Food and Agriculture Organization of the United Nations

Release Note AquaCrop

Version 7.1

AQUACROP

August 2023

Abstract

Updates
1. Fine-tuning of the simulation of perennial herbaceous forage crops The transfer of assimilates between the above (leaves and stems) and below-ground organs (crowns and roots) of perennial herbaceous forage crops has been fine-tuned in Version 7.1. The novel subroutine was evaluated by running simulations for different environments. The comparisons between measurements and the simulations indicated that AquaCrop can well predict the total yield of alfalfa that can be expected in various climates and environments, with and without water stress and soil fertility stress, for three different alfalfa cultivars.
2. Adjustment of the reference Harvest Index (HIo) for inadequate photosynthesis The adjustment has been fine-tuned to avoid a zero Harvest Index and no yield formation when CC is small at the start of yield formation (tuber formation or root enlargement for root/tuber crops or flowering for fruit/grain crops).
3. Update of the MaunaLoa.CO2 file The annual mean concentrations of CO_2 levels measured at the Mauna Loa Observatory are available in the ‘MaunaLoa.CO2’ file in the SIMUL subdirectory of AquaCrop. The observed CO_2 concentrations up to 2022 have been updated with the latest published results on the NOAA website:
4. List of the updates in the AquaCrop open-source Version List of the corresponding updates in the AquaCrop open-source version

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1. Fine-tuning of the simulation of perennial herbaceous forage crops

In AquaCrop Version 7.1, the transfer of assimilates between the above (leaves and stems) and below-ground organs (crowns and roots) has been fine-tuned (Fig. 1):

1. An exponential function (similar to the simulation of the underground storage of assimilates after mid-season) describes now the remobilization of stored assimilates at the start of the season;
2. In the remobilization and storage stages, the transfer of assimilates is corrected for regrowth:
   - Remobilization is no longer considered when the canopy is at or above 90 percent of its maximum canopy cover (CCx) after regrowth;
   - After cutting, the storage is temporarily reduced to consider the assimilates required for the regrowth of the crop canopy.

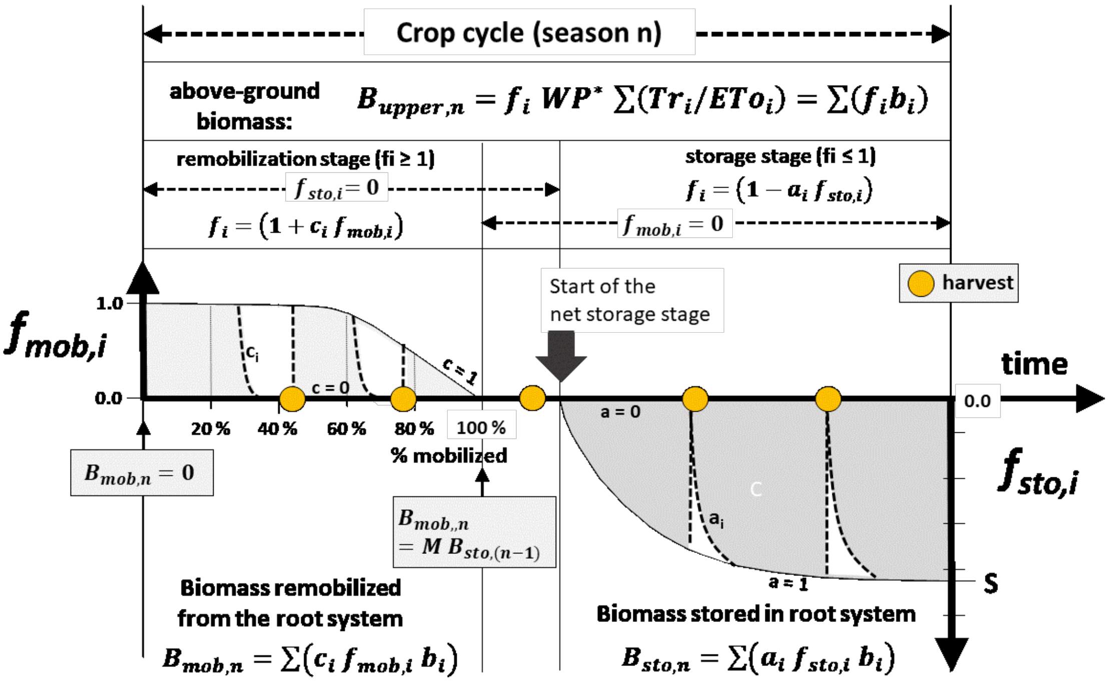

Figure 1. – Schematic representation of the simulation of the total above-ground biomass ($B_{upper,n}$) in the nth season, for alfalfa. During the spring (net remobilization stage), the transfer to the above-ground parts of the Mth fraction of the assimilates stored below ground in the previous season ($B_{sto,(n-1)}$), is simulated by increasing the biomass at day i (b_i) with a fraction ($c_i\, f_{mob,i}$). To stimulate growth, the adjustment factor c_i is 1 as long as CC increase. When the maximum canopy cover is reached, c_i is zero and remobilisation is halted. From mid-season (start of the net storage stage), a fraction ($a_i\, f_{sto,i}$) of b_i is stored in the root system. The adjustment factor a_i for regrowth is zero on a day of harvest, and gradually increases to 1 during regrowth. For further explanation, see text (source: Raes et al., 2023).

1.1 Simulation of the transfer of assimilates

(source: Raes et al., 2023)

By using a biomass water productivity factor (WP*), AquaCrop calculates the daily above-ground biomass (b_i) from daily transpiration normalized for climate (using the reference evapotranspiration, ETo_i):

$$B = \sum b_i = WP^* \sum \left(\frac{Tr_i}{ETo_i}\right) \quad \text{(Eq. 1)}$$

where B is the total above ground biomass produced during the growing cycle, and WP* is normalized for climate and CO_2 concentration.

Perennial herbaceous forage crops allocate the carbon assimilated through photosynthesis (b_i) to above (leaves and stems) and below-ground organs (crowns and roots). Since AquaCrop does not simulate biomass partitioning among various organs, variations in partitioning along the season is simulated by increasing or reducing WP*. The above-ground biomass (B_{upper}) is simulated as:

$$B_{upper} = \sum f_i b_i = f_i \, WP^* \sum \left(\frac{Tr_i}{ETo_i}\right) \quad \text{(Eq. 2)}$$

where f_i is a correction factor which is less than one during the period of assimilate storage in below-ground organs, and greater than one during the period of remobilization of assimilates in spring. The net assimilate storage stage starts after mid-season when the crop transfers an important fraction of b_i to the below-ground organs. During the following spring, which corresponds to the net remobilization stage, the stored assimilates are transferred to the above-ground organs to contribute to enhanced growth (Fig. 1). In the remobilization and storage stages, f_i is corrected for regrowth, since plants use the carbohydrate reserves for regrowth both in the spring and after each cutting.

