1. The APSIM AgPasture model

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2. APSIM description

The Agricultural Production Systems sIMulator (APSIM) is a farming systems modelling framework that is being actively developed by the APSIM Initiative.

It is comprised of:

1. A set of biophysical models that capture the science and management of the system being modelled,
2. A software framework that allows these models to be coupled together to facilitate data exchange between the models,
3. A set of input models that capture soil characteristics, climate variables, genotype information, field management, etc,
4. A community of developers and users who work together to share ideas, data and source code,
5. A data platform to enable this sharing and
6. A user interface to make it accessible to a broad range of users.

The literature contains numerous papers outlining the many uses of APSIM applied to diverse problem domains. In particular Holzworth et al. (2014), McCown et al. (1996) and McCown et al. (1995) have described earlier versions of APSIM in detail, outlining the key APSIM crop and soil process models and presented some examples of the capabilities of APSIM. To illustrate how a simulation works, Figure 1 shows a conceptual representation of a simulation. A “top level” farm (with climate, farm management and livestock) and two fields. The farm and each field are built from a combination of models found in the toolbox. The APSIM infrastructure connects all selected model pieces together to form a coherent simulation.

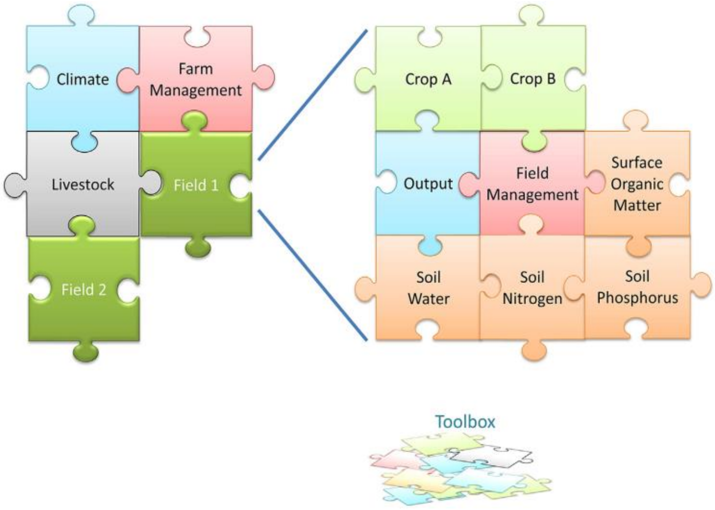

Figure 1 Conceptual representation of an APSIM simulation.

The APSIM initiative has begun developing a next generation of APSIM (APSIM Next Generation or APSIM X) that is written from scratch and designed to run natively on Windows, Linux and MAC OSX. The new framework incorporates the best of APSIM 7.X framework with an improved support framework. The Plant Modelling Framework (PMF), a generic collection of plant building blocks, was ported from the existing APSIM to bring a rapid development pathway for models. The user interface paradigm has been kept the same as the existing APSIM version but completely rewritten to support new application domains and the newer PMF. The ability to describe experiments has been added, which can also be used for rapidly building factorials of simulations. The ability to write C# scripts to control farm and paddock management has been retained. Finally, all simulation outputs are written to a SQLite database to make it easier and quicker to query, filter and graph outputs.

The model described in this documentation is for APSIM Next Generation. However, AgPasture does not run on a PMF basis. This is because AgPasture runs multiple paddocks at the same time and a complex structure as PMF would slow down how simulations run.

APSIM is freely available for non-commercial purposes. Non-commercial use of APSIM means public-good research & development and educational activities. It includes the support the policy development and/or implementation by, or on behalf of, government bodies and industry-good work where the research outcomes are to be made publicly available. For more information visit the licensing page on the APSIM website.

3. AgPasture

AgPasture is a model developed to simulate pasture growth within the APSIM framework. It was initially developed based on the physiological models of Thornley and Johnson (1990), as it was done for the SGS/DairyMod/EcoMod models (Johnson et al., 2008). Several changes have been made to enable AgPasture's integration in the APSIM framework and to incorporate new functionalities to describe plant physiology and its interactions with the environment. Only plant processes have been adapted from the original models presented by Johnson et al. (2008). The environment (soil, weather, etc) and partition of resources are accounted for by other models from the APSIM framework. This makes any direct comparison between AgPasture and the SGS/DairyMod/EcoMod models incorrect.

AgPasture is primarily designed for the simulation of mixed pastures made up of C_3 and C_4 grasses, legumes and forbs. The sward is defined as the mixture of one or several pasture species. The relative amount of each species is allowed to vary according to their relative growth rate. Plant processes are described for each pasture species, each one with its respective set of parameters. The sward is then in charge of the aggregation of outputs and the control of all management aspects, such as grazing. A set of management tools has also been developed to describe basic pasture management like cutting or grazing, irrigation and fertiliser application, among others that will be presented further on.

3.1 Structure description

Most processes and functions controlling plant growth, dry matter (DM) allocation and tissue turnover have been described by Thornley and Johnson (1990), Johnson (2005) and Johnson et al. (2008). This documentation will present these processes, changes done specifically to AgPasture, the general structure of AgPasture and how it relates to other models in the APSIM framework.

The primary structure in AgPasture is the sward, which is the pasture community and it may be formed by one or more pasture species (Figure 2). In classic APSIM (7.X), the sward was responsible for partitioning resources (light, water and nutrients) among species, controlling pasture removal (grazing or cutting) and aggregating species properties to the pasture sward level. In APSIM X, resource partitioning is done by an external model, the ResourceArbitrator. The removal of dry matter can be done directly from a pasture species and for that, the use of the sward could be seen as optional. However, its use is still recommended whenever multiple species are simulated.

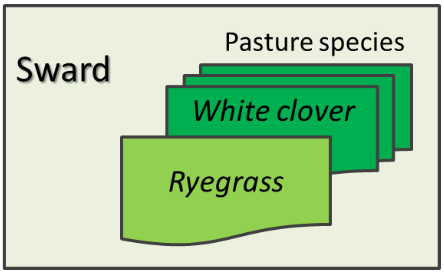

Figure 2 Representation of an example of sward with multiple species.

Plant processes are done at a pasture species level. The base species is a generic temperate C_3 grass parameterised as a generic ryegrass, without cultivar specification. The species used in the simulation can be changed to describe other types of plants, such as C_4 grasses, legumes and forb. However, annual legumes are not included yet. Every species is simulated under the assumption that the sward is already stablished, which means they cannot be developed from seeds. The relative proportion of species is variable and depends on environmental conditions, on each species ability to access resources and on the effects of grazing or cutting on the balance between the species in the sward.

Plant species are described as a set of organs in AgPasture and each organ describes the average state of the various plant parts (Figure 3). Only leaves and stems/sheaths are considered for grazing or cutting. Reproductive growth is not directly simulated, so flowers and seed production are not considered in AgPasture at the moment. Changes in growth rate and DM allocation during the reproductive period are accounted in AgPasture though and will be presented further on.

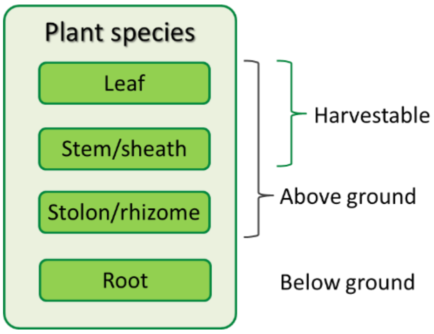

Figure 3. Description of plant species in AgPasture with the indication of a general class for plant parts.

Plant organs are described by a set of tissue pools that represent the developmental stage for these organs, each with its respective average age (Figure 4).

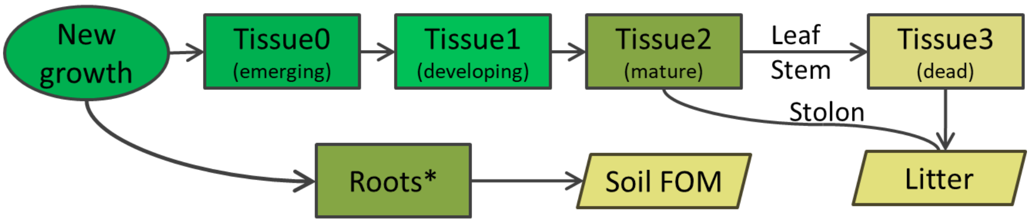

Figure 4. Tissue dynamics in AgPasture, from new growth until senescence.

*Only one tissue pool is considered for roots.

There are three living stages, growing, mature and senescing, that represent green tissues and a dead tissue pool in AgPasture. All green tissue is considered photosynthetically active and any new growth is added to pool Tissue 0 of organs. The dead tissue pool is only present for leaves and stem/sheath because it only considers standing material. Above ground dead material is returned as litter and is controlled by the 'SoilOrganicMatter' model whereas dead roots are added to the soil as fresh organic matter (FOM). The flow of dry matter (DM) and nitrogen (N) through the pools is controlled by turnover processes, which will be presented further on.

In AgPasture there is a series of parameters, which are set at the start of the simulation, that define the basic behaviour of each tissue and a set of variables, which describe the state of that particular tissue (Figure 5). The basic variables record the DM weight, N content and remobilisable N (N luxury). The use of a minimum value for DM as a parameter ensures regrowth and is needed because carbon (C) remobilisation is not simulated in AgPasture. More details on this are provided by Johnson (2005). There are three parameters that describe the N content at the minimum, optimum and maximum levels. The minimum N content is the N from structural tissues, so it cannot be remobilisable and is thus the basic value for dead tissues. The N optimum content is the one above which plant growth is not limited. The N content between the minimum and optimum levels is available for remobilisation as tissues senesce. In AgPasture any N above the optimum level is considered luxury N, which is the amount readily available for remobilisation from any tissue at any stage. The upper limit of luxury N is N maximum.

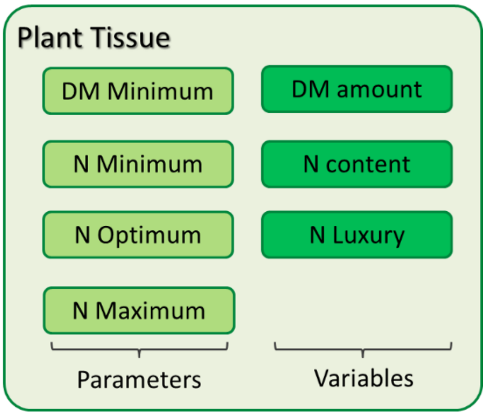

Figure 5. Basic description of a tissue pool in AgPasture

Plant processes, such as photosynthesis, DM allocation, tissue turnover and water and N uptake are modelled at the species levels. These can be grouped, according to the order they are simulated, in a sequence for plant growth and a sequence for tissue turnover (Figure 6).

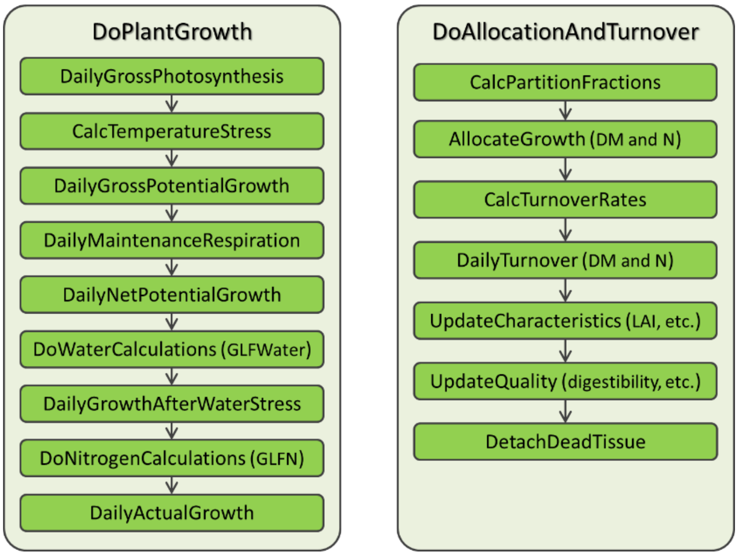

Figure 6. Description of the two major calculation sequences in AgPasture.

As a general description, the calculation of plant growth is based on the estimation of photosynthesis (Figure 7). Respiration rates are then subtracted from this estimate to give the plant net potential growth. Soil factors, such as water and nutrient deficiency, are then discounted from the net potential growth and this results on the plant actual growth. The sequence of calculations for DM allocation and turnover occurs after plant growth is calculated. Firstly, the new growth, in terms of DM and N, is partitioned among the plant organs and added to their respective Tissue 0. Turnover of the various tissues is then done, including senescence and detachment of dead material. Finally, the plant status in relation to LAI, plant height and root distribution is updated. AgPasture works, as it is the default in APSIM, on a daily time-step.

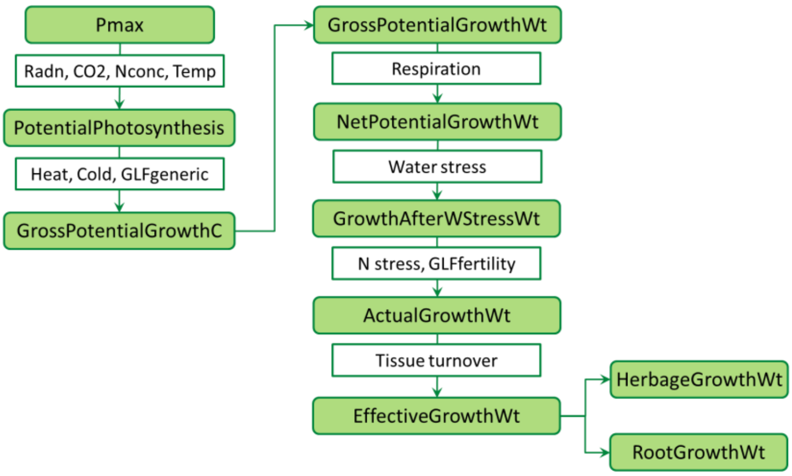

Figure 7. Description of calculations done by AgPasture, from photosynthesis up to the partitioning of growth between shoot and root.

3.2 Plant Growth

3.2.1 Gross photosynthesis

Plant photosynthesis is initially calculated at the leaf level and then scaled to the whole canopy and sward. This is done through calculations based on the light extinction coefficient (k) and LAI of the whole pasture species. In AgPasture, LAI is composed by green leaves and, at certain conditions specified in the LAI section further on, stems and stolons are also considered. Solar radiation and air temperature are the primary factors for the calculation of the instantaneous photosynthetic rate, which is then scaled to daily photosynthesis. Daily photosynthesis will then have the effects of atmospheric CO_2 concentration, plant N content and extreme temperatures subtracted. This results on the gross photosynthesis, which is used to calculate the plant potential growth.

The daily gross potential photosynthetic rate (Equation 1) is given by multiplying the daily canopy photosynthesis by all limiting factors.

Equation 1
$$P_{Gross} = P_{Cd}\varepsilon_{PC}\varepsilon_{PN}(\varepsilon_{PH}\varepsilon_{PF})\ \varepsilon_{PG}$$

In Equation 1 P_c is the potential daily canopy photosynthesis, ε_{PC}, ε_{PN}, ε_{PH}, ε_{PF} and ε_{PG} are the effects of atmospheric CO_2, nitrogen content, high and low temperatures and a generic limiting factor, respectively. These factors will be explained in further sections.

3.2.1.1 Leaf photosynthetic rate

Leaf photosynthesis (P_L in mg CO_2/m^2 leaf/s) is described by a non-rectangular hyperbola (Johnson, 2005) and is expressed as a function of irradiance (I_L in W/m^2), according to Equation 2.

