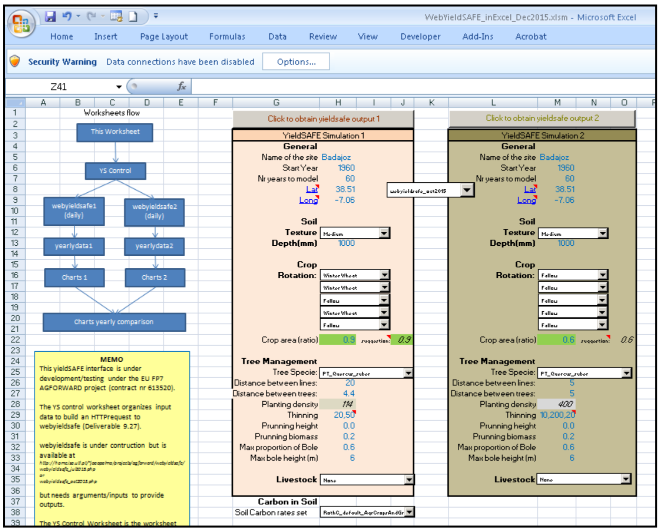

Yield-SAFE Model Improvements

Project name	AGFORWARD (613520)
Work-package	6: Field- and Farm-scale Evaluation of Innovations
Deliverable	Milestone 29 (6.4): Yield-SAFE model improvements
Date of report	20 April 2016; updated 16 June 2016
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Contents

AGFORWARD (Grant Agreement N° 613520) is co-funded by the European Commission, Directorate General for Research & Innovation, within the 7th Framework Programme of RTD. The views and opinions expressed in this report are purely those of the writers and may not in any circumstances be regarded as stating an official position of the European Commission.

1 Context

The AGFORWARD research project (January 2014-December 2017), funded by the European Commission, is promoting agroforestry practices in Europe that will advance sustainable rural development. The project has four objectives:

1. to understand the context and extent of agroforestry in Europe,
2. to identify, develop and field-test innovations (through participatory research) to improve the benefits and viability of agroforestry systems in Europe,
3. to evaluate innovative agroforestry designs and practices at a field-, farm- and landscape scale, and
4. to promote the wider adoption of appropriate agroforestry systems in Europe through policy development and dissemination.

The third objective is addressed partly by work-package 6 which focuses on the field- and farm-scale evaluation of agroforestry systems and innovations. One of the models being used for simulating agroforestry systems is Yield-SAFE (van der Werf et al. 2007), developed under the SAFE project (Dupraz et al. 2005).

The Yield-SAFE model is a parameter-sparse, process-based dynamic model for predicting resource capture, growth, and production in agroforestry systems that has been frequently used by various research organisations in recent years.

Within the AGFORWARD project, the model has been enhanced to more accurately predict the delivery of ecosystem services provided by agroforestry systems relative to forestry and arable systems. This report also summarizes the new developments made in the model which were partially implemented during AGFORWARD modelling workshops held in 1) Monchique in Portugal in May 2015, 2) Kriopigi in Greece in June 2015, 3) Lisbon in Portugal in November 2015 and 4) Lisbon in February 2016.

This report has been partially published as:

Palma JHN, Graves AR, Crous-Duran J, Paulo JA, Oliveira TS, Garcia de Jalon S, Kay S, Burgess PJ, (2016), Keeping a parameter-sparse concept in agroforestry modeling while integrating new processes and dynamics: New developments in Yield-SAFE, III EURAF Conference, Montpellier 23-25 May 2016.

2 Crop

2.1 Transpiration

The crop water uptake state variable (W_c) was a simple relationship between the daily biomass growth and the water use efficiency parameter. Formerly, for the same crop, there was a need to increase the water needed to produce the same amount of biomass (γ_c) for drier Mediterranean climates relative to more humid Atlantic climates. This dual calibration was required mainly due to a higher vapour pressure deficit (VPD) in drier regions. The water use efficiency of the crop is now a reference for a VPD of 1 kPa while the water use responds to the daily VPD calculations. The decision to link the water uptake to VPD led to the increase of climate inputs (minimum temperature, maximum temperature and relative humidity), but the use of these climate variables also increased the potential to assess other aspects of the ecosystem services provided by agroforestry systems. The integration of these relationships was based on Allen et al. (1998) for the VPD calculations and

Tanner and Sinclair (1983) for the water use relationship to VPD. The new state variable and equations used in Yield-SAFE related to crop transpiration are provided in Table 1.

Table 1. New state variables and equations in Yield-SAFE related to crop transpiration

Additional inputs	
*T*min	Minimum temperature (°C)
*T*max	Maximum temperature (°C)
*RH*mean	Mean relative humidity (%)
New state variables	
*E*s	Mean saturation pressure (kPa)
*E*a	Actual vapour pressure (kPa)
VPD	Vapour pressure deficit (kPa)
UME_{Fru}	Utilizable metabolizable energy from fruit yield (MJ ha^{-1})
Interaction with Yield-SAFE state variables	
CanopyCover	
B_t	Above ground tree biomass (g $tree^{-1}$)
ρ	Tree density (trees ha^{-1})
Equations	
$$Es = \frac{0.6108\exp\left[\frac{17.27\,T\max}{T\max + 237.3}\right] + 0.6108\exp\left[\frac{17.27\,T\min}{T\min + 237.3}\right]}{2}$$ $$Ea = \frac{RHmean}{100} * Es$$ $$VPD = Es - Ea$$	
Equations updates in Yield-SAFE	
W_c	= *Wc* * *VPD*

2.2 Maintenance respiration

Unlike annual crops, grass is a perennial crop. As Yield-SAFE did not previously account for crop respiration, the original Yield-SAFE set-up can result in an unrealistic yearly annual accumulation of biomass in the system if the grass was not harvested. Therefore a crop respiration rate was added for the modelling of grass, enabling the reduction of biomass when the daily growth is lower than the carbon used for biomass maintenance (Table 2). The integration was made using the equation proposed by Thornley (1970).

Table 2. New state variables and equations in Yield-SAFE related to crop maintenance respiration

Additional parameters	
Kmainc_m	Maintenance coefficient representing the amount of carbon respired to maintain existing biomass ($g^{-1}g^{-1}$)
Kmainc_g	Amount of carbon respired per unit of carbon used in growth (g^{-1} g^{-1})
New state variables	
R_c	Crop maintenance respiration ($g\ m^{-2}$)
Interaction with Yield-SAFE state variables	
B_c	Crop biomass ($g\ m^{-2}$)
dB_c^{Act}	Actual growth ($g\ m^{-2}$)
Equations	
$R_{c\,k} = Kmainc\_m\, B_{c\,k-1} + Kmainc\_g\, dB_c^{Act}{}_{k-1}$ k-1 denotes the previous day	
Equations updates in Yield-SAFE	
dB_c^{Act}	$= dB_c^{Act} - Rc$

Note: Values of *Kmain_m* = 0.037 and *Kmain_g* = 0.54 can be used for grassland as suggested by Reekie and Redmann (1987).

2.3 Carbon inputs to soil

After harvest, crop roots are considered as a carbon input to the soil. Similarly to the new fine root tree component, crop root biomass is estimated as a root-to-shoot ratio, which by using a carbon content in roots, will estimate the carbon being added to the soil in the day of harvest (Table 3).

Table 3. New state variables and equations in Yield-SAFE related to carbon inputs to soil

Additional parameters:	
RSR_c	Root to shoot ratio (0-1)
f^{CCRc}	proportion of carbon content in crop roots (0-1)
New state variables	
Bc_{Roots}	Biomass of crop roots ($g\ m^{-2}$)
C_{RMc}	Carbon content in crop roots ($kgC\ ha^{-1}$)
Interaction with Yield-SAFE state variables	
B_c	Above ground crop biomass ($g\ m^{-2}$)
Equations	
$Bc_{Roots} = B_c * RSR_c$ $C_{RMc} = B_{cRoots} * f^{CCRc}$	
Equations updates in Yield-SAFE	
None	

3 Tree

3.1 Leaf fall

Trees can affect crop production negatively through competition for light, nutrients and water, as well as positively through increased input of biomass from leaves and roots that often enhance nutrient cycling (Rao et al. 1998). Although growth impact nutrients (i.e. N, P, K) are not implemented in Yield-SAFE, carbon dynamics are now simulated. Leaf fall and leaf biomass is now incorporated in the soil carbon model as plant input material in the soil carbon dynamics module (Section 4.2) using the specific leaf area (*SLA*). The biomass of leaves to fall depends on i) the proportion of leaf area that will fall (values <1 can define perennials), ii) the day of year when leaves start to fall ($DOY_{\text{LeafFallStart}}$) and iii) the number of days leaves are falling ($Leaf_{\text{FallingDays}}$). The amount of biomass falling from the tree is evenly distributed between $Leaf_{\text{FallingDays}}$, and is subtracted from the tree biomass state variable. The carbon from leaf fall (C_{LF}) is given by a parameter (f^{CCL}) defining the fraction of carbon content in the biomass of leaves, which converted to a per hectare basis becomes the input to the soil carbon module (Table 4).