1.1.1 Storage of assimilates below ground (storage stage)

Since perennial herbaceous forage crops transfer a considerable fraction of the assimilates below ground after mid-season, the daily biomass produced, b_i, is reduced by a fraction ($f_{sto,i}$, Eq.3) that exponentially increases from 0 at the start of the net storage stage (t = 0) to a fraction (S) of b_i at the end of the season (t = 1):

$$f_{sto,i} = \left[\frac{(exp^{-5t} - 1)}{(exp^{-5} - 1)}\right] S \quad \text{(Eq. 3)}$$

When the crop is harvested during the storage stage, $f_{sto,i}$ is temporarily reduced to consider the assimilates required for the regrowth of the crop canopy. This is simulated by multiplying $f_{sto,i}$ by another adjustment factor (a_i, Eq.4) for regrowth ($0 \le a_i \le 1$):

$$a_i = \frac{(CC_i - CC_{cut})}{(CC_x - CC_{cut})} \quad \text{(Eq. 4)}$$

where CC_{cut} is the canopy cover after harvest, and CC_i the canopy cover at day i, which increases during regrowth from CC_{cut} to the maximum canopy cover, CCx. At every harvest date, $CC_i = CC_{cut}$, a_i is zero and storage is halted (Fig. 1). When CC_i reaches CCx at the end of regrowth, a_i is 1, and storage is again at maximum rate.

1.1.2 Remobilization of assimilates from below ground (remobilization stage)

Not all assimilates can be recovered from storage. In AquaCrop it is assumed that of the total assimilates stored below ground in the previous season ($B_{sto,(n-1)}$), a fraction (M) is remobilized during the next season ($B_{mob,n}$, Eq. 5). The rest is assumed to be lost by respiration and natural self-thinning, or to remain stored below ground:

$$B_{mob,n} = M\ B_{sto,(n-1)} \qquad \text{(Eq. 5)}$$

Furthermore, it is assumed that at the start of the first year after sowing, only 20% of M is remobilized above ground, as many of the stored assimilates in the sowing year were required in the development and establishment of the perennial plant parts below ground (crown and root system).

To simulate the remobilization of stored assimilates at the start of the season, b_i is increased with a fraction ($f_{mob,i}$, Eq. 6) which decreases gradually as more and more assimilates are remobilized (Fig. 1):

$$f_{mob,i} = \left[\frac{(exp^{-5t}-1)}{(exp^{-5}-1)}\right] \qquad \text{(Eq.6)}$$

$$t = \frac{B_{mob,n} - \sum b_{mob,i}}{B_{mob,n}} \qquad \text{(Eq. 7)}$$

where $b_{mob,i}$ are the assimilates remobilized from the root system on day i, expressed as a fraction ($f_{mob,i}$) of b_i, and t is the relative time in the remobilization stage which gradually decreases from 1 at the start of the season to zero at the end of the remobilization stage.

When the canopy reaches 90 percent of CCx after regrowth, remobilization is no longer considered. This is simulated by multiplying $f_{mob,i}$ with an adjustment factor (c_i) for regrowth ($0 \leq c_i \leq 1$):

$$c_i = \frac{(CC_x - CC_i)}{0.1\ CC_x} \qquad \text{if } CC_i > 0.9\ CCx \qquad \text{(Eq. 8)}$$

At each harvest, c_i is 1 and remobilization starts at its maximum rate. It stays that way until CC has reached 90 percent of its maximum (CCx). When maximum canopy cover is reached (CC = CCx), c_i is zero and remobilization is halted until the next harvest. It is considered that remobilization and storage do not occur at the same time.