Equation 2
$$P_L = 1/2\xi\ (\ \alpha I_L + P_m - [\ (\ \alpha I_L + P_m)^2 - 4\xi\alpha P_m I_L\ ]^{1/2}\ )$$

In Equation 2 P_m (mg CO_2/m^{2}leaf/s) is the reference photosynthetic rate at full canopy irradiance, which gives the asymptote for the photosynthesis curve when it approaches saturating radiation, α (mg CO2/J) is the photosynthetic efficiency and ξ (J/kg/s) is the curvature parameter. Values of photosynthetic efficiency vary between 0.1 and 8%. However, these are usually around 1 to 2% for most crops and approximately 50% higher for C_4 species (Beale andLong, 1995). The default value in the species parameters in APSIM is 1%. The curvature parameter ξ can have values between 0 and 1 and its default value in AgPasture is 0.8 (Johnson, 2005). Figure 8 shows the effects of these parameters on the shape of the photosynthesis curve.

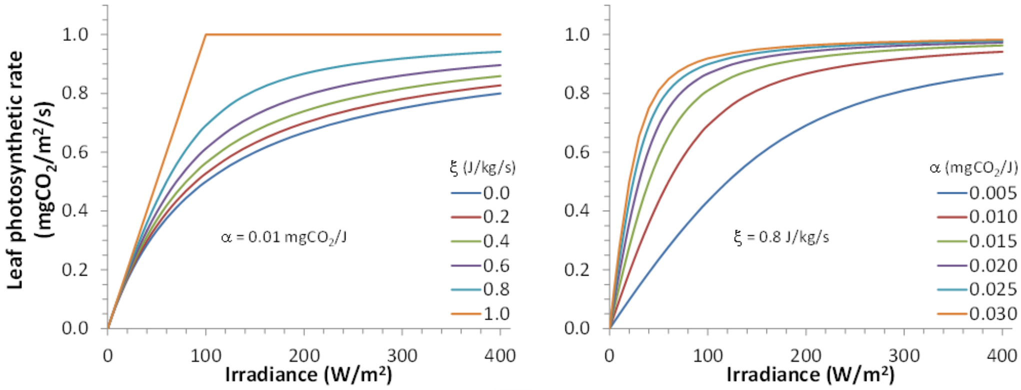

Figure 8. Variation of leaf photosynthetic rate for values of ξ and α.

Reference conditions for P_m are air temperature of 20°C, atmospheric CO_2 concentration of 380 ppm and plant N concentration of 4% for C_3 and 3% for C_4 species. This results in values of P_m between 1 and 1.5 mg CO_2/m^2 leaf/s (Johnson, 2005) and indicates that photosynthetic rates need to be adjusted to environmental conditions different from the reference ones.

3.2.1.2 Plant photosynthesis response to temperature

The photosynthetic rate is sensitive to changes in temperature, especially in C_3 species. AgPasture uses an adaptation of the approach of Thornley (1998) that adjusts the result of Equation 1 by multiplying it by a factor (ε_{PT}), which has values between 0 (no photosynthesis) and 1 (no limitation to photosynthesis). This factor is estimated by Equation 3 for C_3 and Equation 4 for C_4 species.

Equation 3

$$\varepsilon_{PT}=\begin{cases} 0.0 & , T \leq T_{min} \\ \dfrac{(T-T_{min})^q(T_{max}-T)}{(T_{opt}-T_{min})^q(T_{max}-T_{opt})} & , T_{min}<T<T_{max} \\ 1.0 & , T \geq T_{max} \end{cases}$$

Equation 4

$$\varepsilon_{PT}=\begin{cases} 0.0 & , T \leq T_{min} \\ \dfrac{(T-T_{min})^q(T_{max}-T)}{(T_{opt}-T_{min})^q(T_{max}-T_{opt})} & , T_{min}<T<T_{opt} \\ 1.0 & , T\geq T_{opt} \end{cases}$$

In these Equations T is the average air temperature (°C), T_{min}, T_{opt} and T_{max} are the minimum, optimum and maximum temperatures for photosynthesis and q is a curvature parameter. The value of T_{max} is calculated according to Equation 5.

Equation 5

$$T_{max} = T_{opt} + (T_{opt}-T_{min})/q$$

Default values for generic grasses of C_3 species are T_{min} of 1°C, T_{opt} of 20°C and q of 1.5. For C_4 species T_{min} is 10°C, T_{opt} is 30°C and q is 1.2. Figure 9 shows the photosynthesis response for default temperatures in AgPasture.

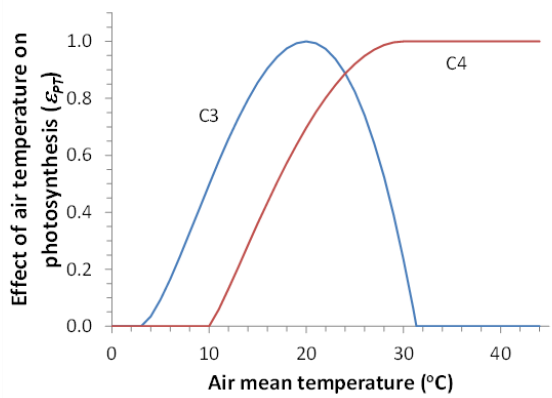

Figure 9. Leaf photosynthesis in response to the default temperatures in AgPasture.

AgPasture also accounts for the effects of extreme temperatures on leaf photosynthesis, which in the code is represented by GlfHeat (equivalent to $\mathcal{E}_H$) and GlfCold ($\mathcal{E}_F$) for heat and cold stress, respectively. The model assumes there is an onset temperature (T_{Onset}, °C) for the effect of extreme temperatures to start and a threshold temperature of full effect (T_{Full}, °C), which results in no photosynthesis. In between these two temperatures, leaf photosynthesis is affected by extremely low (Equation 6) and extremely high temperatures (Equation 7).

Equation 6
$$\varepsilon'_{PH}=\varepsilon_{PH(-1)}\frac{T_{Full,H}-T_{max}}{T_{Full,H}-T_{Onset,H}}$$

Equation 7
$$\varepsilon'_{PF}=\varepsilon_{PF(-1)}\frac{T_{min}-T_{Full,F}}{T_{Onset,F}-T_{Full,F}}$$

In these Equations, $\mathcal{E}_{(-1)}$ indicates the values from the previous day, H is the heat and F the cold (frost) stress and Ɛ' indicates that these are preliminary values that will be adjusted to account for any recovery. The values for T_{onset} and T_{Full} can be set at the parameters list. The default values used for ryegrass are a T_{onset} of 28°C and a T_{Full} of 35°C for heat stress and a T_{onset} of 1°C and a T_{Full} of -5°C for cold stress.

Variations on $\mathcal{E}'_{PH}$ and $\mathcal{E}'_{PF}$ according to temperature are presented in Figure 10.

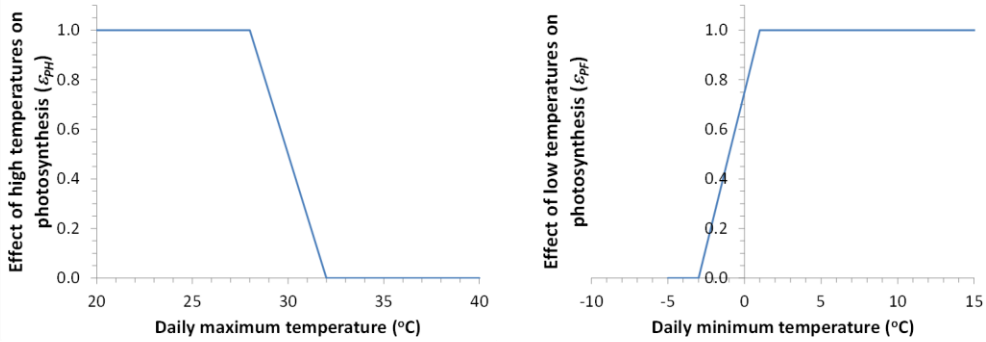

Figure 10. Description of how temperatures act on the effect of extreme temperatures (hot and cold) on photosynthesis.

After plants experience the effect of extreme temperatures, AgPasture simulates plant recovery by assuming that a target thermal time (T_t) requirement (°Cd), accumulated above a temperature threshold (the reference temperature for recovery), is needed to recover from the damage. A recovery factor is calculated through Equation 8, where is the sum of degree-days above the reference temperature T_{Href}, S_{TH} is the T_t requirement for full recovery and q_H is a curve parameter with a default value of 1 for both heat and cold stress. This curve parameter describes how plants recover from stress and a value of $q_H < 1.0$ indicates an easy recovery whereas a value of $q_H > 1.0$ indicates a difficult recovery.

Equation 8
$$f_{RH}=\left(1-\varepsilon_{PH(-1)}\right)\left(\frac{S_{HE}}{S_{TH}}\right)^{q_H}$$

The values for T_t requirement and the threshold temperature can be set at the sward list of parameters. The default value used for ryegrass is a T_t requirement of 30°Cd, accumulated over a reference temperature of 25°C, to recover from heat stress and a T_t requirement of 25°Cd, accumulated over a reference temperature of 0°C, to recover from cold stress. Figure 11 shows how the recovery factor changes with values of q_H.

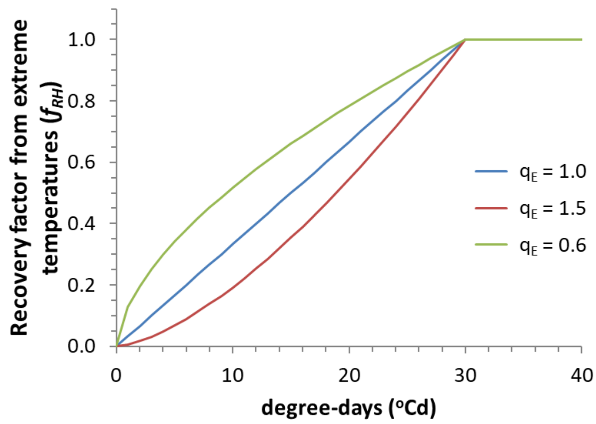

Figure 11. Changes in the recovery factor for values q_H.

The recovery factor is then used to calculate the extreme temperature effect on photosynthesis (Equation 9).

Equation 9 $$\varepsilon_{PH}=\varepsilon'_{PH}+f_{RH}$$

The equations presented here are used in the estimation of heat stress. However, the principle is the same for the calculation of cold stress.

3.2.1.3 Whole canopy photosynthetic rate

To scale photosynthesis from leaf to canopy level, AgPasture assumes that the photosynthetic rate decreases within the canopy at the same rate as light is intercepted through the canopy (Johnson, 2005; Thornley andJohnson, 1990). Equation 10 uses the leaf photosynthetic rate (P_L,0) at the top of the canopy with full irradiance (from Equation 2), the light extinction coefficient (k, 0-1) and LAI to calculate the canopy photosynthetic rate (P_C, mg $CO_2/m^2/s$).

Equation 10 $$P_C=P_{L,0}\frac{1-e^{-kLAI}}{k}$$

The effect of LAI and k on the canopy photosynthetic rate are presented in Figure 12.

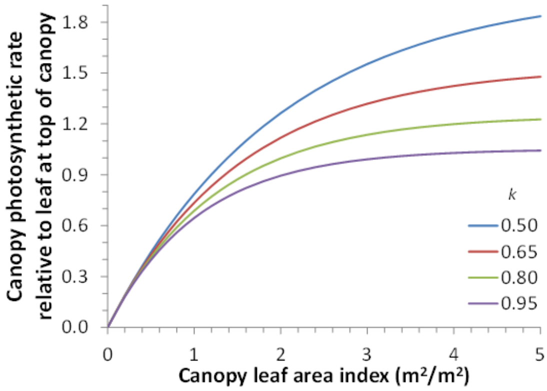

Figure 12. Canopy photosynthetic rate in relation to changes in LAI and k.

3.2.1.4 Daily photosynthetic rate

Temperature and solar irradiance variations throughout the day need to be accounted to integrate the photosynthetic rate over the whole day. AgPasture uses a piece-wise function to describe the daily variation of temperature and irradiance. In this function day length (τ) is split in three segments (Figure 13), where two of them account for the early and late hours of the day and another represents the middle of the day.

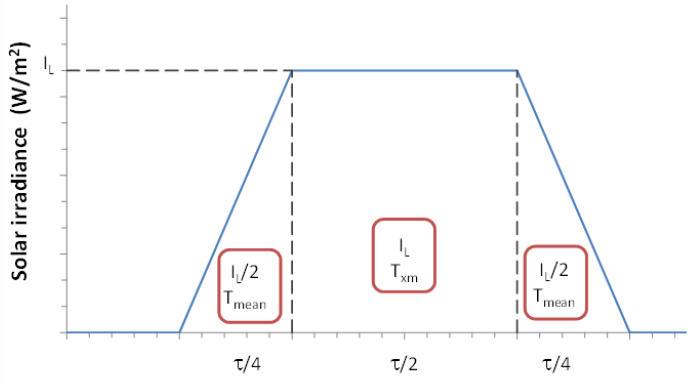

Figure 13. Piece-wise function for the daily distribution of solar irradiance.

It is then assumed that during the early and late parts of the day irradiance is half of the daily average and temperature equals the daily mean (T_{mean}). In the segment for the middle of the day, irradiance equals the daily average (I_L) (Johnson, 2005). Total daily irradiance is then calculated as Equation 11.

Equation 11 $$J_L = \frac{4}{3}\frac{I_L}{\tau}$$

In APSIM T_{mean} is the average between the minimum and maximum daily temperatures. So, the equivalent temperature for the middle of the day (T_{xm}) can be calculated according to Equation 12.

Equation 12 $$T_{xm} = 0.75T_{max} + 0.25T_{min}$$

The daily canopy gross photosynthesis (P_{gross}, mg $CO^2/m^2/s$) is then calculated by the sum of results from Equation 2 and Equation 10 for each of the three segments in Figure 13. Leaf photosynthetic rate for the early or late periods of the day ($P_{L,E}$) is calculated through Equation 2 using half of the total irradiance ($I_L/2$), whereas for the middle of the day, the actual daily irradiance (I_L) is used. In this case, the temperature factor on photosynthesis (ε_{PT}) is also calculated separately for parts of the day, using T_{mean} for the early/late part of the day and T_{xm} for the middle of the day. With this, daily canopy photosynthesis (P_{Cd}) is calculated by Equation 13.

Equation 13 $$P_{Cd} = \left(P_{L,E}\varepsilon_{PTmean} + P_{L,M}\varepsilon_{PTxm}\right)\frac{1-e^{-kL_{AI}}}{k}$$

3.2.1.5 *Normalised growth limiting factors: temperature and radiation*

In AgPasture only one value of ε_{PT} is used, which is the normalised weighted average of factors used in Equation 13. Even though this is not the value actually used, the calculation in Equation 14 gives a single value that is comparable to all the other limiting factors, which vary between 0 and 1.

Equation 14 $$\varepsilon_{PT} = \frac{0.25\varepsilon_{PTmean} + 0.75\varepsilon_{PTxm}}{\varepsilon_{PTopt}}$$

In a similar way, Equation 15 calculates the radiation factor that affects photosynthesis response.

Equation 15 $$\varepsilon_{PR} = \frac{0.25P_{L,M} + 0.75P_{L,E}}{P_m}$$

3.2.1.6 Photosynthetic rate response to CO_2 concentration

The effect of changes in CO_2 concentration are described by a Michaelis-Menten function (Equation 16), where C_{ref} is the reference CO_2 concentration (ppm), C_{amb} is the ambient CO_2 concentration and K_{PC} is the curvature parameter (ppm).

Equation 16

$$\varepsilon_{PC}=\left(\frac{C_{ref}+K_{PC}}{C_{ref}}\right)\frac{C_{amb}}{C_{amb}+K_{PC}}$$

Figure 14 shows how the effect of CO_2 on photosynthesis changes with CO_2 concentration for C_3 and C_4 species, which are less responsive to CO_2 concentration effects because of the lack of photorespiration.