Table 4. New state variables and equations in Yield-SAFE related to tree leaf fall

Additional parameters	
SLA	Specific leaf area (cm^2 g^{-1})
$f^{LeafFall}$	Proportion of leaf area that will fall (0-1)
$\text{DOY}_{\text{LeafFallStart}}$	Day of year when leaves no longer grow and start to fall (1-365)
$Leaf_{\text{LeafFallEnd}}$	Day of year when leaves no longer fall (1-365)
f^{CCL}	Proportion of carbon in leaf biomass (0-1)
New state variables	
$LA_t\text{DOY}_{\text{LeafFallStart}}$	Leaf area when DOY is $\text{DOY}_{\text{LeafFallStart}}$ (m^2 tree^{-1})
f^{LS}	Fraction of leaves that reached the soil (g tree^{-1})
B_{LeafFall}	Cumulative biomass of leaf fall (g tree^{-1})
C_{LF}	Carbon incorporated in soil from leaf fall (Kg C ha^{-1})
Interaction with Yield-SAFE state variables	
DOY	Day of Year (1-365)
LA_{t}	Leaf area of the tree (m^2 tree^{-1})
B_{t}	Above ground tree biomass (g tree^{-1})
ρ	Tree density (trees ha^{-1})
Equations	
$$LA_t\text{DOY}_{\text{LeafFallStart}_k} = \begin{cases} LA_{t_{k-1}} * f^{LeafFall}, & if\ \text{DOY} = \text{DOY}_{\text{LeafFallStart}} \\ LA_t\text{DOY}_{\text{LeafFallStart}_{k-1}}, & if\ DOY_{LeafFallStart} < \text{DOY} \leq DOY_{LeafFallEnd} \\ 0 & otherwise \end{cases}$$ $$f_k^{LS} = \begin{cases} \dfrac{DOY - DOY_{LeafFallStart}}{DOY_{LeafFallEnd} - DOY_{LeafFallStart}}, & DOY_{LeafFallStart} \leq \text{DOY} \leq DOY_{LeafFallEnd} \\ 0, & otherwise \end{cases}$$ $$B_{LeafFall} = \frac{f^{LS} * LA_t\text{DOY}_{\text{LeafFallStart}_k} * 10000}{SLA}$$ $$C_{LF} = \frac{(B_{LeafFall_k} - B_{LeafFall_{k-1}}) * f^{CCL} * \rho}{1000}$$	
Equations updates in Yield-SAFE	
B_{t}	$= B_t - (B_{LeafFall_k} - B_{LeafFall_{k-1}}$
LA_{t}	$= LA_t - \left(f_k^{LS} - f_{k-1}^{LS}\right) * LA_t\text{DOY}_{\text{LeafFallStart}_k}$

3.2 Fine root mortality

Fine root mortality also adds plant material to the soil carbon module. However the turnover rate depends on various factors occurring in soil conditions, e.g. water logging, soil temperature, nutrient availability, mycorrhizae symbiosis, tree physiology and phenology (Pregitzer 2002). Yield-SAFE simplifies this dynamics with an approach that all fine roots will die and become incorporated in soil for decomposing. The timing of the incorporation of fine roots is also complex and arguable but Yield-SAFE simplifies this by linking to the leaf fall period on the basis of “biomass balance” between above and belowground, i.e. fine roots biomass is calculated at the time when leaf fall starts, and root mortality follows the same time pattern of leaf fall.

Root biomass now is estimated as a root-to-shoot ratio, frequently used values are 0.2 and 0.25 for conifers and broadleaf respectively (IPCC 2006). Some literature supports that fine roots can be a proportion of root biomass in the same proportion that leaves have in aboveground biomass (Madeira et al. 2002), therefore in Yield-SAFE, fine roots can be estimated either based on the proportion of leaves to tree aboveground biomass or, alternatively, a user can define the proportion of fine roots in the belowground biomass (Table 5).

Table 5. New state variables and equations in Yield-SAFE related to tree fine root mortality

Additional parameters:	
RSR	Root to shoot ratio (0-1)
f^{FR}	Proportion of fine roots from root biomass
f^{CCRt}	proportion of carbon content in fine roots of the tree (0-1)
New state variables	
$B_{FineRoots}$	Biomass of fine roots (g tree^{-1})
C_{RM}	Carbon incorporated in soil from root mortality (Kg ha^{-1})
Interaction with Yield-SAFE state variable	
$B_{LeafFall}$	Biomass of leaf fall (g tree^{-1})
B_t	Above ground tree biomass (g tree^{-1})
ρ	Tree density (trees ha^{-1})
Equations	
$B_{FineRoots} = B_t * RSR * \frac{B_{LeafFall}}{B_t}$ or $B_{FineRoots} = B_t * RSR * f^{FR}$ $C_{RM} = B_{FineRoots} * f^{CCRt}$	
Equation updates in Yield-SAFE	
None (in Yield-SAFE, tree biomass equations only model aboveground biomass)	

3.3 Cork

If the user is simulating cork oak stands (*Quercus suber* L.) and needs to estimate cork production, we have set the model to estimate cork production based on equations developed by Paulo and Tomé (2014) for the estimation of virgin cork weight (cork resulting from the first cork extraction) and by Paulo and Tomé (2010) for the estimation of non-virgin or mature cork (Table 6).

Table 6. New state variables and equations in Yield-SAFE related to cork production

Additional parameters	
$DOY_{debarking}$	Day of year when debarking takes place (1-365)
dcoef	Debarking coefficient (ratio between vertical debarking height and perimeter at breast height with cork)
H_{debark}	Vertical debarking height (cm)
PBH_{min}	Minimum perimeter at breast height for debarking (cm)
*debark*Calendar	Years of age for each cork extraction (years,years,years, …)
$Age_{startdeb}$	Starting debarking tree age
New state variables	
d	Diameter at breast height with virgin cork (cm)
Debarknr	Sequential number of debarking event (0,1, …)
Daydebark	Day of debarking (0 = true or 1 = false)
wcv	Dry weight of extracted virgin cork (kg)
wca	Dry weight of extracted mature cork (kg)
wc	Dry weight of extracted cork (kg)
Interaction with Yield-SAFE state variables	
dbh	Tree diameter at breast height (without cork) (cm)
DOY	Day of Year (1-365)
B_t	Above ground tree biomass (g tree^{-1})
Equations	

$$d = \begin{cases} d = \dfrac{dbh + 1.5276}{0.8321}, & if\ dbh > 7.5 \\ d = dbh, & otherwise \end{cases}$$

$$Day_{debark} = \begin{cases} 1, & if\ d > \dfrac{PBH_{min}}{\pi}\ and\ DOY = DOY_{debarking} \\ 0, & otherwise \end{cases}$$

$$Debark_{nr} = \begin{cases} Debark_{nr} + 1, & if\ DOY = DOY_{debarking} \\ Debark_{nr}, & otherwise \end{cases}$$

$$wcv = \begin{cases} -19.6723 + 0.00734\, dbh^2 + 4.25364 \ln(\mathrm{dcoef}), & if\ Debark_{nr} = 1\ and\ if\ DOY = DOY_{debarking} \\ 0, & otherwise \end{cases}$$

$$wca = \begin{cases} 0.0203\, dbh^{1.9843}, & if\ Debark_{nr} > 1\ and\ if\ DOY = DOY_{debarking} \\ 0, & otherwise \end{cases}$$

$$\mathrm{wc} = \mathrm{wcv} + \mathrm{wca}$$

Equations updates in Yield-SAFE	
B_t	= *B*t – (*wc* * 1000)

The model simulates the first debarking when the tree diameter is above a certain threshold of a perimeter at breast height (PBH_{min}; cm). For example, PBH_{min} is defined by Portuguese law as 70 cm. The interval between consecutive cork extraction events (cork debarking rotation) is defined for 9 years, as this is the minimum interval allowed by Portuguese and Spanish national legislation and is frequently used by managers, although this calendar can be defined by the user (debarkCalendar). After each cork extraction, cork biomass is subtracted from the tree biomass state variable.

3.4 Fruit production

Fruit production is now considered as a linear relationship between the tree leaf area and a parameter defining the productivity (Table 7). The fruit is defined in terms of energy content and the falling period simulated as a normal distribution. This will enable the estimation of livestock carrying capacity and also the number of sequential grazing days considering the fruit energetic availability.

Table 7. New state variables and equations in Yield-SAFE related to fruit production

Additional parameters	
Fru_{UME}	Fruit utilisable metabolisable energy content (MJ Mg^{-1})
Fru_{p}	Fruit productivity from canopy (g m^{-2})
$DOY_{LeafFallStart}$	Day of year when leaves start to fall (1-365)
$Fru_{FallingDays}$	Number of days when 95% of the fruit have fallen
$Fru_{DOYPeak}$	DOY when fruit falling peak occurs (1-365)
Fru_{Weight}	Weight of a single fruit (g)
New state variables	
DOY_{norm}	False DOY for applying normal distribution
$Fru_{FallPDOY}$	Fruit fall probability in a specific DOY (0-1)
Fru_{Y}	Fruit yield (kg ha^{-1})
UME_{Fru}	Utilizable metabolisable energy from fruit yield (MJ ha^{-1})
Interaction with Yield-SAFE state variables	
DOY	Day of year (1-365)
CanopyCover	Tree canopy cover of the stand (m^2 $tree^{-1}$)
B_t	Above ground tree biomass (g $tree^{-1}$)
ρ	Tree density (trees ha^{-1})
Equations	
$$DOY_{norm} = \begin{cases} DOY + 365 & if\ Fru_{\mathrm{DOYPeak}} + Fru_{\mathrm{FallingDays}} < DOY + 365 \\ DOY & if\ Fru_{\mathrm{DOYPeak}} + Fru_{\mathrm{FallingDays}} < DOY + 365 \end{cases}$$ $$Fru_{FallPDOY} = \frac{1}{\frac{Fru_{FallingDays}}{4}\sqrt{2\pi}} e^{-\frac{(DOY_{norm} - Fru_{DOYPeak})^2}{2(\frac{Fru_{FallingDays}}{4})^2}}$$ $$Fru_{Y} = CanopyCover * \frac{Fru_{p}}{1000} * \rho * Fru_{FallPDOY}$$ $$UME_{Fru} = Fru_{Y} * Fru_{UME} * 1000$$ Note: The normal distribution mean is defined as $Fru_{DOYPeak}$ and the standard deviation as $Fru_{FallingDays}/4$.	
Equations updates in Yield-SAFE	
None	

3.4.1 *Carrying capacity sequential days based on fruit production*

Fruit production is an important energetic asset for some tree species. In this improvement, the fruit production is linked to its energy content and to the livestock energy requirements. There are two main indicators: i) the number of sequential days the daily tree fruit production can handle one livestock unit and ii) given a livestock carrying capacity provided by the user, how many sequential days the system can provide.