1.1.3 Specification in the Perennial crop characteristics menu

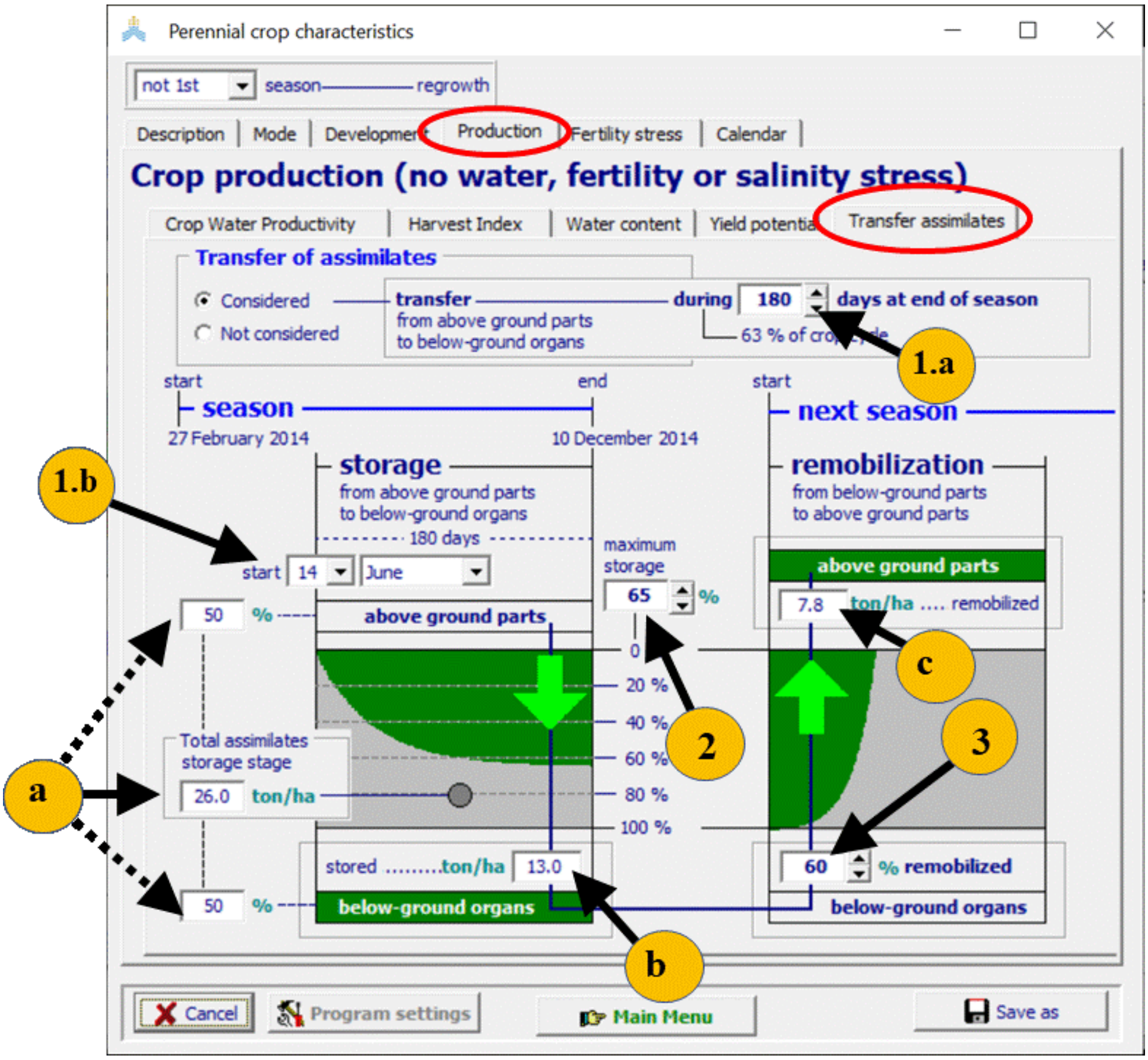

Figure 2. – Input (1 to 3) and information (a to c) on the transfer of assimilates in the "Transfer assimilates" tab-sheet in the *Crop characteristics* menu

In the Transfer assimilates tab-sheet of the Production tab-sheet in the ***Crop characteristics*** menu, the seasonal transfer of the assimilates between the above and below ground organs of the crop is specified (Fig. 2). If the transfer of assimilates is considered, the user can change:

1. The **duration of the transfer period** in which assimilates are stored in the below-ground organs at the end of the season, by specifying (1.a) the number of days or (1.b) the starting date (day and month) of the storage stage. By knowing the total length of the crop cycle and the specified duration of the storage stage, AquaCrop obtains from the input, the time in calendar days at which the transfer starts;
2. **The fraction of produced assimilates that are stored in the below-ground organs during the storage stage**, by specifying the percentage at the last day of the storage stage (when the storage is at its maximum);

3. The **percentage of the stored assimilates that are remobilized** at the start of the next season.

With this information AquaCrop calculates and displays the mass of assimilates that can be stored and remobilized in the absence of water, fertility or salinity stress (Fig 2):

a) the total mass of carbon that can be assimilated through photosynthesis during the storage stage and the percentages that can be stored in the above ground parts and below-ground organs;
b) the mass of assimilates that can be stored in the below-ground organs;
c) the mass of assimilates that can be transferred from below-ground organs to the above ground parts, at the start of the next season.

1.1.4 Display in the Simulation run menu

When running a simulation, the mass of biomass that was remobilized at the start of the season and stored at the end of the season is displayed in the ‘Production’ tab-sheet of ***the Simulation Run*** menu (Fig. 3).

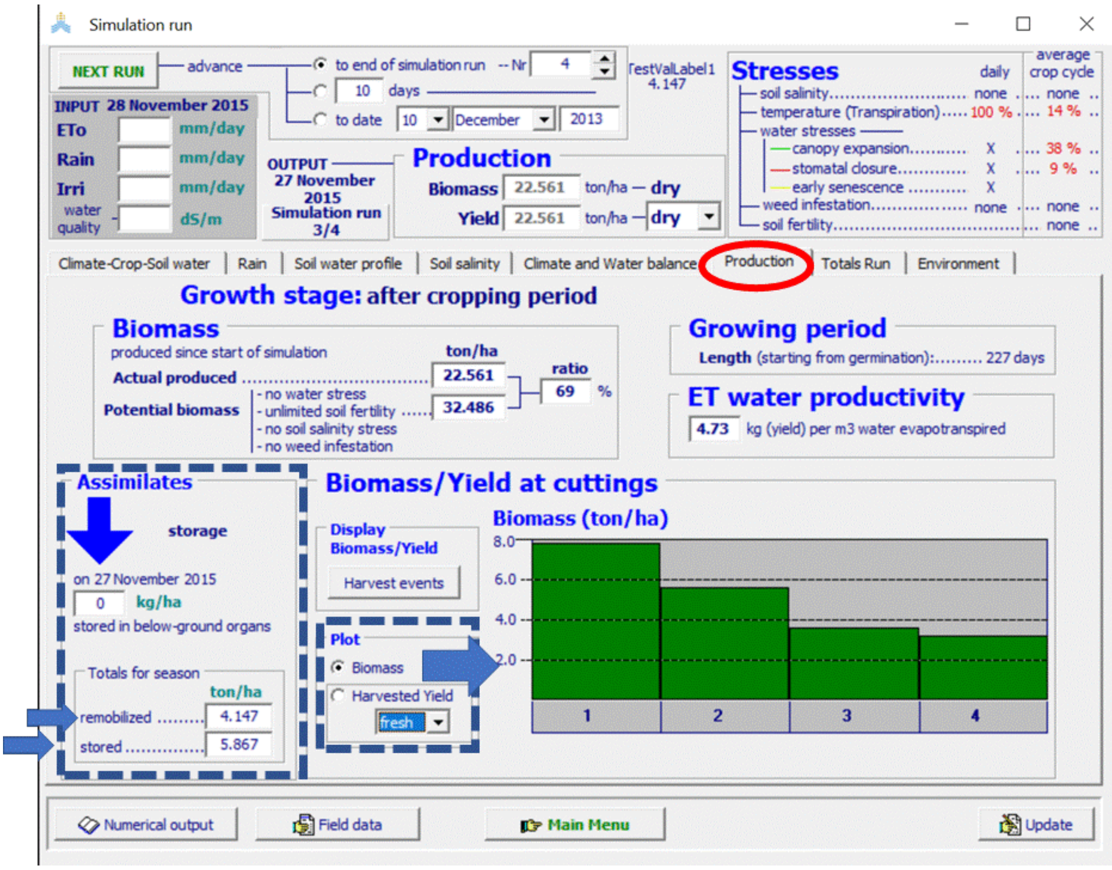

Figure 3. – “Production” tab-sheet of the Run menu with information on the amount of assimilates stored and remobilized, and the harvested biomass or yield at the various cuttings.

In the second sheet of the ***Simulation run*** menu, the user can select a particular parameter (default is ‘Rain’) for further analysis (Tab. 1). The stored biomass is shown as an example in Figures 4 and 5.