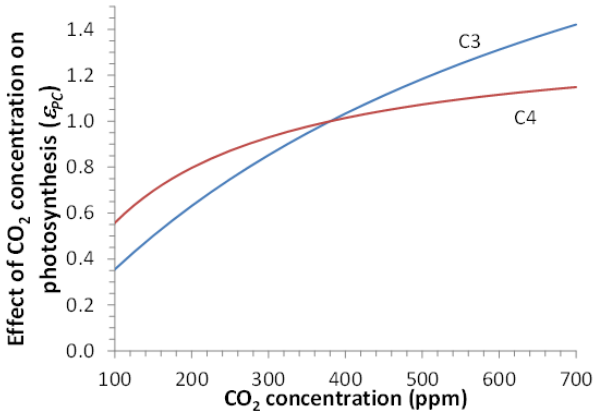

Figure 14. Changes on the effect of CO_2 concentration on photosynthesis for C_3 and C_4 species.

Variation on CO_2 concentration also affects other aspects of plant physiology, such as leaf N content and canopy conductance, which will be described further on.

3.2.1.7 Photosynthetic rate response to nitrogen content

The effect of N content on photosynthesis (ε_{PN}) is calculated according to Equation 17, where the relationship between N content of green tissue (N_G) and photosynthesis rate varies linearly between the minimum (N_{min}) and optimum (N_{opt}) N contents (Figure 15). The default values in AgPasture are 2% for N_{min} and 4% for N_{opt} of C_3 species and 1.5% and 3% for C_4 species. These values can be changed in the list of parameters of the sward.

Equation 17

$$\varepsilon_{PN}=\begin{cases}0.0 & , \quad N_G\leq N_{min}\\ \frac{N_G+N_{min}}{N_{opt}+N_{min}} & , \quad N_{min}<N_G<N_{opt}\\ 1.0 & , \quad N_G\geq N_{opt}\end{cases}$$

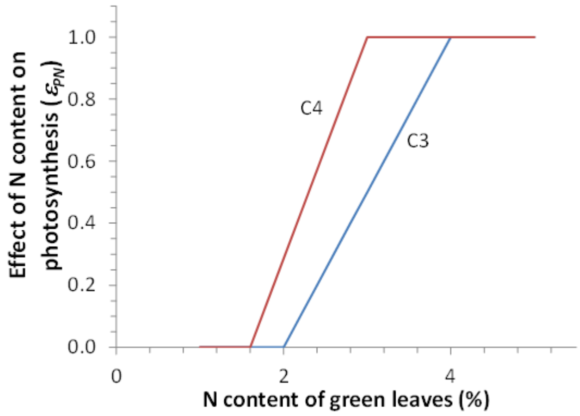

Figure 15. ε_{PN} in relation to N content of green leaves for C_3 and C_4 species.

3.2.1.8 Generic limitation factor

AgPasture has a generic limitation factor (ε_{PG}) that varies between 0 and 1 and can be used to simulate the reduction of photosynthesis due to factors such as disease and the effect of chemicals. The default value for ε_{PG} is 1 (no limitation) and this can be changed in the list of parameters in the sward.

3.2.2 Actual growth

Actual daily growth rate is calculated after the daily gross photosynthesis is converted to gross potential growth and respiration, plus limiting factors, are accounted for.

3.2.2.1 Gross potential carbon assimilation

Carbon assimilation (C_{Assim}, g C/m^2/day) is obtained by Equation 18, where P_{Cd} is multiplied by the ratio between the molecular mass of C (M_C = 12g/mol) and that of CO_2 (M_{CO2} = 44 g/mol), as well as by a conversion factor (f_{Conv}) to get values in g/m^2.

Equation 18
$$C_{Assim}=P_{Cd}\frac{M_C}{M_{CO2}}f_{Conv}$$

3.2.2.2 Gross potential growth

Gross potential growth (G_{gross}, g DM/m^2/day) is calculated by the conversion of carbon assimilated into dry matter weight (Equation 19). AgPasture assumes a value of 0.4 for carbon content in plant tissues (C_{DM}), on a dry matter basis.

Equation 19
$$G_{gross}=\frac{C_{Assim}}{c_{DM}}$$

3.2.2.3 Plant respiration

Daily respiration is separated into growth respiration (or growth efficiency) and maintenance respiration (or dark respiration). Growth respiration (R_{Growth})is a function of the photosynthetic rate (P_{Gross}) and the growth efficiency factor (Y) (Equation 20), which varies between 0 and 0.5, with a typical value of 0.25

Equation 20 $$R_{growth}=P_{Gross}\left(\frac{1-Y}{Y}\right)$$

Maintenance respiration is a function of the live plant dry matter (M_{live}, kg DM/ha) and is affected by the maintenance respiration coefficient (µ), temperature and N content in the plant (Equation 21).

Equation 21 $$R_{maintenance}=(M_{live}c_{DM})\mu\varepsilon_{RT}\varepsilon_{RN}$$

The nitrogen effect (ε_{RN}) is calculated in the same way as ε_{PN}, whereas the temperature effect (ε_{RT}), calculated by Equation 22, is similar to ε_{PT} but it continually increases beyond the optimum temperature and it uses a reference temperature (T_{ref}). If the temperature is too cold (< = 0°C), there is no respiration.

Equation 22 $$\varepsilon_{RT}=\frac{1-e^{\left(\frac{-T}{Tref}\right)^2}}{1-e^{-1}}$$

Figure 16 shows how ε_{RT}, with a T_{ref} of 20°C, changes with temperature.

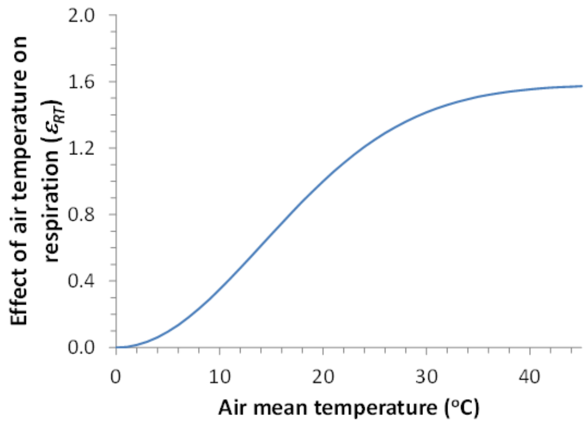

Figure 16. Changes in ε_{RT} in relation to mean air temperature, with a T_{ref} of 20°C.

3.2.2.4 Net potential growth

Daily net potential growth (G_{NetPot}) calculates growth through the conversion of gross photosynthesis (C_{assim}) to DM weight after C losses due to respiration and N fixation (Equation 23).

Equation 23 $$G_{NetPot}=\frac{C_{Assim}+C_{Remob}-R_{growth}-R_{maintenance}}{c_{DM}}$$

The calculation points to the amount of C remobilised from old tissues (C_{Remob}). However, AgPasture does not simulate C remobilisation so, this is not accounted for in this calculation.

3.2.2.5 Water stress effects and soil aeration factor

The effect of soil water content on plant growth is divided into water deficiency and water logging effects in AgPasture. Water deficiency is simulated through the calculation of the water deficit factor (ε_W in Equation 24), which is the ratio between actual plant uptake (W_{Uptake}) and potential transpiration (W_{Demand}) and can be between 0 and 1.

Equation 24 $$\varepsilon_W=\frac{W_{Uptake}}{W_{Demand}}$$

Water logging can reduce growth by affecting the respiration of roots because it reduces the amount of oxygen in the root zone. In this situation in AgPasture, growth is limited if the soil water content is above a given threshold, the minimum water free porosity (θ_{mp}) (Equation 25), where θ_{SAT} is the water content at saturation and p_{min} is the fraction of total porosity that has to be free of water to allow full growth.

Equation 25 $$\theta_{mp}=\theta_{SAT}\left(1-p_{min}\right)$$

The threshold θ_{mp} will be the soil DUL if the θ_{mp} is set to a negative value of -1, in the list of parameters in the sward component. When the water content is greater than the θ_{mp}, growth will then be limited. The growth limiting factor ($\mathcal{E}_A$) is given by the ratio of current air-filled pore space and θ_{mp} (Equation 26). It also depends on the maximum reduction on plant growth when the soil is saturated (S_L), which can be set at the parameters list in the sward component. AgPasture uses a default value of 0.1 for ryegrass.

Equation 26 $$\varepsilon_A=1-s_L\left(\frac{\theta-\theta_{mp}}{\theta_{SAT}-\theta_{mp}}\right)$$

The water logging limitation is based on the cumulative water logging, which means that growth limitation is more severe if water logging conditions are persistent. The maximum increment in one day is the same as the soil water saturation factor and cannot be greater than one. The recovery from water logging happens every day when water content is below the full saturation and is proportional to the water free porosity. The maximum daily recovery rate from water logging can be set at the parameters list in the sward component of AgPasture and it has a default value of 0.25 for ryegrass.

3.2.2.6 Nitrogen deficiency effects

Nitrogen deficiency effect ($\mathcal{E}_N$ in Equation 27) is the ratio between the sum of the amount of N remobilised from old tissues (N_{Remob}), the amount of atmospheric N fixed (N_{Fixed}) and the amount of N supplied by the soil (N_{Uptake}) and the demand for growth at optimum N concentration in the plant ($N_{Demand,Opt}$).

Equation 27 $$\varepsilon_N=\frac{N_{Remob}+N_{Fixed}+N_{Uptake}}{N_{Demand,Opt}}$$

3.2.2.7 Generic nutrient factor

AgPasture uses a generic soil fertility limiting factor ($\mathcal{E}_{SoilFertility}$) to increase the flexibility of the model and account for deficiencies in other nutrients because the only nutrient directly simulated is nitrogen. This factor can be set at the list of parameters in the sward component and the default value for ryegrass is 1.

3.2.2.8 *Actual plant growth*

Net potential growth after the correction for water (and soil aeration) effects ($G_{netPotW}$ in Equation 28) is further corrected for the nutrient limitations and used in the calculation of the actual plant growth (G_{Actual} in Equation 29).

Equation 28 $$G_{NetPotW}=G_{NetPot}\min(\varepsilon_W,\varepsilon_A)$$

Equation 29 $$G_{Actual}=G_{NetPotW}\min(\varepsilon_N,\varepsilon_{GN})$$

3.2.3 Nitrogen content of new growth

3.2.3.1 *Nitrogen demand*

Plant nitrogen demand is calculated based on the net potential growth after water limitation ($G_{netPotW}$). The demand is considered according to the N uptake for optimum N content (Equation 30) and the N demand with luxury N uptake (Equation 31).

Equation 30 $$N_{Demand,Opt}=G_{NetPotW}\left(f_{leaf}\eta_{opt,leaf}+f_{stem}\eta_{opt,stem}+f_{stolon}\eta_{opt,stolon}+f_{root}\eta_{opt,root}\right)$$

Equation 31 $$N_{Demand,Lux}=G_{NetPotW}\left(f_{leaf}\eta_{max,leaf}+f_{stem}\eta_{max,stem}+f_{stolon}\eta_{max,stolon}+f_{root}\eta_{max,root}\right)$$

In these equations η_{opt} and η_{max} are the optimum and maximum N concentrations for each part of the plant, and ƒ is the fraction of new growth allocated to each plant part.

3.2.3.2 *Effect of CO_2 concentration on nitrogen demand*

Plant demand for nitrogen is reduced when the atmospheric concentration of CO_2 increases above a reference value. However, the luxury uptake of nitrogen is not affected by CO_2 variations in AgPasture. The CO_2 effect is expressed as a factor (F_N in Equation 32) that varies between a minimum f_{NC} and 1. This is then used to adjust the optimum N concentration in the plant according to the CO_2 concentration through Equation 33, where C_{ref} is the reference CO_2 concentration, C_{amb} is the ambient CO_2 concentration, K_{NC} is a scaling parameter and q_{NC} is a rate parameter (≥1).

Equation 32 $$F_N=\frac{f_{NC}+F_{CO2}}{1+F_{CO2}}$$

Equation 33 $$F_{CO2}=\left(\frac{K_{NC}-C_{ref}}{C_{amb}-C_{ref}}\right)^{q_{NC}}$$

In AgPasture the default value for f_{NC} is 0.7, C_{ref} is 380 ppm, K_{NC} is 600 ppm and q_{NC} is 2. The variation of the effect of CO_2 on the optimum N concentration, calculated with these default values, is presented in Figure 17.

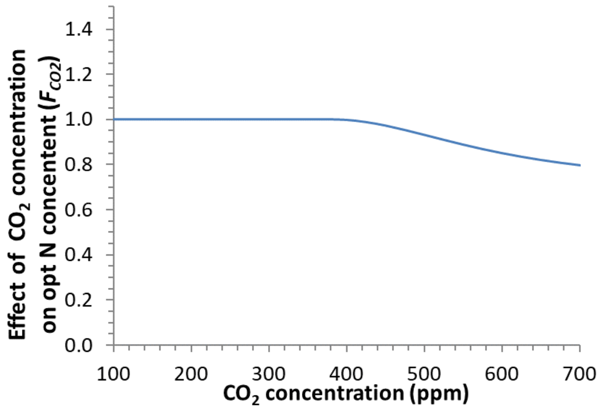

Figure 17. Effect of atmospheric CO_2 concentration on the plant optimum N concentration in relation to changes in CO_2 concentration

3.2.3.3 *Nitrogen fixation*

Biological N fixation (Equation 34) is simulated based on N demand and supply and on the minimum (φ_{min}) and maximum (φ_{max}) fractions of N demand supplied by biological N fixation. However, it cannot supply all demand and, regardless of the amount of N available in the soil, some fixation always occurs. The values of φ_{min} and φ_{max} can be set at the parameters list in the sward component and their default values for white clover in AgPasture are 0.2 and 0.6, respectively.

Equation 34
$$N_{Fixation}=\begin{cases}\phi_{min}N_{Demand,Opt} & ; \quad \frac{N_{AvailableSoil}}{N_{Demand,Opt}}\geq 1-\phi_{min}\\ \phi_{max}N_{Demand,Opt}-N_{AvailableSoil}\left(1-\frac{1-\phi_{max}}{1-\phi_{min}}\right)N_{Demand,Opt} & ; \quad \frac{N_{AvailableSoil}}{N_{Demand,Opt}}<1-\phi_{min}\end{cases}$$

Figure 18 shows the fraction of N demand fixed in relation to the ratio between N available and N demand, when calculations are done with default values in AgPasture.

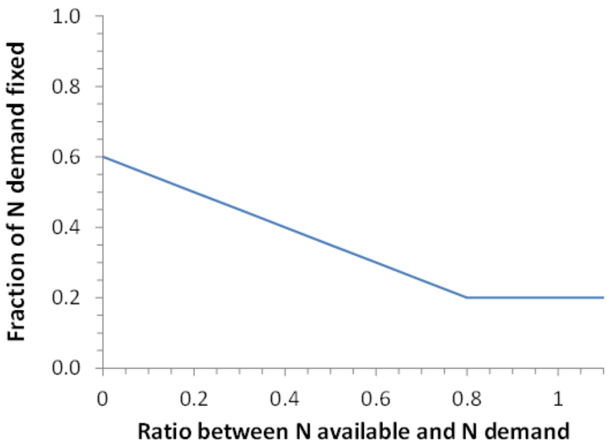

Figure 18. Variation of the fraction of N fixation as a function of N demand relative to supply.

3.2.3.4 Nitrogen uptake

AgPasture has methods available for nitrogen uptake calculation and these can be set at the list of parameters for ryegrass in the sward component in the user interface.

