A gentle introduction to WOFOST

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1 Introduction

This "Gentle introduction to WOFOST" is meant as an introductory text to the WOFOST 7.2 cropping system model. It introduces the basic concepts behind the model and the biophysiological processes that are implemented. Further some guidelines are given on the interpretation of WOFOST output. Since a crop and the soil it grows on are intricately linked, attention is paid to the exchange between crop and soil and the various options available for simulating soil processes with WOFOST. Further, this document describes the different software implementation of the model.

Next to the introductory material several annexes are provided. First a list of all variables in the PCSE implementation of WOFOST is given (Annex I). Moreover, there is guidance for parameter calibration including the procedure that should be followed (Annex II), some insight into parameter selection for model calibration (Annex III) and the experimental data required (Annex IV).

For further information on WOFOST, we strongly suggest reading the following material:

- Wit, Allard de, Hendrik Boogaard, Davide Fumagalli, Sander Janssen, Rob Knapen, Daniel van Kraalingen, Iwan Supit, Raymond van der Wijngaart, and Kees van Diepen. 25 Years of the WOFOST Cropping Systems Model. Agricultural Systems 168 (January 1, 2019): 154–67. https://doi.org/10.1016/j.agsy.2018.06.018
- Wit de, A.J.W., H.L. Boogaard, I. Supit, M. van den Berg (editors). 2020. System description of the WOFOST 7.2 cropping systems model. Wageningen Environmental Research. May 2020. Updated description of Supit, I., A. A. Hooijer, and C. A. Van Diepen. System description of the WOFOST 6.0 crop simulation model implemented in CGMS, vol. 1: Theory and Algorithms. Joint Research Centre, Commission of the European Communities, EUR 15956 (1994): 146. The latest version is available on https://wofost.readthedocs.io

Finally, up to date information is available on our website: http://wageningenur.nl/wofost.

Since July 2024, the WOFOST 7.3 and WOFOST 8.1 cropping system models have been released. Compared with the 7.2 release, these new versions have many improvements (see section 10.4) that extend the capabilities of WOFOST. This "Gentle introduction to WOFOST" does not yet cover the WOFOST 7.3 and 8.1 releases, but will be gradually extended to cover those versions as well.

2 Background

WOFOST (WOrld FOod STudies) is a simulation model for the quantitative analysis of the growth and production of annual field crops. It is a generic crop model which simulates many different crops using the same principles and algorithms. Differences between crops are therefore expressed by differences in the value of model parameters, not by a different modelling concept. With WOFOST, you can simulate crop properties like phenological development, crop yield, total biomass and water use given knowledge about soil, crop, weather and crop management for a particular location.

WOFOST is a mechanistic, dynamic model that explains daily crop growth based on the underlying processes, such as photosynthesis, respiration and how these processes are influenced by environmental conditions. Crop growth is calculated with time steps of one day, based on knowledge of processes at a lower level of integration (such as the instantaneous photosynthesis-light response curve of a single leaf). Next the low-level processes are integrated and combined with other processes (phenology, respiration) to explain system behaviour at a higher level of integration. Nevertheless, some parts of the model are descriptive and/or static. This is mainly because some of the processes involved are yet not adequately understood.

Like all mathematical models of agricultural production, WOFOST is a simplification of reality. In practice, crop yield is a result of the interaction of ecological, technological and socio-economic factors. Not all these factors are considered in WOFOST.

3 Development of WOFOST

WOFOST is a member of the family of models developed in Wageningen by the school of C.T. De Wit (Bouman et al., 1996, Ittersum et al. 2003). WOFOST originated in the framework of interdisciplinary studies on world food security and on the potential world food production by the Center for World Food Studies (CWFS) in cooperation with the Wageningen University & Research, Department of Theoretical Production Ecology (WAU-TPE) and the DLO-Center for Agrobiological Research and Soil Fertility (AB-DLO), Wageningen, the Netherlands. Yield potential of various annual crops in tropical countries were assessed (Van Keulen and Wolf, 1986; Van Diepen et al., 1988; Van Keulen and Van Diepen, 1990). After cessation of CWFS in 1988, the DLO Winand Staring Centre (SC-DLO) has continued development of the model in co-operation with AB-DLO and WAU-TPE. WOFOST 6.0 was developed to simulate the production of annual field crops all over Europe for the Joint Research Center (JRC-Ispra site) of the European Commission. Late nineties WOFOST was further developed and extended with a graphical user interface (GUI) resulting in WOFOST 7.1 and WOFOST Control Centre (WCC). Currently, the WOFOST model is maintained and further developed by Wageningen Environmental Research (WENR) in co-operation with the Plant Production Systems Group (PPS) of Wageningen University & Research and the Food Security unit of the Joint Research Centre in Italy.

4 Production levels

To be able to deal with the ecological diversity of agriculture, three hierarchical levels of crop growth can be distinguished (Ittersum and Rabbinge, 1997): potential production, attainable production and actual production (see Figure 1). Each of these growth levels adds a set of growth factors: defining factors, limiting factors and reducing factors. Reality rarely corresponds exactly to one of these production levels, but it is useful to reduce specific cases to one of them, because this enables you to focus on the principal environmental constraints to crop production, such as light, temperature, water and the macro nutrients nitrogen (N), phosphorus (P) and potassium (K). Other factors can often be neglected because they do not influence the crop's growth rate.

With WOFOST 7.2, you can calculate potential production and attainable production with regard to water limitations. Nutrient limitation and production-reducing factors (e.g. pests, diseases weed etc.) are not included. The production levels are hierarchical within WOFOST.

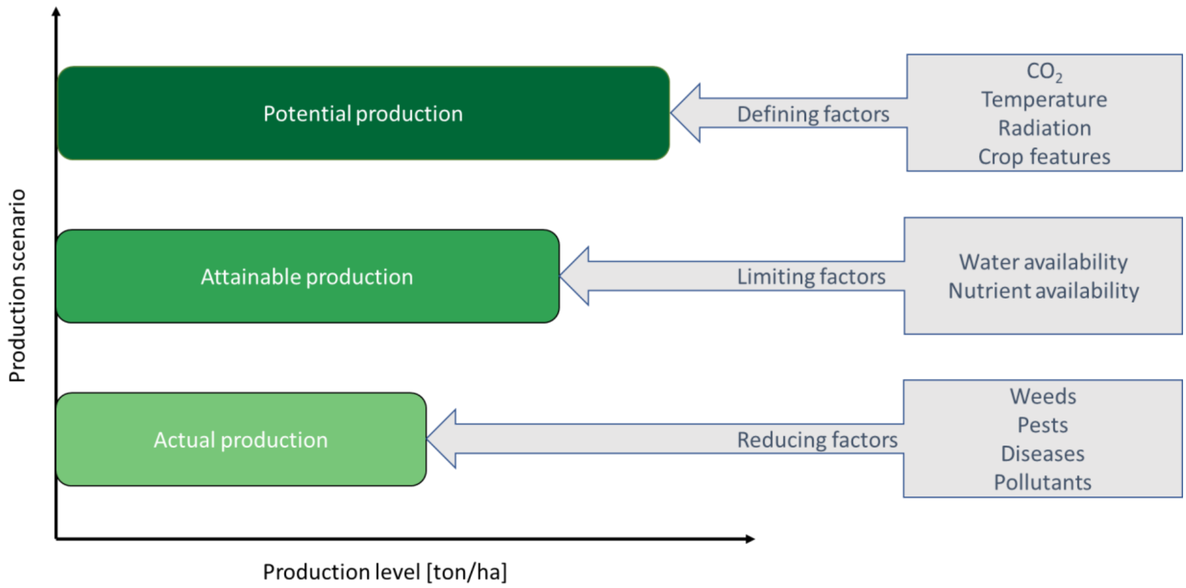

Figure 1. Three hierarchical levels of crop growth

4.1 Potential production

Potential production: Crop growth is determined by CO_2 concentration, irradiation, temperature, plant characteristics and planting date only. Potential production represents the absolute production ceiling for a given crop when grown in a given area under specific weather conditions. It is determined by the crop's response to the temperature and solar radiation regimes during the growing season. Atmospheric CO_2-concentration is assumed to be constant. All other factors are assumed to be optimal (e.g. pest and weed control, no losses caused by traffic or grazing) and in ample supply (nutrients and water).

Because potential yield is also determined by crop properties, yield potential varies over crop varieties and can be increased by breeding. Near to potential yield levels are realized in field experiments by research institutes, seed companies and some front-runner farmers.

4.2 Attainable production

In addition to irradiation, temperature and plant characteristics, the effect of the availability of water and/or nutrients is considered for the attainable production level. In case of yield reduction due to water limitations this implies that the supply of water is sub-optimal during (parts of) the growing season, this leads to water-limited production, which is lower than potential production in terms of total plant biomass. In more detail, the yield limiting effect of water shortages depends on the soil water availability as determined by amounts of rainfall and evapotranspiration, and their distribution over the growing season, by soil type, soil depth and groundwater influence. The difference between potential and water-limited production indicates the production increase that could be achieved by irrigation.

In special cases the water-limited yield (harvestable product) may be higher than potential yield because of a more favourable harvest index. A slight drought stress may limit the growth during the vegetative growth stage, while still sufficient green leaf area is formed to effectuate a maximum assimilation rate. The lower amount of vegetative biomass leads to lower maintenance requirements for the crop, so that more assimilates remain available for the growth of the grains. In situations of heavily fertilized soils a similar growth pattern can be observed, a very heavy vegetative growth, leading to a lower harvest index and a risk of lodging in cereals. A special case of water-limited conditions is related to an excess of soil moisture, causing oxygen shortage for the plant roots. The effect depends on crop sensitivity to oxygen stress, soil properties and drainage measures and is difficult to quantify by modelling.

A lack of macro or micro nutrients in the soil may lead to a reduced growth of the crop because growth and photosynthesis cannot proceed at maximum rate due to missing essential nutrients. Among the macro-nutrients (nitrogen N, phosphorous P and potassium K), nitrogen is required in relatively large quantities and is therefore usually the most limiting factor. Nevertheless a balanced supply of N/P/K as well as secondary nutrients and micro nutrients is required as growth is often limited by the most limiting nutrient. The impact of nutrient limitations also depends on the nutrient type as shortage of some nutrients has impact on yield quality or crop vigor and resistance to disease. Currently, WOFOST 7.2 does not support taking nutrient limitations into account when simulation crop growth. However, WOFOST output can be used as input for the QUEFTS model (Jansen et al. 1990, Ravensberger et al. 2021) which can estimate the impact of N/P/K limitation on yield.

4.3 Actual production

The actual production level corresponds to the yields which are typically obtained on farmers' fields in practice. Under actual field conditions all kind of additional yield reducing factors occur which can be caused by biotic stresses like weed infestations, insect pests and plant diseases as well as by abiotic stresses like frost kill, osmotic stress due to high salt levels in irrigation water and pollutants like ozone or heavy metals. These effects are very difficult to estimate by simulation models because the local impact is difficult to estimate (frost kill), the dynamics are unclear (crop, disease, weather interactions) and the impact on the crop itself is difficult to describe (ozone, heavy metals) in terms of biophysics. Nevertheless, advances are being made on several of those aspects such as modelling the impact of plant pest and disease (Savary et al. 2018) and frost kill (Bergjord et al. 2018, Byrns et al. 2020).

5 Crop growth simulation

To be able to work with WOFOST in a meaningful way, some basic knowledge of its principles is indispensable. Therefore, a brief overview is presented of the concepts used in WOFOST. In WOFOST, crop growth is simulated based on eco-physiological processes. The major processes are phenological development, CO_2-assimilation, leaf dynamics, transpiration, respiration, partitioning of assimilates to the various organs, and dry matter formation. The following paragraphs provide a concise description of the main processes implemented in WOFOST. For extensive literature on the principles of crop growth simulation and system analysis you are referred Wit et al. (2020). This is illustrated in Figure 2.

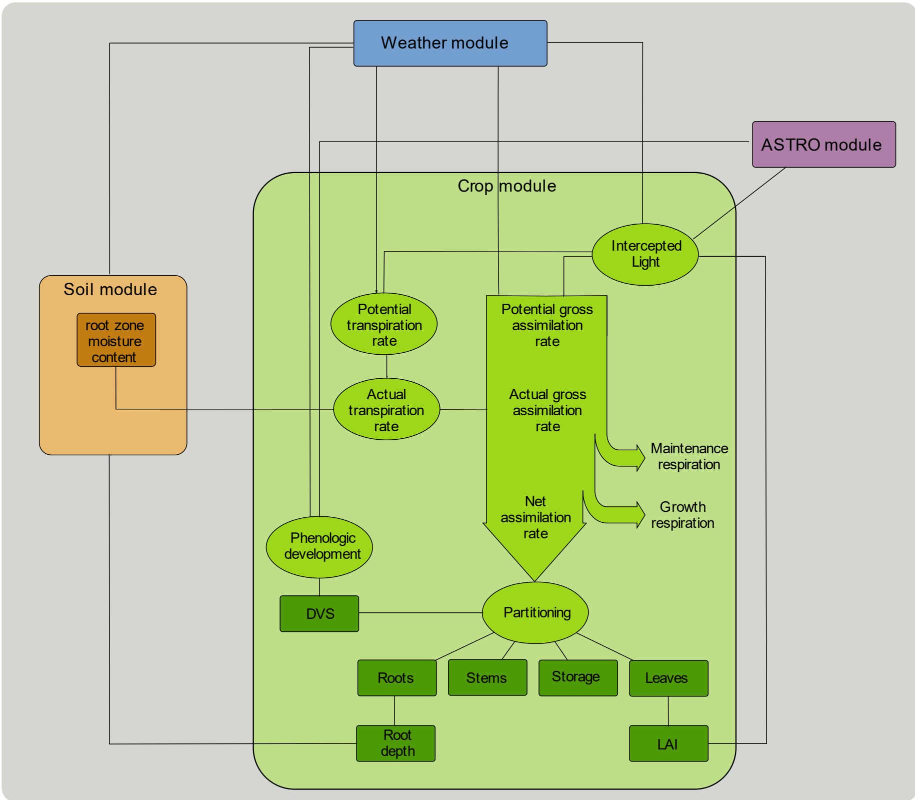

Figure 2. Simplified general structure of the dynamic, explanatory crop growth model WOFOST.