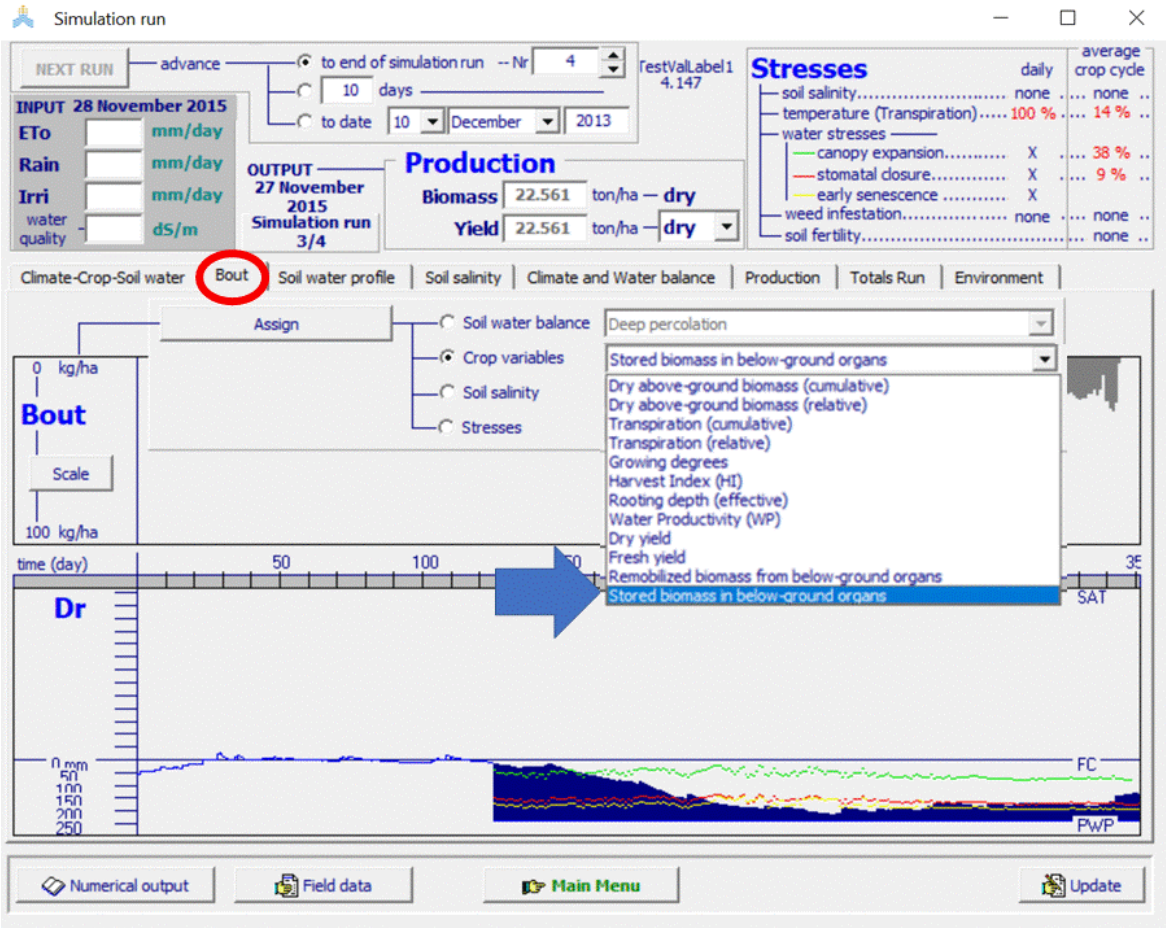

Figure 4. – 2nd tab sheet of the Run menu, in which several displays can be selected

Table 1. – Parameters and variables of the crop that can be selected for display in the Simulation run menu

Symbol	**Description**	**Units**
Crop variables		
Biomass	Dry above ground biomass (cumulative)	ton/ha
B(rel)	Dry above ground biomass (relative)	%
Sum(Tr)	Transpiration (cumulative)	mm
Tr/Trx	Transpiration (relative)	%
GDD	Growing degrees	°C-day
HI	Harvest Index (HI)	%
Z	Rooting depth (effective)	m
WP	Water Productivity (WP)	kg/m^3
Y(dry)	Dry yield	ton/ha
Y(fresh)	Fresh Yield	ton/ha
Bin	Remobilized biomass from below-ground organs	ton/ha
Bout	Stored biomass in below-ground organs	ton/ha

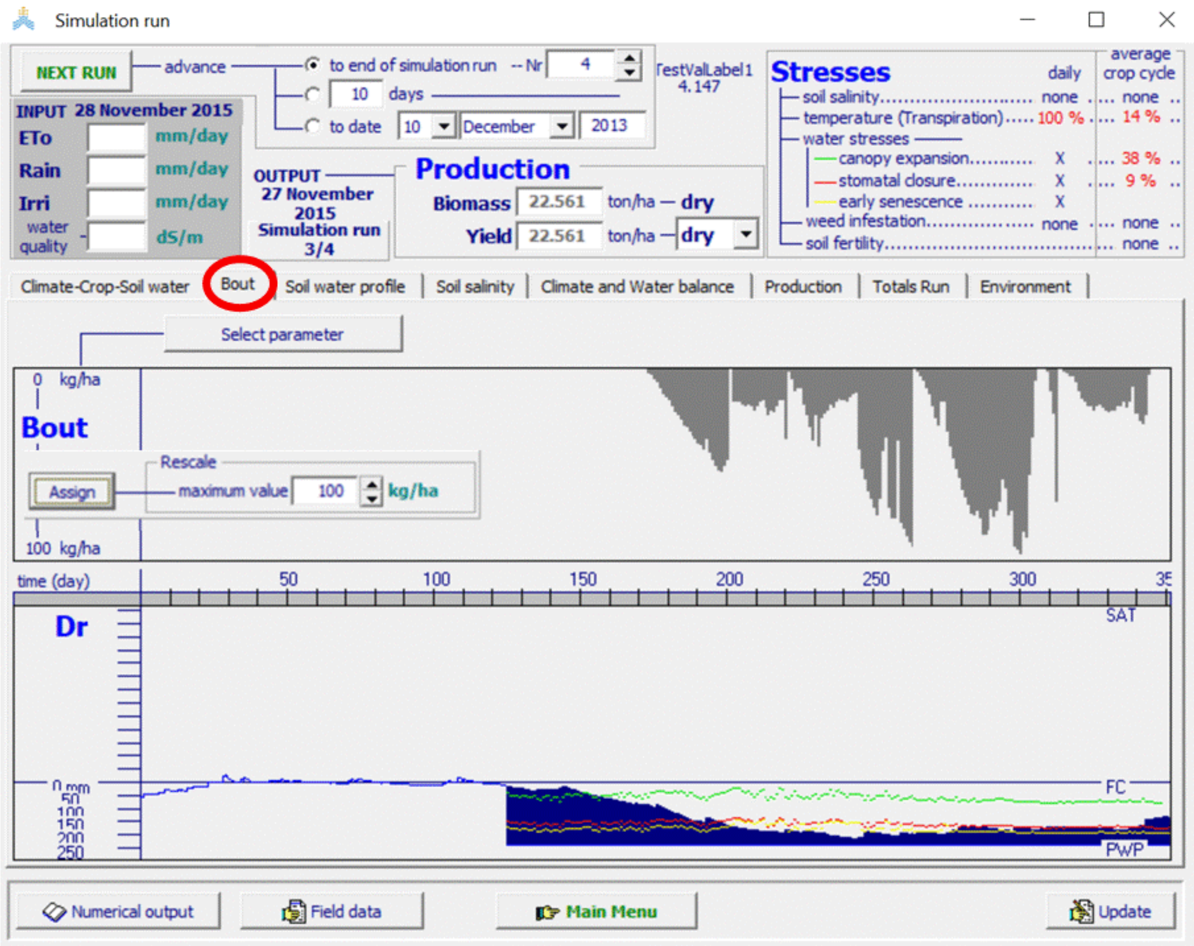

Figure 5. – Graphical display in the 2nd tab sheet of the daily stored biomass in the below-ground organs at the end of the crop cycle.