3.2.3.4.1 DefaultAPSIM

This method estimates the amount of plant available nitrogen in each soil layer of the root zone. The availability of nitrogen, which is a square function of the nitrogen content, is controlled by the soil water status and the uptake coefficient. The amount of NH_4 or NO_3 can be altered due to an uptake factor, which is set at 1 for NH_4 and NO_3 in the code. Uptake is capped for a maximum value plants can take in one day. The default value for this in AgPasture is 10 kg N/ha and it can be changed in the parameters list of the sward component.

3.2.3.4.2 BasicAgPasture

This is a basic method, used as a default in old AgPasture, and it assumes that all nitrogen in the root zone is available for uptake. The amount taken up for each species is calculated based on the relative demands (Equation 35).

Equation 35

$$N_{uptake,\ species}=N_{available}\frac{N_{demand,\ species}}{N_{demand}}$$

The partition of N uptake for all soil layers is made considering the fraction of N taken up and the amount of N in each layer (Equation 36). This is applied for both NH_4 and NO_3, so there is no preference for any forms of N.

Equation 36

$$deltaN_{layer}=N_{uptake}\frac{N_{layer}}{N_{available}}$$

3.2.3.4.3 AlternativeRLD

This method estimates the amount of plant available nitrogen in each soil layer of the root zone and it considers the soil water status and the root length density to define factors controlling nitrogen availability. Soil water status is used to define a factor that varies from 0 at LL, below which no uptake happens, to 1 at DUL, above which there are no restrictions to uptake. Root length density is used to define a factor that varies from 0, if there are no roots, to 1, when root length density is equal to a reference root length density ($Root_{LDRef}$), above which there are no restrictions to uptake. This $Root_{LDRef}$ is set at 5 in AgPasture's code. For this method, factors for each N form (NH_4 or NO_3) can alter the amount of N available. These factors are set at 0.5 for NH_4 and 0.95 for NO_3 in the code. Uptake is caped for the maximum value plants can take in one day.

3.2.3.4.4 AlternativeWUP

This method also estimates the available N for each soil layer of the root zone. It considers water as the main factor controlling N availability/uptake. Nitrogen availability is given by the proportion of water taken up in each layer, further modified by uptake factors. These factors are the same used for NH_4 and NO_3 in the AlternativeRLD method. The uptake is also caped for a maximum daily value of N plants can take

3.2.3.5 Nitrogen remobilisation

The process of N remobilisation calculates the amount of N remobilised into new growth. AgPasture checks if there is still demand for N ($N_{missing}$ in Equation 37), which is the demand for growth at optimum N concentration, and if there is any luxury N remobilisable.

Equation 37 $$N_{missing}=N_{Demand,Opt}*\varepsilon_{GN}-(N_{Fixed}+N_{senescedRemobilised}+N_{uptake})$$

When the remobilisable N is not enough to match demand, the amount of luxury N is evaluated. When this type of N is also not enough, all luxury N is used and the N demand is then subtracted of the amount of luxury nitrogen remobilised (Equation 38)

Equation 38 $$N_{missing} = N_{missing}-N_{luxuryRemobilised}$$

If the available luxury N is enough for optimum growth, AgPasture checks the N content of all tissues and gets what is needed, starting from mature tissues, which for ryegrass are tissues 1 and 2 (Equation 39).

Equation 39 $$N_{luxury} =N_{leafTissue}.N_{Remobilisable}+N_{stemTissue}.N_{Remobilisable}+N_{stolonsTissue}.N_{Remobilisable}$$

If the tissue number is 0, then N remobilisable from the roots will be added to the Nluxury pool. At the moment, AgPasture considers roots in the main zone. Ideally, other root zones should be added to the remobilisable N pool.

3.2.3.6 Nitrogen balance

Nitrogen balance in AgPasture is presented in Figure 19, where we have:

- dGrowth = actual growth weight on a given day (kg DM/ha)
- dN_{nG} = N amount in new growth (kg N/ha)
- $dDM_{()}$ = DM transfer between tissue pools at different growth stages (kg DM/ha)
- $dN_{()}$ = N transfer between tissue pools (kg N/ha)
- dLitter = DM deposited as litter (kg DM/ha)
- dN_{Litter} = N amount deposited as litter (kg N/ha)
- N_{Uptake} and N_{Fixed} = N amounts taken up and fixed from the atmosphere (kg N/ha)
- N_{Remob} = N amount remobilised within the plant (kg N/ha)
- ϒ = DM turnover rate, a fraction for DM transferred daily between tissue pools (0-1)
- ϒd = Turnover rate for dead material, the DM fraction transferred daily from plant to litter (0-1)

- N_{max}, N_{t0}, N_{t1}, N_{t2}, N_{min} = N concentration (%) as maximum (or luxury), in tissues 0, 1, 2 and minimum (or senescent)
- N_{max*} = maximum concentration in new growth

This illustration of N balance is valid for leaves and stems because there is no tissue 3 pool for stolons, therefore changing the DM turnover rate.

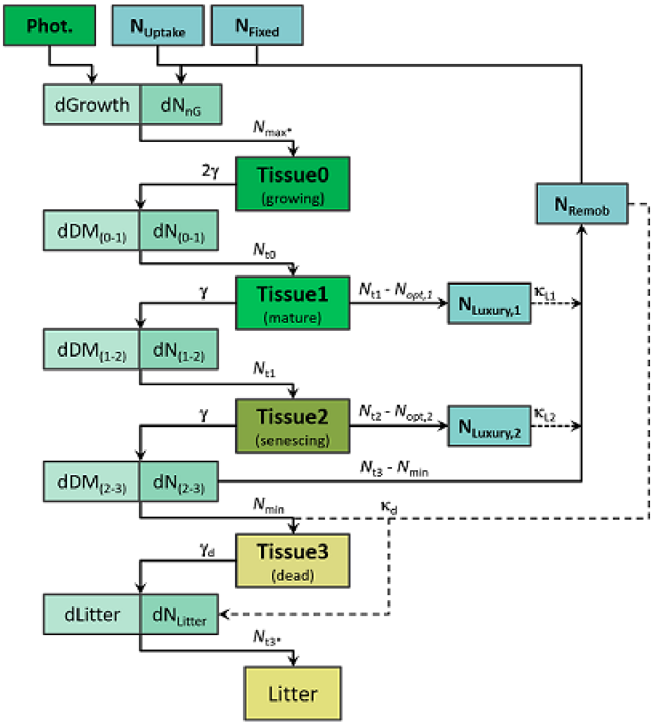

Figure 19. Illustration of N balance and tissue DM transfer in AgPasture

Nitrogen balance was improved in AgPasture for APSIM X, mainly when it comes to how N is remobilised among tissues.

Basically, N is taken up from the soil and fixed by legumes. This amount of N is what is then available for new growth. The N uptake process aims for the maximum concentration of N in new growth (N_{max*}), but often this is not achieved. The current N concentration will be added to the pool of tissue 0, which actively contributes with DM and N transfer for older tissues. The same follows through to tissues 1 and 2. The definition of an adequate N concentration in these pools is one of the modifications presented for APSIM X. These tissues have a target concentration of N and any extra N, considered luxury N, is put through the remobilisable N pool (Vogeler andCichota, 2016). The rate of remobilisation is defined as κ_{L1} and κ_{L2}. This mainly shows that the priority is the first leaf. So, when the first leaf gets deficient, this remobilisation of extra (luxury) N aims to fulfil the N necessity of this tissue pool. At the same time, a minimum N concentration is always transferred to the pool of tissue 3, which results in a constant N concentration of this pool that is then added to the litter pool. The fate of DM depends on its origin, where shoot DM is ends up added to the surface organic matter pool and root DM ends up in the soil fresh organic matter (FOM) pool. When there is an amount of N_{Remob} that was not used, this then is added to the litter. This is the only way the N concentration of this pool can change.

Plant growth is limited by nitrogen only when the concentration is below the optimum N concentration (N_{Opt}). In AgPasture this is only applied to tissue 0 because this is the only one that has new growth. For this reason, the N concentration in other pools is important only to set the amount of N_{Remob} available and not for plant growth.

3.3 Dry matter allocation and tissue turnover

3.3.1 Allocation of new growth

The allocation of new growth is based on an ideal or target shoot:root ratio in AgPasture. This ideal S:R ratio is then adjusted in relation to growth limiting factors.

3.3.1.1 Shoot to root ratio

First the model evaluates the available allocation to shoot. In this process it gets the soil related growth limiting factor, when smaller values result in higher allocation of DM to roots. AgPasture will use the minimum value (Glf_{Min}) among water supply, water logging and nitrogen supply limiting factors and calculate a limiting factor Glf_{Factor} (Equation 40). This factor is calculated using the maximum effect that soil limiting factors (Glfs) have on S:R ratio, represented by 'myShootRootGlfFactor'. Its default value for ryegrass is 0.5 and it can be changed in the list of parameters available in the sward component.

Equation 40 $$Glf_{Factor} = 1 – myShootGlf_{Factor} * 1\text{-}myShootRootGlfFactor * (1\text{-}(Glf_{Min}^{(1/mySHootGlfFactor)}))$$

Then AgPasture calculates the target S:R ratio based on the default value of 4.0 for the ideal S:R ratio, which can be set at the list of parameters in the sward node, and a reproductive factor that adjusts the DM allocation to shoot during reproductive growth, which has a value of 1. This target S:R ratio is then used to update the actual S:R partition, represented as $growth_{SR}$. This is then used to calculate the fraction of DM allocated for the shoot (Equation 41).

Equation 41 $$fraction_{ToShoot} = growth_{SR} / (1.0 + growth_{SR})$$

3.3.1.2 Reproductive growth

Reproductive phase is not simulated in AgPasture. For this reason, a reproductive factor ($Repro_{Fac}$) was included to mimic changes in the S:R ratio and the allocation of DM that occurs during this period (Figure20). The beginning and length of the reproductive phase is calculated as a function of latitude, it occurs later in spring and is shorter the further the location is from the equator. The extent at which allocation to shoot increases is also a function of latitude and maximum allocation is greater for higher latitudes (S-shape function). Changes in the allocation factor follow the broken stick function in Figure

20, where shoulder periods occur before and after the main phase. During these shoulder, phases the allocation changes between the default value for allocation and the allocation value of the main phase.

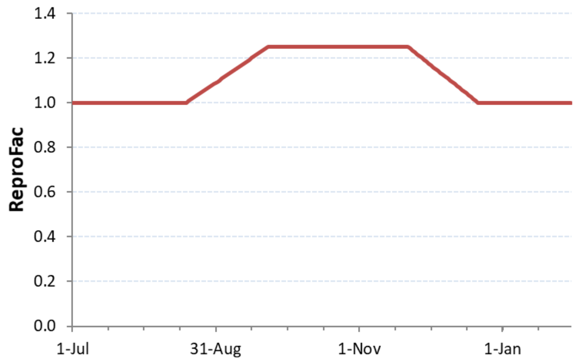

Figure 20. Variation of the factor that changes DM allocation during reproductive growth according to time of the year.

So, AgPasture starts by calculating the day to start the main phase, which is the period with maximum DM allocation to shoot. This is based on a linear function between latitude and the day to start the period with higher shoot allocation, until a given reference latitude (Figure 21) and is calculated as $Repro_{Plateau}$ in Equation 42.

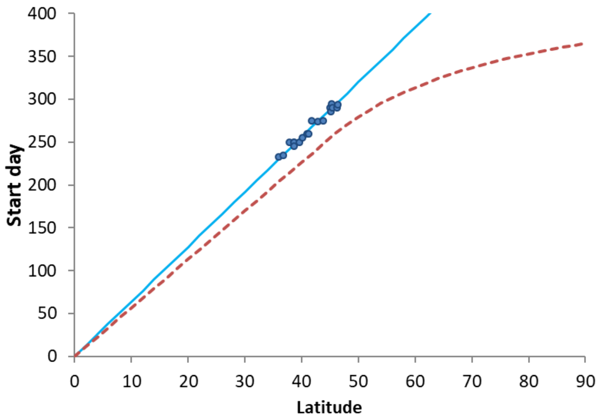

Figure 21. Relationship between the start of the higher allocation of DM to shoot and latitude.

Data points were obtained from earlier work with the 'pasture growth forecaster', which was calibrated with the data from the Radcliff series of trials (Radcliffe, 1974).

Equation 42 $$Repro_{Plateau} = DOY_{WintSolst} + 0.5 * 365.25 / (1 + \delta)$$

The start of the main phase is based on the day of the year for the winter solstice ($DOY_{WintSolst}$) and a value δ (Equation 43). This depends on the coefficient controlling the time to start the reproductive season as a function of latitude, which has a default value of 0.14 and can be set at the list of parameters in the sward node, on the latitude (Lat) of the location and reference latitude that determines the timing for reproductive season (Lat_{Ref}). AgPasture uses a default value for Lat_{Ref} of 41, which comes from the study mentioned in Figure 21.

Equation 43 $$\delta = e^{(-0.14 * (Lat - LatRef)}$$

Then AgPasture calculates the duration of the main phase ($Repro_{PlateauDuration}$), which is also dependent on latitude (Figure 22). This phase has a minimum duration of about 15 days (15.22 in Equation 44) and a maximum of 6 months (167.41 days in Equation 44). It uses a coefficient that controls the duration of the reproductive season as a function of latitude (φ) that has a default value of 2 in the list of parameters for ryegrass in the sward node.

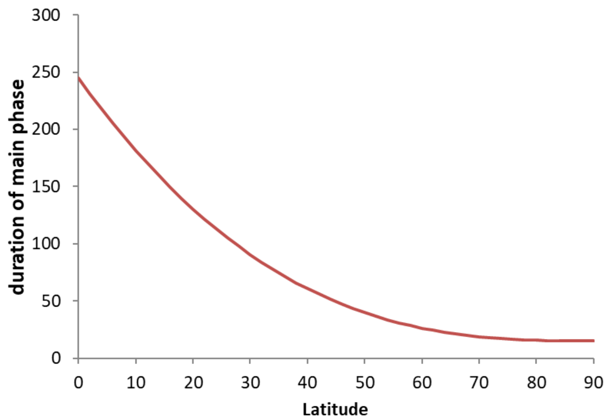

Figure 22. Duration of the main phase in relation to latitude

Equation 44 $$Repro_{PlateauDuration} = 15.22 + 167.41 * (1-(Lat/90))^{\varphi}$$

The broken-stick function has two more phases, of onset and offset, that can last a maximum of 6 months. The duration of these phases is linked to the duration of the main phase and is calculated through Equations 45 and 46, where a factor $\varkappa$ and a default value of 0.6, which sets the proportion of the onset phase of shoulder period with reproductive growth effect, are used. The factor $\varkappa$ is the minimum value between 182.6 days (6 months) and the value presented by Equation 47, where 1 is the default value for the ratio between the length of shoulders and the period with full reproductive growth effect. All the default values mentioned in these equations can be set at the list of parameters for ryegrass in the sward node.

Equation 45 $$Repro_{OnsetDuration} = \varkappa * 0.6$$

Equation 46 $$Repro_{OffsetDuration} = \varkappa * (1-0.6)$$

Equation 47 $$\varkappa = Repro_{PlateauDuration} * 1$$

The last two steps for the reproductive growth simulation are the calculation of the start of the reproductive season (Repro in Equation 48) and the relative increase in the S:R ratio during this season

($S{:}R_{MainPhase}$ in Equation 49). This relative increase in calculated based on the maximum increase in S:R ratio during reproductive growth, which is defaulted at 0.5, and on ϟ (Equation 50). This last term is based on the coefficient controlling the increase in shoot allocation during reproductive growth as a function of latitude, defaulted as 0.1, Lat and Lat_{Ref}.

