combinations of location and crop type as not all crops are cultivated on all locations.

The set of test cases first provides tests for basic components of the model such as astronomical calculations (e.g. day length and extra-terrestrial radiation). Next it provides tests for individual model components including assimilation, respiration, phenological development, partitioning, actual and potential transpiration. Interactions between model components are excluded in these tests and the required external states are directly provided. Finally, it provides tests for the entire model where all interactions between model components can be tested including biomass, yield, leaf area and the impact of water limitations.

All tests have been defined in a file format based on YAML and the format defines different sections for parameters, weather inputs, external states, agromanagement, simulated outputs and the precision required for testing (Table 4). The meaning and units of parameter and variable names that are used in the test files are all defined in Boogaard et al. (2014). Fig. 4 gives a succinct example of a WOFOST test file in YAML format.

Table 4
Explanation of the sections in the WOFOST test cases that are provided.

Section	Purpose	Remark	Shape
ModelParameters	Provides the parameters needed to parameterize the equations in the model components.	Can be empty in case of direct input/output functions such as the ASTRO module.	Container with key:value pairs providing parameter names and values.
ExternalStates	Provides values for states that are external to the model component tested. For example, the crop development stage often needs to be prescribed as an external state	Can be empty if no external states are required.	List where each item in the list is a container with key:value pairs providing the name of the state variable and its value. Each container also specifies the simulation date for which states apply. Note that the dates should match against the list of weather variables.
WeatherVariables	Provides the weather inputs needed to run the model.	Is always required, at least to provide a series of time steps for which input/output should be tested.	List where each item in the list is a container with key:value pairs providing the meteorological variables, the latitude, the longitude and the date of the observation.
AgroManagement	Provides the agromanagement required to run the simulation.	Is only required to run the simulations for which crop management events apply	A dedicated YAML structure as defined by the agromanager in PCSE.
ModelResults	Provides the variables that should be tested against	Is always required	List where each item in the list is a container with key:value pairs proving the name and value of the variable that should be tested. Also specifies the simulation date for each set of test variables. Note that the dates should match against the list of weather variables.
Tolerance	Provides the tolerance for the tests. The difference between simulated and reference results should be smaller than this value.	Is always required	Container with key:value pairs providing variable names and the tolerance with which they should be compared against the simulation results: $\lvert reference - simulated \rvert < tolerance$

```
# Test file for testing the simulation of phenological development in WOFOST 7.1
# All parameter and variable names and their respective units refer to the
# WOFOST manual available from http://wageningenur.nl/wofost
# encoding: UTF-8
# Copyright WageningenUR 2017, allard.dewit@wur.nl
ModelParameters:
  {TBASEM: 0.0, TEFFMX: 30.0, TSUMEM: 120, IDSL: 1, DLO: 14.0, DLC: 8.0, TSUM1: 1000, TSUM2:
  950,
   DTSMTB: [0.0,0.0,30.0,30.0,45.0,30.0], DVSI: 0.0, DVSEND: 2.0}
ExternalStates: null
WeatherVariables:
- {DAY: 1997-01-01, E0: 0.00274, ELEV: 5.0, ES0: 0.0, ET0: 0.0347, IRRAD: 3740000.0,
  LAT: 52.0, LON: 5.0, RAIN: 0.0, TEMP: -10.18, TMAX: -7.58, TMIN: -12.21,
  VAP: 1.967, WIND: 3.21}
- {DAY: 1997-01-02, E0: 0.0, ELEV: 5.0, ES0: 0.0, ET0: 0.02277, IRRAD: 3850000.0,
  LAT: 52.0, LON: 5.0, RAIN: 0.0, TEMP: -10.44, TMAX: -5.99, TMIN: -13.4, VAP: 1.971,
  WIND: 1.846}
...
AgroManagement:
- 1997-01-01:
    CropCalendar:
        crop_name: sugar-beet
        variety_name: sugar_beet_601
        crop_start_date: 1997-04-05
        crop_start_type: sowing
        crop_end_date: 1997-10-20
        crop_end_type: harvest
        max_duration: 300
    TimedEvents: null
    StateEvents: null
ModelResults:
- {DAY: 1997-01-01, DVS: null}
- {DAY: 1997-01-02, DVS: null}
...
- {DAY: 1997-04-05, DVS: 0.}
...
Precision:
  {DVS: 0.001}
```