5.1 Assimilation and respiration

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.

In CO_2-assimilation, or photosynthesis, CO_2 is reduced to carbohydrates (CH_2O) using the energy supplied by the adsorbed light:

$CO_2 + H_2O \rightarrow CH_2O + O_2$

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 considered. One 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 dividing the canopy in different leaf layers. The intercepted radiation by each leaf layer is calculated based on the radiation flux at the top of the canopy and the transmission by overlying layers. Based on the photosynthesis-light response curve for individual leaves, the assimilation of each leaf layer is calculated. This response is dependent on temperature and leaf age. 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. For the integration over the day, a sinusoidal course of incoming radiation over the day is assumed and a three-point Gaussian integration method is applied as described by Goudriaan (1986).

Part of the formed assimilates is used for maintenance respiration of plant organs. The remaining carbohydrates are converted into structural plant material, such as cellulose and proteins (dry matter). There is some net loss of carbohydrates due to this conversion, called the growth respiration. Maintenance respiration is estimated on basis of the dry weight of the different organs and their chemical composition, modified by the ambient temperature. When the canopy fully covers the soil, the increase in biomass, expressed in dry matter, is typically between 150 and 350 kg $ha^{-1}.day^{-1}$.

5.2 Phenological development

The order and the rate of appearance of vegetative and reproductive organs characterize crop phenological development. The order of appearance is a crop characteristic, which is independent of external conditions. The rate of appearance can vary strongly, notably under the influence of temperature and photoperiod (day-length).

In WOFOST phenology is described by the dimensionless state variable development stage (DVS). For most annual crops, DVS is set to 0 at seedling emergence, 1 at flowering (for cereals) and 2 at maturity. The development rate is a crop/variety specific function of ambient temperature, possibly modified by photoperiod and vernalization.

To account for the effect of temperature on development stage, the concept of thermal time is applied, sometimes called temperature sum or growing-degree days. Thermal time is the integral over time of the daily effective temperature (Te) after crop emergence. Te is the difference between the daily average temperature and a base temperature below which no development occurs. Above a certain maximum effective temperature, Te remains constant. DVS is calculated by dividing the thermal time by the thermal time required to pass to the next development stage.

The phenological development of some crops is also influenced by photoperiod. This phenomenon is treated in WOFOST through a photoperiod reduction factor for the development rate until flowering, based on an optimum and a critical photoperiod. Finally, the phenological development of certain crops is influenced by vernalization. The "vernalization requirement" of the crop is the magnitude of the exposure to cold temperature in order to induce flowering. WOFOST counts the number of days with favourable conditions for vernalization and computes a reduction factor by scaling between a base vernalization and a saturated vernalization requirement.

The development stage in WOFOST is an important variable and determines, among other things, the assimilate partitioning over the organs (leaves, stems, roots, storage organs), the specific leaf area and the maximum leaf CO_2 assimilation rate.

5.3 Partitioning of dry matter

Partitioning is the subdivision of the net assimilates over the different plant organs (see Figure 3). After germination, most assimilates are converted into leaf and root tissue and later into stem tissue. The partitioning to root tissue gradually diminishes and is zero if the development stage equals 1 (anthesis in cereals). From development stage 1 onwards the storage organs receive most of the available assimilates.

After emergence the supply of assimilates to the leaves determines leaf area increase, calculated by multiplying the dry matter weight of the leaves with a specific leaf area. However, leaf area expansion may be limited by the maximum daily increase in leaf area index (i.e. a maximum rate of cell division and extension), that is temperature dependent. The increase in leaf area leads to a higher (potential) light interception, and, consequently, to a higher potential growth rate. This leads to exponential crop growth, that lasts until nearly all light is intercepted (leaf area index ≥ 3). From then on, the growth rate is constant, until the leaf area and its photosynthetic capacity decrease because of senescence of the crop.

In WOFOST partitioning is implemented through so-called partitioning tables which describe the fraction of assimilates partitioned to the various organs as a function of the crop development stage. In the calculations, a fraction of the assimilates is assigned to the roots first, the remainder is divided over the above-ground organs (including below ground storage organs such as tubers). To initiate the simulation, the dry weight of the crop at emergence must be known.

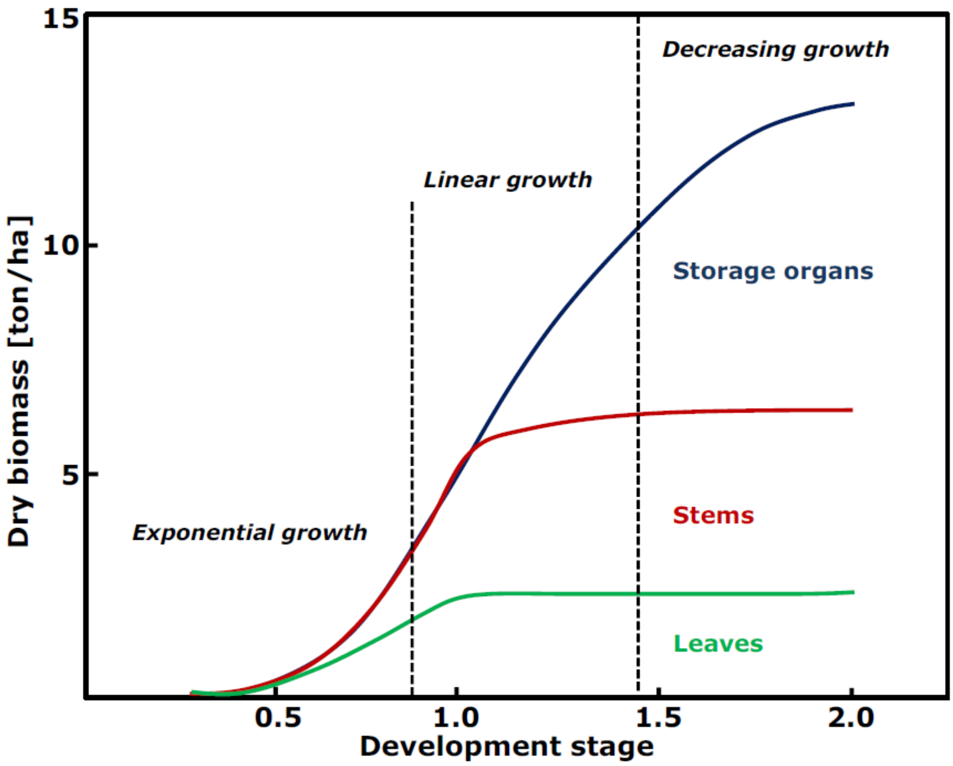

Figure 3. Example of dry matter allocation to the above-ground organs in relation to development stage. The three different growth phases have been indicated as well.

5.4 Transpiration

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.

The potential transpiration rate depends on the leaf area and the evaporative demand of the atmosphere. The evaporative demand is characterized by radiation level, vapour pressure deficit and wind speed. The potential transpiration is calculated for a reference crop. Differences between crops can be accounted for with 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.

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 (see Figure 4). Within the optimum 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. A crop reacts to water stress with closure of the stomata. Therefore, the exchange of CO_2 and O_2 between the crop and the atmosphere diminishes, and hence CO_2-assimilation is reduced. WOFOST applies the ratio of actual over potential crop transpiration (T_a/T_p) as a reduction factor to the gross assimilation rate.

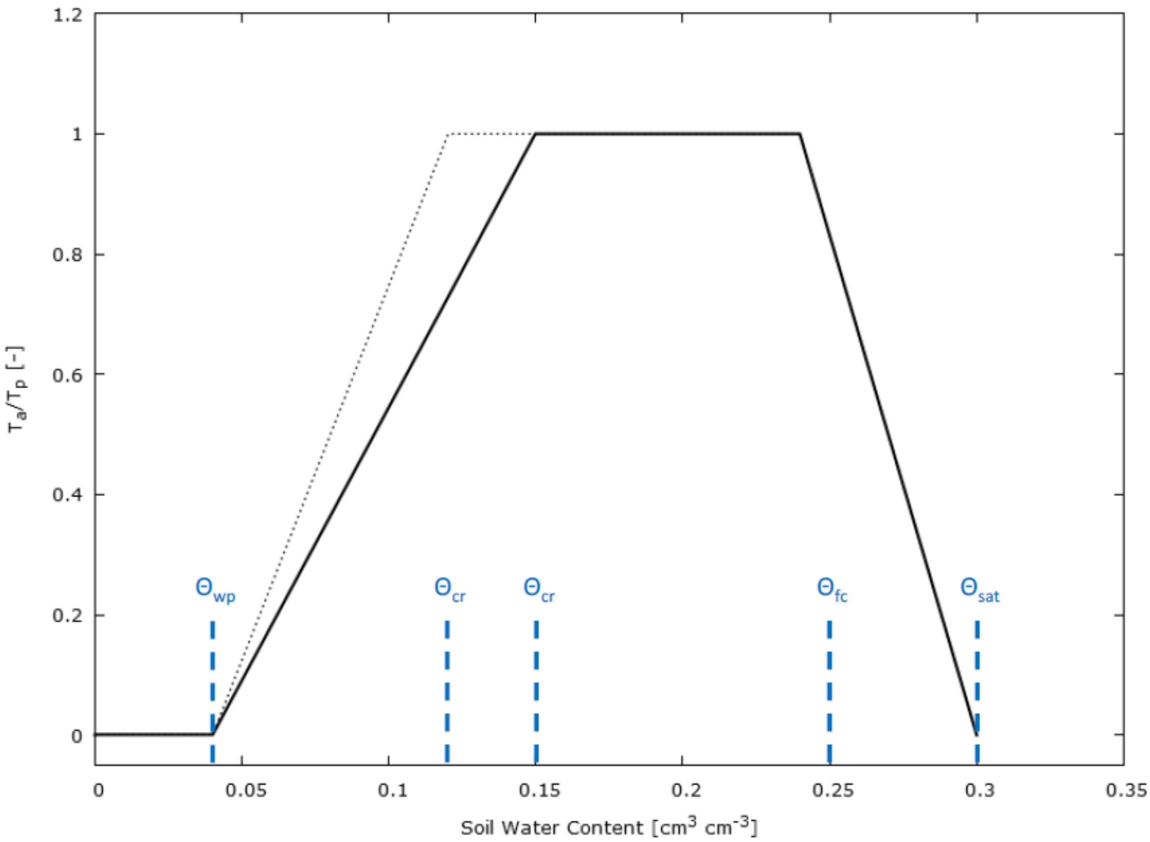

Figure 4. The relation between soil water content, θ, and T_a/T_p for a crop/soil combination. θ_{wp}, θ_{cr}, θ_{fc} and θ_{sat} represent the water content of the soil at wilting point, the critical point for potential transpiration, field capacity and saturation, respectively. The dashed line represents 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).

6 Interpreting WOFOST output

Although WOFOST internally has many variables (see Annex I), there are only a limited set of state/rate variables that are of practical use for most applications. In this section we will provide a short introduction on how to interpret the output of the WOFOST model and what insights can be obtained.

Before going into the explanation of the different variables it is important to understand that the output of WOFOST is directly linked to the production level that is chosen (Figure 1). So, depending on the production level, the variable of interest has a slightly different interpretation although the name of the variable will be the same. So, leaf area index (variable 'LAI') under a potential production run represents the leaf area index that corresponds to a crop growing on under optimal conditions. Similarly, for a water-limited production run, the variable name will still be called 'LAI' but now it represents the leaf area index for a crop growing under water-limited conditions. It is up to the modeler to take proper decisions regarding the production level, the post-processing of results and the conclusions that are drawn from it.

Table 1 shows a time-series output from the WOFOST model. This set of results is typical for the PCSE/WOFOST implementation. The table shows the last five days of a simulated spring wheat season, the example was taken from the "Getting Started" notebook in the PCSE collection[1]. In PCSE/WOFOST it can occur that crop-related variables are not available and are represented by a no data representation (for example *None, NaN or NULL)*. This happens when there is no crop on the field and the variables do not exist at a given day during the simulation.

The first column in Table 1 shows the day to which the simulation results in that row pertain. From left to right the following variables are present:

- **DVS**: the crop development stage. A dimensionless variable that defines the phenological development of the crop. DVS values range from -0.1 at sowing, to 0.0 at emergence, 1.0 at flowering and 2.0 at physiological maturity. DVS values can be easily compared between years in order to determine if the development cycle of crops is slower or faster than the long-term average or any previous year. A footnote in interpreting the crop development stage is that the phenological model used by WOFOST is a typical model for cereals. All other crops are forced into this model. For cereals DVS=1.0 (flowering) starts the reproductive phase and thus the filling of the storage organs (grains). For non-cereals this implies that DVS=1 also corresponds to the start of yield formation. For example, DVS=1 for potatoes means the start of tuber bulking instead of flowering because flowering in potatoes has little agronomic relevance. Also DVS=2 represents physiological maturity. However, for certain crops (e.g. sugar beet) there is no true physiological maturity and the crop is harvested at a given date rather than at maturity. For such crops, DVS=2 has no true meaning and its value can either be smaller or larger than 2 at harvest. Given that the results in Table 1 are for a cereal crop (a spring wheat), the simulation ends neatly with DVS=2. Finally, it should be realized that the DVS is an important variable and nearly all other processes in WOFOST depend on it. Therefore, it is critical that the phenological development is well calibrated and correctly simulated (See Annex II).
- **LAI**: the leaf area index of the crop. It is a dimensionless variable that defines the one-sided area of living (green) leaves per area of ground surface. Table 1 represents the last 5 days of the simulation and the crop canopy has fully senesced with LAI=0. Because LAI=0, there is no photosynthesis anymore and therefore the columns related to biomass (TAGP, TWSO, TWLV, TWST, TWRT) do not increase anymore and the crop transpiration (TRA) is zero as well.
- **TAGP**: the Total Above-Ground Production represents the total above-ground biomass that the crop has produced as dry weight in kg/ha. TAGP is the sum of the individual above-ground plant organs, so it holds that TAGP =TWSO + TWLV + TWST.
- **TWSO**: the Total Weight Storage Organs represents the harvestable product (the yield) of the crop. For cereals these are grains, for potato this represents the tubers, for soybean the beans, etc. It is always represented as dry weight in kg/ha. The latter means that there will be a difference between harvested yield and simulated yield due to the difference between dry weight and fresh weight. The magnitude of this difference depends mainly on the water content in the final yield. For example, cereals only have 10-15% water content while potatoes and sugar beet contain a lot of water and therefore there is a large difference between fresh weight and dry weight estimated by WOFOST.
- **TWLV**: the Total Weight Leaves represents the cumulative amount of leaf biomass that has been formed during the growth cycle. Internally, TWLV is partitioned into dead and living leaf biomass where the latter is used to estimate the crop LAI. The model output in Table 1 demonstrates that LAI=0 which implies that there are no more living (green) leaves and all leaf biomass is in the dead pool.
- **TWST**: the Total Weight Stems represents the amount of biomass that is represented by the stems of the crop as dry weight in kg/ha. The amount of stem material varies a lot between crop species and also between cultivars.