Table 8. New state variables and equations in Yield-SAFE related to the carrying capacity sequential days based on fruit production

Additional parameters	
Fru_{UME}	Fruit utilisable metabolisable energy content (MJ Mg^{-1})
LMER	Livestock unit utilisable metabolisable energy requirement (MJ d^{-1})
SLMER	Selected livestock utilisable metabolisable energy requirement (MJ d^{-1})
SLDCC	Selected livestock carrying capacity
ULU	User defined livestock units (LU ha^{-1})
New state variables	
UME_{Fru}	Daily Utilizable metabolisable energy from fruit yield (MJ ha^{-1})
UME_{FruY}	Yearly cumulative utilizable metabolisable energy from fruit yield (MJ ha^{-1})
$CCFru_{LU}$	Carrying capacity of livestock units from fruit yield (LU ha^{-1})
$CCFru_{SLU}$	Carrying capacity of selected livestock from fruit yield (SL ha^{-1})
CCSDFru	Counter for sequential carrying capacity above 1 livestock unit from fruit yield (nr days)
$CCSDFru_{yr}$	Carrying capacity sequential days from fruit yield (days $year^{-1}$)
SLCCSDFru	Counter for sequential carrying capacity above 1 selected livestock unit from fruit yield (nr days)
$SLCCSDFru_{yr}$	Selected livestock carrying capacity sequential days from fruit yield (days $year^{-1}$)
SDULUFru	Counter for sequential days for user defined livestock units from fruit yield, (nr days)
$SDULUFru_{yr}$	Sequential days for user defined livestock units from fruit yield (days $year^{-1}$)
Interaction with Yield-SAFE state variables	
$Fru_{FallPDOY}$	Fruit fall probability in a specific DOY (0-1) (see Section 3.4)
Fru_Y	Fruit yield (kg ha^{-1}) (see Section 3.4)
Equations	

$$UME_{Fru} = \frac{Fru_Y * Fru_{UME}}{1000}$$

$$UME_{FruY} = \begin{cases} 0 & ,if\ Fru_{FallPDOY} \leq 0.00001 \\ UME_{\mathrm{Fru}} + UME_{\mathrm{Fru-1}} & ,if\ Fru_{FallPDOY} > 0.00001 \end{cases}$$

$$CCFru_{LU} = \frac{UME_{Fru}}{LMER}$$

$$CCFru_{SLU} = \frac{UME_{Fru}}{SLMER}$$

$$CCSDFru_k = \begin{cases} CCSDFru_{k-1} + 1 & ,if\ CC_{\mathrm{FruLU}} \geq 1 \\ 0 & ,if\ CC_{\mathrm{FruLU}} < 1 \end{cases}$$

$$CCSDFru_{yr} = Max_{DOY=1}^{DOY=365}\ CCSDFru$$

$$SLCCSDFru_k \begin{cases} SLCCSDFru_{k-1} + 1 & ,if\ CCFru_{\mathrm{SLU}} \geq 1 \\ 0 & ,if\ CCFru_{\mathrm{SLU}} < 1 \end{cases}$$

$$SLCCSDFru_{yr} = Max_{DOY=1}^{DOY=365}\ SLCCSDFru$$

$$SDULUFru_k \begin{cases} SDULU_{k-1} + 1 & ,\text{if}\ CCFru_{\mathrm{LU}} \geq ULU \\ 0 & ,\text{if}\ CCFru_{\mathrm{LU}} < ULU \end{cases}$$

$$SDULUFru_{yr} = Max_{DOY=1}^{DOY=365}\ SDULUFru$$

3.5 Water assimilation by roots

This module introduces a new state variable φ which determines the ability of trees to assimilate water (Table 9). φ is a factor that moderates growth by limiting the variable W_t. This modifier considers an extinction coefficient governing the absorption of water (k_r), the length of fine root per gram (r), and a ration of structural root mass to the above ground biomass (π_{sr}). These parameters were initially set to values of $k_r = 0.00007$, $r = 30/6378$, and $\pi_{sr} = 0.22$. The latter two were based on empirical measurements taken at the Silsoe agroforestry trial in 2011 for 19 year old poplar trees. The parameter k_r was adjusted to achieve a fit between modelled and actual data. Note that these parameters were introduced along with changes to the soil profile and other tree parameters. A full explanation is given by Upson (2014).

Table 9. New state variables and equations in Yield-SAFE related to water assimilation by roots

Additional parameters	
kr	Extinction coefficient governing the absorption of water per unit of root length (0-1)
r	Length of fine root per mass of structural root (m g^{-1}).
π_{sr}	Ratio of structural root mass to aboveground biomass (0-1)
New state variables	
φ	Modifier for water assimilation (0-1)
Interaction with Yield-SAFE state variables	
Bt	Above ground tree biomass (g $tree^{-1}$)
Ft	Water uptake by trees (mm)
Equations	
$\varphi = 1 - e^{B_t \pi_{sr} r k_r}$	
Equations updates in Yield-SAFE	
Ft	= Ft * φ

Note: If this improvement is causing problems in the usage, r (the length of fine root per gram of structural root) can be set to a high value e.g. 50 000 m g^{-1}.

3.6 Tree effects on microclimate (temperature and wind)

Combining woody perennial and annual crop species modifies microclimatic factors such as wind speed air and understorey temperature, relative humidity, radiation and saturation deficit, and hence evapotranspiration (Luedeling et al. 2016; Muthuri et al. 2014). The effects of trees on temperature and wind speed can now be taken into consideration in Yield-SAFE.

3.6.1 *Effects on temperature*

Tree canopies not only reduce temperature in summer but also increase temperature in winter and reduce evapotranspiration (Gill and Abrol, 1993; Shanker et al. 2005). For example Gill et al. 1990 (in Dagar et al. 2013) and Gill and Abrol 1993 found that under an *Acacia nilotica* canopy, the mean air temperature was lowered by 2-5°C during summer and increased 2-4°C in winter.

A modifier was introduced in Yield-SAFE to change the temperature when tree height reaches a certain threshold (i.e. 4 m) and when the tree leaves are present (Table 10). Assuming a northern hemisphere, the modifier starts reducing temperature from 21 March with a maximum on 21 June before declining to zero on 21 September. From this date, the modifier increases the temperature until 21 December before declining again to 21 March.

Table 10. New variables and equations in Yield-SAFE related to the effect of trees on temperatures

Additional parameters	
Δ_{Summer}	Max reduction of mean temp in summer, i.e. 21st June (°C)
Δ_{Winter}	Max increase of mean temp in winter, i.e. 21st December (°C)
TH_{min}	Minimum height of trees to start effect (m).
New State Variables	
F	Function to describe equinoxes = 0, 21 June = -1, 21 Dec = 1
$T_{addTmin}$	Temperature to add to minimum temperature (°C)
$T_{addTmax}$	Temperature to add to maximum temperature (°C)
D	Slope of saturation vapour pressure curve without tree effect
Interaction with Yield-SAFE climate input:	
*T*min	Maximum temperature (°C)
*T*max	Minimum temperature (°C)
Interaction with Yield-SAFE state variables:	
DOY	Day of Year (1-365)
H	Tree Height (m)
Equations	
$F = \cos(rad\left(\frac{360}{N}\right) * (DOY + 10), N = 365\ or\ N = 366 \text{ in leap year}$	
$T_{addTmax} = \begin{cases} F * (\Delta_{Summer} * 2), & if\ 80 \leq DOY < 265 \text{ and } H > TH_{min} \\ 0, & if\ 80 > DOY > 265 \text{ or } H < TH_{min} \end{cases}$	
$T_{addTmin} = \begin{cases} F * (\Delta_{Winter} * 2), & if\ 80 > DOY > 265 \text{ and } H > TH_{min} \\ 0, & if\ 80 \leq DOY < 265 \text{ or } H < TH_{min} \end{cases}$	
Climate updates in Yield-SAFE	
*T*max	= *T*max + $T_{addTmax}$
*T*min	= *T*min + $T_{addTmin}$

Changing temperature affects a number of related state variables. For example, VPD is affected and consequently alters crop water use and soil evaporation which in turn, affects the water balance of the soil. Also, new features of Yield-SAFE such as carrying capacity are modified, because by reducing temperature in summer, there are fewer stress days for livestock, and the canopy therefore helps to promote weight gain in livestock relative to a no shade scenario, counteracting the negative impact on grass yield caused by reduced light penetration. Additionally, increasing temperature in winter may increase number of growing days for the crop.