Fig. 4. Example of a WOFOST test file in YAML format. Ellipsis signs (…) have been placed to indicate that part of the file contents has been omitted.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2018.06.018.

References

Akkermans, W., Roller, J., te Boogaard, H.L., Wit, A.J.W., de Wolf, J., Hessel, R., 2008. CALPLAT: platform for calibrating CGMS. pp. 188. http://marswiki.jrc.ec.europa.eu/agri4castwiki/images/8/80/CALPLAT_manual.pdf.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. FAO, Rome.

Arino, O., Gross, D., Ranera, F., Leroy, M., Bicheron, P., Brockman, C., Defourny, P., Vancutsem, C., Achard, F., Durieux, L., 2007. GlobCover: ESA service for global land cover from MERIS. In: Geoscience and Remote Sensing Symposium, 2007. IGARSS 2007. IEEE International. IEEE, pp. 2412–2415.

Asseng, S., Ewert, F., Rosenzweig, C., Jones, J., Hatfield, J., Ruane, A., Boote, K.J., Thorburn, P.J., Rötter, R.P., Cammarano, D., 2013. Uncertainty in simulating wheat yields under climate change. Nat. Clim. Chang. 3, 827–832.

Bellocchi, G., Villalobos, F., Donatelli, M., Christensen, O., Rojas, O., Confalonieri, R., Athanasiadis, I., Carpusca, I., Stöckle, C., 2014. Extending existing models to capture vegetation response to extreme weather: the MODEXTREME project. In: International Congress on Environmental Modelling and Software, . http://scholarsarchive.byu.edu/iemssconference/2014/Stream-H/11.

Bergjord Olsen, A., Persson, T., de Wit, A., Nkurunziza, L., Sindhøj, E., Eckersten, H., 2018. Estimating winter survival of winter wheat by simulations of plant frost tolerance. J Agro Crop Sci 204, 62–73.

Bergjord, A.K., Bonesmo, H., Skjelvåg, A.O., 2008. Modelling the course of frost tolerance in winter wheat: I. Model development. Eur. J. Agron. 28, 321–330.

Boogaard, H.L., Wit, A.J.W.d., Roller, J., te Diepen, C.A.V., 2014. User's guide for the WOFOST Control Centre 2.1 and WOFOST 7.1.7 crop growth simulation model. Alterra. Wageningen University & Research Centre, Wageningen, pp. 133. http://www.wur.nl/web/file?uuid=5c0873c3-8c07-4ddf-85a3-dd98bdb38781&owner=b875561e-c6d9-442d-b599-58e9d13cb80d.

Bouman, B., Van Keulen, H., Van Laar, H., Rabbinge, R., 1996. The 'School of de Wit'crop growth simulation models: a pedigree and historical overview. Agric. Syst. 52, 171–198.

Brisson, N., Gary, C., Justes, E., Roche, R., Mary, B., Ripoche, D., Zimmer, D., Sierra, J., Bertuzzi, P., Burger, P., 2003. An overview of the crop model STICS. Eur. J. Agron. 18, 309–332.

Ceglar, A., van der Wijngaart, R., de Wit, A., Lecerf, R., Boogaard, H., Seguini, L., van den Berg, M., Toreti, A., Zampieri, M., Fumagalli, D., Baruth, B., 2018. Improving WOFOST model to simulate winter wheat phenology in Europe: Evaluation and effects on yield. Agricultural Systemshttps://doi.org/10.1016/j.agsy.2018.05.002.