[1] https://github.com/ajwdewit/pcse_notebooks

- **TWRT**: the Total Weight Roots represents the amount of biomass that is represented by the roots of the crop as dry weight in kg/ha. The partitioning schema of WOFOST first divides (partitions) the assimilates between roots (below-ground) and shoots (above-ground). Next, it partitions between the above ground plant organs (leaves, stems, storage). Root biomass is often difficult to validate because observations of plant root biomass are difficult to obtain. Note that in WOFOST there is no relationship between root biomass and root depth.
- **TRA**: The crop transpiration (excluding soil evaporation) in cm/day which represents the amount of water that the crop obtains from the soil and which is transpired through its leaves.
- **RD**: The crop rooting depth in cm. As the example relates to the end of the season RD represents the depth to which the roots are able to penetrate the soil. It is computed as the minimum between maximum crop rootable depth (a crop parameter) and the maximum soil rootable depth (as soil parameters). Table 1 represents the results of a spring wheat crop which has maximum crop rootable depth of around 125 cm. The current results are thus for a soil where rooting depth is limited to 60 cm.
- **SM**: In this case it represents the root zone soil moisture as a volumetric fraction. A completely dry soil has value zero while the maximum value pertains to a fully saturated soil (soil dependent but usually around 0.4 for mineral soils). However, its interpretation may depend on the type of soil moisture balance that is used. Also the naming of the variable can differ between the model configurations. In this case, the results demonstrate that SM is a constant value of 0.3175. This is because we are running for a potential production situation where soil moisture is kept constant and sufficiently high in order to be non-limiting for growth.
- **WWLOW**: this represents the amount of water in cm available in the rooted zone (variable W) plus the lower (unrooted) zone (variable WLOW). In the current model run, its value equals *None* which means that the value does not exist. This is because the variable does not exist in a potential production simulation.

Table 1. Example of PCSE/WOFOST 7.2 model simulation output for potential production level of spring-wheat in Southern Spain (last five entries).

day	DVS	LAI	TAGP	TWSO	TWLV	TWST	TWRT	TRA	RD	SM	WWLOW
2000-05-27	1.934169	0.0	18091.006102	8729.399813	3126.21567	6235.390619	1613.465879	0.0	60.0	0.3175	None
2000-05-28	1.953874	0.0	18091.006102	8729.399813	3126.21567	6235.390619	1613.465879	0.0	60.0	0.3175	None
2000-05-29	1.974056	0.0	18091.006102	8729.399813	3126.21567	6235.390619	1613.465879	0.0	60.0	0.3175	None
2000-05-30	1.995758	0.0	18091.006102	8729.399813	3126.21567	6235.390619	1613.465879	0.0	60.0	0.3175	None
2000-05-31	2.000000	0.0	18091.006102	8729.399813	3126.21567	6235.390619	1613.465879	0.0	60.0	0.3175	None

Besides the time-series results, most WOFOST implementations also provide summary results (Table 2). The summary results provide a brief overview of the simulation results at the end of the crop cycle which is often sufficient when multiple runs are compared. Moreover, it provides some variables that are otherwise difficult to obtain such as the day when certain phenological stages where reached. Note that multiple sets of summary results will be available when multiple crop cycles are simulated (crop rotations).

Table 2. Summary results from the PCSE/WOFOST 7.2 implementation for potential production.

Variable	**Value**	**Description**
DVS	2.000000	The crop development stage
LAIMAX	6.232406	The maximum LAI reached during the growth cycle
TAGP	18091.006102	The final TAGP
TWSO	8729.399813	The final TWSO
TWLV	3126.215670	The final TWLV
TWST	6235.390619	The final TWST
TWRT	1613.465879	The final TWRT

CTRAT	26.975472	The cumulated crop transpiration at the end of the growth cycle
RD	60.000000	The final rooting depth
DOS	None	The day-of-sowing, can be None if crop starts at emergence
DOE	2000-01-01	The day-of-emergence (DVS=0)
DOA	2000-03-28	The day-of-flowering (DVS=1)
DOM	2000-05-31	The day-of-maturity (DVS=2)
DOH	None	The day-of-harvest, can be None of crops run up till maturity
DOV	None	The day-of-vernalization, when vernalization requirements are reached. Can be None for crops that do not require vernalization.
CEVST	6.173598	The cumulated soil evaporation during the crop cycle at the end of the crop cycle

We can now compare the results from the potential and water-limited level and interpret the results. In Figure 5 you will find the graphical representation of the most important variables from Table 1 for both the potential and water-limited level. First of all, the development stage (DVS) is the same for both levels. Currently there is no impact of drought stress on phenological development although in practice drought stress may accelerate phenological development in some crops which is not simulated currently.

In the charts with the leaf area index (LAI), total above-ground biomass (TAGP) and total weight storage organs (TWSO) we do see a clear difference between the two production levels. Leaf area index drops slightly from mid-March onwards and the total crop biomass and weight storage organs start to deviate from the potential production run. This difference can be nicely corelated with the figure showing the crop transpiration (TRA) which demonstrates that transpiration is dropping in the water-limited production run due to lack of water in the root zone from mid-March onwards. When comparing with the root-zone soil moisture level (SM) we can conclude that a soil moisture level < 0.2 starts to generate water stress on the crop. This occurs mainly during March; in April some rain showers increase the soil moisture content above or slightly below 0.2 causing only minor drought stress. The impact of the drought stress during March on total biomass is around 2500 kg/ha and the impact on yield (TWSO) is slightly below 2000 kg/ha. The results demonstrate that the impact of the drought stress during March is already considerable but is alleviated by rainfall events in April and May and the crop can recover.

The reason for the recovery is that the drought had a limited impact on the crop LAI. Even with LAI decreasing due to leaf death because of drought stress, the maximum LAI remained above 4 allowing full light interception and thus photosynthesis was able to recover the maximum capacity when the drought stress was reduced by rainfall. In cases where drought stress reduces LAI to low levels (< 3) the impact of drought can become very severe and the crop is not able to recover even when soil moisture goes up to favorable levels again.

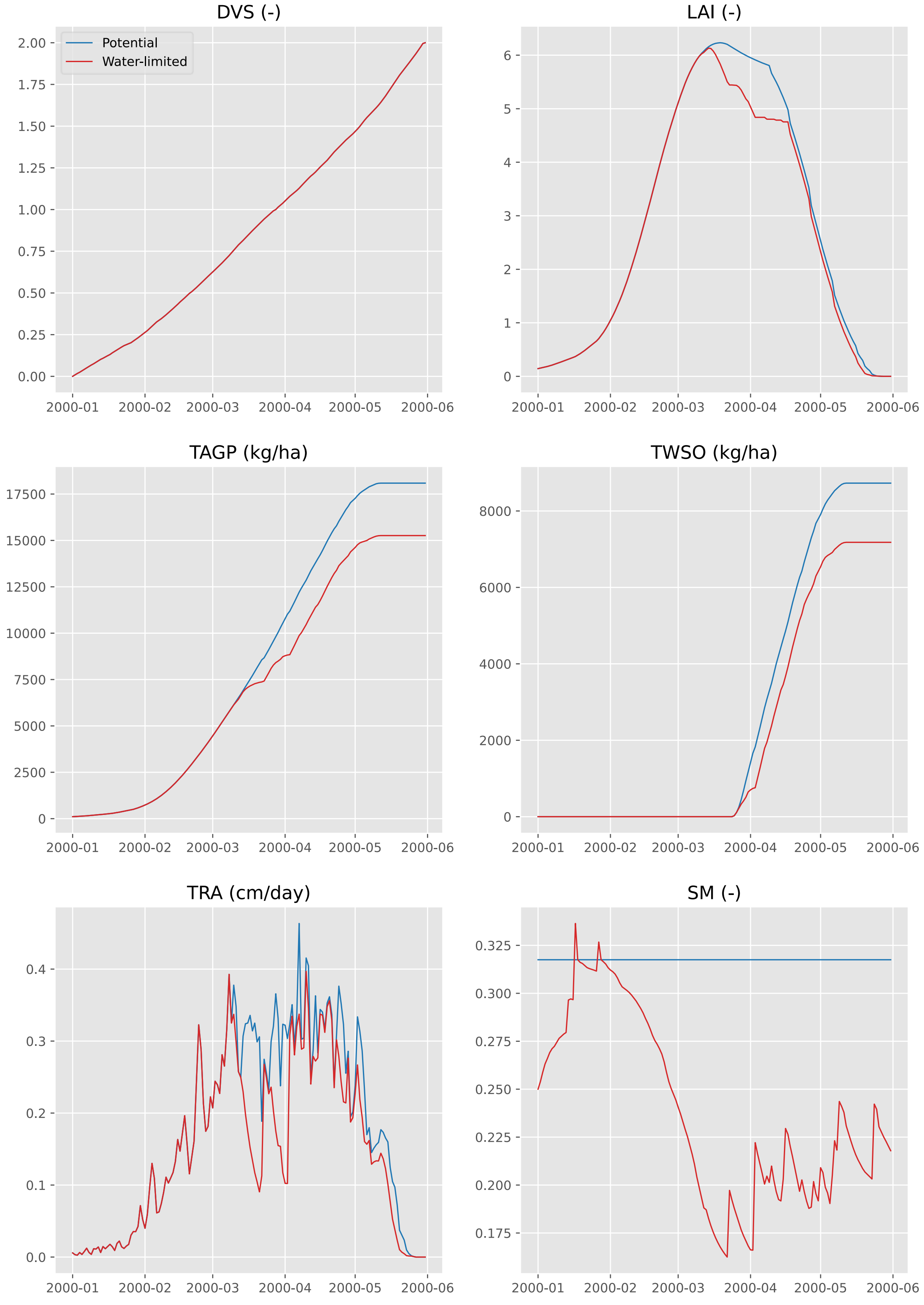

Figure 5. Comparison of PCSE/WOFOST 7.2 simulations results for the potential and water-limited production levels for spring-wheat in Southern Spain.

7 Interfaces: atmosphere and soil

The growth and development of crops is influenced by its environment: the atmosphere (weather, CO_2) and the underlying soil (host, supply of water and nutrients). In the current implementations the soil interface is limited to host the plant roots and supply of water.

7.1 Atmosphere

To run the crop simulation, WOFOST needs meteorological variables that drive the processes that are being simulated. WOFOST requires the following daily meteorological variables (Table 5).

Table 3. Daily meteorological variables required by WOFOST.

Name	**Description**	**Unit**
TMAX	Daily maximum temperature	°C
TMIN	Daily minimum temperature	°C
VAP	Mean daily vapour pressure	hPa
WIND	Mean daily wind speed at 2 m above ground level	$m.sec^{-1}$
RAIN[2]	Precipitation (rainfall or water equivalent in case of snow or hail).	$cm.day^{-1}$
IRRAD	Daily global radiation	$J.m^{-2}.day^{-1}$
SNOWDEPTH	Depth of snow cover (optional)	cm

The snow depth is an optional meteorological variable and is only used for estimating the impact of frost damage on the crop (if enabled). Snow depth can also be simulated by the SnowMAUS module if observations are not available daily. Furthermore, there are some meteorological variables which are derived from the previous ones (Table 4).

Table 4. Derived meteorological variables required by WOFOST.

Name	**Description**	**Unit**
E0	Penman potential evaporation for a free water surface	$cm.day^{-1}$
ES0	Penman potential evaporation for a bare soil surface	$cm.day^{-1}$
ET0	Penman or Penman-Monteith potential evaporation for a reference crop canopy	$cm.day^{-1}$
TEMP	Mean daily temperature (TMIN + TMAX)/2	°C
DTEMP	Mean daytime temperature (TEMP + TMAX)/2	°C
TMINRA	The 7-day running average of TMIN	°C

7.2 Soil moisture in the root zone

The soil moisture in the root zone is the main link between the WOFOST crop simulation model and the underlying soil model. In order to make the connection, WOFOST provides the crop rooting depth and required crop transpiration rate to the soil model, while the soil model provides the soil moisture content (or matric suction) to WOFOST. The root-zone soil moisture has influence on the actual crop transpiration rate and consequently on the crop CO_2 assimilation because the latter is reduced by the ratio of actual to potential crop transpiration. In turn, a reduced crop transpiration reduces the water extraction from the soil which completes the coupling between the crop and soil model.

Given this clear separation between the crop model and the soil model, it is relatively easy to connect WOFOST to different approaches for simulating the behaviour of water in the soil. As a result, there are several implementations of WOFOST connected to different soil modules with different purposes. Table 5 provides an overview of the different water models available from Wageningen Research groups, their purpose and the various implementation details.

[2] Water supply by surface run-off from higher positions on the slope is not taken into account in WOFOST.

Table 5. Overview of available water balance modules connected to WOFOST.

		Implementations			Boundary conditions	
Production level[1]	Description	PCSE	WISS	SWAP	Freely draining	Ground-water
PP	Simple constant-level soil moisture model	•	•	•	n.a.	n.a.
WLP	Simple one-layer tipping bucket model	•	•		•	
WLP	A simple multi-layer model driven by both differences in gravity and matric suction (7.3 and 8.1 only)	•			•	•
WLP	A complex Richards-equation based multi-layer model driven by both differences in gravity and matric suction			•	•	•

[1] PP = potential production level, WLP = water-limited production level

Simple constant-level soil moisture model:
The first and most simple soil water balance applies to the potential production level. Assuming a continuously moist soil, the crop water requirements are quantified as the sum of crop transpiration and evaporation from the shaded soil under the canopy.