3.6.2 *Effects on wind speed*

Windbreaks received increased attention after the drought and dust storms of the 1930s in the United States of America, leading to a response by planting more than 200 million trees and shrubs throughout the Great Plains. Increases of yield can occur by providing shelter (Nuberg, 1998) and therefore an attempt to consider this effect on Yield-SAFE is suggested. Böhm et al. (2014) describes a relationship between alley width and the relative wind speed to an open field. The relationships are now integrated in Yield-SAFE (Table 11). However, this process should be used with caution (e.g. assuming alleys perpendicular to wind direction) because alleys in the same direction of the dominant winds can increase wind speed (venturi effect).

Table 11. New variables and equations in Yield-SAFE related to the effect of trees on wind speed

Additional parameters	
A_w	Alley width (m)
Interaction with Yield-SAFE climate input	
wss	Wind speed (m s^{-1})
New state variables	
f^{Wind}	Wind speed modifier
Interaction with Yield-SAFE state variables	
H	Tree height (m)
Equations	
$f^{Wind} = -0.0069 * Aw^2 + 1.4783 * Aw + 17.257$ $f^{Wind} = \begin{cases} \dfrac{-0.0069 * Aw^2 + 1.4783 * Aw + 17.257}{100}, & if\ H > 1 \\ 1, & if\ H \leq 1 \end{cases}$	
Climate updates in Yield-SAFE	
Wss	= *wss* * f^{wind}

3.6.3 *Combined effects on evapotranspiration*

Air temperature and wind speed can affect evapotranspiration (e.g. Luedeling et al. 2016; Muthuri et al. 2014). As described in Section 2.1 including the Vapor Pressure Deficit (VPD) in Yield-SAFE means that the VPD can interact with crop transpiration. The new addition is to include the effect of wind speed on soil evaporation in Yield-SAFE. To avoid replacing the soil evaporation equation, a modifier was added to the soil evaporation based on the reference evapotranspiration (*ET*o). *ET*o is calculated with and without the tree canopy effect (Table 12. The ratio between evapotranspiration with and without canopy represents a modifier factor affecting the soil evaporation equations in Yield-SAFE.

Table 12. New variables and equations in Yield-SAFE related to the effect of trees on evapo-transpiration

Additional parameters	
Z	Altitude (m)
Auxiliary calculated parameters	
P	Atmospheric pressure (kPa)
γ	??
New State Variables	
Δ^{svp}	Slope of saturation vapour pressure, (kPa °C^{-1})
ETo	Reference Evapotranspiration without tree effect (mm)
$\Delta^{svp'}$	Δ^{svp} calculated with new *Tmin* and *Tmax* (see Section 3.6.1)
ETo'	*ETo* calculated with new $\Delta^{svp'}$, wss (see Section 3.6.2) and VPD (see Section 2.1)
f^{ETo}	Fraction between *ETo* with and without canopy effect
Interaction with Yield-SAFE state variables	
Eact	= *Eact* * f^{ETo}
Equations	

$$P = 101.3 * \left(\frac{293 - 0.0065 * Z}{293}\right)^{5.26}$$

$$\gamma = 0.665 * 10^{-3} * P$$

$$\Delta^{svp} = \frac{4098\left[0.6108 * exp\left(\frac{17.27 * \frac{Tmin + Tmax}{2}}{\frac{Tmin + Tmax}{2} + 237.3}\right)\right]}{\left(\frac{Tmin + Tmax}{2} + 237.3\right)^2}$$

$$ET_o = \frac{0.408 * \Delta^{svp} * Rad + \gamma * \frac{900}{\frac{Tmin + Tmax}{2} + 273} * wss * VPD}{\Delta^{svp} + \gamma * (1 + 0.34 * u)}$$

$$ET_o' = \frac{0.408 * \Delta^{svp'} * Rad + \gamma * \frac{900}{\frac{Tmin' + Tmax'}{2} + 273} * wss' * VPD'}{\Delta^{svp'} + \gamma * (1 + 0.34 * wss')}$$

$$f^{ETo} = \frac{ET_o'}{ET_o}$$

4 Soil

4.1 Soil carbon model (RothC integration)

The Rothamsted Carbon Model (RothC) is a model that can predict the turnover of soil organic carbon (SOC) that was developed by researchers at Rothamsted Research in the UK (Coleman and Jenkinson, 2014). The original model uses a monthly time step to calculate total organic carbon (Mg ha^{-1}), microbial biomass (Mg ha^{-1}) and $\Delta^{14}C$ (which allows the calculation of the radiocarbon age of the soil) between a year and a century timescale.

In brief, the model takes incoming organic matter inputs, and splits these into one inert (IOM) and four active soil organic matter pools. Active organic matter is split between two pools: Decomposable Plant Material (DPM) and Resistant Plant Material (RPM) following a ratio depending on the type of plant material (Table 12). These two fractions are further split into three products of decomposition: CO_2, microbial biomass (BIO), and Humified Organic Matter (HUM). The proportion of SOC that is lost to CO_2 is determined by soil clay content (as this plays a function in the ability of organic matter to be immobilised in organo-mineral complexes). Both the BIO and HUM fraction are split again into subsequent CO_2, BIO, and HUM pools. A proportion of 46% BIO and 54% HUM for the BIO+HUM compartment is considered. BIO and HUM both decompose again to form more CO_2, BIO and HUM. For example farmyard manure applied as input material is considered to content 49% of DPM, 49% of RPM and 2% of HUM.

After the implementation the three main inputs required by RothC are calculated by Yield-SAFE instead of being defined by the user. Firstly the input plant material is estimated considering the daily tree leaf fall, daily root litter stored and crop residues after harvest (including straw and roots) calculated by Yield-SAFE. Secondly daily evapotranspiration values are now calculated by Yield-SAFE as the sum of actual evapotranspiration due to daily crop water uptake and daily tree water uptake. Thirdly manure carbon inputs are linked to the livestock carrying capacity of the system.

Table 13. New variables and equations in Yield-SAFE related to the RothC model.

Additional parameters	
CC_{soil}	Clay content of the soil (0-1)
$Soil_{Depth}$	Organic Top Soil depth (cm)
DOY_{manure}	DOY when manure is applied (0-365)
M_{app}	Manure application (m^3 ha^{-1})
M_{BD}	Manure bulk density (kg m^{-3})
CCM	Ratio of carbon content in manure bulk (0-1)
DPM_RPM_r	An estimate of the decomposability of the incoming plant material (unitless)
DPM_M	Fraction of carbon in farmyard manure as DPM (0-1)
RPM_M	Fraction of carbon in farmyard manure as RPM (0-1)
BIO_M	Fraction of carbon in farmyard manure as BIO (0-1)
FracSolidToBIO	Fraction of carbon from BIO + HUM that goes to BIO (0-1)
CCRc	Ratio of carbon content in crop roots (0-1)
CCAGstraw	Ratio of carbon content in crop straw (0-1)
CCAGgrain	Ratio of carbon content in crop grain (0-1)
StrawResidue	Above ground biomass left after harvest (0-1)

Soil decomposition rates	
k_{DPM}	Decomposition rate constant (k) for compartment Decomposable Plant Material–DPM ($year^{-1}$)
k_{RPM}	Decomposition rate constant (k) for compartment Resistant plant Material–RPM ($year^{-1}$)
k_{BIO}	Decomposition rate constant (k) for Microbial Biomass (BIO) compartment ($year^{-1}$)
k_{HUM}	Decomposition rate constant (k) for Humified Organic Matter (HUM) compartment (1/year)
Auxiliary calculated parameters	
DPM_P	Fraction of carbon in input plant residues to DPM (0-1)
RPM_P	Fraction of carbon in plant residues to RPM(0-1)
DPM/RPM fractioning	
RatioCO2ToSolids	Ratio CO_2/BIO+HUM (0-1)
DcmpFracCO2_CO2	Ratio CO_2/BIO+HUM to CO_2 (0-1)
DcmpFracCO2_BIOHUM	Ratio CO_2/BIO+HUM to BIO or HUM (0-1)
FracSolidToHUM	Fraction of carbon from BIO + HUM that goes to HUM (0-1)
FracToBIO	Ratio of carbon in DPM, RPM, BIO that goes to BIO (0-1)
FracToHUM	Ratio of carbon in DPM, RPM, BIO that goes to HUM (0-1)
Composition of farmyard manure	
HUM_M	Fraction of carbon in farmyard manure as HUM (0-1)
New State Variables	
CR_{straw}	Carbon content in straw after harvest (Kg C ha^{-1})
CR_{roots}	Carbon content in roots after harvest (Kg C ha^{-1})
$CR_{afterharvest}$	Total carbon from residues after harvest (Kg C ha^{-1})
InPM	Input plant Material (t C ha^{-1})
InMA	Input Manure (t C ha^{-1})
ET	Evapotranspiration (mm)
F_{temp}	Roth C rate modifying factor for temperature (unitless)
F_{soil}	Roth C rate modifying factor for soil cover (unitless)
MaxTSMD	Maximum topsoil moisture deficit (mm)
AccTSMD	Accumulated topsoil moisture deficit (mm)
F_{moist}	Roth C rate modifying factor for moisture (unitless)
DPM_t	Decomposable Plant Material in soil at day *t*(t C ha^{-1})
RPM_t	Resistant Plant Material in soil at day *t*(t C ha^{-1})
BIO_t	Microbial Biomass in soil at day *t*(t C ha^{-1})
HUM_t	Humified Organic Matter in soil at day *t*(t C ha^{-1})
IOM_t	Inert Organic Material in soil at day *t*(t C ha^{-1})
SOC_t	Total Soil Organic Carbon in soil at day *t* (t C ha^{-1})
$SoilCO_2em$	CO2 emissions from soil decomposition (t CO_2 ha^{-1})
SoilCem	Carbon emissions from soil decomposition (t C ha^{-1})
AccSoilCem	Accumulated Carbon soil emissions from decomposition (t C ha^{-1})
Interaction with Yield-SAFE state variables	
DOY	Day of Year (1-365/6)
$\delta LFt\ C_{LF}$	Carbon incorporated in soil from leaf fall (Kg C ha^{-1})
$\delta CRLs\ C_{RM}$	Carbon incorporated in soil from root mortality (Kg ha^{-1}) (see section 3.2)
Bc	Crop aboveground biomass (g m^2)
E_{act}	Soil evaporation (mm)
F_c	daily crop water uptake (mm)
F_t	daily tree water uptake (mm)