Challinor, A.J., Wheeler, T.R., Craufurd, P.Q., Slingo, J.M., 2005. Simulation of the impact of high temperature stress on annual crop yields. Agric. For. Meteorol. 135, 180–189.

Cheng, Z., Meng, J., Wang, Y., 2016. Improving spring maize yield estimation at field scale by assimilating time-series HJ-1 CCD data into the WOFOST model using a new method with fast algorithms. Remote Sensing. https://doi.org/10.3390/rs8040303.

Combe, M., Wit, A.J.W., Vilà-Guerau de Arellano, J., Mole, M.K., van der Molen Magliulo, V., 2017. Grain yield observations constrain cropland CO_2 fluxes over Europe. Journal of Geophysical Research: Biogeosciences. https://doi.org/10.1002/2017JG003937.

Confalonieri, R., Rosenmund, A.S., Baruth, B., 2009. An improved model to simulate rice yield. Agron. Sustain. Dev. 29, 463–474. https://doi.org/10.1051/agro/2009005.

de Wit, A.J.W., van Diepen, C.A., 2007. Crop model data assimilation with the Ensemble Kalman filter for improving regional crop yield forecasts. Agric. For. Meteorol. 146, 38–56. http://www.sciencedirect.com/science/article/B6V8W-4P3TY91-1/2/1c0dd70bbe18ad300ab4b11e2ef686c4.

De Wit, C., Van Keulen, H., 1987. Modelling production of field crops and its requirements. Geoderma 40, 253–265.

De Wit, A.J.W., Baruth, B., Boogaard, H.L., Diepen, C.A.v., Kraalingen, D.V., Micale, F., Roller, J., te Supit, I., van de Wijngaart, R., 2010. Using ERA-INTERIM for regional crop yield forecasting in Europe. Climate Research 41–53. https://doi.org/10.3354/cr00872.

de Wit, A., d'Andrimont, R., Bartalev, S., Defourny, P., Kleshchenko, A., Roerink, G., Virchenko, O., 2012a. MOCCCASIN (Monitoring crops in continental climates through assimilation of satellite information), Let's Embrace Space Volume II. European Commission, Publications Office of the European Union, Luxembourg, Larnaca, Cyprus, pp. 70–78. https://doi.org/10.2769/31208.

de Wit, A., Duveiller, G., Defourny, P., 2012b. Estimating regional winter wheat yield with WOFOST through the assimilation of green area index retrieved from MODIS

