1 Soil

1.1 Water and leaching

Only the water contained in the first 1 meter depth of the soil is consider in the model. Each soil type (1) is characterised 2 parameters representing its hydraulic properties : the soil hydraulic conductivity at saturation (SatConD; Rawls *et al.*, 1982) and the water infiltration capacity (InfRate).

Table 1: Soil hydraulic conductivity at saturation (SatConD) and water infiltration capacity (InfRate) of the 11 soil types described

Soil type	Code	SatCondDay (mm.day$^-1$)	InfRate (mm.day$^-1$)
Sand	1	504	696
Loamy sand	2	146.64	600
Sandy loam	3	62.16	696
Loam	4	31.68	360
Silty loam	5	16.32	288
Sandy clay loam	6	10.32	240
Clay loam	7	5.52	168
Silty clay loam	8	3.6	168
Sandy clay	9	2.88	120
Silty clay	10	2.16	96
Clay	11	1.44	24

The soil water content (water, mm) is calculated daily. Different variables are required to determine how much water is received by and leaves the paddock everyday. The following equations (eqs. 1 to 5) are intermediate calculation leading to the calculation of the soil water content (eq. 6).

The first step consists on calculating the amount of water present in the soil and at the surface of the paddock from the previous day, and how much is added by the rain (minus what is evapotranspirated). This first variable is an intermediate variable (water1, mm). It is proportional to the soil water content of the previous day (water$_{day-1}$, mm), the water surplus of the previous day (mm, notRunOff$_{day-1}$),and either the difference between the daily rainfall (mm, rain) and evapotranspiration (mm, ETP), if rainfall are lower or equal to infiltration rate (mm, InfRate) or difference between infiltration rate and ETP otherwise. The equation is as follow :

$$water1 = \begin{cases} water_{day-1} + (rain - ETP) \times 10000 + notRunOff_{day-1}, & \textit{if } rain \leq InfRate \\ water_{day-1} + (InfRate - ETP) \times 10000 + notRunOff_{day-1}, & \textit{otherwise} \end{cases} \tag{1}$$

Rainfalls contribute to the soil water content, but the soil ability to drain the rain received at the surface is limited by it's physicochemical properties. Depending on the infiltration rate relative to the amount of rain received, part of the later cannot be drained (waterExtra, mm) and will either run off or stay at the paddock surface (notRunOff, mm). The amount of water staying at the surface of the paddock at the end of the day is dependent on soil water content (water1, mm), the soil water content at capacity and saturation, the proportion of water running off ((propRunOff, 80%) and on the infiltration rate (InfRate, mm). The equations are as follow:

$$waterExtra \begin{cases} rain - InfRate, & \textit{if InRate} < \textit{rain} \\ 0, & \textit{otherwise} \end{cases} \tag{2}$$

$$notRunOff = \begin{cases} (1 - propRunOff) \times (water1 - Saturation + waterExtra), & \textit{if } water1 > Saturation \\ waterExtra \times 10000 \times (1 - propRunOff), & \textit{else if waterExtra} > \textit{0} \\ 0, & \textit{otherwise} \end{cases} \tag{3}$$

If the amount of water present in the soil exceeds the soil water capacity, part of it will be drained (eq. 4). In that case, the quantity drained is equal to the difference between soil water content, or saturation if at saturation, and soil water capacity when it is lower than the product of the hydraulic conductivity (SatCondDay and NoneSatConDay , mm.day^{-1}) and this difference divided by 100. The equation is as follow :

$$Drained = \begin{cases} 0 & \textit{if } water1 < Capacity \\ \min\left(\frac{NoneSatConDay \times (water1 - Capacity)}{100}, water1 - Capacity\right) & \textit{if } Capacity \leq water1 \leq Saturation \\ \min\left(\frac{SatCondD \times (Saturation - Capacity)}{100}, Saturation - Capacity\right) & \textit{otherwise} \end{cases} \tag{4}$$

With :

$$NoneSatConDay = \begin{cases} SatConD \times e^{48.2 \times (water1 - Saturation) \times 10^{-7}}, & \textit{if } Capacity \leq water1 \leq Saturation \\ 0 & \textit{otherwise} \end{cases} \tag{5}$$