Equation 48 $$Repro = Repro_{Plateau} - Repro_{OnsetDuration}$$

Equation 49 $$S{:}R_{MainPhase} = 0.5 / (1 + ϟ)$$

Equation 50 $$ϟ = e^{(-0.1 * (Lat - LatRef))}$$

Ideally, the drive for changes in S:R ratio should come from aspects such as influence of photoperiod, thermal time or even photothermal time on the start of the reproductive growth. So, this is a point that could be further improved in AgPasture.

3.3.1.3 Leaf growth

The method used to calculate the fraction of new shoot DM that is allocated to leaves in AgPasture reduces the proportion of leaves as plants grows. This is used for species that allocate proportionally more DM to stolon/stems when the whole plant DM is high. So, to avoid little allocation of DM to leaves in the case of grazing, the current S:R ratio is evaluated and used to modify the targeted value in a similar way as S:R ratio.

First, AgPasture calculates the new target fraction leaf ($Leaf_{TargetFraction}$). This will be the maximum target allocation of new growth to leaves, which has a default value of 0.7. However, if the minimum target allocation of new growth to leaves ($Leaf_{Minimium}$) is smaller than the maximum target allocation ($Leaf_{Maximum}$) and if the DM weight of live tissues above ground ($DM_{AboveGround}$) is higher than the shoot DM at which allocation of new growth to leaves start to decrease ($Leaf_{DMthreshold}$), the new target fraction leaf will be calculated as Equation 51. The default values for $Leaf_{Minimium}$, $Leaf_{Maximum}$ and $Leaf_{DMthreshold}$ are presented in the list of parameters for ryegrass in the sward node. Equation 51 uses $Leaf_{Aux}$, which is calculated as Equation 52, where $Leaf_{FractionFactor}$ is the shoot DM when allocation to leaves is halfway between maximum and minimum allocation and $Leaf_{Exponent}$ is the exponent controlling the DM allocation to leaves. All these values, apart from $DM_{AboveGround}$, have their default values in the list of parameters for ryegrass in the sward node.

Equation 51 $$Leaf_{TargetFraction} = Leaf_{Minimium} + (Leaf_{Maximum} - Leaf_{Minimium}) / (1 + Leaf_{Aux})$$

Equation 52 $$Leaf_{Aux} = ((DM_{AboveGround} - Leaf_{DMthreshold}) / (Leaf_{FractionFactor} - Leaf_{DMthreshold}))^{LeafExponent}$$

Then, AgPasture gets the current leaf:stem ratio ($L{:}S_{Current}$) and the target leaf:stem ratio ($L{:}S_{Target}$ in Equation 53), which will then be adjusted ($L{:}S_{Adjusted}$) to avoid excess allocation to stem/stolons

(Equation 54). Finally, it calculates the fraction of new shoot growth allocated to leaves ($Leaf_{Fraction}$ in Equation 55).

Equation 53 $$L{:}S_{Target} = Leaf_{TargetFraction} / (1 - Leaf_{TargetFraction})$$

Equation 54 $$L{:}S_{Adjusted} = L{:}S_{Target} * (L{:}S_{Target} / L{:}S_{Current})$$

Equation 55 $$Leaf_{Fraction} = L{:}S_{Adjusted} / (1 + L{:}S_{Adjusted})$$

3.3.1.3.1 Leaf area index (LAI)

AgPasture considers the leaves plus an additional effect of stems and stolons on the value of LAI. Firstly, AgPasture converts the amount of green leaves DM (kg/ha) to kg/m^2. To this amount of green leaves ($Tissue_{LeafGreen}$), it adds a proportion of green tissue from stolons using the stolons live DM (DM_{Stolon}) and the fraction of stolon tissue used when computing green LAI ($LAI_{StolonEffect}$ in Equation 56), which results on $Tissue_{S+LGreen}$. The $LAI_{StolonEffect}$ is set as 0 as a default for ryegrass and this can be changed in the list of parameters in the sward node.

Equation 56 $$Tissue_{S+LGreen} = Tissue_{LeafGreen} + (DM_{Stolon} * LAI_{StolonEffect} / 10000)$$

When the plant used is not a legume and the above ground live weight is lower than the maximum above ground biomass for considering stems when calculating LAI ($LAI_{MaxShootEffect}$), the DM amount is considered low. In this case, AgPasture considers some green tissue from stems in the calculation of LAI. This is done as a way to improve pasture resilience after unfavourable conditions, such as low residual DM. By considering stems on the calculation of LAI, it is assumed that the green cover will be higher for the same amount of DM than when only leaves are used. This mimics a greater light extinction coefficient, because leaves will be more horizontal than in dense high swards, more parts (stems) turning green for photosynthesis and thinner leaves during growth burst following unfavourable conditions. The calculation of the amount of green tissue from stems ($Tissue_{StemsGreen}$ in Equation 57) to be added to the $Tissue_{LeafGreen}$, to give the total green tissue ($Tissue_{TotalGreen}$), uses the stem live DM (DM_{Stem}) and a shoot factor (Fac_{Shoot}), determined in Equation 58. In this equation, $LAI_{MaxStemEffect}$ is the fraction of stem tissue used when computing green LAI. The default values of $LAI_{MaxShootEffect}$ and $LAI_{MaxStemEffect}$ for ryegrass are in the list of parameters in the sward node.

Equation 57 $$Tissue_{StemsGreen} = DM_{stem} * Fac_{Shoot} / 10000$$

Equation 58 $$Fac_{Shoot} = LAI_{MaxStemEffect} * \sqrt{1 - (DM_{AboveGround} / LAI_{MaxShootEffect}}$$

Finally, AgPasture calulates the LAI for all green (LAI_{Green} in Equation 59) and dead tissues (LAI_{Dead} in Equation 60). This value is based on a default specific leaf area (SLA) value of 25 m^2/kg DM, which can be changed in the list of parameters in the sward node, and on the leaf dead DM amount ($DM_{DeadLeaf}$) for the LAI_{Dead} calculation.

Equation 59 $$LAI_{Green} = Tissue_{TotalGreen} * SLA$$

Equation 60 $$LAI_{Dead} = (DM_{DeadLeaf} / 10000) * SLA$$

3.3.1.4 Dry matter allocation to roots

AgPasture calculates the allocation of new growth to roots for each layer of the root zone. The current target distribution for roots changes whenever root depth changes. This is used to allocate new growth to each layer and the existing distribution is used on any DM removal. Therefore, it may take some time for the actual distribution to evolve to be equal to the target distribution.

Firstly, because root DM changes with growth, the model needs to check the potential changes occurring in root distribution ($Root_{GrowthFraction}$). It evaluates the current root target ($Root_{CurTarget}$) by calculating the current target distribution of roots in the soil profile ($Root_{CurDistrTarget}$). If the root DM fraction for each layer ($Root_{FractionWt}$) is the same as $Root_{CurTarget}$, then the distribution does not change. If the distribution needs to change, AgPasture calculates the preliminary $Root_{GrowthFraction}$ by averaging $Root_{FractionWt}$ and $Root_{CurTarget}$ and then the distribution is normalised to the total number of layers.

The next step is the allocation of new growth to each layer of the root zone ($Root_{DMTransfLayer}$), which depends on the actual growth of roots ($Root_{GrowthDM}$) and $Root_{GrowthFraction}$ (Equation 61). The same process is done to calculate the allocation of N.

Equation 61 $$Root_{DMTransfLayer} = Root_{GrowthDM} * Root_{GrowthFraction}$$

Currently AgPasture only considers roots in the main zone. Therefore, a point of improvement for the model is the consideration of other root zones.

3.3.2 Tissue turnover

A representation of how DM is transferred across tissues and how turnover rates act is presented in Figure 19. Basically, AgPasture calculates the rates for each tissue pool of all plant organs. These rates are passed on to each organ and the amounts potentially turned over are calculated for each tissue pool.

AgPasture calculates the DM turnover ($Turnover_{DM}$) and the N turnover ($Turnover_{N}$) in the same way, so here we will present calculations as $Turnover_{DM}$. Generic calculations for tissues (Equation 62) start with the $Turnover_{DM}$ for the emerging tissue pool (tissue 0). In these calculations $DM_{Tissue[t]}$ refers to the DM weight of the tissue pool t, which can be 0 to 3, and $Turnover_{Rate}$ is the turnover rate for each tissue.

Equation 62 $$Turnover_{DM} = DM_{Tissue[t]} * Turnover_{Rate}$$

The new $Turnover_{DM}$ is added to the amount of DM transferred out ($DM_{TransfOut}$) from this tissue pool. The incoming transferred DM ($DM_{TransfIn}$) is then given to each layer ($DM_{TransfInLayer}$) of the following tissue pool (Equation 63), as a fraction of the DM ($DM_{Fraction}$) for tissue (Tissue[t+1]). On the next day, this amount of DM transferred in will be the sum of the DM transferred in at each layer.

Equation 63 $$DM_{TransfInLayerTissue[t+1]} = Turnover_{DM} * DM_{Fraction[layer]Tissue[t]}$$

So, at the start, $DM_{TransfOut}$ will be 0. Then on the following days, DM will be transferred from tissue 0 to other tissues and distributed to the layers of tissues in each pool.

3.3.2.1 Turnover rate

To calculate the daily DM turnover rate for live shoot (leaf and stem) tissues (γ in Equation 64) AgPasture considers a reference daily DM turnover rate for shoot tissues ($Turnover_{RefRateShoot}$), a tissue turnover factor due to variations in temperature ($Turnover_{TemperatureFactor}$), a factor for variations in moisture ($Turnover_{MoistureShoot}$) and a factor related to the number of leaves ($Turnover_{LeafNumber}$).

Equation 64 $$\gamma = Turnover_{RefRateShoot} * Turnover_{TemperatureFactor} * Turnover_{MoistureShoot} * Turnover_{LeafNumber}$$

The $Turnover_{RefRateShoot}$ is set at 0.05 in the list of parameters for ryegrass in the sward component. The $Turnover_{TemperatureFactor}$ is dependent on the average temperature ($Temp_{Average}$) and the temperature effect on tissue turnover ($Turnover_{EffectTemp}$ in Equation 65), which is based on the minimum temperature for tissue turnover ($Turnover_{MinTemp}$) and the reference temperature for tissue turnover ($Turnover_{RefTemp}$). These values can be set at the list of parameters for ryegrass in the sward component and their default values are 2°C and 20°C, respectively. If the current temperature is higher than $Turnover_{MinTemp}$ and less or equal to $Turnover_{RefTemp}$, $Turnover_{EffectTemp}$ is calculated as Equation 66. In this equation, $Turnover_{TempExponent}$ is the exponent of the function for temperature effect on tissue turnover. If the temperature is higher than $Turnover_{RefTemp}$, then $Turnover_{EffectTemp}$ is 1.0.

Equation 65 $$Turnover_{TemperatureFactor} = Turnover_{EffectTemp} * Temp_{Average}$$

Equation 66 $$Turnover_{EffectTemp} = (Temp - Turnover_{MinTemp}) /(Turnover_{RefTemp} - Turnover_{MinTemp})^{Turnover_{TempExponent}}$$

The $Turnover_{MoistureShoot}$ depends on if a growth limiting factor due to water (ε_W), whichever is the minimum value between the growth limiting factor due to water stress (ε_W) and water logging (ε_A), is lower than the minimum ε_W that does not affect tissue turnover ($Turnover_{Min\varepsilon W}$) (set as a default of 0.5 in the list of parameters for ryegrass in the sward component). If this is true, then $Turnover_{MoistureShoot}$ is calculated as Equation 67. If not, then a value of 1 is used as $Turnover_{MoistureShoot}$. In this equation, ε_W refers to the minimum value between the ε_W and ε_A and $Turnover_{Max\varepsilon W}$ is the maximum increase in tissue turnover due to water deficit. This can be set at the list of parameters for ryegrass in the sward component and its default value is 1.

Equation 67 $$Turnover_{MoistureShoot} = 1 + Turnover_{MaxƐW} * ((Turnover_{MinƐw} - Ɛ_W) / Turnover_{MinƐw})$$

The $Turnover_{LeafNumber}$ considers the number of leaves and is calculated as Equation 68, where 3 refers to the number of stages used in the model and $Leaf_{LiveTiller}$ is the number of live leaves per tiller.

Equation 68 $$Turnover_{LeafNumber} = 3 / Leaf_{LiveTiller}$$

To simulate the turnover rate for stolons (γS in Equation 69), AgPasture needs to make sure that the plant is a legume and then it uses the same γ from the shoot turnover calculation, which works as a base rate, with an addition of the defoliation effect on turnover of tissues ($Turnover_{DefolEffect}$ in Equation 69).

Equation 69 $$γS = γ + Turnover_{DefolEffect} * (1 – γ)$$

The calculation of $Turnover_{DefolEffect}$ depends on a set of rules. This effect is calculated differently across multiple days because this approach spreads the effect over a few days after defoliation, being larger at the start and decreasing with time. In this process, it is assumed that a defoliation of 100% of harvestable material will result in a full decay of stolons. On the first day, $Turnover_{DefolEffect}$ is computed based on $Turnover_{DefolFactor}$ being 0. On the following day, the calculation of the $Turnover_{DefolEffect}$ depends on the $Turnover_{DefolFactor}$ computed on the previous day plus the fraction of standing DM harvested used on tissue turnover ($Turnover_{DefolFraction}$ in Equation 70), which is relative to the given day. AgPasture will then continue to calculate a reduced factor for defoliation following Equation 71. This is done until the $Turnover_{DefolEffect}$ reaches a minimum value, which is set as when the $Turnover_{DefolFactor}$ minus the $Turnover_{TodayFactor}$ is lower than the minimum significant daily effect of defoliation on tissue turnover rate ($Turnover_{MinDefolEffect}$). The $Turnover_{TodayFactor}$ is calculated as Equation 72, where the $Turnover_{DefolCoefficient}$ is the coefficient of the function increasing the turnover rate due to defoliation. This value is set as a default of 0.5 in the list of parameters for ryegrass in the sward component. When the minimum value for $Turnover_{DefolEffect}$ is reached, the $Turnover_{DefolFactor}$, and therefore $Turnover_{DefolEffect}$, is again set back to 0.

Equation 70 $$Turnover_{DefolEffect} = Turnover_{DefolFactor} + Turnover_{DefolFraction}$$

Equation 71 $$Turnover_{DefolEffect} = Turnover_{DefolFactor} - Turnover_{TodayFactor}$$

Equation 72 $$Turnover_{TodayFactor} = Turnover_{DefolFactor}^{(Turnover_{DefolCoefficient} + 1)} / (Turnover_{DefolCoefficient} + 1)$$

The turnover rate for roots (γR in Equation 73) depends on the reference daily DM turnover rate for root tissues ($Turnover_{RateRoot}$), $Turnover_{TemperatureFactor}$, $Turnover_{MoistureRoot}$, the effect of defoliation on root turnover relative to stolon ($Turnover_{DefolRootEffect}$) and $Turnover_{DefolEffect}$.

Equation 73 $\gamma R = Turnover_{RefRateRoot} * Turnover_{TemperatureFactor} * Turnover_{MoistureRoot} + (Turnover_{DefolRootEffect} * Turnover_{DefolEffect}) * (1 - Turnover_{RateRoot} * Turnover_{TemperatureFactor} * Turnover_{MoistureRoot})$

Default values of 0.02 for the $Turnover_{RefRateRoot}$ and of 0.1 for the $Turnover_{DefolRootEffect}$ can be set at the parameters list for ryegrass in the sward component.

3.3.2.2 Dead tissue detachment and senescing

The turnover for dead material (γ_D in Equation 74) depends on the reference daily detachment rate for dead tissues ($Detachment_{RateShoot}$), the moisture factor for littering rate ($Turnover_{MoistureLitter}$), digestibility of dead material ($Digest_{Dead}$), carbon fraction in DM ($DM_{CFraction}$ set at 0.4) and a stocking rate factor affecting the transfer of dead material to litter ($Turnover_{StockFactor2Litter}$).