observations. Agric. For. Meteorol. 164, 39–52. http://www.sciencedirect.com/science/article/pii/S0168192312001414.
de Wit, A., Hoek, S., Ballaghi, R., El Hairech, T., Qinghan, D., 2013. Building an operational system for crop monitoring and yield forecasting in Morocco. IEEE 466–469.
Diepen, C.A.v., Wolf, J., Keulen, H.v., Rappoldt, C., 1989. WOFOST: a simulation model of crop production. Soil Use Manag. 5, 16–24.
Djaby, B., De Wit, A., Kouadio, L., Jarroudi, M.E., Tychon, B., 2013. Spatial distribution of calibrated wofost parameters and their influence on the performances of a regional yield forecasting system. Sustainable Agriculture Research 2, 15. https://doi.org/10.5539/sar.v2n4p12.
Donatelli, M., Rizzoli, A., 2008. A design for framework-independent model components of biophysical systems. In: International Congress onEnvironmental Modelling and Software iEMSs 2008 Proceedings of the iEMSs Fourth Biennial Meeting, Barcelona, Catalonia, 7–10 July 2008, pp. 727–734.
Donatelli, M., Russell, G., Rizzoli, A.E., Acutis, M., Adam, M., Athanasiadis, I.N., Balderacchi, M., Bechini, L., Belhouchette, H., Bellocchi, G., 2010. A component-based framework for simulating agricultural production and externalities. In: Environmental and Agricultural Modelling. Springer, pp. pp. 63–108.
Doorenbos, J., Kassam, A.H., 1979. Yield response to water. Irrigation and drainage paper. 33. pp. 257.
Driessen, P.M., 1986. The water balance of the soil. In: Keulen, H.v., Wolf, J. (Eds.), Modelling of Agricultural Production: Weather, Soils and Crop. Pudoc, Wageningen, The Netherlands, pp. 76–116.
Ewert, F., Rötter, R.P., Bindi, M., Webber, H., Trnka, M., Kersebaum, K.C., Olesen, J.E., van Ittersum, M.K., Janssen, S., Rivington, M., 2015. Crop modelling for integrated assessment of risk to food production from climate change. Environ. Model Softw. 72, 287–303.
Eweys, O.A., Elwan, A.A., Borham, T.I., 2017. Integrating WOFOST and Noah LSM for modeling maize production and soil moisture with sensitivity analysis, in the east of The Netherlands. Field Crop Res. 210, 147–161.
Feranec, J., Jaffrain, G., Soukup, T., Hazeu, G., 2010. Determining changes and flows in European landscapes 1990–2000 using CORINE land cover data. Appl. Geogr. 30, 19–35.
Frere, M., Popov, G.F., 1979. Agrometeorological Crop Monitoring and Forecasting. F.A.O., Rome.
Goudriaan, J., 1986. A simple and fast numerical method for the computation of daily totals of crop photosynthesis. Agric. For. Meteorol. 38, 249–254.
Grassini, P., van Bussel, L.G.J., Van Wart, J., Wolf, J., Claessens, L., Yang, H., Boogaard, H., de Groot, H., van Ittersum, M.K., Cassman, K.G., 2015. How good is good enough? Data requirements for reliable crop yield simulations and yield-gap analysis. Field Crop Res. 177, 49–63.
Groot, J.J.R., De Willigen, P., 1991. Simulation of the nitrogen balance in the soil and a winter wheat crop. Nutr. Cycl. Agroecosyst. 27, 261–271.
Holzworth, D.P., Huth, N.I., Zurcher, E.J., Herrmann, N.I., McLean, G., Chenu, K., van Oosterom, E.J., Snow, V., Murphy, C., Moore, A.D., 2014. APSIM–evolution towards a new generation of agricultural systems simulation. Environ. Model Softw. 62, 327–350.
Holzworth, D.P., Snow, V., Janssen, S., Athanasiadis, I.N., Donatelli, M., Hoogenboom, G., White, J.W., Thorburn, P., 2015. Agricultural production systems modelling and software: current status and future prospects. Environ. Model Softw. 72, 276–286.
Huang, Q., Chen, Z., Wu, W., Wit, A.d, Teng, F., Li, D., 2011. China crop growth monitoring system-methodology and operational activities overview. In: 2011 IEEE International Geoscience and Remote Sensing Symposium, pp. 2961–2964. https://doi.org/10.1109/igarss.2011.6049837.
