# *Operational Research Assessment Tool for Organic Resources - ORATOR*

# *Description of model development*

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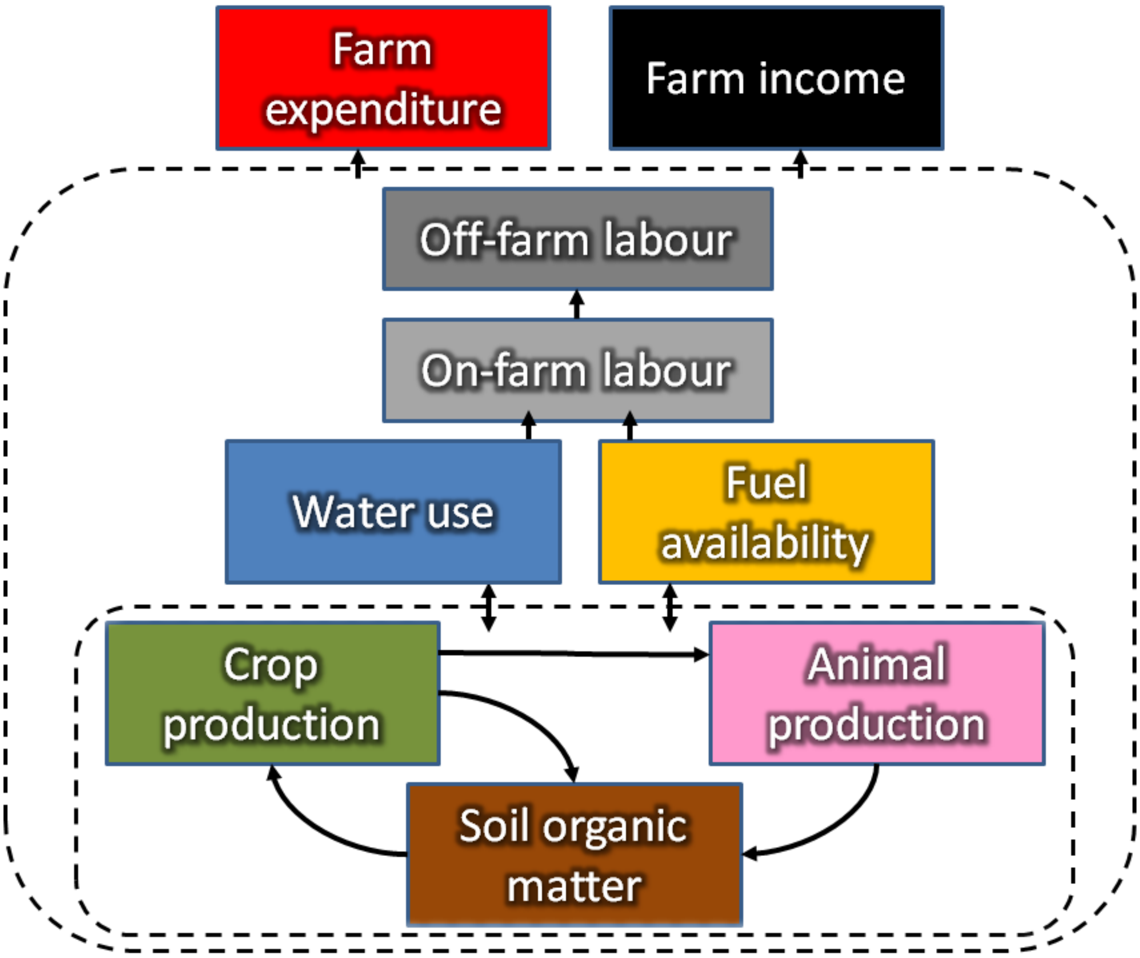
## Contents