Equation 74 $\gamma_D = ((Detachment_{RateShoot} * Turnover_{MoistureLitter} * Digest_{Dead}) / DM_{CFraction}) + Turnover_{StockFactor2Litter}$

AgPasture checks if senescence will not result in a lower amount of DM than the minimum above ground DM, set at the ryegrass parameters list in the sward node, when γ is higher than 0. For that, it will calculate the minimum DM amount of standing live leaves and stems ($Standing_{MinimumLive}$ in Equation 75). Then it will calculate the amount of green DM that is and will be available ($DM_{GreenToBe}$) via Equation 76. In this equation, the $DM_{CurrentGreen}$ is the sum of the amount of live DM leaf and stem tissues, while the $DM_{CurrentMature}$ is the sum of the amount of DM of leaf and stem in the pool of tissue 2.

Equation 75 $Standing_{MinimumLive} = Leaves_{MinimumLiveDM} + Stems_{MinimumLiveDM}$

Equation 76 $DM_{GreenToBe} = DM_{CurrentGreen} – (DM_{CurrentMature} * \gamma)$

If $DM_{GreenToBe}$ is lower than $Standing_{MinimumLive}$, then AgPasture will reduce the daily turnover rate by recalculating γ (γ_{Recalc} in Equation 77). In this situation, AgPasture will also reduce the stolon and root turnover (Equation 78) by dividing by half the reduction that was done for leaf/stem (Equation 79).

Equation 77 $\gamma_{Recalc} = (DM_{CurrentGreen} - Standing_{MinimumLive}) / DM_{CurrentMature}$

Equation 78 $\gamma S_{Reduced}$ or $\gamma R_{Reduced} = \gamma S$ (or γR) $* Factor_{DMTurnover}$

Equation 79 $Factor_{DMTurnover} = 0.5 * (\gamma + \gamma_{Recalc})/ \gamma$

3.4 Root distribution

In AgPasture there is one root pool for each plant species, represented by variables related to the total root mass and N content. The root pool is updated daily as new biomass is added and a fraction is removed as senescence. Roots are not differentiated according to growth stages or soil layer.

AgPasture calculates the target (or ideal) distribution of roots in the soil profile. This distribution is mainly based on root parameters, such as maximum depth and distribution parameters. These values will then be used to allocate initial root DM and any growth over the profile. The model considers a homogeneous distribution close to the soil surface followed by an exponential decrease with depth (Figure 23).

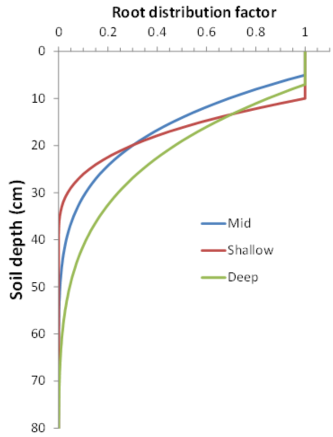

Figure 23. Example of a shallow ($Depth_{FirstStage}$ = 10 cm, $Root_{DefaultMaxDepth}$ = 40 cm, $Root_{DistrExponent}$ = 3), mid ($Depth_{FirstStage}$ = 5 cm, $Root_{DefaultMaxDepth}$ = 80 cm, $Root_{DistrExponent}$ = 5) and deep ($Depth_{FirstStage}$ = 7 cm, $Root_{DefaultMaxDepth}$ = 100 cm, $Root_{DistrExponent}$ = 5) root distribution in AgPasture.

The first phase of root distribution shows a uniform base distribution of roots from surface down to a fraction of root depth, which is the depth for constant root proportion. Then, the second phase of root distribution starts and the proportion of root decreases below the depth for constant root proportion. This decrease follows a power function, which has an exponent that controls the root distribution as a function of depth. The proportion of roots reaches 0 slightly below the maximum root depth, which is defined by the root bottom distribution factor. However, the function is truncated at the maximum root depth and the values are not normalised. Further on, the values are adjusted using the values of the exploration factor (XF). Therefore, there will be less roots at these layers.

So, for the first stage, when the bottom depth ($Depth_{Bottom}$) is less or equal the depth for the first stage ($Depth_{FirstStage}$), the root distribution ($Root_{Distribution}$) will be uniformly calculated as Equation 80. The $Depth_{FirstStage}$ will be whichever is the minimum value between the default value for maximum root depth ($Root_{DefaultMaxDepth}$) and the depth from surface where root proportion starts to decrease ($Root_{DistrDepthParam}$). Both of these values are set at the parameters list for ryegrass at the sward component. The calculation in Equation 80 will consider the soil layer thickness ($Soil_{LayerThick}$) and the soil exploration factor (XF), from the soil component.

Equation 80

$$Root_{Distribution} = Soil_{LayerThick}\ XF$$

For any other condition of $Depth_{Bottom}$ (such as $Depth_{Bottom}$ > $Depth_{FirstStage}$), a maximum root depth ($Root_{MaxDepth}$) will be calculated (Equation 81) based on $Root_{DefaultMaxDepth}$ and the root bottom distribution factor ($Root_{BottomDistrFactor}$). This is a factor to calculate root distribution that controls where, below the $Root_{MaxDepth}$, the function is 0. This factor has a default value of 1.05 in AgPasture.

Equation 81 $$Root_{MaxDepth} = Root_{DefaultMaxDepth} * Root_{BottomDistrFactor}$$

Then, AgPasture will calculate $Root_{Distribution}$ decrease as a power function (Equation 82). This calculation will consider a $Depth_1$ that will be equivalent to whichever value is highest between the top layer ($Depth_{Top}$) and $Depth_{FirstStage}$, a $Depth_2$ that will be whichever value is the lowest between $Depth_{Bottom}$ and $Root_{DefaultMaxDepth}$, and the exponent that controls root distribution as a function of depth ($Root_{DistrExponent}$), which can be set at the list of parameters for ryegrass in the sward component. If this exponent is set at 1, it means that the variation of the root distribution as a function of depth will be linear.

Equation 82 $$Root_{Distribution} = ((Root_{MaxDepth\text{-}}Depth_1)^{Root_{DistrExponent}+1}) - ((Root_{MaxDepth\text{-}}Depth_2)^{Root_{DistrExponent}+1}) \, / \, (Root_{DistrExponent} + 1) \, ((Root_{MaxDepth\text{-}}Depth_{FirstStage})^{Root_{DistrExponent}}$$

4. Water demand and uptake

4.1 Water demand

The water uptake process in AgPasture calculates the potential water uptake. AgPasture does not account for different layers of soil, so here, only one layer is considered. AgPasture starts by getting the amount of water available ($Water_{Supply}$). This value is the amount of plant available water in the soil (PAW) summed over all soil layers. Then, AgPasture gets the amount of soil water demanded ($Water_{Demand}$), which is the amount of water demanded for new growth ($Water_{DemandNG}$) that comes from the calculation of potential evapotranspiration, done by micromet (Snow andHuth, 2004). Micromet receives information about plant height, total and green LAI and cover from AgPasture and calculates the water demand. After that, AgPasture estimates the fraction of water used up ($Water_{FractionUsed}$). This is calculated as Equation 83, where Min means that this value will be whichever is the lowest value between 1 and the ratio between $Water_{Demand}$ and $Water_{Supply}$.

Equation 83 $$Water_{FractionUsed} = Min\,(1, Water_{Demand} / Water_{Supply})$$

Then, the model gets the amount of water actually taken up ($Water_{Uptake}$ in Equation 84).

Equation 84 $$Water_{Uptake} = PAW * Water_{FractionUsed}$$

AgPasture partitions $Water_{Demand}$ between the existing species ($Water_{DemandSp}$) based on green LAI (LAI_{Green}) and light extinction coefficient (K) (Equation 85). If water uptake is set to calculate

$Water_{Demand}$ for the whole sward, then the partition between species is purely cosmetic. Ideally, $Water_{Demand}$ should be calculated by micromet for each species but this option has not been implemented because it clashes with the routines used by SWIM.

Equation 85 $$Water_{DemandSp} = Water_{Demand} * (LAI_{GreenS}\, K_S / \Sigma LAI_{GreenS}\, K_S)$$

4.1.1 Water uptake through SWIM

In simulations using SWIM, water uptake is controlled by the water module. AgPasture sends the total water demand and root information to SWIM. After SWIM does its calculations, the values for actual plant uptake, by layer, are passed back to AgPasture. These values are all added to make up the actual water uptake, which is used to calculate the growth limiting factor (ε_W). This is all done without any partitioning between species.

4.2 Water availability

4.2.1 DeafultAPSIM method

The DefaultAPSIM method for water availability estimates the amount of available water for each soil layer of the root zone. It is the default APSIM method with kL representing the daily rate for water extraction. So, for each soil layer, PAW calculation will follow Equation 86. This equation will use $Root_{FractionLayer}$, which calculates how much of the layer is actually explored by roots, considering only depth. Also, in Equation 86, Max refers to whichever is the highest value between 0 and the result of Equation 87. In Equation 87, W refers to the amount of water in each soil layer, LL is the lower limit for each layer.

Equation 86 $$PAW = (Max\,(0, Ш)) * Root_{FractionLayer} * kL$$

Equation 87 $$Ш = W - (LL * Soil_{LayerThick})$$

4.2.2 Alternative kL

This is an alternative method to estimate the amount of plant available water in each layer of the root zone. In this method, kL represents a soil limiting factor for water extraction. This method also uses a plant related factor ($Root_{LDFactor}$) based on root length density ($Root_{LD}$). This limits conditions when $Root_{LD}$ is below the reference $Root_{LD}$ ($Root_{LDRef}$), which has a default value of 5 for water and nitrogen availability. Equation 88 shows that $Root_{LDFactor}$ will be the minimum value between 1 and the ratio between $Root_{LD}$ and $Root_{LDRef}$.

Equation 88 $$Root_{LDFactor} = Min\,(1, Root_{LD} / Root_{LDRef})$$

Then, AgPasture uses a soil water factor ($Water_{SoilFactor}$) to further calculate the actual plant available water. When soil water (SW) is higher or equal to the drained upper limit (DUL), $Water_{SoilFactor}$ is 1.0. When SW is less or equal to the lower limit (LL), WaterSoilFactor is 0. If these conditions are not satisfied, $Water_{SoilFactor}$ will be calculated as Equation 89. In this equation, $Water_{Ratio}$ is calculated as Equation 90, and $Soil_{MoistureExponent}$ is the exponent controlling the effect of soil moisture variations on water extractability. This exponent has a default value of 1.5 in AgPasture.

Equation 89 $$Water_{SoilFactor} = 1 - (1 - Water_{Ratio})^{Soil_{MoistureExponent}}$$

Equation 90 $$Water_{Ratio} = (W - LL15) / (DUL - LL15)$$

Finally, the actual plant available water (PAW_{Actual}) is calculated as Equation 91. In this equation, AgPasture will use the highest (Max) value between 0 and the result of Equation 92 and the lowest (Min) value between 1 and the result of Equation 93.

Equation 91 $$PAW_{Actual} = (Max\ (0, \text{Ơ})) * Root_{FractionLayer} * (Min\ (1, \text{Ƣ}))$$

Equation 92 $$\text{Ơ} = W - (LL * Soil_{LayerThick})$$

Equation 93 $$\text{Ƣ} = kL * Water_{SoilFactor} * Root_{LDFactor}$$

4.2.3 Alternative kS

This is an alternative method that does not use kL, but a factor based on kS, which is an amount of mm per day that is allowed to drain from a layer when the soil water is above saturation. This is then modified by soil water (SW) content and a plant related factor, based on $Root_{LD}$. All three factors will then be normalised using a reference kS (kS_{Ref}) for kS, a reference $Root_{LD}$ ($Root_{LDRef}$) for $Root_{LD}$, and DUL for SW. The effect of all factors is assumed to vary between 0 and 1, following exponential functions so that the effect of the factors is 90% at the reference value.

This method will use the same principles as the Alternative kL method to establish the value of $Water_{SoilFactor}$ that is used. This way, the calculation of PAW_{Actual} (Equation 94) uses the same Ơ previously used and the Min value between the result of Equation 95 and 1. This equation uses a $Root_{LD}$ factor ($Root_{LDFactorkS}$), calculated as Equation 96 and a previously defined $Water_{SoilFactor}$. It also uses a factor (kS_{Factor}), calculated as Equation 97, where kS_{Ref} is the reference value of kS for a water availability function, which has a default value of 15 in AgPasture.

Equation 94 $$PAW_{Actual} = (Max\ (0, \text{Ơ})) * Root_{FractionLayer} * (Min\ (1, \text{Ƥ}))$$

Equation 95 $$\text{Ƥ} = Root_{LDFactorkS} * kS_{Factor} * Soil_{LayerThick}$$

Equation 96 $$Root_{LDFactorkS} = 1 - (10^{(-\frac{Root_{LD}}{Root_{LDRef}})})$$

Equation 97 $$kS_{Factor} = 1 - (10^{(-\frac{kS}{kS_{Ref}})})$$

5. Cut, grazing and pasture parameters

5.1 Grazing and biomass removal

AgPasture has the Graze and RemoveBiomass methods to simulate biomass removal. Each method has a way to give the amounts of biomass to be removed. This can be done in a simple way (Graze) or through the control of the amount to be removed from different organs (RemoveBiomass). Both methods are dependent on a minimum green dry matter amount (the minimum above ground green dry matter, $Minimum_{GreenWtDefault}$, with a default value of 100 kg DM/ha), which is never removed. This minimum amount of dry matter is composed by a default proportion of leaves of 0.7 ($Minimum_{GreenLeafPropDefault}$). In both methods, a series of checks are done to guarantee a mass balance at the end of the biomass removal process. The model also has default values for grazing preferences, such as the relative preference for live over dead material ($Pref_{DeafultGreen/Dead}$) and the relative preference for leaf over stem-stolon ($Pref_{DefaultLeaf/StemStolon}$), set at 1.

5.1.1 Graze method

This method is used so that AgPasture removes a given amount of biomass simulating a grazing event. It uses a parameter Amount, which refers to the amount of DM set, and Type, which defines how the value of Amount is interpreted. Type can be set as $Type_{ResidueAmount}$, where the Amount set is the amount of residual DM that will be left after biomass removal, or $Type_{RemoveAmount}$, where the Amount set is the total biomass to be removed (Figure 24).

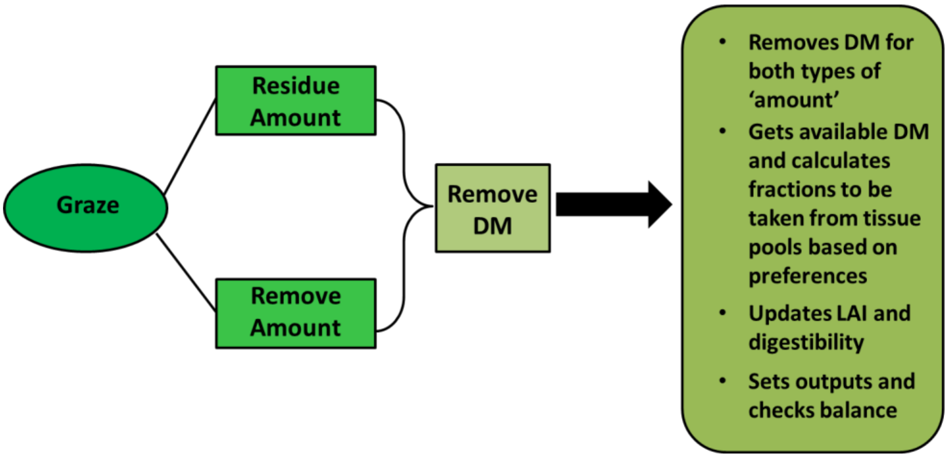

Figure 24. Summary of the 'Graze' method for biomass removal

So first, AgPasture gets the amount required. If $Type_{ResidueAmount}$ is used, then all DM above the set residual amount will be removed (Equation 98). The amount required ($Amount_{Required}$) is based on whichever is the highest value between 0 and the difference between the DM weight of standing herbage ($DM_{StandingHerbWt}$) and the set DM amount.