Janssen, B.H., Guiking, F.C.T., Van der Eijk, D., Smaling, E.M.A., Wolf, J., Van Reuler, H., 1990. A system for quantitative evaluation of the fertility of tropical soils (QUEFTS). Geoderma 46, 299–318.
Janssen, S.J.C., Porter, C.H., Moore, A.D., Athanasiadis, I.N., Foster, I., Jones, J.W., Antle, J.M., 2017. Towards a new generation of agricultural system data, models and knowledge products: Information and communication technology. Agric. Syst. 155, 200–212.
Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L., Wilkens, P.W., Singh, U., Gijsman, A.J., Ritchie, J.T., 2003. The DSSAT cropping system model. Eur. J. Agron. 18, 235–265.
Kersebaum, K.C., Boote, K.J., Jorgenson, J., Nendel, C., Bindi, M., Frühauf, C., Gaiser, T., Hoogenboom, G., Kollas, C., Olesen, J.E., 2015. Analysis and classification of data sets for calibration and validation of agro-ecosystem models. Environ. Model Softw. 72, 402–417.
Kluyver, T., Ragan-Kelley, B., Pérez, F., Granger, B.E., Bussonnier, M., Frederic, J., Kelley, K., Hamrick, J.B., Grout, J., Corlay, S., 2016. Jupyter Ncible computational workflows. pp. 87–90.
Kroes, J.G., Wesseling, J.G., Van Dam, J.C., 2000. Integrated modelling of the soil–water–atmosphere–plant system using the model SWAP 2· 0 an overview of theory and an application. Hydrol. Process. 14, 1993–2002.
Kroes, J.G., van Dam, J.C., Bartholomeus, R.P., Groenendijk, P., Heinen, M., Hendriks, R.F.A., Mulder, H.M., Supit, I., van Walsum, P.E.V., 2017. SWAP Version 4: Theory Description and User Manual. Wageningen Environmental Research, Wageningen. http://edepot.wur.nl/416321C1.
Laar, H.H.v., Goudriaan, J., Keulen, H.v., 1997. SUCROS97: Simulation of Crop Growth for Potential and Water-Limited Production Situations: As Applied to Spring Wheat. AB-DLO, Wageningen, NL.
Monteith, J.L., 1965. Evaporation and Environment, 205-23 ed, p. 4.
Müller, C., Elliott, J., Chryssanthacopoulos, J., Arneth, A., Balkovic, J., Ciais, P., Deryng, D., Folberth, C., Glotter, M., Hoek, S., 2017. Global gridded crop model evaluation: benchmarking, skills, deficiencies and implications. Geosci. Model Dev. 10, 1403–1422.
Penman, H.L., 1956. Estimating evaporation. Eos, Transactions American Geophysical Union 37, 43–50.
Penning de Vries, F.W.T., Jansen, D.M., ten Berge, H.F.M., 1989. Simulation of ecophysiological processes of growth in several annual crops. Pudoc, Wageningen, http://edepot.wur.nl/108856C1-1289D21.
Porter, C.H., Villalobos, C., Holzworth, D., Nelson, R., White, J.W., Athanasiadis, I.N., Janssen, S., Ripoche, D., Cufi, J., Raes, D., 2014. Harmonization and translation of crop modeling data to ensure interoperability. Environ. Model Softw. 62, 495–508.
Rosenzweig, C., Jones, J.W., Hatfield, J.L., Ruane, A.C., Boote, K.J., Thorburn, P., Antle, J.M., Nelson, G.C., Porter, C., Janssen, S., 2013. The agricultural model intercomparison and improvement project (AgMIP): protocols and pilot studies. Agric. For. Meteorol. 170, 166–182.
Sattari, S.Z., Van Ittersum, M.K., Bouwman, A.F., Smit, A.L., Janssen, B.H., 2014. Crop yield response to soil fertility and N, P, K inputs in different environments: testing and improving the QUEFTS model. Field Crop Res. 157, 35–46.
Shibu, M.E., Leffelaar, P.A., Van Keulen, H., Aggarwal, P.K., 2010. LINTUL3, a simulation model for nitrogen-limited situations: Application to rice. Eur. J. Agron. 32, 255–271.
Supit, I., Van der Goot, E., 2003. Updated system description of the WOFOST crop growth simulation model as implemented in the crop growth monitoring system applied by the European Commission. Treemail, Heelsum, The Netherlands.