YES_t	Tree presence (0=no, 1=yes)
YES_c	Crop presence (0=no, 1=yes)
Interactions with climate inputs	
Tmin	Minimum temperature (ºC)
Tmax	Maximum temperature (ºC)
Prec	Precipitation (mm)
Equations for auxiliary parameters	

$$DPM_P = \frac{DPM\_RPM_r}{1 + DPM\_RPM_r}$$

$$RPM_P = 1 - DPM_P$$

$$RatioCO2ToSolids = 1.67 * (1.85 + 1.6e^{-7.86*CCsoil})$$

$$DcmpFracCO2\_CO2 = \frac{RatioCO2ToSolids}{1 + RatioCO2ToSolids}$$

$$DcmpFracCO2\_BIOHUM = 1 - DcmpFracCO2\_CO2$$

$$FracSolidToHUM = 1 - FracSolidToBIO$$

$$FracToBIO = \frac{FracSolidToBIO}{1 + RatioCO2ToSolids}$$

$$FracToHUM = \frac{FracSolidToHUM}{1 + RatioCO2ToSolids}$$

$$HUM_M = 1 - DPM_M - RPM_M - BIO_M$$

Equations for state variables

$$CR_{straw} = \begin{cases} StrawResidue * Bc * 10 * CCAG_{straw}, & when\ harvest\ day \\ 0, & otherwise \end{cases}$$

$$CR_{roots} = \begin{cases} RSR * Bc * 10 * CCR_c, & when\ harvest\ day \\ 0, & otherwise \end{cases}$$

$$CR_{afterharvest} = CR_{roots} + CR_{straw}$$

$$InPM = \mathrm{\delta LFtC_{LF}} + \mathrm{\delta CRLsC_{RM}} + CR_{afterharvest}$$

$$InMA = \begin{cases} M_{app} * M_{BD} * CCM * 1000, & if\ DOY = DOY_{manure} \\ 0, & otherwise \end{cases}$$

$$ET = E_{act} + F_c + F_t$$

$$F_{temp} = \frac{47.91}{1 + e^{\left(\frac{106.06}{\frac{T_{min}+T_{max}}{2} + 18.27)}\right)}}$$

$$F_{soil} = \begin{cases} 0.6, & \text{if } YES_t + YES_c > 0 \\ 1, & otherwise \end{cases}$$

$$MaxTSMD = \begin{cases} -\left(20 + 130CC_{soil} - (CC_{soil} * 100)^2\right), & if\ YESt + YESc > 0 \\ \dfrac{\left(\dfrac{-(20 + 130CC_{soil} - (CC_{soil} * 100)^2)}{23}\right) Soil_{depth}}{1.8}, & otherwise \end{cases}$$

$$AccTSMD_t = \begin{cases} 0, & \text{if } Prec - 0.75 * ET \geq 0 \\ AccTSMD_{t-1} + Prec - 0.75 * ET, & \text{if } Prec - 0.75 * ET < 0 \\ MaxTSMD, & \text{if } AccTSMD_t > MaxTSMD \end{cases}$$

$$F_{moist} = \begin{cases} 1, & \text{if } AccTSMD_t < 0.444\ MaxTSMD \\ 0.2 + 0.8 \left(\dfrac{MaxTSMD - AccTSMD_t}{MaxTSMD - 0.4\ MaxTSMD}\right), & \text{if } AccTSMD_t \geq 0.444\ MaxTSMD \end{cases}$$

$$DPM_t = (DPM_{t-1} + InPM * DPM_P + InMA * DPM_M)e^{F_{temp}*F_{moist}*F_{soil}*(k_{DPM}/365)}$$
$$RPM_t = (RPM_{t-1} + InPM * RPM_P + InMA * RPM_M)e^{F_{temp}*F_{moist}*F_{soil}*(k_{DPM}/365)}$$

$$BIO_t = (BIO_0 + \frac{1}{1+RatioCO2ToSolids}(DPM_{t-1} - DPM_{t-2}) * FracSolidToBIO + \frac{1}{1+RatioCO2ToSolids}(RPM_{t-1} - RPM_{t-2}) * FracSolidToBIO + \frac{1}{1+RatioCO2ToSolids}(BIO_{t-1} - BIO_{t-2}) * FracSolidToBIO + \frac{1}{1+RatioCO2ToSolids}(HUM_{t-1} - HUM_{t-2}) * FracSolidToBIO + InMA * BIO_M)\ e^{Ftemp*Fmoist*Fsoilcov*(kBIO/365)}$$

$$HUM_t = (HUM_0 + \frac{1}{1+RatioCO2ToSolids}(DPM_{t-1} - DPM_{t-2}) * FracSolidToHUM + \frac{1}{1+RatioCO2ToSolids}(RPM_{t-1} - RPM_{t-2}) * FracSolidToHUM + \frac{1}{1+RatioCO2ToSolids}(BIO_{t-1} - BIO_{t-2}) * FracSolidToHUM + \frac{1}{1+RatioCO2ToSolids}(HUM_{t-1} - HUM_{t-2}) * FracSolidToHUM + InMA * HUM_M)\ e^{Ftemp*Fmoist*Fsoilcov*(kHUM/365)}$$

$$IOM_t = 0.049\ (SOC_{t-1}{}^{1.139})$$

$$SOC_t = DPM_t + RPM_t + BIO_t + HUM_t + IOM_t$$

$$SoilCO2em = DcmpFracCO2\_CO2 * (DPM_t - DPM_{t-1}) + DcmpFracCO2\_CO2 * (RPM_t - RPM_{t-1}) + DcmpFracCO2\_CO2 * (BIO_t - BIO_{t-1}) + DcmpFracCO2\_CO2 * (HUM_t - HUM_{t-1})$$

$$SoilCem = SoilCO2em\ \frac{12}{44}$$

$$AccSoilCem = \sum_{t=0}^{t} SoilCem$$

4.2 Nitrogen leaching

Nitrogen leaching is based on the methodology suggested by Palma et al. (2007) which can be considered a Yield-SAFE downstream approach as it does not interact with the model dynamics (i.e. nitrogen content of the soil does not relate with yields). Furthermore, nitrogen leaching estimation is calculated on an annual basis (Table 14).

Table 14. New variables and equations in Yield-SAFE related to nitrogen leaching

Additional parameters	
β	Recovery factor (0-1)
Y_{max}	Maximum crop yield (kg ha^{-1})
N_{grain}	Nitrogen content in crop grain (or harvested grass) (0-1)
N_{straw}	Nitrogen content in crop straw (or grass remain after harvest) (0-1)
N_{TreeAG}	Nitrogen content in tree above ground biomass (0-1)
N_{TreeBG}	Nitrogen content in tree below ground biomass (0-1)
A_{dep}	Atmospheric nitrogen deposition (kg ha^{-1})
D	Denitrification (kg ha^{-1})
V_{minF}	Volatilization from mineral fertilizer (0-1)
N_{fix}	Biological nitrogen fixation (kg ha^{-1})
New state variables	
α	Slope of "quadrant a" in van Keulen (1982) (unitless)
λ	Conversion factor to derive N uptake from tree biomass (0-1)
U	Nitrogen uptake (kg ha^{-1})
N_{fert}	Nitrogen fertilizer applied (kg ha^{-1})
N_{leach}	Nitrogen leaching (kg ha^{-1})
EF	Soil water exchange factor (unitless)
Interaction with Yield-SAFE state variables	
S	Crop straw biomass – crop by product (kg ha^{-1})
B_t	Above ground tree biomass (g tree^{-1})
F_{GW}	Flow to ground water (mm)
Interaction with existing Yield-SAFE parameters	
HI	Crop harvest index (0-1)
RSR	Root-to-shoot ratio (0-1) (New parameter added in Section 2.3)
θ_{fc}	Volumetric water content at field capacity (%)
$Soil_{Depth}$	Soil depth (mm)
Equations	