As can be observed in Fig. 6, the simulated transfer of assimilates can be very different from the theoretical functions (dotted lines) describing the remobilization (Eq. 6) and storage (Eq. 3) of the assimilates, because the transfer can be affected by: (i) cold stress, which might be severe at the start and end of the season; (ii) the frequency of cuttings; and (iii) soil water deficits. The cold and water stresses affect the canopy development, crop transpiration and as such carbon assimilation, while cuttings reduce (Eq. 4) or stimulate (Eq. 8) the transfer of the assimilates.

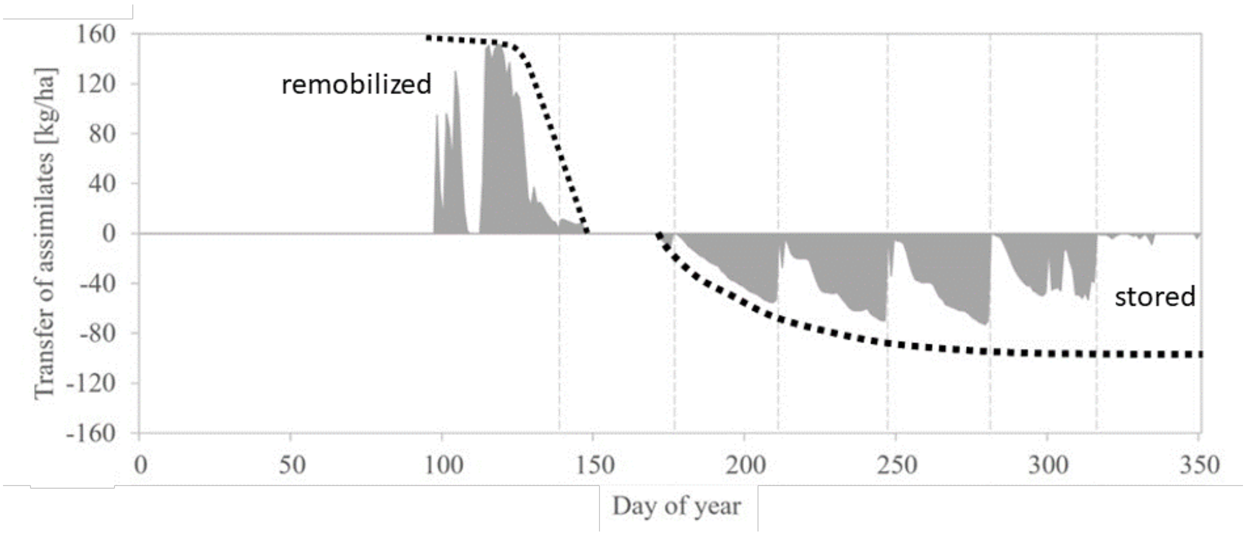

Figure 6. – The simulated (grey area) transfer of assimilates (remobilization (positive) and storage (negative)) with indication (dotted line) of the theoretical (Fig. 1) remobilization (Eq. 6) and storage (Eq. 3) function (adapted from Raes et al., 2023).

1.2 Field management

1.2.1 Canopy Growth Coefficient after cuttings

To avoid overparameterization, the adjustment of the Canopy Growth Coefficient (CGC) after cutting needs no longer be specified in Version 7.1 (option available in the ***Field management*** menu). The crop specific CGC is assumed to describe already the accelerated growth after cutting.

1.2.2 Field management file

Despite the removal of the adjustment of the Canopy Growth Coefficient after cutting (specified in the field management file), the structure of the Field Management file is not altered in Version 7.1. Line 15 (where the adjustment is specified) pesists, but the specified value is no longer considered (Table 2 and 3).

Table 2. – Structure of the field management file (files with extension 'MAN')

Line	Description	Format
1	First line is a description of the file content	String of characters
2	Version number of AquaCrop	Real (1 digit)
3	Percentage (%) of ground surface covered by mulches in the growing period	Integer
4	Effect (%) of mulches on the reduction of soil evaporation, which depends on the type of mulches (see Table 2.)	Integer
5	Degree of soil fertility stress (%)	Integer

	The effect of the selected soil fertility stress on crop production depends on calibration since the biomass – stress relationship (calibrated in the ***Crop characteristic*** menu), determines the corresponding biomass production that can be expected under well-watered conditions for the selected soil fertility stress. The expected biomass production is expressed as a percentage of the maximum biomass production for unlimited soil fertility. In the absence of a calibration, the adjustment of biomass production to the specified soil fertility stress will not be simulated.	
6	Height (m) of soil bunds	Real (2 digits)
7	Surface run-off may or may not be affected by field surface practices. A number (0 or 1) is used as code to specify if surface runoff is affected/prevented by field surface practices: 0: surface runoff is not affected by field surface practices 1 : surface runoff is affected or completely prevented by field surface practices (Default = 0)	Integer
8	Percent increase/decrease of soil profile CN value (is zero (not applicable) when surface runoff is not affected or completely prevented by surface practices)	Integer
9	Relative cover of weeds (%) at canopy closure	Integer
10	Increase/decrease (%) of relative cover of weeds in mid-season	Integer
11	Shape factor of the CC expansion function in a weed infested field	Real (2 digits)
12	Replacement (%) by weeds of the self-thinned part of the CC - only applicable to perennial crops	Integer
13	Multiple cuttings may or may not be considered. A number (0 or 1) is used as code to specify if multiple cuttings are considered: 0: multiple cuttings are considered 1: multiple cuttings are not considered (Default = 0)	Integer
14	Canopy cover (%) after cutting	Integer
15	***Parameter no longer considered***	***Integer***
16	Start day for generating harvests (1 = start of growth cycle)	Integer
17	Number of days in which harvests can be generated (use -9 for total growth cycle)	Integer
18	Timing of multiple cuttings. A number (-9, 0 or 1) is used as code to indicate how the time of harvest is determined: -9: Timing of multiple cuttings: Not Applicable 0: Harvest events are specified by the user 1: Multiple cuttings are generated by a time criterion	Integer