Simple one-layer tipping bucket model:
In this model, the soil profile is divided in two compartments, the rooted zone and the lower zone between actual rooting depth and maximum rooting depth. The subsoil below the maximum rooting depth is not defined. The second zone merges gradually with the first zone as the roots grow deeper towards the maximum rooting depth. The principle of this soil water balance is a cascade (overflowing bucket). The rainfall infiltrates, a part may be temporarily stored above the surface or runs off. Evapotranspiration loss is calculated. The infiltrated water that exceeds the retention capacity of a soil compartment percolates downward. There is no capillary rise. This water balance is often used for applications with limited information on soil properties where often only the soil water holding capacity is known.

A simple multi-layer model driven by both differences in gravity and matric suction:
This water balance uses a simple but elegant solution to estimate water flow through the soil taking into account both gravitational flow as well the flow due to differences in matric suction. It is targeted at making good estimates of crop water availability under conditions when properties of the soil are well known, but without going into the complexity of Richards equation type of soil water models. This model has recently been extended with a simple approach for estimating the impact of shallow groundwater on crop water availability.

A complex multi-layer model driven by both differences in gravity and matric suction:
The WOFOST implementation connected to the SWAP model has a detailed water balance, based on the Richard's Equation, including soil temperature and solute transport which allows to make detailed simulations of the behavior of water and solutes in the soil and its impact on plant growth. Currently, the SWAP model is the only model which can take the impact of shallow groundwater into account in a physically realistic manner. The model also provides different options to prescribe the bottom boundary condition. Detailed information on the SWAP model can be found at: https://swap.wur.nl/.

8 Temporal and spatial scale

From a spatial perspective WOFOST is a one-dimensional simulation model, i.e. without reference to a geographic scale. However, the size of a region to which WOFOST can be applied is limited. This is due to aggregation effects caused by non-linear response of crop models to model inputs. The non-linear behaviour implies that aggregating input data and then running the model provides different results compared to running the model on the original data and then aggregating the model output.

In practice, this is resolved by splitting the model spatial domain into small spatial units where the model inputs (weather, crop, soil, management) can be assumed constant. Aggregation of simulation results is carried out by aggregating the simulation results for the individual spatial units to larger spatial units. In Europe, WOFOST is typically applied at spatial units of 25x25 km for which scaling errors are negligible.

From a temporal perspective, WOFOST typically simulates crop growth with a temporal resolution of one day. Variation in timing of crop production can be taken into account by varying the starting date of the growing season and/or by selecting crop varieties with different growth duration.

9 Implementation of crop dynamics

WOFOST is a dynamic, mechanistic model that simulates crop growth with time steps of one day, based on knowledge of processes at a lower level of integration. To ensure that the results of the simulation are correct, the different types of calculations (integration, driving variables and rate calculations)[3] should be strictly separated. In other words, first all states should be updated, then all driving variables should be calculated, after which all rates of change should be calculated. If this rule is not applied rigorously, there is a risk that some rates will pertain to states at the current time whereas others will pertain to states from the previous time step. In WOFOST, the calculations of rates and states are not mixed during a time step but are all executed separately. This is taken care of by grouping all the state calculations into one block as do all the rate calculations for the different components of the model.

10 Concluding remarks

10.1 Sensitivity and uncertainty

WOFOST is a model, hence a simplification of reality. The user always must be cautious when drawing conclusions from the simulation results. The quality of the model output cannot surpass the quality of the input data. Therefore, the careful selection of the input data is of utmost importance. As a rule, you should not simulate crop growth without experimentation. Experimentation is needed to obtain specific crop parameters and to calibrate and verify the model results.

Before calibrating WOFOST on experimental data it is important to understand which parameters relate to which processes and which parameters are sensitive as well as varying across varieties of a crop. A confounding factor is that the sensitivity of WOFOST parameters may vary between crops, locations and seasons. Moreover, sensitivity of the model parameters is also related to the selected target variable: sensitivities of parameters can differ depending on whether the target variable is crop yield, crop total biomass or crop water use. Therefore it is difficult to provide exact estimates of parameter sensitivity although the calibration guidelines in Annex II and III provide good insight in which parameters to choose for a sensitivity analysis. Moreover, jupyter notebooks are provided on github that guide the user through a sensitivity analysis with PCSE/WOFOST.

When performing a sensitivity analysis it is also important to estimate representative ranges of model parameters. We have observed that in literature sometimes results of sensitivity analyses are reported which have parameter ranges that are far too wide to be representative for a given crop. Often, these parameter ranges have been obtained by scanning the values of model parameter across all crops in the crop library of WOFOST. For example, the conversion efficiency to storage organs (CVO) ranges from 0.4 (rapeseed) to 0.85 (potato) but this range is determined by the type of substance that the storage organs are composed of. Storage organs with a high concentration of proteins and lipids have much lower conversion efficiencies compared to crops with storage organs that store mostly starch (potato) or sugar (sugar beets). However, setting the parameter range for CVO to the full range (0.4 to 0.85) will

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[3] State variables are quantities such as biomass. Driving variables (or forcing functions) characterize the influence of external factors on the system but are not influenced by the processes within the system. Examples are meteorological variables such as radiation and air temperature. Rate variables indicate the rate at which the state variables change at a certain moment, and over a certain time step. Rate variables are calculated based on the state and driving variables.

erroneously determine that CVO is a sensitive parameter which is prone to calibration, while in reality CVO can only be determined from laboratory experiments and not from field observed data. In general, the range over which parameters can be tested for sensitivity decreases from the 'free' parameters towards the 'static' parameters (see Annex II). The former can be modified over fairly large ranges, while the latter ones are generally fixed and should not be modified over more than 10% of their current value. See also Section 3.7 in the WOFOST System Description for details and sensitivity of WOFOST parameters.

A second point of confusion with sensitivity analysis is that WOFOST contains a number of parameters that are not scalar but tabular describing the parameter value as a function of some other state (usually development stage or temperature). Calibrating such parameters and/or determining their sensitivity is quite difficult because the XY pairs in such a tabular parameter cannot be regarded as independent from the other XY pairs (often they have a functional shape). The best approach for a sensitivity analysis on tabular parameters is therefore to replace them by functions that can mimic the shape of the parameter but allow for adjustments by modifying the values of the function parameters. Such an approach has been successfully implemented for the partitioning tables by replacing them with logistic functions. An example is available as a Jupyter notebook on github.

Uncertainty is another aspect of the model simulation results, which covers the broader requirements of applying WOFOST rather than model parameterization and sensitivity only. First of all, results from WOFOST pertain to a certain theoretical production level (Figure 1) which assume either fully optimal conditions, or limitations due to water or macro-nutrients. However, in practice (e.g. farmers' fields) many other limiting factors are often present such as weeds, pest/disease or lack of (micro) nutrients. The more the actual situation deviates from the theoretical production levels simulated by WOFOST, the less representative and more uncertain the model output will be. In many cases, the model results can still be used in a relative way (e.g. how is the current season doing compared the previous one) but the absolute values predicted by the model cannot be used directly and have to be corrected through empirical adjustments.

A second source of uncertainty is represented by model inputs which can be divided in weather, crop, soil and initial conditions. The availability and quality of weather variables has greatly improved in recent years particularly due to the availability of reanalysis data such as AgERA5 (XXX) or NASA POWER (XXX). As a result, the uncertainty in weather inputs has been greatly reduced for variables like radiation, temperature and windspeed. However, rainfall data is still a difficult variable to estimate or predict and uncertainty in rainfall estimates is often considerable in areas with few weather stations. Uncertainty on soil properties is often large because of the lack of detailed soil maps in many parts of the world. Depending on the weather conditions this can translate into a large uncertainty on the simulated results. The availability of new soil resources such as SoilGrids (de Sousa et al., 2020) has been a major improvement over previous soil maps and particularly for regional applications this is often sufficient. However, for local applications the impact of soil parameters must be carefully evaluated in order to have representative results for water and nutrient-limited simulation results. Initial conditions such as initial soil moisture can also have a large impact on the simulation results. Fortunately often the uncertainty can be decreased by taking a large lead time before the crop starts. This allows uncertainties in the simulated soil moisture levels to decrease (De Wit et al. 2013).

Finally, agromanagement can represent a major source of uncertainty when the exact cropping calendars and/or crop varieties are now known for a given location. Ratallino et al. (2021) demonstrated that poorly defined crop calendars due to poor knowledge of the local agronomy has a major impact on estimates of yield potential and yield gaps. This demonstrates that any application of WOFOST requires a good knowledge of the agronomic practices of the area of interest in order to reduce uncertainty on WOFOST results.

Despite the uncertainty, which often is unavoidable with applications of complex models like WOFOST, there are tools available in order to reduce uncertainty on the simulation results. Particularly the use of external observations (local observations, satellite observations or IOT sensors) of crop variables (LAI, plant height, leaf N concentration) combined with data assimilation algorithms can be a powerful tool to better estimate emergence dates, adjust temperature sums and modify canopy parameters which leads to better simulation results with lower uncertainty (Gaso et al. 2021, Huang et al. 2019, Pan et al. 2019, Wit et al. 2012). With the increasing volumes of available data at the level of individual fields (and beyond) it is expected that the application of DA becomes part of the operational setup of many applications of WOFOST.

10.2 Validation

The WOFOST model has been applied and validated by many researchers in studies across the globe covering a wide range of crop types and cropping systems (an overview of studies can be found on the WOFOST website). Nevertheless, there are differences in the rigor with which WOFOST has been validated for different crop types. In general, WOFOST has been applied and validated most thoroughly for crops grown in Europe including cereals like maize, wheat and barley as well as root and tuber crops like potato and sugar beet. Oil crops like rapeseed and sunflower as well as tropical cereals like rice, millet and sorghum have also been studied relatively well. The number of studies that applied and validated WOFOST is considerable smaller for sugar cane and legumes, with soybean and field beans included in some studies, while legumes like mungbean, pidgeonpea or cowpea received very little attention. Finally, simulating fiber crops like cotton has received limited attention.

Overall, it is valid to state that the concepts implemented by WOFOST to simulate growth and production of arable crops has been validated exhaustively in many studies. However, for crop types which have seen little testing in practice there will be more uncertainty and detailed crop experiments will be required in order to parameterize and validate the WOFOST model more thoroughly.

10.3 Fitness for use and applications

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 yield gap analysis (Van Ittersum et al., 2013), crop yield forecasting (Wit de et al., 2020), climate change (Ewert et al., 2015), understanding crop responses in field trials and circumstances (Asseng et al., 2013) and including crop productivity effects in water management decisions (Hack-ten Broeke et al., 2019). Within these different domains WOFOST was successfully implemented, both at local and regional scale, and was validated against observed phenology and yield data (see also Annex II, III and IV on calibration and validation).

For example, WOFOST has been applied operationally over the last 25 years as part of the European MARS crop yield forecasting system (MCYFS). Many methodological and software implementation improvements have been introduced due to requirements in the operational system. Methodological improvements included approaches to large scale calibration (see Boons-Prins et al., 1993; Ceglar et al., 2019), improvements in robustness and representation of winter crops (incl. winterkill and vernalisation). See for more information Wit, et al. (2019).

Within the Global Yield Gap Atlas (GYGA) WOFOST is used to estimate the untapped crop production potential (see chapter on production levels) on existing farmland, based on current climate and available soil and water resources (e.g. Schils et al., 2018; Van Ittersum et al., 201). It includes specific guidelines to calibrate and validate models within the frame of GYGA.

The Dutch WaterVision Agriculture applies WOFOST to evaluate hydrological management decisions on agricultural production at field level. Production losses through water, oxygen and/or salinity stresses are calculated for current climate and future climate scenarios.

In the domain of climate change WOFOST has been used to investigate the effect of changes in temperature and atmospheric carbon dioxide concentration on potential and rainfed crop yields (e.g. Supit et al., 2012). The performance of crop growth models in assessing effects of climate changes was investigated in several initiatives such as AGMIP (the Agricultural Model Intercomparison and Improvement Project; Bassu at al., 2014; Ruane et al., 2016) and MACSUR (Modelling European Agriculture with Climate Change for Food Security; Ewert et al., 2015). Recently, WOFOST is being extended with additional processes to better simulate crop responses to critical temperature (both cold and heat) and the response of crop assimilation to changes in ambient CO_2 level (see Wit et al., 2019).

In addition, WOFOST has been used by many researchers over the world and has been applied for many crops over a large range of climatic and management conditions (see WOFOST portal - link). WOFOST has been used to analyze:

- yield risk and inter-annual yield variability;
- yield variability over soil types, or over a range of agro-hydrological conditions;
- differences among cultivars;
- relative importance of growth determining factors;
- sowing strategies;
- effects of climate change;
- critical periods for use of agricultural machinery.
- regional assessments of crop yield potential;
- estimation of maximum benefits from irrigation;
- detection of adverse growing conditions;
- regional yield forecasts.

In summary, WOFOST has proven its value in different application domains as a robust, practical and reliable tool.

10.4 Further development of WOFOST

Crop simulation models require continuous investment in order to remain relevant as a tool for scientific studies as well as practical applications like farm management or estimating fertilizer requirements. Such investments need to be made covering all aspects of model maintenance:

- Software development to ensure that the model implementations remain up to date with recent ICT developments (e.g. cloud computing, interfaces with new data sources, etc.)
- Collection of crop experimental data for calibration and validation. This is necessary to obtain validated crop parameter sets for modern varieties.
- Inclusion of new and improved crop physiological insights to include new processes that are relevant under current and future (climate) conditions

Over the last decade considerable effort has been dedicated to developing new implementations of the WOFOST model. One implementation was developed in python which integrates well with the scientific software stack and is very suitable for science and education. A second implementation was developed in java which features high model performance which makes it highly suitable for large scale application requiring millions of model runs.

In contrast to the software development, limited attention has been paid to experimentation for updating the crop model library. Some experiments have been carried out for wheat and more recently dedicated experiments have been carried out for potato (as part of the Holland Innovative Potato project) but for many other crops the parameters essentially date back to 1970-1980. Particularly for those crop types for which WOFOST has been hardly applied this is problematic.