$$\alpha = \frac{1}{N_{grain} + N_{straw}\frac{S}{Y_c}}$$

$$\lambda = N_{TreeeAG} + N_{TreeBG}\,RSR$$

$$U = \begin{cases} \dfrac{Y_c}{\alpha} + \lambda B_t, & if\ Y_c < \dfrac{Y_{max}}{2} \\ \dfrac{4Y_c - Y_{max}}{2\alpha} + \lambda B_t, & if\ Y_c \geq \dfrac{Y_{max}}{2} \end{cases}$$

$$N_{fert} = \frac{U}{\beta}$$

$$N_{bal} = \left(N_{fert} + A_{dep} + N_{fix}\right) - (D + V + U)$$

$$EF = \begin{cases} 1, & if \ \dfrac{F_{gw}}{\theta_{fc} * Soil_{Depth}} \geq 1 \\ \dfrac{F_{gw}}{\theta_{fc} * \ Soil_{Depth}}, & if \ \dfrac{F_{gw}}{\theta_{fc} * \ Soil_{Depth}} < 1 \end{cases}$$

$$N_{leach} = 4.43 * \ N_{bal} * EF$$

5 Livestock

5.1 Carrying capacity

Carrying capacity depends on the combination between the utilisable metabolisable energy (UME) provided by the feedstock and the livestock metabolisable energy requirements (LMER) (Table 15). The UME requirements of a livestock unit is suggested by Hodgson (1990), referring to a lactating dairy cow with a live weight of 500 kg and milk yield of 10 kg d^{-1}. Based on this assumption, a livestock unit would need a 103.2 MJ d^{-1}. In the case of pasture, UME is a value for the whole biomass but for many other crops, there are different values of UME for the crop (e.g. grain) and the by-product (e.g. straw), and these need to be estimated accordingly. In the absence of UME references per species, some studies can support the estimation of UME given the chemical analysis of feedstock.

Table 15. New variables and equations in Yield-SAFE related to livestock carrying capacity

Additional parameters	
IsPasture	Is the crop a pasture (0 = false, 1 = true)
UME_c	Utilisable metabolisable energy of grain (or pasture) (MJ Mg^{-1} DM)
UME_{bp}	Utilisable metabolisable energy of by-product, e.g. straw (MJ Mg^{-1} DM)
LMER	Livestock utilisable metabolisable energy requirement (MJ d^{-1})
New state variables	
$UME_{production}$	Utilizable metabolisable energy production (MJ ha^{-1})
CC	Carrying capacity (LU ha^{-1})
CCSD	Counter for sequential carrying capacity above 1 livestock unit (nr days)
$CCSD_{yr}$	Carrying capacity sequential days (days $year^{-1}$)
SDULU	Counter for sequential days for user defined livestock (nr days)
$SDULU_{yr}$	Sequential days for user defined livestock units (days $year^{-1}$)
Interaction with Yield-SAFE state variables	
Y_c	Crop biomass (kg ha^{-1})
Y_{bp}	By-product biomass (kg ha^{-1})
$CCFru_{LU}$	Carrying capacity from fruit production (LU ha^{-1})
Equations	

$$UME_{production} = \begin{cases} UME_c Y_c + UME_{bp} Y_{bp}, & if\ IsPasture = 0 \\ UME_c Y_c, & ,otherwise \end{cases}$$

$$CC = \frac{UME_{production}}{LMER} + CCFru_{LU}$$

$$CCSD_k = \begin{cases} CCSD_{k-1} + 1 & ,if\ CC \geq 1 \\ 0 & ,if\ CC < 1 \end{cases}$$

$$CCSD_{yr} = Max_{DOY=1}^{DOY=365}\ SCCSD$$

$$SDULU_k \begin{cases} SDULU_{k-1} + 1 & ,if\ CC \geq ULU \\ 0 & ,if\ CC < ULU \end{cases}$$

$$SDULU_{yr} = Max_{DOY=1}^{DOY=365}\ SDULU$$

5.2 Shade effect on carrying capacity

Numerous authors have reported the effect of heat stress on livestock weight gain, milk production, pregnancy rates or semen quality (e.g. Mayer et al. 1999; Mader et al. 2006; Amundson et al. 2006; Coleman et al. 1984). Agroforestry systems can provide shade and an attempt to model this effect is proposed. McDaniel and Roark (1956) and McIlvain and Shoop (1971) studied the effect of shade on liveweight and reported a 5-11% increase due to shade. The gains were most evident on "hot muggy days", defined as days when temperature + humidity where above 130 (temperature in Fahrenheit, humidity in %). In other words, the daily energy needs of a livestock unit under shade can be 5-11% less than that in a non-shaded field. Therefore we implemented a modifier to the livestock metabolisable energy requirement ($LMER_m$) for "hot moggy days" when shade is present (Table 16).

Table 16. New variables and equations in Yield-SAFE related to the effect of shade on livestock carrying capacity

Additional parameters	
$LMER_r$	Ratio of LMER under shade (0-1)
H_{ts}	Tree height threshold for shadow effect (m)
New state variables	
THI	Temperature and humidity index (unitless)
$LMER_m$	Modified LMER (MJ d^{-1})
Interaction with Yield-SAFE state variables	
H	Tree height (m)
Interaction with Yield-SAFE climate inputs	
T	Average temperature (°C)
RH	Relative humidity (0-100)
Interaction with Yield-SAFE parameters	
LMER	Livestock utlisable metabolisable energy requirement (MJ d^{-1})
Parameter updates in Yield-SAFE	
LMER	= LMER * $LMER_m$
Equations	

$$THI = \left(T * \frac{9}{5}\right) + 32 + RH$$

$$LMER_m = \begin{cases} LMER_r, & THI \geq 130 \; and \; H > H_{ts} \\ 1, & if \;\; THI < 130 \end{cases}$$

6 Yield-SAFE interfaces

6.1 Microsoft Excel

The developments described above have been implemented in the Microsoft Excel version of the Yield-SAFE model. However adding new state variables does increase the file size and this results in the model becoming increasingly slow when used to model tree species grown on long rotations of for example 60 years.

The updated Microsoft Excel version is available and is being used in workshops where Yield-SAFE is used to model innovations and agroforestry systems across Europe (Palma et al. 2015). A further step is to translate the implementation to a new programming language to ease the usage of the model (see Section 6.2, 6.3 and 6.4).

6.2 Python/WebYield-SAFE

Yield-SAFE is being programmed in Python which is globally popular. It is an intuitive language which is compatible with most operating systems, it can be used for intensive simulations, can be used with geographical information systems, and can be run in a web environment.

As we have updated Yield-SAFE, we have also updated the Python version. The Python version can be used to link to any interface able to execute a HTTP request. For example, MS Excel can also be used to retrieve data from the WebYield-SAFE version (see Section 6.3) and the model can deliver other user friendly interfaces directly in the web browser. An experimental site has been set to demonstrate this:
http://home.isa.utl.pt/~joaopalma/projects/agforward/webYield-SAFE/webinterface/index3.php
Although not envisaged as a deliverable in the AGFORWARD project, the interest generated in this version has led to discussions to bring the interface to fruition.

Furthermore, the web-based Yield-SAFE model has been implemented with modules of fruit, livestock, carbon and cork oak. The implementation of these modules still need validation but this process can be run independently of the use of WebYield-SAFE (e.g. with Farm-SAFE, see Section 6.4), i.e. the updates will be automatic when using Microsoft Excel with WebYield-SAFE (see Section 6.3) or a Farm-SAFE Excel file linked with WebYield-SAFE (see section 6.4).

It is noted that WebYield-SAFE has a built-in link to CliPick (Palma, 2015) allowing the retrieval of climate data given co-ordinates and the start year of simulation. Furthermore the use of CliPick offers the potential to run simulations under future climates.

The information needed to run WebYield-SAFE and the association outputs are presented in Appendix A. Appendix A describes the set of files listing the tree, crop, soil, livestock and soil decomposition rates. Appendix B describes i) the arguments needed to run Yield-SAFE, ii) the outputs of the model and iii) the parameters needed for the tree, crop and soil components.

6.3 Microsoft Excel / WebYield-SAFE

With a version of Yield-SAFE implemented in Python and with a web-based interface (see section 6.2), an Excel version was developed to access the model results, and provide a visual interface for visual interpretation of the results.

A typical run of the Yield-SAFE model through an HTTP request is not visually attractive or friendly to set (Table 17), but the result from a HTTP request can be automatically imported to a spreadsheet and further worked to present graphical results.

Table 17. A typical HTTP request, with webYield-SAFE_oct2015 version, running for all modules available

http://home.isa.utl.pt/~joaopalma/projects/agforward/webYield-SAFE/webYield-SAFE_oct2015.php?timespan=D&format=htmltable&nyears=60&startyear=1990&startmonth=1&startday=1&lon=-7.06&lat=38.51&siteid=Silsoe%20%28Anil%20PlotSAFE%29&treeid=1&soilid=2&wateruseswitch=1&soildepth=1500&theta0=0.435&plantdensity=357&thinnings=20,250,30,100&doyplanting=2&doyprunning=350&doythinning=300&prunningheight=1.5&pbiomass=0.1&pshoots=0.1&maxpropbole=0.5&maxbheight=8&croprotation=10,1,1,1,1&croparea=0.8&livestockid=25&rothcratescode=1&omperc=5&bulkdensity=1.1&chorizondepth=230&dpmperc=0.45&rpmperc=13.24&bioperc=1.97&humperc=76.36&iomperc=7.97&modfruitswitch=1&modlivestockswitch=1&modrothcswitch=1&modcorkoakswitch=1&mindebarkingdbh=20&debarkingcalendar=9,9,9,9,9,9,9,9,9,9&coefcortvirgem=2&coefcortamadia=2.5

Figure 1 shows an example of a spreadsheet using form objects to build the http request, a text string in the format of Box 1. Results are then retrieved and process for charting. The example MS Excel, can request several http requests to ease a scenario comparison analysis.