<table>
<tr><td>19</td><td colspan="2">Time criterion for multiple cutting. A number (0 to 5) is used as code to specify the time criterion for multiple cutting:
0: Time criterion: Not Applicable
1: Time criterion: Interval in days
2: Time criterion: Interval in Growing Degree Days
3: Time criterion: Mass (ton/ha) dry above ground biomass
4: Time criterion: Mass (ton/ha) dry crop yield
5: Time criterion: Mass (ton/ha) fresh crop yield</td><td>Integer</td></tr>
<tr><td>20</td><td colspan="2">Final harvest at crop maturity may be or may not be considered, when generating harvests. A number (0 or 1) is used as code to specify if final harvest at crop maturity is considered
0: final harvest at crop maturity is not considered
1: final harvest at crop maturity is considered</td><td>Integer</td></tr>
<tr><td>21</td><td colspan="2">Day number of the reference day for the harvest calendar (use -9 if the reference is the start of the growing period)</td><td></td></tr>
<tr><td colspan="4">
Extra lines provide the details of the Multiple harvests
(only required if multiple cuttings are considered)</td></tr>
<tr><td>22</td><td colspan="2">Empty line</td><td></td></tr>
<tr><td></td><td colspan="2">A. When harvest days are specified (Code is 0 in line 18 for timing of multiple cuttings)</td><td></td></tr>
<tr><td>23</td><td colspan="2">Title (‘Harvest Day’)</td><td>String of characters</td></tr>
<tr><td>24</td><td colspan="2">==============</td><td>String of characters</td></tr>
<tr><td>25</td><td colspan="2">Number of days after the reference day of the 1st harvest</td><td>Integer</td></tr>
<tr><td>26..</td><td colspan="2">Number of days after the reference day of next harvest (if any)</td><td>Integer</td></tr>
<tr><td></td><td colspan="2"></td><td></td></tr>
<tr><td></td><td colspan="2">B. When Multiple cuttings are generated by a time criterion (Code is 1 in line 18 for timing of multiple cuttings)</td><td></td></tr>
<tr><td></td><td>Title</td><td>Time criterion (line 19)</td><td></td></tr>
<tr><td>23</td><td>‘From day Interval (days)’
‘From day Interval (GDDays)’
‘From day Dry biomass (ton/ha)’
‘From day Dry yield (ton/ha)’
‘From day Fresh yield (ton/ha)’</td><td>1
2
3
4
5</td><td>String of characters</td></tr>
<tr><td>24</td><td colspan="2">============================</td><td>String of characters</td></tr>
<tr><td>25</td><td colspan="2">Day Number Interval
or
Day Number Biomass or Yield</td><td>Integer/ Integer
or
Integer/Real(3 digits)</td></tr>
<tr><td>26..</td><td colspan="2">Etc. ..</td><td></td></tr>
</table>

Table 3. – Example of field management file

Soil fertility stress, organic mulches, practices affecting surface run-off, weed infestation and multiple harvests

```
 Description…
     7.1       : AquaCrop Version (August 2023)
     0         : percentage (%) of ground surface covered by mulches IN growing period
    50         : effect (%) of mulches on reduction of soil evaporation
     0         : Non-limiting soil fertility
     0.00      : height (m) of soil bunds
     1         : surface runoff affected or completely prevented by field surface practices
     0         : N/A (surface runoff is not affected or completely prevented)
     0         : relative cover of weeds at canopy closure (%)
     0         : increase of relative cover of weeds in mid-season (+%)
    -0.01      : shape factor of the CC expansion function in a weed infested field
   100         : replacement (%) by weeds of the self-thinned part of the CC - only for perennials
     1         : Multiple cuttings are considered
    25         : Canopy cover (%) after cutting
    -9         : parameter no longer considered
     1         : First day of window for multiple cuttings (1 = start of growth cycle)
    -9         : Number of days in window for multiple cuttings (-9 = total growth cycle)
     0         : Multiple cuttings schedule is specified
     0         : Time criterion: Not Applicable
     0         : final harvest at crop maturity is not considered
 40909         : dayNr for Day 1 of list of cuttings

 Harvest Day
==============
   174
   203
   244
   293
```

No soil fertility stress, no organic mulches, no practices affecting or preventing surface run-off, perfect weed management and no multiple harvests

```
 Description….
     7.1       : AquaCrop Version (August 2023)
     0         : percentage (%) of ground surface covered by mulches IN growing period
    50         : effect (%) of mulches on reduction of soil evaporation
     0         : Non-limiting soil fertility
     0.00      : height (m) of soil bunds
     0         : surface runoff NOT affected by field surface practices
     0         : N/A (surface runoff is not affected or completely prevented)
     0         : relative cover of weeds at canopy closure (%)
     0         : increase of relative cover of weeds in mid-season (+%)
    -0.01      : shape factor of the CC expansion function in a weed infested field
   100         : replacement (%) by weeds of the self-thinned part of the CC - only for perennials
     0         : Multiple cuttings are not considered
    30         : Canopy cover (%) after cutting - not considered
    -9         : parameter no longer considered
     1         : First day of window for multiple cuttings (1 = start of growth cycle)
    -9         : Number of days in window for multiple cuttings (-9 = total growth cycle)
    -9         : Timing of multiple cuttings: Not Applicable
     0         : Time criterion: Not Applicable
     0         : final harvest at crop maturity is not considered
    -9         : Start of the growing cycle is Day 1 in list of cuttings
```

1.3 Evaluation

To evaluate the simulation of alfalfa, yield data collected in Louvain-La-Neuve (Belgium), Isparta (Turkey), and Ottawa (Canada) for different alfalfa cultivars, various years and field and irrigation management strategies were used. To assess the accuracy and robustness of the simple assimilate remobilization process, simulations were run for the three different environments with a common set of crop parameters which were parameterized (Raes et al., 2023). The dispersion between the observed and simulated cumulative dry above-ground biomass during the growing cycle was small ($r^2 = 0.97$; nRMSE = 11%; Nash-Sutcliffe model EF = 0.97), and a systematic over- or underestimation by the model was not observed (Willmott's index of agreement, d = 0.99).