Finally, the soil water content (water, mm) (eq. 6) is calculated at the end of each day. It corresponds to the total amount of water received in the soil and eventually present at the surface of the paddock (eq. 1) minus the amount of water Drained (eq. 4).

$$water = \begin{cases} water1 - Drained, & \textit{if } water1 > waterCapacity \\ Saturation - Drained, & \textit{else if } water1 > Saturation \\ water1, & \textit{otherwise} \end{cases} \tag{6}$$

1.1.1 Extra layer of water

In case of a drought, plants will rely on the first cm of soil to restart their growth (section). The water content of the soil layer corresponding to the first 10cm is calculated as follow (water10, mm). It is dependent on how the amount of water accumulated during the day compares to the wilting point (wilting, mm) and the water content at saturation (saturation, mm). This is calculated as follow:

$$\textit{water10} =$$

$$\max\left[wilting \times \frac{10}{depth}, \min\left(water10_{day-1} + (rain - ETP) \times 10000 + notRunOff_{day-1}), (Saturation \times \frac{10}{depth})\right)\right] \tag{7}$$

1.2 Mineralisation rate

1.2.1 Potential mineralisation rate

Of the total amount of organic nitrogen (Norg) present in the soil organic matter (OM) , only a fraction is available for mineralisation ($Norg_{corr}$), of which the amount is calculated based on the soil organic matter content (OM, %) as follow (eq. 8).

$$Norg_{corr} = \begin{cases} \left(3 + 6 \times (1 - e^{-0.22 \times (OM-3)})\right) \times \frac{4200}{1.75}, & \textit{if OM > 3} \\ OM \times \frac{4200}{1.75}, & \textit{otherwise} \end{cases} \tag{8}$$

This nitrogen is mineralised at a rate Vp (potential mineralisation rate) calculated as follow using the soil organic N content (Norg, kg N.ha^{-1}) and fraction of organic N available for mineralisation (Norg$_{corr}$).

$$Vp = 0 \leq \left[\left(0.0929 + (0.1833 - 0.0929) \times e^{-0.2173 \times \frac{Norg}{1000}}\right) \times \frac{Norg_{corr}}{1000} \right] \leq 2.2 \tag{9}$$

1.2.2 Temperature parameter of mineralisation

Mineralisation is affected by temperature, the temperature parameterfT_M accounts for it. It is assumed that mineralisation is driven by average daily temperature (T^o_{mean}, ^{o}C) and starts at 0 ^{o}C before slowly increasing up to 4^{o}C. Above this temperature, the equation is as proposed by Mary *et al.* (1999). The process gets exponentially facilitated as temperatures increases, particularly after reaching the reference temperature for mineralisation (Tref$_{Min}$, 15^{o}C). The coefficient K is the temperature coefficient.

$$fT_M = \begin{cases} 0 & \textit{if } T^o_{mean} < 0 \\ \frac{T^o_{mean}}{4} \times 0.28 & \textit{if } 0 \leq T^o_{mean} < 4 \\ e^{K \times (T^o_{mean} - Tref_{Min})} & \textit{otherwise} \end{cases} \tag{10}$$

1.2.3 water parameter for mineralisation

Mineralisation is affected by soil water availability, the parameter $g0$ accounts for it and is calculated as follow based based on the moisture function used by Mary *et al.* (1999). It is dependent on the mineralisation rate at wilting point relative to field capacity (c), water content, and water content at capacity and wilting point. The equation is as follow :

$$g0 = c \leq \left[(1 - c) \times \frac{water \times wiltingPoint}{waterCapacity \times wiltingPoint} + c \right] \leq 1 \tag{11}$$

1.2.4 Mineralisation

The actual rate of mineralisation (eq. 12) is the product of the potential rate of mineralisation (Vp) reduced by the environmental factors (temperature, fT_M, and water availability , $g0$) (Mary *et al.,* 1999).