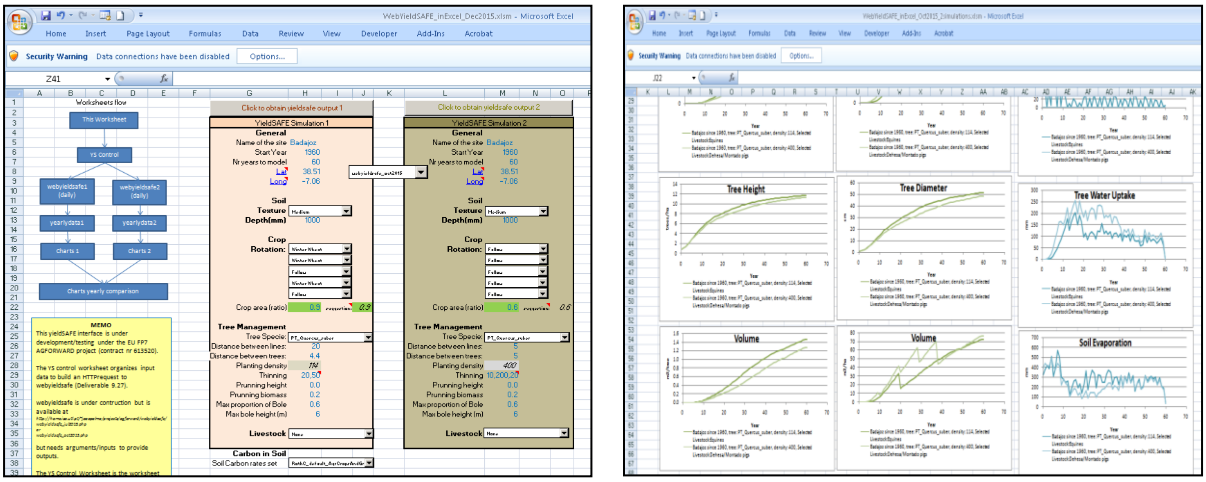

Figure 1. Screenshot of WebYield-SAFE with an interface in MS Excel. Left: From to build the http request. Right: Graphical results from the http request, with scenario comparison.

6.4 Merging WebYield-SAFE and Farm-SAFE

Yield-SAFE is now merged within Farm-SAFE (so far as an experimental prototype for proof of concept). A worksheet now allows the control of HTTP requests to webYield-SAFE (Figure 2). The worksheet allows requesting up to four model outputs fitting the needs for the four Farm-SAFE plots. This direct link between Yield-SAFE and Farm-SAFE enables, on one hand, Farm-SAFE to be more dynamic with the biophysical inputs and, on the other hand, behaving like having four Yield-SAFE models within Farm-SAFE, something that could not have been possible with the older version due to Microsoft Excel file size limitations.

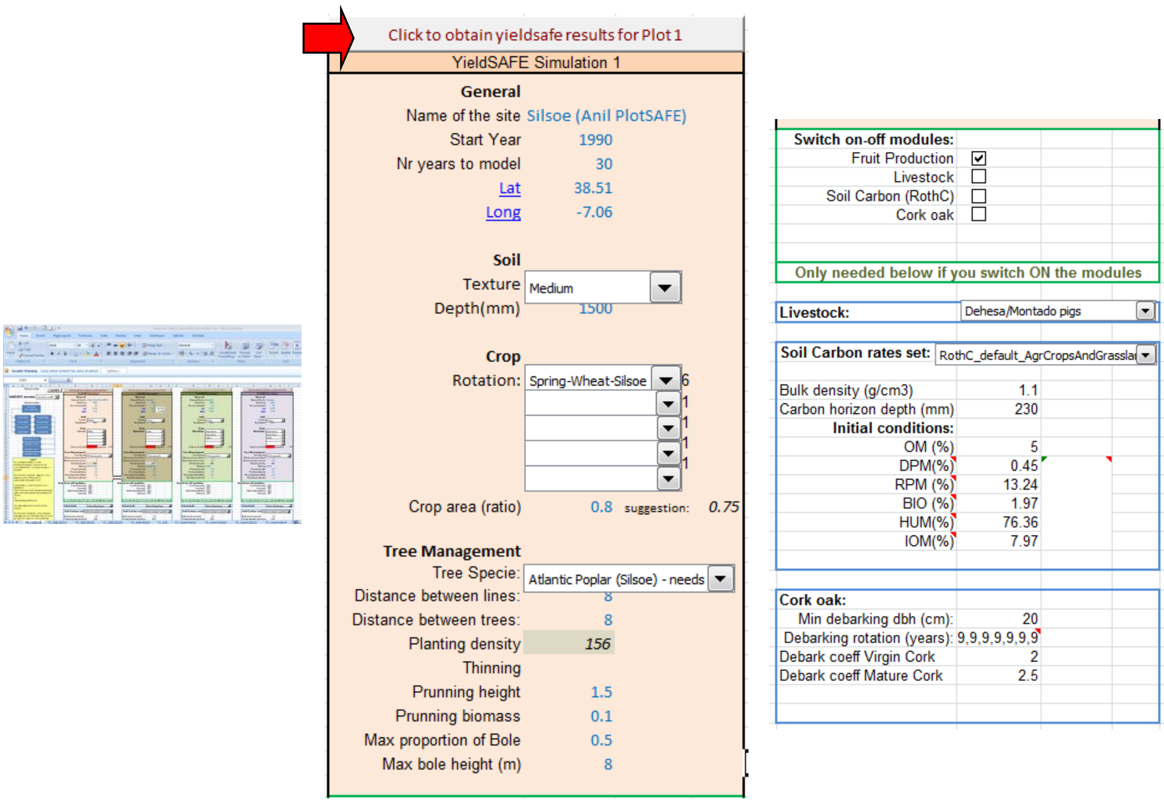

Figure 2. Farm-SAFE worksheet “Yield-SAFE control”, allowing to request up to four Yield-SAFE instances of the Yield-SAFE model

The metadata presented in the Appendix A and Appendix B, are linked to Farm-SAFE. These metadata is provided in two new auxiliary worksheets (ListOfOutputs and TCSL) that automatically pull information from the files listed in the appendices. These will be updated when WebYield-SAFE is updated online, “telling” Farm-SAFE if, for example, there are additional trees or crops that can be modelled. Additionally the list of outputs can also be updated and the formulas under YS_dailydataX are ready to update YS_yearlydataX independently of the new outputs that Yield-SAFE will produce in future.

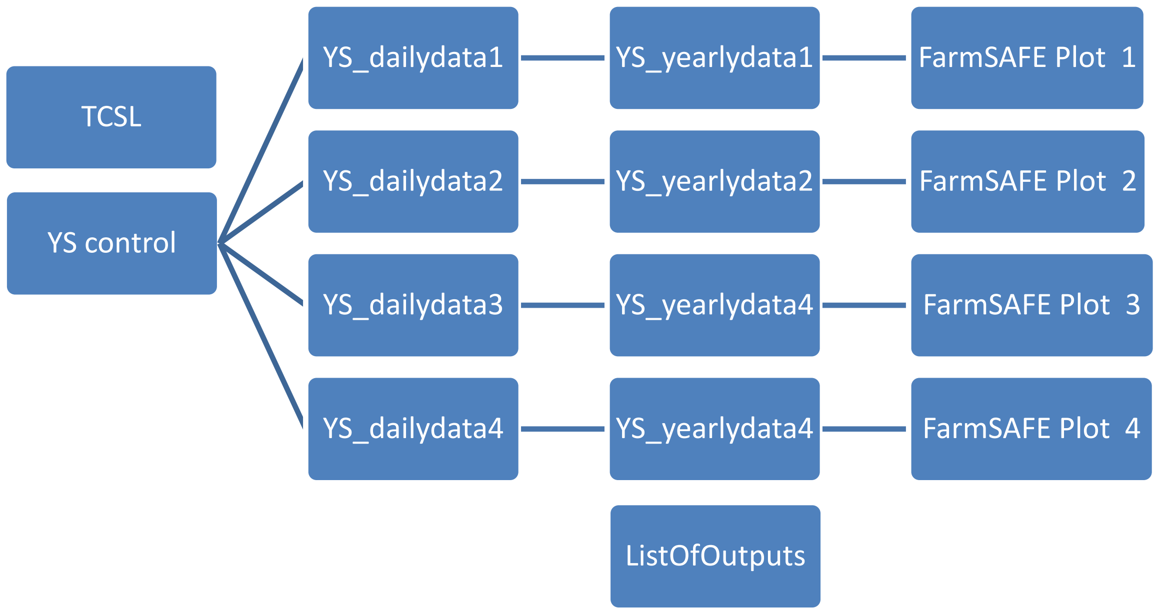

Figure 3. Worksheet flow integrated in Farm-SAFE. TCSL provides a live updated list of trees, crops, soil and livestock species. ListofOutputs provides a live updated list of the outputs according to the newest modules implementations of Yield-SAFE.