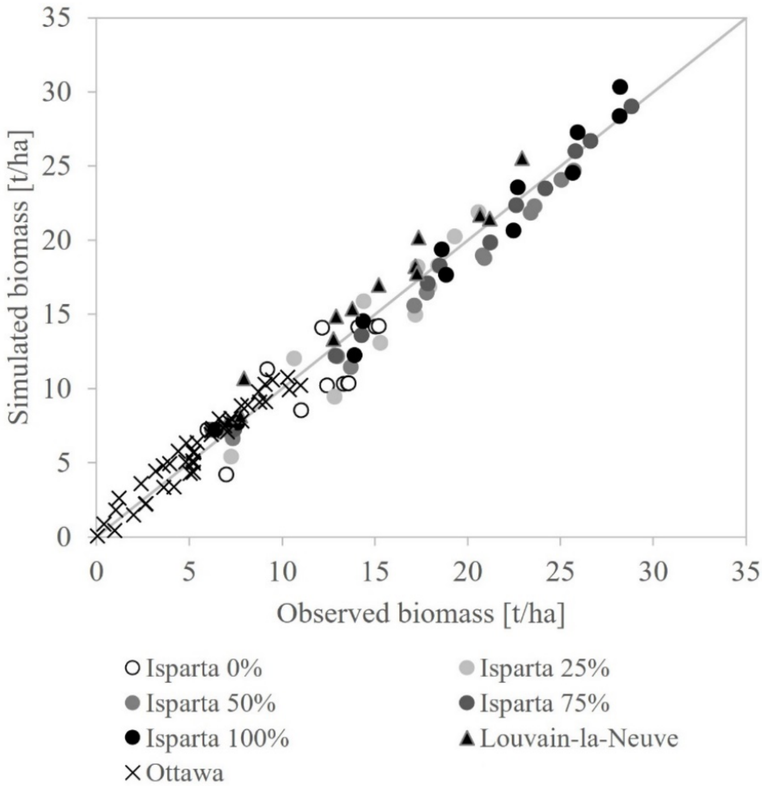

Figure 7. – Observed and simulated cumulative dry above ground biomass, increasing at each harvest, for alfalfa for all years and irrigation strategies for Louvain-La-Neuve (triangles), Isparta (circles), and Ottawa (crosses).

The comparisons between measurements and the simulations indicated that AquaCrop can well predict the total yield of alfalfa that can be expected in various climates and environments, with and without water stress and soil fertility stress, for three different alfalfa cultivars.

1.4 Reference

Raes, D., Fereres, E., García Vila, M., Curnel, Y., Knoden, D., Kale Çelik, S., Ucar, Y., Türk, M., Wellens, J. 2023. Simulation of alfalfa yield with AquaCrop. Agricultural Water Management (284), 108341. https://doi.org/10.1016/j.agwat.2023.108341.

2. Adjustment of the reference Harvest Index for inadequate photosynthesis

During the yield formation stage, the Harvest Index for root/tuber crops and fruit/grain producing crops, gradually increases until the Reference Harvest (HIo) is reached at about the end of the crop growing cycle. However, when due to early canopy senescence, the remaining green canopy cover (CC) drops below a threshold (CC_{min}), the Harvest Index can no longer increase (Fig. 8). In that case there is not enough green canopy left, so that photosynthesis becomes insufficient.

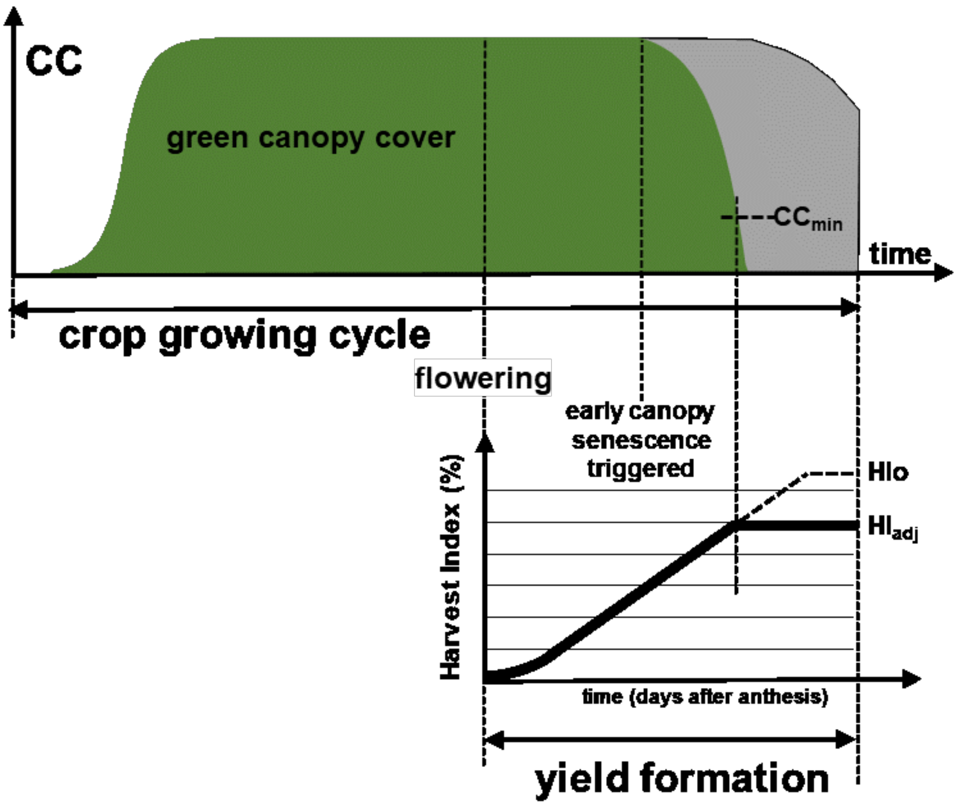

Figure 8. – Harvest index development (bold line) when insufficient green canopy cover remains during yield formation for fruit/grain producing crops.

In Version 7.1, this adjustment remains valid but is now limited to the case of a decline of the green canopy cover due to severe water stress, triggering an early senescence. This restriction avoids a zero HI (and no yield formation) when CC is small (as a result of stresses) at the start of yield formation (tuber formation or root enlargement for root/tuber crops or flowering for fruit/grain crops). The adjustment of HI is only valid for root/tuber crops and fruit/grain producing crops, and does not apply to leafy vegetable and forage crops.