Equation 98 $$Amount_{Required} = Max\,(0, DM_{StandingHerbWt} - Amount)$$

If $Type_{RemoveAmount}$ is used, then AgPasture calculates the $Amount_{Required}$ through Equation 99.

Equation 99 $$Amount_{Required} = Max\ (0, Amount)$$

Then, AgPasture gets the actual amount to be removed ($Amount_{ToRemove}$ in Equation 100), which is based on whichever is the lowest value (Min) between the required amount and the DM weight available for harvesting ($DM_{HarvestableWt}$). If $Amount_{ToRemove}$ is above epsilon, the actual removal of DM is done via the function $Remove_{DM}$.

Equation 100 $$Amount_{ToRemove} = Max\ (0, Min\ (Amount_{Required}, DM_{HarvestableWt}))$$

The $Remove_{DM}$ function (Figure 24) acts on the biomass amount to be removed and this is then partitioned among organs and pools. This occurs according to the relative available biomass, which is the existing biomass minus the minimum dry matter, and preferences, such as $Pref_{DeafultGreen/Dead}$ and $Pref_{DefaultLeaf/StemStolon}$.

5.1.2 RemoveBiomass method

This method allows the control of the amounts of each organ and pool that is being removed. It has the parameters $Removal_{Type}$ and $Removal_{Data}$ to establish the fractions to be removed (Figure 25).

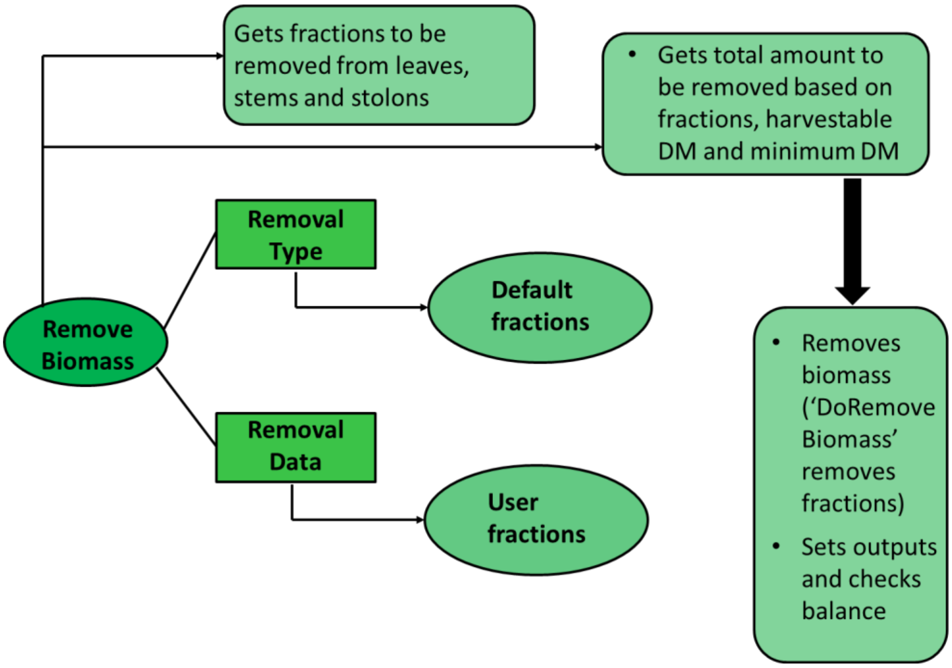

Figure 25. Summary of the 'RemoveBiomass' method for biomass removal.

The $Removal_{Type}$ is based on default fractions for organs (leaves, stems and stolons) with fractions for live and dead pools of DM to be removed and residual DM. The $Removal_{Type}$ can be divided into default values for harvest, graze and cut. The current default values for each organ do not change for each type of $Removal_{Type}$ though (Table 1). The $Removal_{Data}$ is an optional APSIM X construct 'OrganBiomassRemovalType' that holds the fraction of biomass to be removed from each organ. In this case, fractions are set by the user. If no $Removal_{Data}$ information is supplied, the RemoveBiomass method uses the default values set up for $Removal_{Type}$.

Table 1. Default values for the fractions to be removed by the RemoveBiomass method, $Removal_{Type}$ type of biomass removal.

Organs	Type	Fraction	Default	Organs	Type	Fraction	Default	Organs	Type	Fraction	Default
Leaves	Harvest	LiveToRemove	0.5	Stems	Harvest	LiveToRemove	0.5	Stolons	Harvest	LiveToRemove	0.5
		DeadToRemove	0.5			DeadToRemove	0.5			DeadToRemove	0.0
		LiveToResidue	0.0			LiveToResidue	0.0			LiveToResidue	0.0
		DeadToResidue	0.0			DeadToResidue	0.0			DeadToResidue	0.0
	Graze	LiveToRemove	0.5		Graze	LiveToRemove	0.5		Graze	LiveToRemove	0.5
		DeadToRemove	0.5			DeadToRemove	0.5			DeadToRemove	0.0
		LiveToResidue	0.0			LiveToResidue	0.0			LiveToResidue	0.0
		DeadToResidue	0.0			DeadToResidue	0.0			DeadToResidue	0.0
	Cut	LiveToRemove	0.5		Cut	LiveToRemove	0.5		Cut	LiveToRemove	0.5
		DeadToRemove	0.5			DeadToRemove	0.5			DeadToRemove	0.0
		LiveToResidue	0.0			LiveToResidue	0.0			LiveToResidue	0.0
		DeadToResidue	0.0			DeadToResidue	0.0			DeadToResidue	0.0

5.1.3 $Remove_{DM}$ function

This is how a given amount of DM ($Amount_{ToRemove}$) and N are removed using preferences for green over dead material to partition the amount to remove between plant parts. Here we will only exemplify calculations based on DM. This method should only be called after a test checks if $DM_{HarvestableWt}$ is greater than 0.

First, AgPasture gets the existing DM ($DM_{PreRemovalShoot}$), which is the DM of the plant above ground ($DM_{AboveGroundWt}$). Then, it gets the DM weights for each pool, considering preferences and available DM. The preference for the green pool ($Pref_{Green}$), calculated as Equation 101, is based on $Pref_{DeafultGreen/Dead}$. It has a default value of 1 that can be set at the list of parameters for ryegrass in the sward component. The model also calculates the preference for the dead pool ($Pref_{Dead}$ in Equation 102).

Equation 101 $$Pref_{Green} = Pref_{DeafultGreen/Dead} + (Amount_{ToRemove} / DM_{HarvestableWt})$$

Equation 102 $$Pref_{Dead} = 1 + (Pref_{DeafultGreen/Dead} * Amount_{ToRemove} / DM_{HarvestableWt})$$

Then AgPasture gets the removable amount of green DM ($Removable_{Green}$ in Equation 103), based on the DM in the live (green) tissues available for harvest for leaves ($Leaf_{LiveDMHarvestable}$), stems ($Stems_{LiveDMHarvestable}$) and stolons ($Stolons_{LiveDMHarvestable}$). It also gets the removable amount of dead DM ($Removable_{Dead}$), which is the same as the DM weight of dead standing herbage ($DM_{StandingDeadWt}$).

Equation 103 $$Removable_{Green} = Max\ (0,\ (Leaf_{LiveDMHarvestable} + Stems_{LiveDMHarvestable} + Stolons_{LiveDMHarvestable}))$$

Then, AgPasture does the partitioning between dead (Equation 104) and live (Equation 105) materials ($DM_{FractionHarvDead}$ and $DM_{FractionHarvGreen}$ respectively), which are based on the total removable amount ($Removable_{Total}$) calculated in Equation 106.

Equation 104 $$DM_{FractionHarvDead} = Removable_{Dead} * Pref_{Dead} / Removable_{Total}$$

Equation 105 $$DM_{FractionHarvGreen} = Removable_{Green} * Pref_{Green} / Removable_{Total}$$

Equation 106 $$Removable_{Total} = Removable_{Green} * Pref_{Green} + Removable_{Dead} * Pref_{Dead}$$

The partitioning will be used to calculate the amounts to be removed ($Amount_{ToRemoveGreen}$ in Equation 107 and $Amount_{ToRemoveDead}$ in Equation 108).

Equation 107 $$Amount_{ToRemoveGreen} = Amount_{ToRemove} * DM_{FractionHarvGreen}$$

Equation 108 $$Amount_{ToRemoveDead} = Amount_{ToRemove} * DM_{FractionHarvDead}$$

AgPasture will then give the fraction of DM remaining in the field ($Ramining_{Fraction}$) for each tissue pool, which will usually be 1. However, if the standing herbage DM weight ($DM_{StandingWt}$), of each pool, is higher than epsilon, then AgPasture will calculate the remaining fractions according to Equation 109. This will be done for the green ($Remaining_{GreenFraction}$), dead ($Remaining_{DeadFraction}$) and stolon ($Remaining_{StolonFraction}$) tissue pools in the same way and here it will be exemplified as the calculation for the green pool.

Equation 109 RemainingGreenFraction = Max (0, Min (1, 1 - AmountToRemoveGreen / DMStandingLiveWt))

The digestibility of the DM being harvested will be calculated based on the average digestibility of the harvested plant material, which is based on the amount of DM and the fraction to be harvested from the live and dead pools for leaves, stems and stolons. Then the various tissue pools are updated and Agpasture finally sets the outputs ($Defoliated_{Fraction}$ in Equation 110) and checks the mass balance.

Equation 110 $$Defoliated_{Fraction} = (DM_{PreRemovalShoot} - DM_{AboveGroundWt}) / DM_{PreRemovalShoot}$$

5.2 Available managers

AgPasture has managers that allow the user to set up the most adequate pasture management for the simulation. Managers are available in the Management toolbox and their use is exemplified through the example simulations. Some of the options of management available via managers are presented next.

5.2.1 Regular cut and remove

Through this manager the harvested biomass is removed from the pasture on fixed intervals between harvests. It also has the option to return or not nitrogen and carbon.

5.2.2 Regular harvest or grazing

This manager works in the same way as the previous one, but the return of nutrients can be done via animal excreta, through dung and urine. This is dependable on the type of animal and digestibility of the ingested material. The default nitrogen removal by sheep and beef is 15% and 25% for dairy grazed pastures. However, these values can be changed by the user if needed.

5.2.3 Harvest on fixed dates

The user can set up the dates when biomass removal is done. These can be done through a previously set up manager or can be done via the ‘operations’ manager, available in APSIM X. An example on how the ‘operations’ manager can be used is available in AgPasture.

5.2.4 Target for harvest

The user can set up in the managers a target amount of residual biomass to be left after harvest/grazing, a target amount of dry matter to be removed at each harvest/grazing event or just set up the harvest to happen based on time interval (either fixed or specific days).

5.3 Output variables

AgPasture has outputs that generate information about general properties, dry matter and carbon, dry matter dynamics for growth and senescence, water, growth limiting factors, dry matter allocation and turnover rates, LAI and cover, root depth and distribution, harvest, dry matter of tissues (Table 2). It also has outputs that provide information about nitrogen in the system, such as nitrogen amount, nitrogen concentrations, nitrogen flows in the system, nitrogen concentration of tissues (Table 3).

Table 2. Outputs for general properties, dry matter and carbon

Type of output	Function	public double
General properties	If plant is alive	IsAlive
	Plant status	PlantStatus
	Plant development stage	Stage
	Radiation intercepted by the canopy	InterceptedRadn
	Radiance on top of the canopy	RadiationTopOfCanopy
DM and C	Total amount of C in the plant	TotalC
	Total DM weight of the plant	TotalWt
	DM weight of the plant above ground	AboveGroundWt
	DM weight of live tissues above ground	AboveGroundLiveWt
	DM weight of dead tissues above ground	AboveGroundDeadWt
	DM weight of plant below ground	BelowGroundWt
	DM weight of live tissues below ground	BelowGroundLiveWt
	DM weight of standing herbage	StandingHerbageWt
	DM weight of live standing herbage	StandingLiveHerbageWt
	DM weight of dead standing herbage	StandingDeadHerbageWt
	DM weight of leaves	LeafWt
	DM weight of live leaves	LeafLiveWt
	DM weight of dead leaves	LeafDeadWt
	DM weight of stems and sheath	StemWt
	DM weight of alive stems and sheath	StemLiveWt
	DM weight of dead stems and sheath	StemDeadWt
	DM weight of stolons	StolonsWt
	DM weight of roots	RootWt
DM growth and senescence	Base potential photosynthetic rate after damages	BasePotentialPhotosynthesis
	Gross potential photosynthetic rate after damages	GrossPotentialPhotosynthesis
	Respiration cost	RespirationLossC
	N fixation cost	NFixationCostC
	Remobilised carbon from senesced tissues	RemobilisedSenescedC
	Gross potential growth rate	GrossPotentialGrowthWt
	Net potential growth rate, after respiration	NetPotentialGrowthWt
	Net potential growth rate after water stress	NetPotentialGrowthAfterWaterWt
	Net potential growth rate after nutrient stress	NetPotentialGrowthAfterNutrientWt
	Net or actual plant growth rate	NetGrowthWt
	Net herbage growth rate	HerbageGrowthWt
	Net root growth rate	RootGrowthWt
	DM weight of detached dead material deposited on soil surface	LitterDepositionWt
	DM weight of detached dead roots added to soil FOM	RootDetachedWt
	Gross primary productivity	GPP
	Net primary productivity	NPP
	Net above ground primary productivity	NAPP
	Net below ground primary productivity	NBPP
Water	Soil wate content at lower limit for plant uptake	LL
	Amount of water demanded by the plant	WaterDemand
	Amount of plant available water in each soil layer	WaterAvailable
	Amount of water taken up from each soil layer	WaterUptake
Growth limiting factors	Growth factor due to intercepted radiation	GlfRadnIntercept
	Growth factor due to CO2	GlfCO2
	Gorwth factor due to plant N concentration	GlfNContent
	Growth factor due to air temperature	GlfTemperature
	Growth factor due to heat damage stress	GlfHeatDamage
	Growth factor due to cold damage stress	GlfColdDamage
	Growth factor due to water deficit	GlfWaterSupply
	growth factor due to water logging	GlfWaterLogging
	Growth factor due to soil N availability	GlfNSupply
	Temperature factor for respiration	TemperatureRespiration
DM allocation and turnover rates	Fraction of new growth allocated to shoot	FractionGrowthToShoot
	Fraction of new growth allocated to roots	FractionGrowthToRoot
	Fraction of new growth allocated to leaves	FractionGrowthToLeaf
	Turnover rate for live shoot tissues	TurnoverRateLiveShoot
	Turnover rate for dead shoot tissues	TurnoverRateDeadShoot
	Turnover rate for stolon tissues	TurnoverRateDeadStolons
	Turnover rate for root tissues	TurnoverRateRoots
	Temperature factor for tissue turnover	TemperatureFactorTurnover
	Moisture factor for tissue turnover	MoistureFactorTurnover
LAI and cover	Leaf area index of green tissues	LAIGreen
	Leaf area index of dead tissues	LAIDead
	Fraciton of soil covered by dead tissues	CoverDead
Root depth and distribution	Average depth of root zone	RootDepth
	Layer at the bottom of root zone	RootFrontier
	Fraction of root dry matter for each soil layer	RootWtFraction
	Root length density by volume	RootLengthDensity
Harvest	Above ground biomass	Biomass AboveGround
	DM available for harvest	HarvestableWt
	Amount of DM removed by harvest	HarvestedWt
	Fraction of available DM actually harvested	HarvestedFraction
	Amount of plant N removed by harvest	HarvestedN
	Average N concentration in harvested material	HarvestedNConc
	Average digestibility of harvested material	HarvestedDigestibility
	Average metabolisable energy concentration harvested	HarvestedME
	Average digestibility of standing herbage	HerbageDigestibility
	Average metabolisable energy concentration of standing herbage	HerbageME
DM tissues	DM weight of emerging tissues for above ground organs	EmergingTissueWt
	DM weight of developing tissues for above ground organs	DevelopingTissuesWt
	DM weight of mature tissues for above ground organs	MatureTissuesWt
	DM weight of dead tissues for above ground organs	DeadTissuesWt
	DM weight of emerging tissues of leaves	LeafStage1Wt
	DM weight of developing tissues of leaves	LeafStage2Wt
	DM weight of mature tissues of leaves	LeafStage3Wt
	DM weight of dead tissues of leaves	LeafStage4Wt
	DM weight of emerging tissues of stems	StemStage1Wt
	DM weight of developing tissues of stems	StemStage2Wt
	DM weight of mature tissues of stems	StemStage3Wt
	DM weight of dead tissues of stems	StemStage4Wt
	DM weight of emerging tissues of stolons	StolonStage1Wt
	DM weight of developing tissues of stolons	StolonStage2Wt
	DM weight of mature tissues of stolons	StolonStage3Wt