Supit, I., Hooijer, A.A., van Diepen, C.A., 1994. System Description of the WOFOST 6.0 Crop Simulation Model Implemented in CGMS (Volume 1: Theory and Algorithms), European Commission. Office for Official Publications of the European Communities, Luxembourg (Agricultural series, Catalogue number: CL-NA-15956-EN-C).
Teixeira, E.I., Fischer, G., van Velthuizen, H., Walter, C., Ewert, F., 2013. Global hot-spots of heat stress on agricultural crops due to climate change. Agric. For. Meteorol. 170, 206–215.
van Bussel, L.G.J., Stehfest, E., Siebert, S., Müller, C., Ewert, F., 2015. Simulation of the phenological development of wheat and maize at the global scale. Glob. Ecol. Biogeogr. 24, 1018–1029. https://doi.org/10.1111/geb.12351.
van Diepen, C.A., Rappoldt, C., Wolf, J., 1988. CWFS Crop Growth Simulation Model WOFOST Documentation: Version 4.1. Centre for World Food Studies, Amsterdam, http://edepot.wur.nl/360520C1-796E48.
van Ittersum, M.K., Leffelaar, P.A., van Keulen, H., Kropff, M.J., Bastiaans, L., Goudriaan, J., 2003. On approaches and applications of the Wageningen crop models. Eur. J. Agron. 18, 201–234. http://www.sciencedirect.com/science/article/B6T67-47FDS23-1/2/7d7c03ac9d8555e462304b3845918f8a.
van Keulen, H., Wolf, J., 1986. Modelling of agricultural production: weather, soils and crops. Pudoc, Wageningen, http://edepot.wur.nl/168025C1-800E30.
Van Kraalingen, D.W.G., Rappoldt, C., Van Laar, H.H., 2003. The Fortran simulation translator, a simulation language. Eur. J. Agron. 18, 359–361.
van Laar, H.H., Goudriaan, J., van Keulen, H., 1992. Simulation of Crop Growth for Potential and Water - Limited Production Situations: As Applied to Spring Wheat. CABO-DLO, Wageningen, http://edepot.wur.nl/359573C1-NN36696,27.
Vanuytrecht, E., Thorburn, P.J., 2017. Responses to atmospheric CO_2 concentrations in crop simulation models: a review of current simple and semicomplex representations and options for model development. Glob. Chang. Biol. 23, 1806–1820.
Wang, E., Engel, T., 1998. Simulation of phenological development of wheat crops. Agric. Syst. 58, 1–24.
Wang, X., Williams, J., Gassman, P., Baffaut, C., Izaurralde, R., Jeong, J., Kiniry, J., 2012. EPIC and APEX: model use, calibration, and validation. Trans. ASABE 55, 1447–1462.
Wit, A.J.W.D., 2018. PCSE: The Python Crop Simulation Environment. Version 5.3.3. June 2018. Available at: http://pcse.readthedocs.io (web archive link, 16 June 2018), Accessed date: 16 June 2018. http://pcse.readthedocs.io.
Wolf, J., Mandryk, M., Kanellopoulos, A., van Oort, P.A.J., Schaap, B.F., Reidsma, P., Van Ittersum, M.K., 2010. Methodologies for analyzing future farming systems in Flevoland as applied within the AgriAdapt project. (Wageningen UR).
Wolf, J., Hessel, R., Boogaard, H.L., De Wit, A., Akkermans, W., van Diepen, C.A., 2011. Modelling Winter Wheat Production across Europe with WOFOST - The Effect of Two New Zonations and Two Newly Calibrated Model Parameter Sets. In: Ahuja, L.R., Ma, L. (Eds.), Methods of Introducing System Models into Agricultural Research. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, pp. 297–326. https://doi.org/10.2134/advagricsystmodel2.11.
Wolf, J., Reidsma, P., Schaap, B.F., Mandryk, M., Kanellopoulos, A., Ewert, F., Van Oort, P.A.J., Angulo, C., Rumbaur, C., Lock, R., 2012. Assessing the adaptive capacity of agriculture in the Netherlands to the impacts of climate change under different market and policy scenarios (AgriAdapt project). In: Climate Changes Spatial Planning.
Xinyou, Y., Van Laar, H., 2005. Crop Systems Dynamics: An Ecophysiological Simulation Model for Genotype-By-Environment Interactions. Wageningen Academic Pub.