Finally, the inclusion of new crop physiological insights related to WOFOST has received very little attention. WOFOST 7.2 inherits its biophysical core from WOFOST 6.0 with only small modifications to the phenological development routines. Fortunately, the now released WOFOST 7.3 and WOFOST 8.1 versions introduce important new development:

- WOFOST 8.1 simulates the N dynamics in the crop and computes N-limited growth rates by linking leaf-level gross CO_2 assimilation rate with the specific leaf N content. Moreover, it includes options for biomass reallocation which allows to take into account the transfer of biomass from stems/leaves to storage organs which can be important for some crops.

- A new layered soil water balance with much improved soil water dynamics. This waterbalance holds the middle ground between the simple tipping-bucket waterbalance and the SWAP model.
- A new soil C/N module called SNOMIN which was designed to estimate the amount of N becoming available from decomposition of soil organic matter, organic soil amendments and synthetic fertilizers.
- WOFOST 7.3 does not include the N dynamics but does include the CO_2 response on assimilation, options for biomass reallocation and a link to the layered soil water balance.

Together these improvements provide new opportunities for simulating the carry-over of carbon, nitrogen and water between crops in a rotation and allow WOFOST to work more on the level of a cropping system rather than a single crop in a rotation.

For future development around WOFOST we recommend to target funding at the following aspects:

- Obtaining crop experimental data suitable for updating and validating the WOFOST crop parameter sets for modern cultivars as well as the man power to carry out these calibration/validation exercises. This is particularly relevant for C4 crops, which cannot yet be simulated with WOFOST 8.1. Part of this experimental data may be available from open data repositories (e.g. CGIAR Guardian). Part of it will have to be obtained by setting up new experimental studies. The latter should be done in cooperation with other Wageningen groups in order to maximize the value of such experiments through multiple use. See also Table 6 for an overview of the different crops in WOFOST with regard to their validation/evaluation status.
- Including new and improved physiological insights in WOFOST, including (but not limited to):
  - Impact of extreme events such as cold and heat stress and their impact on various other processes such as phenology, assimilation, respiration and partitioning.
  - Further development of root physiology and crop/soil interactions in cooperation with Wageningen soil groups including the SWAP model.
- Further development of field-scale and within-field scale applications of WOFOST thereby ingesting external observation through data assimilation techniques. Such efforts are underway as part of the Digital Future Farm but will require more effort, testing and finally validation on farmers yields to demonstrate the benefits.
- Increase visibility of Wageningen UR and the WOFOST model, for example through improving the current WOFOST-Online application which could be further developed to give the use more options to add their own data and observations and optimize WOFOST for their specific case.

Table 6. Status of different crops within the WOFOST crop library.

Crop simulated	**Status**	**Recommendation**
Wheat, barley, maize, potato, sugar beet, rice, millet, sorghum, sunflower, rapeseed	Well tested and validated	Update parameterization for modern varieties and include new physiological insights
Sugar cane, field bean, soybean	Limited testing and validation	Update and validate current parameter sets with standard field trials. Test model at multiple sites in order to test stability of model results.
Mungbean, pidgeon pea, cowpea, cassava, cotton, fababean, groundnut, sweet potato	Hardly any testing and validation	Detailed field experiments are required in order to estimate/validate basic plant traits (AMAX, SLA, etc.). Next, adaptation for different cultivars and locations. Finally, test model for multiple sites to test stability of the model
New crops	New full parameterization required	Detailed field experiments are required in order to estimate basic plant traits (AMAX, SLA, etc.). Next, adaptation for different cultivars and locations. Finally, test model for multiple sites to test stability of the model

11 Implementations

We provide several implementations of WOFOST in different programming languages (FORTRAN, Python, java). Moreover, we provide the parameter sets required to run WOFOST for difference crops and a set of jupyter notebooks that demonstrate capabilities of PCSE/WOFOST.

Currently, four implementations of WOFOST are available from Wageningen University & Research:

- **PCSE/WOFOST**: Python-based, version 7.2, 7.3 and 8.1: WOFOST implemented in the Python Crop Simulation Environment (PCSE);
- **WISS/WOFOST**: Java-based, version 7.2: WOFOST implemented in the Wageningen Integrated Systems Simulator (WISS), a Java framework targeting the agro-ecological modelling domain;
- **SWAP/WOFOST**: Fortran-based, version 7.2 embedded in the Soil-Water-Atmosphere-Plant modelling system (SWAP) written in Fortran90.
- **WOFOST Control Centre**: Fortran-based, version 7.1.7: the original implementation of WOFOST written in FORTRAN77 and embedded in a graphical user interface. This implementation is still available, but is not actively maintained anymore;

All these implementations inherit their biophysical core from WOFOST 6.0 but differ in their abilities to deal with I/O (file, database), their user interface or general flexibility. Differences between 7.1.7 and 7.2 are the integration of the effect of vernalization on phenological development.

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Annex I - Overview of model variables

The variable names pertain to the PCSE/WOFOST implementation and are alphabetically sorted within each PCSE module

VARIABLES	DESCRIPTION	UNIT	MIN	MAX	PCSE MODULE
campaign_start_date	Start date of this campaign	yyyy-mm-dd			Agromanagement
comment	Additional information crop management event	-			Agromanagement
crop_end_date	End date crop simulation	yyyy-mm-dd			Agromanagement
crop_end_type	End type crop simulation	maturity/harvest			Agromanagement
crop_name	Crop name	-			Agromanagement
crop_start_date	Start date crop simulation	yyyy-mm-dd			Agromanagement
crop_start_type	Start type crop simulation	sowing/emergence			Agromanagement
event_signal	Crop management event	e.g. apply_npk or irrigate			Agromanagement
event_state	State variable triggering cop management event	-			Agromanagement
events_table	Quantifies crop management for certain day or state variable value	-			Agromanagement
max_duration	Maximum duration crop simulation	days			Agromanagement
name	Name crop management event	-			Agromanagement
next_campaign_start_date	Start date of next campaign	yyyy-mm-dd			Agromanagement
variety_name	Variety name	-			Agromanagement
zero_condition	How crop management is triggered in case of state variable	rising, falling, neither			Agromanagement
AMAX	Maximum leaf CO2 assimilation rate	-;kg $ha^{-1}hr^{-1}$	1	70	Assimilation
AMAXTB	Maximum leaf CO2 assimilation rate as a function of development stage	-;kg ha^{-1} hr^{-1}	1	70	Assimilation
CO2	Atmospheric CO2 level (ppm), default 360	ppm	0	700	Assimilation
CO2AMAXTB	Multiplication factor for AMAX to account for an increasing CO2 concentration	ppm; -	0	3	Assimilation
CO2EFFTB	Multiplication factor for EFF to account for an increasing CO2 concentration (function of CO2)	ppm; -	0	3	Assimilation
DTGA	Daily total gross assimilation	kg CH2O $ha^{-1}day^{-1}$	0	1000	Assimilation
EFF	Initial light-use efficiency of CO2 assimilation of single leaves	°C; (kg ha^{-1} hr^{-1})/(J m^{-2} s^{-1})	0.4	0.5	Assimilation
EFFTB	Initial light-use efficiency of CO2 assimilation of single leaves as function of mean daily temperature	°C; (kg $ha^{-1}hr^{-1}$)/(J m^{-2} s^{-1})	0.4	0.5	Assimilation

VARIABLES	DESCRIPTION	UNIT	MIN	MAX	PCSE MODULE
KDIF	Extinction coefficient for diffuse visible light	-	0.44	1	Assimilation
PGASS	Potential assimilation rate	kg CH2O $ha^{-1}day^{-1}$	0	1000	Assimilation
TMNFTB	Reduction factor of gross assimilation rate as function of low minimum temperature	-;°C	0	1	Assimilation
TMPFTB	Reduction factor of AMAX as function of average temperature	-;°C	0	1	Assimilation
KDIFTB	Extinction coefficient for diffuse visible light as function of development stage	-	0.44	1	Assimilation / Evapotranspiration / Leaf_dynamics
ANGOT	Angot radiation at top of atmosphere	J m^{-2} day^{-1}	0	36000000	Astro
ATMTR	Daily atmospheric transmission	-	0	1	Astro
COSLD	Amplitude of sine of solar height	-	-1	1	Astro
DAYL	Astronomical daylength (base = 0 degrees)	h	0	24	Astro
DAYLP	Astronomical daylength (base =-4 degrees)	h	0	24	Astro
DIFPP	Diffuse irradiation perpendicular to direction of light	J/m2.s	0	36	Astro
DSINBE	Daily total of effective solar height	s	0	86400	Astro
SINLD	Seasonal offset of sine of solar height	-	-1	1	Astro
CFET	Correction factor for evapotranspiration in relation to the reference crop	-	0.8	1.2	Evapotranspiration
CO2TRATB	Multiplication factor for maximum transpiration rate TRAMX to account for an increasing CO2 concentration (function of CO2)	ppm; -	0	3	Evapotranspiration
DEPNR	Crop group number for soil water depletion (from 1 = drought-sensitive to 5 = drought-resistant)	-	1	5	Evapotranspiration
IDOS	Indicates oxygen stress on this day	true or false			Evapotranspiration
IDOST	Nr of days with oxygen stress	days	0	250	Evapotranspiration
IDWS	Indicates water stress on this day	true or false			Evapotranspiration
IDWST	Nr of days with water stress	days	0	250	Evapotranspiration
IOX	Flag controlling calculation of water-limited yield without (0) or with (1) accounting for oxygen shortage in root zone	-	0	1	Evapotranspiration
RFOS	Reduction factor for oxygen stress	-	0	1	Evapotranspiration
RFTRA	Reduction factor for crop transpiration	-	0	1	Evapotranspiration
RFWS	Reduction factor for water stress	-	0	1	Evapotranspiration
TRA	Actual transpiration rate from the specific crop canopy	cm day^{-1}	0	2	Evapotranspiration
TRAMX	Maximum transpiration rate from the plant canopy	cm day^{-1}	0	2	Evapotranspiration

VARIABLES	DESCRIPTION	UNIT	MIN	MAX	PCSE MODULE
IAIRDU	Presence (1) or absence (0) of airducts in the roots (1=can tolerate waterlogging)	-	0	1	Evapotranspiration/Root_dynamics
DALV	Death rate leaves due to aging	kg $ha^{-1}day^{-1}$	0	1000	Leaf_dynamics
DRLV	Death rate leaves as a combination of DSLV and DALV	kg $ha^{-1}day^{-1}$	0	1000	Leaf_dynamics
DSLV	Maximum of DLSV1, DSLV2, DSLV3	kg $ha^{-1}day^{-1}$	0	1000	Leaf_dynamics
DSLV1	Death rate leaves due to water stress	kg $ha^{-1}day^{-1}$	0	1000	Leaf_dynamics
DSLV2	Death rate leaves due to self-shading	kg $ha^{-1}day^{-1}$	0	1000	Leaf_dynamics
DSLV3	Death rate leaves due to frost kill	kg $ha^{-1}day^{-1}$	0	1000	Leaf_dynamics
DWLV	Dry weight of dead leaves	kg ha^{-1}	0	100000	Leaf_dynamics
FYSAGE	Increase in physiological leaf age	-			Leaf_dynamics
GLAIEX	Sink-limited leaf expansion rate (exponential curve)	ha $ha^{-1}day^{-1}$	0	0.5	Leaf_dynamics
GLASOL	Source-limited leaf expansion rate (biomass increase)	ha $ha^{-1}day^{-1}$	0	0.5	Leaf_dynamics
GRLV	Growth rate leaves	kg $ha^{-1}day^{-1}$	0	1000	Leaf_dynamics
LAI	Leaf area index	-	0	12	Leaf_dynamics
LAIEM	LAI at emergence	-			Leaf_dynamics
LAIEXP	Leaf area according to exponential growth curve	-	0	12	Leaf_dynamics
LAIMAX	Maximum LAI reached during growth cycle	-			Leaf_dynamics
LASUM	Total leaf area as sum of LV*SLA, not including stem and pod area	-			Leaf_dynamics
LV	Leaf biomass per leaf class	kg ha^{-1}	0	100000	Leaf_dynamics
LVAGE	Leaf age per leaf class	day	0	200	Leaf_dynamics
LVSUM	Sum of LV	kg ha^{-1}	0	100000	Leaf_dynamics
PERDL	Maximum relative death rate of leaves due to water stress	-; kg kg^{-1} day^{-1}	0	0.1	Leaf_dynamics
RGRLAI	Maximum relative increase in LAI	ha ha^{-1} day^{-1}	0.007	0.5	Leaf_dynamics
SLA	Specific leaf area per leaf class	kg ha^{-1}	0	100000	Leaf_dynamics
SLAT	Specific leaf area for current time step, adjusted for source/sink limited leaf expansion rate	$ha.kg^{-1}$	0	0.0042	Leaf_dynamics
SLATB	Specific leaf area as a function of development stage	-; ha kg^{-1}	0.0007	0.0042	Leaf_dynamics
SPAN	Life span of leaves growing at 35°C	day	17	50	Leaf_dynamics