Table 3. Outputs for nitrogen in the system

Type of output	Function	public double
N amount	Total amount of N in the plant	TotalN
	Amount of N in the plant above ground	AboveGroundN
	Amount of N in live tissues above ground	AboveGroundLiveN
	Amount of N in dead tissues above ground	AboveGroundDeadN
	Amount of N in plant below ground	BelowGroundN
	Amount of N in live tissues below ground	BelowGroundLiveN
	Amount of N in standing herbage	StandingHerbageN
	Amount of N in live standing herbage	StandingLiveHerbageN
	N content of standing dead plant material	StadingDeadHerbageN
	N content of leaves	LeafN
	N amount of live leaves	LeafLiveN
	N amount of dead leaves	LeafDeadN
	N amount of stems and sheath	StemN
	N amount of live stems and sheath	StemLiveN
	N amount of dead stems and sheath	StemDeadN
	N amount of plant stolons	StolonN
	N amount of roots	RootN
N concentration	Average N concentration in the plant above ground	AboveGroundNConc
	Average N concentration in standing herbage	StandingHerbageNConc
	Average N concentration in leaves	LeafNConc
	Average N concentration in stems	StemNConc
	Average N concentration in stolons	StolonNConc
	Average N concentration in roots	RootNConc
N flows	Amount of senesced N potentially remobilisable	RemobilisableSenescedN
	Amount of senesced N actually remobilised	RemobilisedSenescedN
	Amount of luxury N potentially remobilisable	RemobilisableLuxuryN
	Amount of luxury N actually remobilised	RemobilisedLuxuryN
	Amount of atmospheric N fixed by simbiosis	FixedN
	Amount of N required with luxury uptake	DeamandAtLuxuryN
	Amount of N required for optimum growth	DeamandAtOptimumN
	Amount of N demanded from the soil	SoilDemandN
	Amount of plant available N in the soil	SoilAvailableN
	Amount of taken up from soil	SoilUptakeN
	Amount of N in detached dead material on the soil surface	LitterDepositionN
	Amount of N in detached dead roots added to soil FOM	RootDetachedN
	Amount of N in new growth	NetGrowthN
	Amount of plant available NH4-N in each soil layer	SoilNH4Available
	Amount of plant available NO3-N in each soil layer	SoilNO3Available
	Amount of NH4-N taken up from each soil layer	SoilNH4Uptake
	Amount of NO3-N taken up from each soil layer	SoilNO3Uptake
N tissues	N concentration of emerging tissues for above ground organs	EmergingTissueWt
	N concentration of developing tissues for above ground organs	DevelopingTissuesWt
	N concentration of mature tissues for above ground organs	MatureTissuesWt
	N concentration of dead tissues for above ground organs	DeadTissuesWt
	N concentration of emerging tissues of leaves	LeafStage1Wt
	N concentration of developing tissues of leaves	LeafStage2Wt
	N concentration of mature tissues of leaves	LeafStage3Wt
	N concentration of dead tissues of leaves	LeafStage4Wt
	N concentration of emerging tissues of stems	StemStage1Wt
	N concentration of developing tissues of stems	StemStage2Wt
	N concentration of mature tissues of stems	StemStage3Wt
	N concentration of dead tissues of stems	StemStage4Wt
	N concentration of emerging tissues of stolons	StolonStage1Wt
	N concentration of developing tissues of stolons	StolonStage2Wt
	N concentration of mature tissues of stolons	StolonStage3Wt

6. Parameters and default values used in AgPasture

The following tables 4 and 5 show a summary of the main parameters and default values used in AgPasture.

Table 4. Parameters and default values for initial state of plants, potential growth, respiration, nitrogen concentration thresholds, allocation of new growth, effect of reproductive season and tissue turnover and senescence.

Function of the parameter	Public double	Deafault Value
Initial above ground DM weight	InitialShootDM	2000 kg DM/ha
Initial below ground DM weight	InitialRootDM	500 kg DM/ha
Initial rooting depth	InitialRootDepth	750 mm
Reference leaf CO_2 assimilation rate for photosynthesis	ReferencePhotosyntheticRate	1 mg CO_2/m^2leaf/s
Leaf photosynthetic efficiency	PhotosyntheticEfficiency	0.01 mg CO_2 /J
Photosynthesis curvature parameter	PhotosynthesisCurveFactor	0.8 J/kg/s
Light extinction coefficient	LightExtinctionCoefficient	0.5
Reference CO_2 concentration for photosynthesis	ReferenceCO2	380 ppm
Scaling parameter for the CO_2 effect on photosynthesis	CO2EffectScaleFactor	700 ppm
Scaling parameter for CO_2 effects on N requirements	CO2EffectOffsetFactor	600 ppm
Minimum value for the CO_2 effect on N requirements	CO2EffectMinimum	0.7
Exponent controlling CO_2 effect on N requirements	CO2EffectExponent	2
Minimum temperature for growth	GrowthTminimum	1
Optimum temperature for growth	GrowthToptimum	20
Curve parameter for growth response to temperature	GrowthTEffectExponent	1.7
Onset temperature for heat effects on photosynthesis	HeatOnsetTemperature	28
Temperature for full heat effect on photosynthesis	HeatFullTemperature	35
Cumulative degree-days for recovery from heat stress	HeatRecoverySumDD	30^{o}Cd
Reference temperaturefor recovery from heat stress	HeatRecoveryTReference	25^{o}C
Onset temperature for cold effects on photosynthetis	ColdOnsetTemperature	1^{o}C
Temperature for full cold effect on photosynthesis	ColdFullTemperature	-5^{o}C
Cumulative degree-days for recovery from cold stress	ColdRecoverySumDD	25^{o}Cd
Reference temperature for recovery from cold stress	ColdRecoverytReference	0^{o}C
Maintenance respiration coefficient	MaintenanceRespirationCoefficier	0.03
Growth respiration coefficient	GrowthRespirationCoefficient	0.25
Reference temperature for maintenance respiration	RespirationTReference	20^{o}C
Exponent controlling the effect of temperature on respiration	RespirationExponent	1.5
N concentration threshold for leaves (optimum, minimum and maximum)	NThresholdForLeaves	0.04, 0.012, 0.05 kg N/kg DM
N concentration threshold for stems (optimum, minimum and maximum)	NThresholdForStems	0.02, 0.006, 0.025 kg N/kg DM
N concentration threshold for roots (optimum, minimum and maximum)	NThresholdForRoots	0.02, 0.006, 0.025 kg N/kg DM
Target or ideal shoot:root ratio	TargetShootRootRatio	4
Maximum fraction of DM growth allocated to roots	MaxRootAllocation	0.25
Maximum effect that soil Glfs have on shoot:Root ratio	ShootRootGlfFactor	0.5
Reference latitude determining timining for reproductive season	ReproSeasonReferenceLatitude	41
Coefficient controlling the time to start the reproductive season as function of latitude	ReproSeasonTimingCoeff	0.14
Coefficient controlling the duration of the reproductive season as a function of latitude	ReproSeasonDurationCoeff	2
Ratio between the length of shoulders and the period with full reproductive growth effect	ReproSeasonShouldersLengthFact	1
Proportion of the onset phase of shoulder period with reproductive growth effect	ReproSeasonOnsetDurationFactor	0.6
Maximum increase in shoot:root ratio during reproductive growth	ReproSeasonMaxAllocationIncreas	0.5
Coefficient controlling the increase in shoot allocation during reproductive growth as a function of latitude	ReproSeasonAllocationCoeff	0.1
Maximum target allocation of new growth to leaves	FractionLeafMaximum	0.7
Minimum target allocation of new growth to leaves	FractionLeafMinimum	0.7
Shoot DM at which allocation of new growth to leaves start to decrease	FractionLeafDMThreshold	500 kg DM/ha
Shoot DM when allocation to leaves is halfway between maximum minimum	FractionLeafDMFactor	2000 kg DM/ha
Exponent controlling the DM allocation to leaves	FractionLeafExponent	3
Fraction of new shoot growth to be allocated to stolons	FractionToStolon	0
Specific leaf area	SpecificLeafArea	25 m^2/kg DM
Specif root length	SpecificRootLength	100 m/g DM
Maximum above ground biomass to consider stems in the calculation of LAI	ShootMaxEffectOnLAI	1000 kg DM/ha
Fraction of stem tissue used when calculating green LAI	MaxStemEffectOnLAI	1
Number of live leaves per tiller	LiveLeavesPerTiller	3
Reference daily DM turnover rate for shoot tissues	TissueTurnoverRateShoot	0.05
Reference daily DM turnover rate for root tissues	TissueTurnoverRateRoot	0.02
Relative turnover rate for emerging tissues	RelativeTurnoverEmerging	2
Reference daily detachment rate for dead tissues	DetachmentRateShoot	0.08
Minimum temperature for tissue turnover	TurnoverTemperatureMin	2^{o}C
Reference temperature for tissue turnover	TurnoverTemperatureRef	20^{o}C
Exponent of function for temperature effect on tissue turnover	TurnoverTemperatureExponent	1
Maximum increase in tissue turnover due to water deficit	TurnoverDroughtEffectMax	1
Minimum Glfwater without the effect on tissue turnover	TurnoverDroughtThreshold	0.5
Coefficient controlling detachment rate as a function of moisture	DetachmentDroughtCoefficient	3
Minimum effect of drought on detachment rate	DetachmentDroughtEffectMin	0.1
Factor increasing tissue turnover rate due to stock trampling	TurnoverStockFactor	0.01
Coefficient of function increasing the turnover rate due to defoliation	TurnoverDefoliationCoefficient	0.5
Minimum significant daily effect of defoliation on tissue turnover rate	TurnoverDefoliationEffectMin	0.025
Effect of defoliation on root turnover rate relative to stolon	TurnoverDefoliationRootEffect	0.1
Fraction of luxury N remobilisable each day for each tissue age (emerging, developing and mature)	FractionNLuxuryRemobilisable	0.1, 0.1, 0.1

Table 5. Parameters and default values for nitrogen fixation (for legumes), growth limiting factors, plant height, root depth and distribution, digestibility and feed quality, harvest limits and preferences, water and nitrogen uptake process in the soil and constants used in AgPasture.

Function of the parameter	Public double	Deafault Value
Minimum fraction of N demand supplied by biologic N fixation	MinimumNFixation	0.2
Maximum fraction of N demand supplied by biologic N fixation	MaximumNFixation	0.6
Respiration cost factor due to the presence of symbiotic bacteria	SymbioticCostFactor	0
Respiration cost factor due to the activity of symbiotic bacteria	NFixingCostFactor	0
Maximum reduction in plant growth due to water logging, saturated soil	SoilSaturationEffectMax	0.1
Minimum water-free pore space for growth with no limitations	MinimumWaterFreePorosity	-1
Maximum daily recovery rate from water logging	SoilSaturationRecoveryFactor	0.25
Exponent for modifying the effect of N deficiency on plant growth	NDillutionCoefficient	0.5
Generic growth limiting factor representing an arbitrary limitation to potential growth	GlfGeneric	1
Generic growth limiting factor representing an arbitrary soil limitation	GlfSoilFertility	1
Minimum shoot height	PlantHeightMinimum	25 mm
Maximum shoot height	PlantHeightMaximum	600 mm
DM weight above ground for maximum plant height	PlantHeightMassForMax	10000 kg DM/ha
Exponent controlling shoot height as function of DM weight	PlantHeightExponent	2.8
Minimum rooting depth at emergence	RootDepthMinimum	50 mm
Maximum rooting depth	RootDepthMaximum	750 mm
Daily root elongation rate at optimum temperature	RootElongationRate	25 mm/day
Depth from surface where root proportion starts to decrease	RootDistributionDepthParam	90 mm
Exponent controlling the root distribution as function of depth	RootDistributionExponent	3.2
Factor to calculate root distribution (controls where, below maxRootDepth, the functon is zero)	RootBottomDistributionFactor	1.05
Digestibility of cell walls for each tissue age (emerging, developing, mature and dead)	DigestibilitiesCellWall	0.6, 0.6, 0.6, 0.2
Digestibility of proteins in plant tissues	DigestibilitiesProtein	1
Fraction of soluble carbohydrates in newly grown tissues	SugarFractionNewGorwth	0.5
Minimum above ground green DM, leaf and stems	MinimumGreenWt	100 kg DM/ha
Leaf proportion in the minimum green weight	MinimumGreenLeafProp	0.8
Minimum root amount relative to minimum green weigth	MinimumGreenRootProp	0.5
Proportion of stolon DM standing, availbale for removal	FractionStolonStanding	0
Relative preference for live over dead material during graze	PreferenceForGreenOverDead	1
Relative preference for leaf over stem/stolon material during graze	PreferenceForLeafOverStems	1
Sets which module will do the water uptake process	WaterUptakeSource	
Sets which method to calculate soil available water will be used	WaterAvailableMethod	DefaultAPSIM, AlternativeKL, AlternativeKS
Sets which module will perform the nitrogen uptake process	NitrogenUptakeSource	
Sets which method to calculate available soil nitrogen will be used	NitrogenAvailableMethod	BasicAgPasture, DefaultAPSIM, AlternativeRLD, AlternativeWup
Maximum fraction of water or N in the soil that is available to plants	MaximumFractionAvailable	0.999
Reference value for root length density for the water and N availability	ReferenceRLD	5
Exponent controlling the effect of soil moisture variations on water extractability	ExponentSoilMoisture	1.5
Reference value of Ksat for water availability function	ReferenceKSuptake	15
Exponent of function determining soil extractable N	NuptakeSWFactor	0.25
Maximum daily amount of N that can be taken up by the plant	MaximumNUptake	10 kg/ha
Ammonium uptake coefficient	KNH4	1
Nitrate uptake coefficient	KNO3	1
Availability factor for NH4	kuNH4	0.5
Availability factor for NO3	kuNO3	0.95
Average carbon content in plant dry matter	CarbonFractionInDM	0.4
Potential ME concentration in herbage material	PotentialMEOfHerbage	16 MJ/kg
Factor for converting nitrogen to protein	NitrogenToProteinFactor	6.25
Carbon to nitrogen ratio of proteins	CNRatioProtein	3.5
Carbon to nitrogen ratio of cell walls	CNRatioCellWall	100
Minimum significant difference between two values	Epsilon	0.000000001

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