The incorporation of WebYield-SAFE into Farm-SAFE provides the user with the option to generate biophysical data. Thus the model becomes more flexible as now the user can select existing biophysical and economic data or generate his/her own biophysical (coming from "YS_yearlydata" spreadsheets) and economic data (coming from "DB-arable" and "DB-tree" spreadsheets). As Farm-SAFE utilises annual data the output from WebYield-SAFE for the economic assessment is found in "YS_yearlydata" spreadsheets. These "YS_yearlydata" spreadsheets are linked to the Farm-SAFE spreadsheets for biophysical data ("arable system", "forestry system" and "agroforestry system"). Thus in "Options and Results" spreadsheet the user can select the biophysical data that he/she has generated from WebYield-SAFE. Moreover, the financial analysis of Farm-SAFE has been written in "R" software. Thus a next step could be to incorporate WebYield-SAFE into the Farm-SAFE version of R which will allow R users to simultaneously run multiple Yield-SAFE and Farm-SAFE simulations. Figure 4 shows a screenshot of "Options and Results" spreadsheet which shows how the user can generate his/her own biophysical data through WebYield-SAFE. Figure 5 depicts a screenshot of the data generated in WebYield-SAFE that is used for the economic assessment in Farm-SAFE.

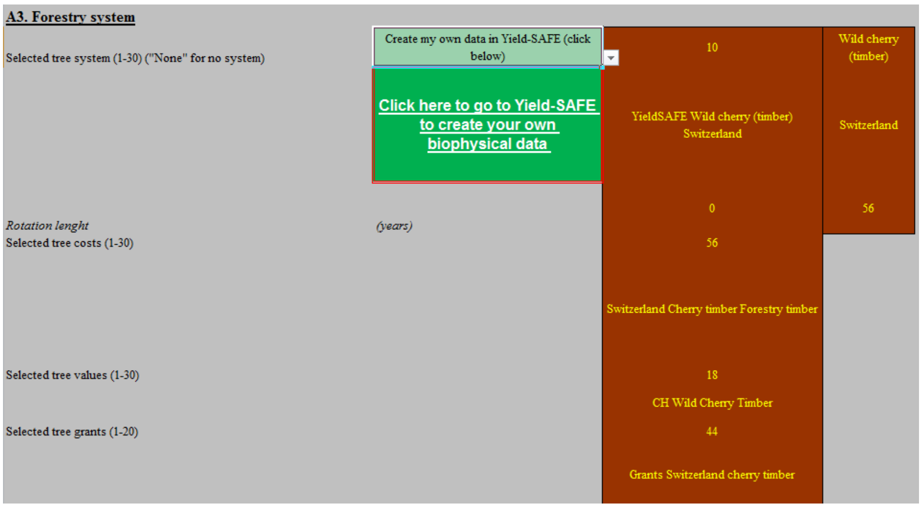

Figure 4. Screenshot of “Options and Results” spreadsheet showing where the user can generate his/her own biophysical data through WebYield-SAFE

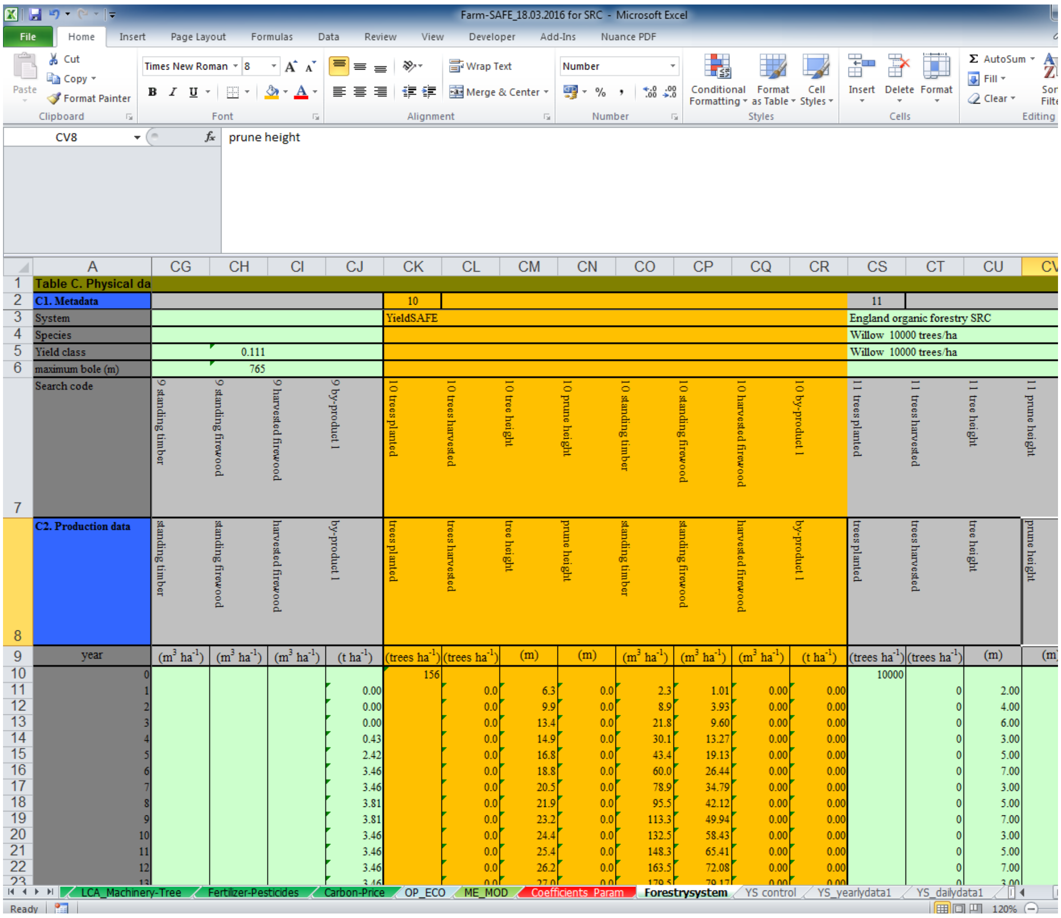

Figure 5. Screenshot of “Forestry system” spreadsheet showing the data generated in WebYield-SAFE. The data comes from “YS_yearlydata” spreadsheets that have been generated as a result of clicking “Click to obtain results for Plot” in “YS control” spreadsheet.

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Appendix A. Information to use WebYield-SAFE and the source link

Description	File location
Location of the file with info regarding Yield-SAFE inputs, outputs and species and soil parameters	http://home.isa.utl.pt/~joaopalma/projects/agforward/webyieldsafe/webyieldsafe.xml
List of trees	http://home.isa.utl.pt/~joaopalma/projects/agforward/webyieldsafe/input/par_list.php?f=par_trees.xml
Trees and related parameters	http://home.isa.utl.pt/~joaopalma/projects/agforward/webyieldsafe/input/par_trees.xml
List of crops	http://home.isa.utl.pt/~joaopalma/projects/agforward/webyieldsafe/input/par_list.php?f=par_crops.xml
Crops and related parameters	http://home.isa.utl.pt/~joaopalma/projects/agforward/webyieldsafe/input/par_crops.xml
List of soils	http://home.isa.utl.pt/~joaopalma/projects/agforward/webyieldsafe/input/par_list.php?f=par_soils.xml
Soils and related parameters	http://home.isa.utl.pt/~joaopalma/projects/agforward/webyieldsafe/input/par_soils.xml
List of livestock	http://home.isa.utl.pt/~joaopalma/projects/agforward/webyieldsafe/input/par_list.php?f=par_livestock.xml
Livestock and related parameters	http://home.isa.utl.pt/~joaopalma/projects/agforward/webyieldsafe/input/par_livestock.xml
Sets for soil decomposition rates (RothC)	http://home.isa.utl.pt/~joaopalma/projects/agforward/webyieldsafe/input/par_list.php?f=par_rothc.xml
Sets for soil decomposition rate parameters	http://home.isa.utl.pt/~joaopalma/projects/agforward/webyieldsafe/input/par_rothc.xml

Appendix B. Arguments needed to run an HTPP request of the WebYield-SAFE

Description	Link to list
Output options (including time step, format, number of years)	http://home.isa.utl.pt/~joaopalma/projects/agforward/webyieldsafe/output_list.php?f=webyieldsafe.xml&parent=ARGUMENTS&family=OUTPUTOPTIONS
Site data (including longitude, latitude, soil texture and depth)	http://home.isa.utl.pt/~joaopalma/projects/agforward/webyieldsafe/output_list.php?f=webyieldsafe.xml&parent=ARGUMENTS&family=SITEDATA
Tree management (including tree id and planting density)	http://home.isa.utl.pt/~joaopalma/projects/agforward/webyieldsafe/output_list.php?f=webyieldsafe.xml&parent=ARGUMENTS&family=TREEMANAGEMENT
Crop management (crop rotation)	http://home.isa.utl.pt/~joaopalma/projects/agforward/webyieldsafe/output_list.php?f=webyieldsafe.xml&parent=ARGUMENTS&family=CROPMANAGEMENT
Livestock management	http://home.isa.utl.pt/~joaopalma/projects/agforward/webyieldsafe/output_list.php?f=webyieldsafe.xml&parent=ARGUMENTS&family=LIVESTOCKMANAGEMENT
Modules switches for fruit, livestock, RothC, cork oak	http://home.isa.utl.pt/~joaopalma/projects/agforward/webyieldsafe/output_list.php?f=webyieldsafe.xml&parent=ARGUMENTS&family=MODULES