$$mineralisation = Vp \times fT_M \times g0 \tag{12}$$

1.3 Immobilisation rate

1.3.1 Temperature parameter for immobilisation

Immobilisation is affected by temperature, the temperature parameterfT_I accounts for it. It is based on the same concept than the temperature parameter for mineralisation (eq. 10) and increases exponentially along with average daily temperature (T^o_{mean}). Immobilisation gets more efficient at lower temperatures than mineralisation so the reference temperature ($Tref_{Im}$) is lower (10^oC). The equation is as follow:

$$fT_I = \begin{cases} 0 & \textit{if } T^o_{mean} < 0 \\ \frac{T^o_{mean}}{4} \times 2 & \textit{if } 0 \leq T^o_{mean} < 4 \\ e^{-K \times (T^o_{mean} - Tref_{Im})} & \textit{otherwise} \end{cases} \tag{13}$$

1.3.2 Immobilisation rate

The actual immobilisation rate (kg N.ha.day^{-1}) is the product of the potential immobilisation rate (*Ip*, 0.0004) reduced by environmental factors (temperature, fT_I, and water availability, $g0$). It is proportionnal to the amount of soil mineral N, and is considered that the Nmin won't have any further negative impact on immobilisation below 60. It is calculated as follow :

$$Immobilisation = \begin{cases} Ip \times Nmin \times g0 \times 2.5 & \textit{if } Nmin \leq 60 \\ Ip \times 60 \times g0 \times 2.5 & \textit{otherwise} \end{cases} \tag{14}$$

1.4 Soil N nitrification and denitrification

Denitrification occurs when nitrates (NO_3) and nitrites (NO_2) are reduced to nitric oxide (NO) , nitrous oxide (N_2O) and dinitrogen (N_2). The model simulates two forms of N emission, either through nitrous oxide (N_2O) or complete denitrification into dinitrogen (N_2) .

1.4.1 Repartition N_2/N_2O

The gaseous form in which N exits the soil after denitrification is influenced by the soil physico-chemical properties. The ratio N_2/N_2O is used to determine how much of the total denitrification products does N_2 represent (opposed to N_2O), in other word how much of the denitrification was complete. The closer the result is from 0, the more N_2 is produced, conversely the closer it is from 1, the more N_2O is produced. One factor influencing the ratio of loss is the soil type as clay soils are more prone to lose N through N_2 than N_2O. Therefore, the ratio is proportional to the soil clay content (clay, %).

$$repartitionN_2N_2O = 0.189 + \frac{(1.71 \times clay) \times 0.01}{1 + (1.36 \times clay) \times 0.01} \tag{15}$$

1.4.2 N_2 and N_2O emissions

The global emission (eq. 16) represents the total amount of N lost through denitrification that leaves the soil through N_2 and N_2O. Using the total amount of losses and the N_2 ratio (eq. 15) the amount of gas produced can be calculated for N_2 (eq. 17) and N_2O (eq. 18). The equations are as proposed in Vinther (2005) and based on the soil mineral N (Nmin, kg $N.ha^{-1}$), temperature (fT_M) and water (g0) parameter for mineralisation , N_2/N_2O ratio (repartitionN_2N_2O). The equations are as follow :

$$globalEmission = \frac{Nmin}{1000} \times fT_M \times g0 \tag{16}$$

$$N_2 = (1 - repartitionN_2N_2O) \times globalEmission \tag{17}$$

$$N_2O = repartitionN_2N_2O \times globalEmission \tag{18}$$

1.5 Rain deposition

The nitrogen present in the atmosphere is deposited through rainfalls, mainly in form of NH_4^+ and NO_3^-, and contributes to N cycling. Those wet deposition of N (kg $Nmin.ha_1$) feed the inorganic N pool and are directly proportionnal to daily rainfall (rain, mm). The equation is as follow :

$$increaseNminRain = 0.035 \times rain \tag{19}$$

1.6 Soil water components

Soil water capacity (eq. 20), water saturation (eq. 21) and wilting point (eq. 22) are calculated based on Dunne *et al.,* (1996). They are dependent on soil type and proportional to sand and clay content (%) and soil depth (m). The equations are as follow :

$$waterCapacity = (0.2576 - 0.002 \times sand + 0.0036 \times clay + 0.0299 \times OM) \times 10^7 \times \frac{depth}{100} \tag{20}$$

$$waterSaturation = \frac{100}{88} \times waterCapacity \tag{21}$$

$$wiltingPoint = (0.026 + 0.005 \times clay + 0.0158 \times OM) \times 10^7 \times \frac{depth}{100} \tag{22}$$