VARIABLES	DESCRIPTION	UNIT	MIN	MAX	PCSE MODULE
TBASE	Lower threshold temperature for ageing of leaves	°C	-10	10	Leaf_dynamics
TWLV	Total weight of leaves	kg ha^{-1}	0	100000	Leaf_dynamics
WLV	Dry weight of living leaves	kg ha^{-1}	0	100000	Leaf_dynamics
TDWI	Initial total crop dry weight	kg ha^{-1}	0.5	300	Leaf_dynamics/Root_dynamics/Stem_dynamics/Storage_organ_dynamics
FL	Fraction partitioned to leaves	-	0	1	Partitioning
FLTB	Fraction of above ground dry matter increase partitioned to leaves as a function of development stage	-;mass $mass^{-1}$	0	1	Partitioning
FO	Fraction partitioned to storage organs	-	0	1	Partitioning
FOTB	Fraction of above ground dry matter increase partitioned to storage organs as a function of development stage	-;mass $mass^{-1}$	0	1	Partitioning
FR	Fraction partitioned to roots	-	0	1	Partitioning
FRTB	Fraction of total dry matter increase partitioned to roots as a function of development stage	-;mass $mass^{-1}$	0	1	Partitioning
FS	Fraction partitioned to stems	-	0	1	Partitioning
FSTB	Fraction of above ground dry matter increase partitioned to stems as a function of development stage	-;mass $mass^{-1}$	0	1	Partitioning
DLC	Critical daylength for development (lower threshold)	hr	6	18	Phenology
DLO	Optimum daylength for development	hr	6	18	Phenology
DOA	Anthesis date	-			Phenology
DOE	Emergence date	-			Phenology
DOH	Harvest date	-			Phenology
DOM	Maturity date	-			Phenology
DOS	Sowing date	-			Phenology
DOV	Date when vernalisation requirements are fulfilled	-			Phenology
DTSMTB	Daily increase in temperature sum as function of average temperature	°C.day	0	38	Phenology
DTSUM	Increase in temperature sum for anthesis or maturity	°C	0	30	Phenology
DTSUME	Increase in temperature sum for emergence	°C	0	30	Phenology
DVR	Development rate	day^{-1}	0	1	Phenology
DVS	Crop development state (-0.1 = sowing; 0 = emergence; 1 = flowering; 2 = maturity)	-	-0.1	2	Phenology

VARIABLES	DESCRIPTION	UNIT	MIN	MAX	PCSE MODULE
DVSEND	Development stage at harvest (= 2.0 at maturity) (WOFOST-WISS has default DVS = 2 as end value)	-	1	2.5	Phenology
DVSI	Initial crop development stage	-	-0.1	0.5	Phenology
ISVERNALISED	Boolean reflecting the vernalisation state of the crop	true or false			Phenology
STAGE	Current phenological stage	emerging, vegetative, reproductive, mature			Phenology
TBASEM	Lower threshold temperature for emergence	°C	-10	8	Phenology
TEFFMX	Maximum effective temperature for emergence	°C	18	32	Phenology
TSUM	Temperature sum	°C.day	0	3000	Phenology
TSUM1	Temperature sum from emergence to anthesis	°C.day	150	1050	Phenology
TSUM2	Temperature sum from anthesis to maturity	°C.day	600	1550	Phenology
TSUME	Temperature sum for emergence	°C.day	0	170	Phenology
TSUMEM	Temperature sum from sowing to emergence	°C.day	0	170	Phenology
VERN	Vernalisation state	day	0	100	Phenology
VERNBASE	Base vernalization requirement in pre-yield formation phase	day	0	100	Phenology
VERNDVS	Critical DVS for vernalization to switch off in pre-yield formation phase	-	0	1	Phenology
VERNFAC	Reduction factor on development rate due to vernalisation effect	-			Phenology
VERNR	Rate of vernalisation	-			Phenology
VERNRTB	Temperature response function for vernalization in pre-yield formation phase	°C; -	0	1	Phenology
VERNSAT	Saturated vernalization requirement in pre-yield formation phase	day	0	100	Phenology
IDSL	Switch for phenological development options	0 = temperature only, 1= including daylength, 2 = including vernalization	0	1	Phenology/Abioticdamage
ANGSTA	Ångström coefficient A	-	0	1	Reference_ET
ANGSTB	Ångström coefficient B	-	0	1	Reference_ET
ETMODEL	Method to calculate canopy reference	PM = Penman-Monteith method, P = modified Penman method			Reference_ET
PMRES	Potential maintenance respiration rate	kg CH2O $ha^{-1}day^{-1}$	0	1000	Respiration
Q10	Relative change in respiration rate per 10°C temperature change	-	1.5	2	Respiration

VARIABLES	DESCRIPTION	UNIT	MIN	MAX	PCSE MODULE
RFSETB	Reduction factor for senescence as function of development stage	-	0.25	1	Respiration
RML	Relative maintenance respiration rate leaves	kg(CH2O) kg^{-1} day^{-1}	0.002	0.03	Respiration
RMO	Relative maintenance respiration rate storage organs	kg(CH2O) kg^{-1} day^{-1}	0.002	0.03	Respiration
RMR	Relative maintenance respiration rate roots	kg(CH2O) kg^{-1} day^{-1}	0.002	0.03	Respiration
RMS	Relative maintenance respiration rate stems	kg(CH2O) kg^{-1} day^{-1}	0.002	0.03	Respiration
DRRT	Death rate root biomass	kg $ha^{-1}day^{-1}$	0	1000	Root_dynamics
DWRT	Dry weight of dead roots	kg ha^{-1}	0	100000	Root_dynamics
GRRT	Growth rate root biomass	kg $ha^{-1}day^{-1}$	0	1000	Root_dynamics
GWRT	Net change in root biomass	kg $ha^{-1}day^{-1}$	0	1000	Root_dynamics
RD	Rooting depth	cm	10	150	Root_dynamics
RDI	Initial rooting depth at emergence	cm	10	50	Root_dynamics
RDMCR	Maximum rooting depth of mature crop (plant characteristic)	cm	50	400	Root_dynamics
RDRRTB	Relative death rate of roots as a function of development stage	-; kg kg^{-1} day^{-1}	0	0.02	Root_dynamics
RR	Growth rate root depth	cm	0	3	Root_dynamics
RRI	Daily increase in rooting depth	cm day^{-1}	0	3	Root_dynamics
TWRT	Total weight of roots	kg ha^{-1}	0	100000	Root_dynamics
WRT	Dry weight of living roots	kg ha^{-1}	0	100000	Root_dynamics
DRST	Death rate stem biomass	kg $ha^{-1}day^{-1}$	0	1000	Stem_dynamics
DWST	Dry weight of dead stems	kg ha^{-1}	0	100000	Stem_dynamics
GRST	Growth rate stem biomass	kg $ha^{-1}day^{-1}$	0	1000	Stem_dynamics
GWST	Net change in stem biomass	kg $ha^{-1}day^{-1}$	0	1000	Stem_dynamics
RDRSTB	Relative death rate of stems as a function of development stage	-; kg kg^{-1} day^{-1}	0	0.04	Stem_dynamics
SAI	Stem Area Index	-			Stem_dynamics
SSATB	Specific stem area as a function of development stage	-; ha kg^{-1}	0.0003	0.0003	Stem_dynamics
TWST	Total weight of stems	kg ha^{-1}	0	100000	Stem_dynamics
WST	Dry weight of living stems	kg ha^{-1}	0	100000	Stem_dynamics

VARIABLES	DESCRIPTION	UNIT	MIN	MAX	PCSE MODULE
DRSO	Death rate storage organs	kg $ha^{-1}day^{-1}$	0	1000	Storage_organ_dynamics
DWSO	Dry weight of dead storage organs	kg ha^{-1}	0	100000	Storage_organ_dynamics
GRSO	Growth rate storage organs	kg $ha^{-1}day^{-1}$	0	1000	Storage_organ_dynamics
GWSO	Net change in storage organ biomass	kg $ha^{-1}day^{-1}$	0	1000	Storage_organ_dynamics
PAI	Pod Area Index	-			Storage_organ_dynamics
SPA	Specific pod area	ha kg^{-1}	0.0008	0.003	Storage_organ_dynamics
TWSO	Total weight of storage organs	kg ha^{-1}	0	100000	Storage_organ_dynamics
WSO	Dry weight of living storage organs	kg ha^{-1}	0	100000	Storage_organ_dynamics
DSLR	Days since last rainfall	day	0	200	WaterbalanceFD
DSOS	Days since start of oxygen shortage	day	0	10	WaterbalanceFD
EVST	Cumulated evaporation from soil	cm	0	100	WaterbalanceFD
EVWT	Cumulated evaporation from surface water layer	cm	0	100	WaterbalanceFD
IFUNRN	Flag indicating the way the non-infiltrating fraction of rainfall is determined: 0 = fraction is fixed at NOTINF; 1 = fraction depends on NOTINF and on daily rainfall as given by NINFTB	-	0	1	WaterbalanceFD
K0	Hydraulic conductivity of saturated soil	cm day^{-1}	0.1	14	WaterbalanceFD
KSUB	Maximum percolation rate of water to subsoil	cm day^{-1}	0.1	14	WaterbalanceFD
LOSST	Cumulated loss of water by deep drainage	cm	0	100	WaterbalanceFD
NOTINF	Non-infiltrating fraction: if IFUNRN=0 non-infiltrating fraction of rainfall, if IFUNRN=1 maximum non-infiltrating fraction	-	0	1	WaterbalanceFD
PERCT	Cumulated percolation	cm	0	100	WaterbalanceFD
RAINT	Total precipitation since start of season	cm	0	100	WaterbalanceFD
RDM	Maximum rooting depth (determined by crop and soil)	cm	10	150	WaterbalanceFD
SM	Actual soil moisture content in rooted zone	-	0.01	0.9	WaterbalanceFD
SMLIM	Maximum initial soil moisture in rooted zone (will be forced between SMW and SM0)	cm	0	10	WaterbalanceFD
SOPE	Maximum percolation rate of water through the root zone	cm day^{-1}	0	10	WaterbalanceFD
SS	Surface storage	cm	0	2	WaterbalanceFD
SSI	Initial surface storage	cm	0	2	WaterbalanceFD
SSMAX	Maximum surface storage capacity	cm	0	2	WaterbalanceFD

VARIABLES	DESCRIPTION	UNIT	MIN	MAX	PCSE MODULE
TOTINF	Cumulated infiltration	cm	0	100	WaterbalanceFD
TOTIRR	Total amount of effective irrigation	cm	0	100	WaterbalanceFD
TSR	Surface runoff	cm day^{-1}	0	14	WaterbalanceFD
W	Amount of water (=depth) in rooted zone	cm	0	150	WaterbalanceFD
WAV	Initial amount of water in rootable zone in excess of wilting point, but not exceeding SMLIM (will be cutoff)	cm	0	50	WaterbalanceFD
WBALRT	Checksum for root zone waterbalance	cm	0	0.0001	WaterbalanceFD
WBALTT	Checksum for total waterbalance	cm	0	0.0001	WaterbalanceFD
WDRT	Water addition to rooted zone by root growth (WDRT starts with initial water)	cm	0	20	WaterbalanceFD
WI	Initial amount of water in the root zone	cm	0	150	WaterbalanceFD
WLOW	Amount of water (=depth) in unrooted zone (zone between current rooting depth and maximum rooting depth)	cm	0	150	WaterbalanceFD
WLOWI	Initial amount of water in the subsoil	cm	0	150	WaterbalanceFD
WTRAT	Total water lost as transpiration as calculated by the water balance	cm	0	100	WaterbalanceFD
WWLOW	Amount of water in whole rootable zone	cm	0	150	WaterbalanceFD
CRAIRC	Critical soil air content for aeration (used when IOX = 1)	cm^3 cm^{-3}	0.04	0.1	WaterbalanceFD/Evapotranspiration
EVSMX	Maximum evaporation rate from a soil surface below the crop canopy	cm day^{-1}	0	1	WaterbalanceFD/Evapotranspiration
EVWMX	Maximum evaporation rate from a water surface below the crop canopy	cm day^{-1}	0	1	WaterbalanceFD/Evapotranspiration
SM0	Soil moisture content of saturated soil	cm^3 cm^{-3}	0.3	0.9	WaterbalanceFD/Evapotranspiration
SMFCF	Soil moisture content at field capacity	cm^3 cm^{-3}	0.05	0.74	WaterbalanceFD/Evapotranspiration
SMW	Soil moisture content at wilting point	cm^3 cm^{-3}	0.01	0.35	WaterbalanceFD/Evapotranspiration
RDMSOL	Maximum rootable depth of soil	cm	10	150	WaterbalanceFD/Root_dynamics
ELEV	Altitude	m	-300	7000	WeatherDataContainer
IRRAD	Global radiation sum at earth surface	J m^{-2} day^{-1}	0	36000000	WeatherDataContainer
LAT	Latitude	dd	-90	90	WeatherDataContainer
LON	Longitude	dd	0	360	WeatherDataContainer
RAIN	Precipitation sum of the day	cm day^{-1}	0	14	WeatherDataContainer

VARIABLES	DESCRIPTION	UNIT	MIN	MAX	PCSE MODULE
SNOWDEPTH	Snow depth	cm	0	100	WeatherDataContainer
TEMP	Mean daily temperature (TMIN + TMAX)/2	°C	-35	50	WeatherDataContainer
TMAX	Maximum temperature	°C	-20	50	WeatherDataContainer
TMIN	Minimum temperature	°C	-35	35	WeatherDataContainer
VAP	Mean vapour pressure	hPa	0	35	WeatherDataContainer
WIND	Mean windspeed at 2 m above earth surface	$m\ s^{-1}$	0	15	WeatherDataContainer
E0	Potential evaporation rate from a free water surface	$cm\ day^{-1}$	0	2	WeatherDataContainer/Reference_ET
ES0	Potential evaporation rate from a bare soil surface	$cm\ day^{-1}$	0	2	WeatherDataContainer/Reference_ET
ET0	Potential evapo(transpi)ration rate from a general crop canopy	$cm\ day^{-1}$	0	2	WeatherDataContainer/Reference_ET
ADMI	Aboveground dry matter increase	$kg\ ha^{-1}day^{-1}$	0	1000	Wofost
ASRC	Net available assimilates (GASS - MRES)	$kg\ CH2O\ ha^{-1}day^{-1}$	0	1000	Wofost
CTRAT	Cumulated crop transpiration	cm	0	100	Wofost
CVL	Conversion efficiency of assimilates into leaf	$mass\ mass^{-1}$	0.6	0.76	Wofost
CVO	Conversion efficiency of assimilates into storage organ	$mass\ mass^{-1}$	0.45	0.85	Wofost
CVR	Conversion efficiency of assimilates into root	$mass\ mass^{-1}$	0.65	0.76	Wofost
CVS	Conversion efficiency of assimilates into stem	$mass\ mass^{-1}$	0.63	0.76	Wofost
DAY	Date	-			Wofost
DMI	Total dry matter increase, calculated as ASRC times a weighted conversion efficiency	$kg\ ha^{-1}day^{-1}$	0	1000	Wofost
DOF	Date representing the day of finish of the crop simulation	-			Wofost
FINISH_TYPE	String representing the reason for finishing the simulation: maturity, harvest, leave death, etc	-			Wofost
GASS	Assimilation rate corrected for water stress	$kg\ CH2O\ ha^{-1}day^{-1}$	0	1000	Wofost
GASST	Total gross assimilation	$kg\ CH2O\ ha^{-1}$	0	400000	Wofost
HI	Harvest Index	-			Wofost
MRES	Actual maintenance respiration rate, taking into account that MRES <= GASS	$kg\ CH2O\ ha^{-1}day^{-1}$	0	1000	Wofost
MREST	Total gross maintenance respiration	$kg\ CH2O\ ha^{-1}$	0	400000	Wofost

VARIABLES	DESCRIPTION	UNIT	MIN	MAX	PCSE MODULE
TAGP	Total above ground production	kg ha^{-1}	0	150000	Wofost

Annex II - Procedures for calibration of WOFOST crop parameters

To apply WOFOST for a specific crop variety and for specific conditions with respect to climate and soil conditions, a model calibration is often required. In a model calibration, the number of model variables that can be varied, is enormous. Hence, the model calibration should be done in certain order. A calibration procedure for the different parts of WOFOST is described in this Annex. While this Annex gives a good introduction to the calibration procedure and the main parameters to be calibrated, Annex III provides a complete overview of parameters that could be calibrated in certain circumstances. In Annex IV, the required experimental information for the calibration of WOFOST is given.