3. Update of the Mauna Loa CO2 file

The annual mean concentrations of CO_2 levels measured at the Mauna Loa Observatory are available in the 'MaunaLoa.CO2' file in the SIMUL subdirectory of AquaCrop. The concentrations for the various years are used to adjust the normalized biomass water productivity (WP*) for atmospheric [CO_2] of the year in which the crop was or will be cultivated. For the future years an increase of 2.0 ppm is still assumed, which might be valid for the next decade. The observed CO_2 concentrations up to 2022 have been updated (Table 1) with the latest published results on the NOAA website:
http://co2now.org/Current-CO2/CO2-Now/noaa-mauna-loa-co2-data.html

Table 1. – The default CO_2 concentrations in the MaunaLoa.CO2 file

Year	Annual Mean [CO_2] ppm	Year	Annual Mean [CO_2] ppm	Year	Annual Mean [CO_2] ppm
1902	297.4	1969	324.62	1997	363.88
1905	298.2	1970	325.68	1998	366.84
1912	300.7	1971	326.32	1999	368.54
1915	301.3	1972	327.46	2000	369.71
1924	304.5	1973	329.68	2001	371.32
1926	305.0	1974	330.19	2002	373.45
1929	305.2	1975	331.12	2003	375.98
1932	307.8	1976	332.03	2004	377.70
1934	309.2	1977	333.84	2005	379.98
1936	307.9	1978	335.41	2006	382.09
1938	310.5	1979	336.84	2007	384.02
1939	310.1	1980	338.76	2008	385.83
1940	310.5	1981	340.12	2009	387.64
1944	309.7	1982	341.48	2010	390.10
1948	310.7	1983	343.15	2011	391.85
1953	311.9	1984	344.85	2012	394.06
1954	314.1	1985	346.35	2013	396.74
1958	315.29	1986	347.61	2014	398.81
1959	315.98	1987	349.31	2015	401.01
1960	316.91	1988	351.69	2016	404.41
1961	317.64	1989	353.20	2017	406.76
1962	318.45	1990	354.45	2018	408.72
1963	318.99	1991	355.70	2019	411.66
1964	319.62	1992	356.54	2020	414.24
1965	320.04	1993	357.21	2021	416.45
1966	321.37	1994	358.96	2022	418.57
1967	322.18	1995	360.97	2025	424.57
1968	323.05	1996	362.74	2099	572.57

4. List of the updates in the AquaCrop open-source Version

4.1 Fine-tuning of the simulation of perennial herbaceous forage crops

- Fine-tuning of the transfer of assimilates between the above and below-ground organs of a perennial forage crop, such as alfalfa. It consists of adjustments in units GLOBAL, TempProcessing, RUN and SIMUL.

- The procedure adjusting the calendar days for a perennial crop starting as regrowth at the start of the growing cycle, requires (as input) also the required growing degree days to reach the initial green canopy cover (Global variable: Crop.GDDaysToCCini). Adjusted input in the procedures 'AdjustCalendarCrop' and 'AdjustCalndarDays'. Adjustment in unit TempProcessing.

- Correction of the calculation of the required time (in calendar days) from the start of the growing cycle to the start of the senescence for perennial forage crops (Procedure AdjustCropFileParameters). Adjustment in TempProcessing.

- Making the GDDays undefined for the time from the start of the growing cycle to (i) its end and (ii) to the start of the senescence, if the calculation mode is 'Calendar days' (in the procedure SaveCrop). Adjustment in unit GLOBAL.

- In the calculation procedure for the time to the initial canopy (TimeToCCini), the Elapsed time is no longer explicitly calculated in the procedure but given by the function 'DaysToReachCCwithGivenCGC' (which is the same since the canceled calculation lines are identical to what is specified in the procedure 'DaysToReachCCwithGivenCGC'. This has no effect on the simulations. Adjustment in unit GLOBAL.

4.2 Adjustment of the reference Harvest Index for inadequate photosynthesis

- Adjustments in units GLOBAL, and SIMUL.

4.3 Eliminating the risk of a division by zero

- To avoid a division by zero, the calculation of the start value for the soil evaporation in Stage 2 is adjusted. The value is put at zero when the soil is too dry (Procedure PrepareStage2). Adjustment in unit SIMUL.

4.4 Cosmetic changes and cleanup, without affecting the simulation results

- **Updated AquaCrop Version Number and Date** (Version 7.1 – August 2023) in the heading of the output files. This does not affect the simulation results. Adjustments in RUN.

- Removal of the **PROCEDURE 'HIadjColdHeat'**, displaying the cold or heat stress affecting pollination during the flowering period. This procedure is only required to display the stress in some of the menus of the Aquacrop with the user interface (when displaying the potential production for the selected cultivar, in the specified climate and for the given planting date). The removal does not affect the simulation results. Adjustment in unit TempProcessing.

- Removal of the **variable 'CCxWitheredTpot"** since it is never used (on the other hand the Global variable 'CCxWitheredTpotNoS' remains). The removal does not affect the simulation results. Adjustment in units SIMUL and RUN.

- When **intermediate results** (daily, 10-daily, or monthly) are requested in the seasonal output file, the daily, 10-daily, or monthly value of the Harvest Index (HI) is presented. This does not affect the simulation results. Adjustment in unit RUN.

- In case **Soil Fertility stress** is considered and the crop is calibrated for soil fertility stress, the specified soil fertility stress should always be given as output, even if the biomass production at the beginning of the crop growing cycle is still very small (although it does not affect the simulation results, it was assumed to be zero in version 7 as long as the biomass production did not exceed 1 kg/ha). Adjustment in unit SIMUL.

- The status report (file: "**ListProjectsLoaded.OUT**" in the OUTP directory), provides information about the specific missing environmental or simulation file(s) for each of the project files that failed to load. In case the project file failed to load due to (a) missing file(s), the status report provides information about the specific missing environmental or simulation file(s) in the particular Run. After finding errors in a Simulation Run, the program no longer checks subsequent runs (Table 2).

Table 2. – Example of the Status Report ('ListProjectsLoaded.OUT' file) in the OUTP directory of an unsuccessfully loaded project

```
Intermediate results: monthly results

Daily output results: None created

Particular results:
1. - biomass and yield at multiple cuttings (for herbaceous forage crops)
2. - evaluation of simulation results (when Field Data)

Projects handled:
1. - Project123.PRM : Project NOT loaded - Missing Environment and/or Simulation file(s) in Run number 3
        - Cannot find file(s) for: Crop (CRO), Field Management (MAN), Soil profile (SOL), Field data (OBS),
        - Check file Name(s), Path(s) or Structure of project file.
```

- Updated files in the **SIMUL subdirectory** accompanying the AquaCrop executable of the stand-alone versions:

  The AquaCrop executable of the stand-alone versions is accompanied by the subdirectories:

  - **LIST** (containing the pre-defined project files);
  - **PARAM** (containing the pre-defined program parameters files. In absence of a program parameter file, the project will run with the default settings for the program parameters);
  - **OUTP** (containing the seasonal and the requested daily and/or particular simulation results); and
  - **SIMUL** (containing options for output and the files: MaunaLoa.CO2, and the default Crop and Soil files):
    - The published (NOAA website) mean annual CO_2 concentration of 2022 has been added to the **MaunaLoa.CO2 file**;
    - The AquaCrop Version Number and Date has been updated in the **DEFAULT.CRO** and **DEFAULT.SOL** files (Version 7.1 – August 2023).

- The reading of optional program parameter files *PP1 or *PPn was not functional in Version 7.0 which is corrected in Version 7.1.