1.7 Water availability effect on growth

The amount of water the soil can hold is mostly dependent on its texture and depth. The water stress variable is calculated by comparing the actual soil water content to the its water capacity and wilting point. The closer to the field capacity, the higher. This is calculated using the entire depth and it is assumed that water is evenly distributed along it. The water stress perceived by the plant is measured using the water content, water capacity and wilting point, and is equal to 0 if the soil water content is inferior to the wilting point. The equation is as follow :

$$waterStress_{\phi_{depth}} = 0 < \left[\begin{cases} 0 & \text{if } water < wiltingPoint \\ \frac{water - wiltingPoint}{waterCapacity - wiltingPoint} & \text{if } water - wiltingPoint \geq 0 \end{cases} \right] < 1 \tag{23}$$

In case of a drought, the water content will drop, possibly below the wilting point, and cause the water stress to be equal to 0 and compromises the growth. The overall soil moisture will have to raise above wilting point before the water stress declines, which can take a long time. But in reality, the water first infiltrates the uppermost layers before percolating. This can delay the plant recovery compared to the reality as the first layers of the soil might already have received enough water for the plant to have started to recover. For this reason and to better reflect how grass recovers after a drought, a second water stress variable is calculated using only the first 10cm of soil. For the first 10 centimetres, the water the soil holds in the first 10 cm (water10, mm) is compared to the wilting point and water capacity of this layer. The equation is as follow :

$$waterStress_{\phi_{10cm}} = \frac{water10 - wiltingPoint \times \frac{10}{depth}}{(waterCapacity - wiltingPoint) \times \frac{10}{depth}} \tag{24}$$

The model then selects the one with the highest value as the actual water stress variable :

$$waterStress_{\phi} = \begin{cases} waterStress_{\phi_{10cm}} & \text{if } waterStress_{\phi_{depth}} < waterStress_{\phi_{10cm}} < 1 \\ waterStress_{\phi_{depth}} & \text{otherwise} \end{cases} \tag{25}$$

Then the water stress variable is used to calculate the actual water stress response function which is dependent on the maximum temperature of the day (maxT, ^oC). The equation is as follow :

$$Fw_{\phi} = (-1.2387 \times waterStress_{\phi}^2 + 2.2387 \times waterStress_{\phi} - 0.0056) \times \frac{18}{maxT} \tag{26}$$

variable	definition	unit
capacity	soil water capacity	mm
clay	soil clay content	%
depth	soil depth	m
ETP	evapotranspiration	mm
InfRate	Infiltration rate	$mm.day^{-1}$
Nmin	soil mineral N content	kg $N_{org}.ha^{-1}$
NoneSatConDay	soil hydraulic conductivity when not saturated	$mm.day^{-1}$
Norg	soil organic N content	kg $N_{org}.ha^{-1}$
$Norg_{corr}$	fraction of soil organic N available for mineralisation	
notRunOff	water surplus (not drained through infiltration or run off at the end of the day)	mm
OM	Soil organic matter content	%
rain	daily rainfall	mm
sand	soil sand content	%
SatCondDay	soil hydraulic conductivity at saturation	$mm.day^{-1}$
saturation	soil water content at saturation	mm
T^o_{mean}	average temperature of the day	^{o}C
water	soil water content	mm
vp	potential mineralisation rate	
water1	intermediate vaeiable for water content calculation	mm
water10	water content of the first soil layer (10cm)	mm
waterExtra	water surplus	

Table 2: Description of the variables used in the soil and water section

parameter	definition	unit	value
c	N mineralisation rate at wilting point relative to field capacity		0.2
Ip	potential immobilisation rate		0.004
K	temperature coefficient (Van't Hoff) for N mineralisation	K^{-1}	0.115
propRunOff	proportion of water not drained running off paddock		0.8
$Tref_{Im}$	reference temperature for immobilisation	^{o}C	10
$Tref_{Min}$	reference temperature for mineralisation	^{o}C	15

Table 3: Description of fixed parameters used in the soil and water section