The model calibration is done first for a potential production situation. This requires information from crop experiments under potential production conditions. This means that the crop growth is not limited by water excess or shortage or by nutrient shortage, yield losses by weed competition, pest and disease infestation are practically nil and growth reduction due to other factors (poor soil structure, salinity or acidity) are also prevented. This requires optimum crop management and nutrient supply, irrigation and drainage, crop protection etc. which in general is found only in well-kept trials. Next, the model calibration is done for the water-limited production situation. This requires information from crop experiments under water-limited conditions. This means that the crop growth may be limited by water excess or shortage, as no irrigation water is applied and possibly drainage may be limited. However, crop management, nutrient supply and crop protection should be optimum in these experiments too.

The model calibration is done for first the potential (aspects no. 1, 2 and 3 of WOFOST) and next the water-limited production situation (aspects no. 4, 5 and 6) in the following order:

1. Length of growth period and phenology;
2. Light interception and potential biomass production;
3. Assimilate distribution between crop organs;
4. Water availability;
5. Evapotranspiration;
6. Water-limited production.

In the next section several crop parameters are introduced between brackets. For more information on these crop parameters and detailed process descriptions please check Annex I and the system description of the WOFOST 7.2 cropping systems model (Wit de et al, 2020.).

1 Length of growth period and phenology

The length of the growth period is the period between crop emergence and the date of crop maturity or senescence (yellowing of leaves). The total biomass production is equal to the mean daily biomass production times the total growth duration; hence this growth duration should be simulated well for a reliable biomass and yield prediction.

The date of sowing date or crop emergence is important management input for WOFOST. If the sowing date is used as input, then the emergence date is calculated based on a temperature sum from sowing to emergence (TSUMEM). In that case, TSUMEM should be calibrated on observed sowing and emergence dates from field experiments with the same crop variety.

The crop maturity date in WOFOST is calculated based on two parameters describing the required temperature sum: TSUM1 describes the temperature sum from emergence to anthesis (flowering) and TSUM2 from anthesis to maturity. The daily increase in temperature sum is generally equal to the mean daily temperature minus a base temperature (e.g. 0 °C for wheat). The crop phenology is expressed as a development stage (variable DVS) which is the ratio between the accumulated temperature sum and the TSUM1 and TSUM2 parameters. DVS reaches 1 at anthesis and 2 at maturity.

A crop produces not only biomass but goes through several phenological development stages. In dependence of the phenological stage (i.e. DVS), WOFOST allocates the produced biomass to the different crop organs (see also aspect 3). For example, if DVS >1, all assimilates produced by a wheat crop are allocated to the grains. This indicates the importance of, for example, calibrating TSUM1 and TSUM2 properly leading to a correct anthesis date. For instance, an anthesis date that is simulated too late, results in a too high green biomass and a low grain yield.

2 Light interception and potential biomass production

The daily biomass production in a potential production situation mainly depends on the intercepted amount of irradiation. For most crops, the canopy during the main growth period is completely closed and almost all irradiation is intercepted. As on a weekly (or longer) basis the variation in irradiation is generally limited, the biomass production per week is often quite constant during the main part of the growth period. This results in a linear increase in biomass with time during the main growth period. The time course of total biomass production for most crops can be described by three phases:

a) exponential growth phase with small plants during first growth period, incomplete (but exponentially increasing) light interception and hence low but rapidly increasing biomass production;
b) linear, main growth phase with almost complete light interception and large production of biomass;
c) decreasing growth phase with dying leaves and rapidly decreasing biomass production until final death of canopy.

The total biomass production can be roughly estimated from the mean daily biomass production during the linear growth phase times the length of linear growth phase plus one fourth of the lengths of both exponential and decreasing growth phases. This indicates the strong relationship between the attainable biomass production and thus yield level, and the length of the linear growth phase. Rapid canopy establishment due to optimum growing conditions and high sowing rate on the one hand and an optimum control of pest and diseases which delays leaf senescence and damage on the other hand, results in the longest linear growth phase and the highest biomass production.

If the simulated leaf area index (LAI) or the fraction of light intercepted is too high but the amount of leaf biomass is simulated well, LAI can be lowered by entering a lower specific leaf area (SLATB, ha leaf area/kg leaf mass). If the LAI becomes lower, the simulated values for light interception and hence biomass production become lower too.

If the simulated total above-ground production is too low compared to the observed biomass production at harvest, calibration should be focused on the daily photosynthesis rate. This rate depends on the photosynthesis-light response curve, of which the initial angle (EFFTB) is mostly constant and of which the maximum (AMAXTB) may be changed. The maximum is often crop variety specific and decreases in case of nutrient shortage and canopy ageing due to a decrease in chlorophyll content.

The simulated time course of LAI and light interception at the beginning and at the end of the growth period may also be calibrated in a different way from that described above. During the initial phase of crop establishment LAI is largely based on the LAI at emergence (calculated from TDWI) and the maximum (sink or leaf growth limited) relative increase in LAI (RGRLAI). These two parameters strongly affect the initial increase in LAI and hence the duration till the linear growth phase with complete light interception. The simulated time course of LAI during the final growth period is strongly affected by the life span of leaves (SPAN). A higher value for SPAN results in a longer time period that the leaves stay green and productive and hence, results in a higher LAI and thus biomass production near crop maturity.

3 Assimilate distribution between crop organs

A crop produces not only biomass but goes through several phenological stages. For example, wheat has periods of establishment and first growth, a period of vegetative growth (tillering and head development), a period of flowering (anthesis) and a period of grain filling and ripening. The lengths of these periods can be calculated based on temperature sums (see aspect 1: Length of growth period and phenology). WOFOST does not really describe the organ formation of the crop but it allocates the produced assimilates to the different crop organs in dependence of the phenological development stage of the crop. The allocation of produced assimilates to the different crop organs in the WOFOST simulation is important for mainly two reasons: first it determines the leaf mass and thus the LAI and light interception; second it determines the allocation to the economical products (grains, roots, etc.) and thus the yield level and the harvest index.

For the allocation, WOFOST uses partitioning factors (FLTB, FOTB, FSTB and FRTB) in dependence of DVS. For example, for wheat, if DVS<0.3, the main part of assimilates is allocated to roots and leaves and when DVS >1, all assimilates are allocated to the grains. In this way, different crop varieties can be described in the WOFOST simulations. For example, a wheat variety with a relatively long period till anthesis (high TSUM1) and a relatively short period from anthesis till maturity date (low TSUM2) results in a large green biomass, a low grain yield, and thus a relatively low harvest index. For a higher wheat grain production, the variety should produce less green biomass and should produce and fill grains during a longer period, resulting in a higher ratio of grain yield over total biomass (e.g. harvest index – HI). This requires a variety with lowered TSUM1 and increased TSUM2.

In a situation where the simulated allocation of assimilates to the different crop organs is clearly different from the observed allocation of assimilates and the dates for the main phenological stages (i.e. emergence, anthesis, maturity) are simulated well, the partitioning factors FLTB, FOTB, FSTB and FRTB need to be changed.

4 Water availability

The following sections (4-6) describe the calibration of the WOFOST model for water-limited conditions. In this section the water availability is discussed and in the next sections the water use by evapotranspiration and the resulting water-limited production.

The water availability is determined by first the soil physical characteristics and second the water balance. In section 4-6 we focus on a simple one-layer water bucket model implementation. The water balance in the rooted zone during the growth period is equal to the difference between the water supply from precipitation and irrigation and the water losses by crop transpiration, soil evaporation and percolation to deeper soil layers. The soil physical characteristics determine the amount of water that can be stored at maximum in the soil and that can be supplied to the crop.

At a few locations, the groundwater level is shallow and capillary rise from groundwater may result in considerable additional water supply. This requires additional location-specific information that is often not available, such as the relationship between hydraulic conductivity and soil capillary rise, the time course of groundwater level, and the degree of artificial drainage. As these areas with shallow groundwater (low-lying river basins and river delta's) do not occur very often, this contribution of groundwater to the water availability is not treated in the following. However, note the different implementations of water balances for WOFOST include solutions to deal with the groundwater effect on water availability (see section on interfaces).

The maximum soil-water holding capacity in a free drainage situation is determined by the maximum crop's rooting depth and by the maximum available moisture fraction in the soil. This last variable is equal to the difference between soil moisture content at field capacity, SMFCF, (i.e. moisture content after one or two days of free drainage of a wetted soil) and soil moisture content at wilting point, SMW, (pF=4.2 which is about soil suction at which plants irreversibly die). The maximum rooting depth (RDMCR) is determined by the crop. For example, for wheat RDMCR is 125 cm. However, many wheat roots may go deeper than 125 cm. However, this means that from a wet soil this maximum amount of available water (i.e. 125 cm * maximum available moisture fraction) can be used by a wheat crop. For soils which are shallow or have unfavourable soil structures or layers, a shallower rooting depth due to soil limitation (RDMSOL) can be set. Hence if RDMSOL < RDMCR, the maximum rooting depth is equal to RDMSOL.

The values for the soil moisture contents at field capacity (SMFCF) and wilting point (SMW) are determined by the soil type and mainly differ with respect to soil texture class and the organic matter content. The maximum soil-limited rooting depth (RDMSOL) and the maximum available moisture fraction can be derived with so-called pedotransfer functions from common soil characteristics like texture and organic matter. However, for reliable water-limited production simulations with WOFOST, it is preferred to measure the moisture contents at field capacity and wilting point (i.e. mean value for the maximum rooting depth) for each soil type for which simulations are done.

The initial water availability at crop emergence depends on the water supply by precipitation and irrigation and the water use by crop transpiration and soil evaporation during the months before crop emergence. For growth simulations with WOFOST, the initial water availability is generally not known. In that case it is often assumed that initially the maximum rooting depth is at field capacity. In humid areas with rainfall exceeding evapotranspiration during the winter, this assumption works well for the crop growth starting in spring. However, in areas with dry periods (e.g. semi-arid areas) preceding crop emergence, the initial water availability may be largely overestimated. This may result in a strongly overestimated water supply during the growth period in the WOFOST simulation. This indicates the need for measuring the initial water availability at crop emergence or start to simulate the water balance well before the emergence date (e.g. 2-3 months before the emergence data starting with available moisture fraction halfway between field capacity and wilting point).

The simulated water balance can, in addition to the time course of water-limited production and soil moisture in the root zone, be used for checking and calibrating the simulated water-limited production.

The initial water conditions in the root zone are determined in a WOFOST simulation by two variables. First, the variable SMLIM which specifies the initial soil moisture content in the initial root zone (0-10 cm depth). Second, the variable WAV which specifies the initially available (above moisture content at wilting point) amount of soil moisture in the maximum root zone. The sensitivity of the water-limited production to these initial water conditions appears to be quite strong.

The water-limited production is also determined by the maximum soil water holding capacity of the soil. This capacity is determined by first the maximum rooting depth (RDMSOL), as discussed above, and the available soil moisture fraction (i.e. soil moisture content at field capacity, SMFCF, minus that at wilting point, SMW). The water-limited production from WOFOST can change if the available soil moisture fraction or RDMSOL changes and at the same time rainfall is insufficient.

5 Evapotranspiration

The potential evapotranspiration from a bare soil surface, a water surface and a crop surface are usually calculated with the Penman and Penman-Monteith approach. This approach is universal and in general works well in most situations. However, some possibilities for calibration of the actual evapotranspiration are given in the following.

In WOFOST, the actual crop transpiration is equal to the potential evapotranspiration times correction factors for the degree of light interception, the degree of water stress, and for the crop in general. This last factor, variable CFET, is in general 1.0. However, its value may be increased to e.g. 1.15 if the WOFOST simulation underestimates the actual transpiration due to the relatively great height and thus large transpiration of, for example, a maize crop. The reason is that the Penman and Penman-Monteith approaches are mainly developed for a short crop like grass. In (semi-)arid areas with advection, simulated transpiration may also be too low compared to observations and may need a correction.

The degree of drought stress and the resulting reduction in transpiration rate, and proportionally in photosynthesis too, are determined by the soil moisture content in the root zone. If the soil moisture content becomes lower than the critical moisture content, the water-stress correction factor is gradually reduced from 1.0 to 0.0 at a moisture content equal that at wilting point. However, the critical soil moisture content is not a constant value. It differs between crop species and varieties but also depends upon the evapotranspiration itself. The latter is caused by plants being more prone to drought stress when the atmospheric evaporative demand is high and thus the potential plant evapotranspiration is high. In WOFOST, crop sensitivity to drought stress is indicated by variable DEPNR with higher values indicating a less drought sensitive crop (e.g. 4.5 for wheat and 3.0 for potato). Differences in drought sensitivities between crop varieties may be included by changing DEPNR.

Soil moisture content may become too high for crop growth too, in general in soils where drainage is limited. If the air content becomes less than the value for the variable CRAIRC, both transpiration and photosynthesis are reduced due to oxygen shortage. Hence, in wet growing conditions, this variable CRAIRC may need more precise calibration. In free draining soils, oxygen shortage in general does not occur.

6 Water-limited production

The model calibration is done first for a potential production situation. If this is done well, the model should next be calibrated based on information from crop experiments under water-limited conditions. In this section we focus on the simple one-layer water bucket model implementation.

The water-limited production is determined by the water availability and the water use during the crop growth period. The water use is mainly determined by crop transpiration and soil evaporation, and sometimes percolation to deep soil layers. This water use is in general calculated well by the model. As described in the previous section, crop transpiration may need some calibration in (semi)-arid conditions.

The water availability during the growth period is determined by both the initial water availability, the maximum soil-water holding capacity as dependent on rooting depth and the available soil moisture fraction, and the balance of water inputs (mainly precipitation) and use (see above) during the growth period. The initial soil water availability in the maximum rooting depth should be based on measurement of soil moisture content at crop emergence or should be based on calculation of the water balance during the months before crop emergence. Often only a rough estimate for the initial soil water availability is available for the WOFOST simulation, however, the sensitivity of water-limited production to this initial soil water availability is often quite strong.

The maximum soil-water holding capacity is determined by the maximum rooting depth (of full-grown crop) and the available soil moisture fraction (moisture content at field capacity minus that at wilting point). For these three variables reliable values should be available for each soil type for which WOFOST simulations are done, to achieve precise water-limited crop production analyses. However, for regional-scale studies, often regional mean values (based on pedo-transfer functions) are only available for these variables that determine the maximum soil-water holding capacity.

In many studies at the regional, national or continental scale, information on initial soil water availability and on the maximum soil-water holding capacity is missing. In that case, it is important to calibrate WOFOST based on the limited information from representative field experiments under water-limited conditions. If mainly biomass production or grain yield data are available from such field experiment the initial soil water availability and/or the maximum soil-water holding capacity can be calibrated to arrive at comparable biomass and grain yield levels.

Annex III - Considerations for parameter selection and calibration

The text below provides an overview of the difference physiological processes implemented in WOFOST and the parameters involved. Each process contains "free" parameters that can be freely calibrated, "additional" parameters that can be modified if required and "static" parameters that are not likely to require calibration.

1 Phenology

Type	Parameters	Considerations
Free	TSUMEM, TSUM1, TSUM2	Temperature sums can be adjusted over a wide range depending on the local varieties and crop type.
Additional	DLO, DLC, VERNSAT, VERNBASE	Optical and critical daylength (DLO, DLC) may be adjusted but often these are difficult to calibrate when the range in day length in the experimental data is limited. Similarly, the base and saturated vernalization are hard to calibration and are often estimated based on the local climatic conditions (see Ceglar et al., 2019) https://doi.org/10.1016/j.agsy.2018.05.002
Static	DTSMTB, TBASEM, TEFFMX, VERNRTB, VERNDVS	The temperature response functions for emergence (TBASEM, TEFFMX), phenology (DTSMTB) and vernalization (VERNRTB) are hard to calibrate. Nevertheless, sometimes change can be made when there are strong indications that crops do develop under certain conditions while WOFOST simulates no development. For example, for maize varieties grown in temperate regions a base temperature of 6 C is applied in WOFOST, while for tropical varieties 8 C is used.

2 Assimilation

See also the considerations in section 3.7 in the WOFOST system description at http://wofost.readthedocs.io

Type	Parameters	Considerations
Free	AMAXTB	Measurements of AMAX show large variations. However, one should take into consideration that AMAX in WOFOST should refer to the AMAX for leaves at the top of the canopy at optimal growing conditions. The major differences found in WOFOST are between C3 (AMAX 30-40) and C4 (AMAX ~70) crops[4]. Besides AMAX is often crop variety specific and decreases in case of nutrient shortage and canopy ageing due to a decrease in chlorophyll content. Changes in AMAX in the order of 10% are probably acceptable.
Additional	TMNFTB, TMPFTB	The temperature response functions for day-time temperature (TMPFTB) is not likely to require calibration, except under conditions of very high temperature as the photosynthesis response under such conditions is not well known for WOFOST. The temperature response to low (night-time) temperature (TMNFTP) is known to require adaption in certain cases. For example, it has been demonstrated that WOFOST could not simulate wheat growth for

[4] There are only two major pathways for CO_2 assimilation in crops: C3 and C4 (ignoring CAMS). This is mainly determining the AMAX value. Please note that the value of AMAX is defined for a certain CO_2 level. There are two strategies to work with an appropriate AMAX value for simulating for recent years. Most attractive, but in many cases not so realistic as it requires experiments, is determining the AMAX via experiments for the governing CO_2 levels (~ 410 ppm). Second approach is to use previously determined AMAX values under past CO_2 levels (e.g. ~ 360 ppm). Within WOFOST a specific CO2AMAXTB is defined to correct AMAX value for increased CO_2 levels. This correction factor uses the ambient CO2 concentration. This can also be used to explore crop growth under climate change scenarios.

		certain regions properly with the standard WOFOST TMNFTP parameter due to a too strong reduction of the assimilation rate by this parameter.
Static	EFFTB, KDIFTB, CO2AMAXTB, CO2EFFTB	EFFTB is known to vary little between crops and varieties. KDIFTB is the light diffusivity coefficient which is largely dependent on leaf properties. The assimilation response to CO2 (CO2AMAXTB, CO2EFFTB) are better not touched unless there is strong evidence of differences in the photosynthesis response to the selected parameterization.

3 Respiration

See also the considerations in section 3.7 in the WOFOST system description at http://wofost.readthedocs.io

3.1 Maintenance respiration

Type	**Parameters**	**Considerations**
Free		
Additional	Q10, RFSETB	The Q10 parameter doubles the maintenance respiration for each 10 degrees increase in temperature. Maintenance respiration is hard to measure and therefore introduces a significant uncertainty in simulating the rate of crop growth, especially when the standing biomass is large compared to the current rate of photosynthesis, as at the end of the growth period. Q10 should be adjusted particularly when growth rates are deviating from the experimental data. This is particularly effective under high temperature conditions at the end of the growth cycle. RFSETB is an empirical correction factor that takes the impact of senescence on maintenance respiration into account. Reduction of maintenance respiration can therefore be adjusted using the parameter as a function of development stage.
Static	RML, RMO, RMR, RMS	The maintenance coefficients for leaves, organs, roots and stems are based on measurements which show a large variation among species and varieties. However, adjusting the parameters requires very specific measurements which are usually not available from experimental trials. In such cases it is better to adjust Q10 or RFSETB instead of calibration individual maintenance respiration coefficients.

3.2 Growth respiration

Type	**Parameters**	**Considerations**
Free		
Additional		
Static	CVL, CVO, CVR, CVS	The conversion coefficients describe the efficiency with which a unit of carbohydrate (CH2O) can be converted into a particular plant tissue. The different plant organs and in particular the storage organs (grains, tubers, etc.) vary too much in composition among species for one general value. For example species with storage organs that contain starch or sugar have high conversion efficiency (potato: 0.82, sugar beet: 0.85) while species with storage organs that have a high concentration of protein or lipids have lower conversion efficiency (soybean: 0.48, rapeseed: 0.45). The values of CVL, CVO, CVR and CVS are bound to

		the efficiency of a chemical conversion and are therefore relatively static. Only for varieties which have deviating properties for storage organs (e.g. a high protein wheat cultivar), the values of CVO may be adjusted in the order of +/- 10%.

4 Partitioning

Type	Parameters	Considerations
Free	FRTB FOTB, FSTB, FLTB	For calibrating the partitioning coefficients it is crucial that the phenological development of the crop is simulated correctly. Next, the partitioning between below/above-ground biomass (FRTB) should be checked. Finally, the partitioning tables for leaves (FLTB), stems (FSTB) and storage organs (FOTB) can be calibrated. There is a fairly large variability in partitioning coefficients between crops and even within between crop varieties so adjustments to partitioning tables are often required. Calibration of the partitioning coefficients can be done efficiently by replacing them with logistic functions. See the example notebook at: https://github.com/ajwdewit/pcse_notebooks.
Additional		
Static		

5. Crop transpiration

Type	Parameters	Considerations
Free	CFET, DEPNR	The correction factor for evapotranspiration (CFET) can be used to adjust for crops whose transpiration rates systematically differ from the reference evapotranspiration rate. Currently, all crops have CFET=1 but adjustments in the order of +/- 10% can be applied if experimental data indicates deviations in transpiration rates. The dependency number (DEPNR) is a classification of the drought tolerance of the crop. Higher numbers indicate higher drought tolerance. Adjustments can be made for cultivars that are more or less drought tolerant.
Additional		
Static	CO2TRATB	The CO_2 dependence is better not touched unless clear experimental evidence is available on the impact of CO_2 concentration of crop transpiration.

6 Leaf dynamics

Type	Parameters	Considerations
Free	RGRLAI, SLATB, SPAN	The crop relative growth rate (RGRLAI) limits the LAI expansion during the early growth stages. It can be adjusted when experimental data shows that LAI expansion is faster than WOFOST simulates. SLATB describes the specific leaf area (leaf thickness) as a function of development stages. SLA can vary considerably between crops and cultivars and can be adjusted for this reason. However, one should keep into account that the SLA provided by SLATB is used in WOFOST is applied to the leave growth at each time step (“instantaneous” SLA). SLA derived from field experiment is often computed as leaf area/leaf

		biomass during the course of the season which provides an "integrated" SLA. Leaf span of leaves (SPAN) defines the senescence of leaves and is highly variable among crops and cultivars (20 to 50 days). Short duration cultivars often have lower SPAN values.
Additional	SSATB, SPA	SSATB and SPA define the contribution of stems and pods to the photosynthetic active area and are added to LAI. Currently both are zero for all crops due to lack of data, although for some crops it is known that contribution of stems/pods can be significant.
Static	TBASE, PERDL	The base temperature for leaf aging is better not touched unless detailed experimental data is available. Moreover, there is interaction between TBASE and SPAN and therefore calibrating SPAN is often sufficient. PERDL is the maximum relative death rate of leaves due to water stress and is a static parameter.

7 Stem dynamics

Type	Parameters	Considerations
Free		
Additional		
Static	RDRSTB	Relative death rate of stems (RDRRTB) can be adjusted but it has little on the simulation results, except for lowering maintenance respiration costs because of a decrease of living stem material.

8 Root dynamics

Type	Parameters	Considerations
Free	RDMCR	Moreover, the maximum crop rootable depth (RDMCR) can be adjusted as it is known that there are differences between cultivars in maximum rootable depth. Note that the actual rootable depth is always the minimum of the crop rootable depth (RDMCR) and the soil rootable depth (RDMSOL)
Additional	RRI	Root increase rate (RRI) determines the speed at which roots grow deeper. It can be adjusted if there strong indications of slower/faster root growth.
Static	RDRRTB, RDI	Relative death rate of roots (RDRRTB) can be adjusted but it has little impact on the simulation results, except for lowering maintenance respiration costs because of a decrease of living root material. Initial rooting depth (RDI) is a not likely to require calibration. Moreover, setting a very small RDI should be avoided as it could create simulation artifacts due to strong drought stress in the shallow initial soil layer.

9 Other parameters

Type	Parameters	Considerations
Free	TDWI	The total initial dry weight (TDWI) specifies the initial amount of biomass that is supplied to the field. This could be either in the form of seed weight, or in initial seedling plants (transplanted rice). As a result there is a large variability in TDWI ranging from 0.5 kg/ha for tiny sugar beet seed up till 600 kg/ha for transplanted sugarcane. TDWI can have a large impact on the initial growth rate because of its exponential shape. Often there is also an interaction with the crop sowing date:

		early sowing with low TDWI will give similar results as late sowing with high TDWI.
Additional		
Static		

Annex IV - Required experimental data for calibration of WOFOST

Crop data

From experiments which are representative for the studied region, crop data are required, i.e. for

- the main crops
- under the main range of environmental conditions (main soil types, climates, hydrological, etc. conditions)
- with representative types of management (optimal nutrient supply and crop protection both with and without irrigation (i.e. potential and water-limited production))

The following information from experiments is needed:

- Initial crop values: a. weight of seed or planting material; b. sowing density; c. sowing/planting date;
- Crop information during the growth period: a. phenological development or sowing/planting date, emergence date, anthesis date and maturity date; b. leaf area index or light interception; c. plant density;
- Crop information from intermediate and final harvests: a. total biomass; b. distribution of biomass over plant organs; c. living and dead leaf weight; d. crop composition at final harvest: e.g. plants/m^2, ears per plant, grains per ear and grain weight;
- Other crop information such as, for example: a. leaf damage; b. yield losses by pest and disease infestation and/or weed competition; c. yield losses by nutrient shortage.

Soil data

From experiments which are representative for the main crops and environmental conditions in the studied region, the following soil information is needed:

- Soil information, initial: a. soil physical characteristics (pF curve or soil moisture contents at field capacity and wilting point and soil porosity); b. soil-limited rootable depth; c. possibly, hydraulic conductivity; d. for paddy rice, surface water storage (bund height);
- Soil information during the growth period: a. soil moisture content in rooted soil; b. ground water level;
- Special soil and landscape characteristics (if applicable and of importance for crop growth and/or water availability): a. hydrology; b. salinity; c. sodicity; d. special soil layers or structure; e. slope and degree of surface runoff.

Weather data

To simulate with WOFOST the observed crop growth at experimental locations and to use this experimental information for the model calibration, also weather information from these locations is needed.

Name	Description	Unit
TMAX	Daily maximum temperature	°C
TMIN	Daily minimum temperature	°C
VAP	Mean daily vapour pressure	hPa
WIND	Mean daily wind speed at 2 m above ground level	$m.sec^{-1}$
RAIN[5]	Precipitation (rainfall or water equivalent in case of snow or hail).	$cm.day^{-1}$
IRRAD	Daily global radiation	$J.m^{-2}.day^{-1}$

[5] Water supply by surface run-off from higher positions on the slope is not considered in WOFOST.

SNOWDEPTH	Depth of snow cover (optional)	cm

Other additional information

- Applied inorganic fertilizer, animal and green manure;
- Crop management and protection;
- Crop rotation;
- Irrigation method and amount of applied irrigation water;
- Soil tillage method;
- Drainage system.