## 1. Introduction

The "Operational Research Assessment Tool for Organic Resources in Africa" (ORATOR-Africa), developed for the BREAD and IPORE projects, is designed to account for the impact of different uses of farm resources on soil organic matter, crop production, animal production, water use, fuel availability, on- and off-farm labour, and farm income and expenditure. From this, it aims to use simple approaches to simulate resilience to drought and floods, and the impact that changes in resource management will have on resilience. It particularly focusses on organic resources, but because the whole system is represented, the impact of changing use of other resources is also simulated (for instance increasing expenditure on fertilisers). Different inputs of organic resources to the soil affect resource use in the whole system; increased inputs of carbon (C) to the soil lead to increases in the soil organic matter, which impacts the water holding capacity and nutrients available in the soil. This affects crop production, which has an impact on animal production using on-farm feeds. The water holding capacity of the soil and growth of crops and animals all affect the requirement for water. The growth of crops determines the amount of crop residues available to feed to animals and for use as a fuel, and so determines fuel availability (both as crop residues and as dung) and the labour required to collect additional fuel (such as wood). Water use, crops grown and the animals maintained also impact the labour required on the farm. This then impacts the remaining labour available for off-farm activities. The income and expenditure of the farm are a function of the purchases made by the household (e.g. food, feed, fuel & fertilisers) and the products and labour available within the household (e.g. grain, milk & animals for sale).



## 2. Soil

The simulation of changes in soil organic matter are based on the RothC model (Coleman and Jenkinson, 1996). RothC is a simple five-pool model that describes soil organic matter turnover using information about soil physicochemical properties, weather conditions, land-use and land management. The model represents soil organic matter as decomposable plant material (DPM), resistant plant material (RPM), biomass (BIO), humus (HUM) and inert organic matter (IOM). Plant material enters the soil as DPM and RPM, in proportions dependent on the land-use type. The DPM and RPM then decompose to produce BIO, HUM and carbon dioxide ($CO_2$), in proportions dependent on the clay content of the soil. The BIO and HUM pools then further decompose to BIO, HUM and $CO_2$ using the same proportions as for DPM and RPM decomposition. The rate of decomposition in each pool is modified by the temperature, moisture content, pH and salinity of the soil. Because the soil organic C (SOC) pools have different decomposition rate constants, including different proportions of these pools provides a representation of SOC with different activities. In a soil that is at steady state, the relative proportions of SOC pools can be determined by running the model to steady state (until no further changes in SOC content are observed), and then adjusting the plant inputs and re-running until the simulated SOC content matches the measured values (Smith et al., 2005). This initializes the model so that the impact of future land-use, weather and management conditions on SOC turnover can be simulated with greater accuracy (e.g. Smith et al., 1997). Interpolating the observations in the field in this way gives the model less work to do, and increases the accuracy with which it can simulate SOC turnover for a wide range of conditions around the world.

### 2.1. Carbon pools and plant inputs at steady state

***Definition of steady state***

For simulations of the impact of drought and subsequent floods or changes to organic inputs, it is assumed that the soil is in steady state before the change occurs. This may not be the case if soils have undergone recent land use change, are eroding or have recently undergone a recent change in management of organic inputs. However this assumption allows us to assess the impact on the *change* in SOC of the altered conditions compared to a typical year.

***Soil organic carbon pools***

The simulation starts using default SOC pools and plant inputs. The SOC pools can have any value as the steady state simulation will adjust the pool sizes according to the measured SOC. The value of the total annual plant inputs will also be determined by the steady state simulation, but the *distribution* of the plant inputs should follow the cropping patterns observed in the field.

The simulation is continued for 100 years, after which time, the C in the DPM, RPM, BIO, HUM and IOM pools are summed and compared to the measured soil C, $C_{\text{meas}}$ (t ha$^{-1}$). The soil C pools are then re-initialised with the values calculated after 100 years and the plant inputs, $C_{\text{PI}}$, are adjusted according to the ratio of measured and simulated total soil C;

$$C_{\text{PI}}{}^{*} = C_{\text{PI}} \times \frac{C_{\text{meas}}}{C_{\text{sim}}} \qquad \text{(eq.2.1.1)}$$

where $C_{\text{PI}}{}^{*}$ is the adjusted plant inputs of carbon to the soil (t ha$^{-1}$ y$^{-1}$) and $C_{\text{sim}}$ is the simulated total soil C (t ha$^{-1}$).

This process is continued until $C_{\mathrm{meas}}$ = $C_{\mathrm{sim}}$ after 10 years, at which point the soil is considered to be in steady state, with plant inputs and pool sizes defined as given in the final iteration.

For a 10 year rotation, the average plant inputs over the 10 years are used (as plant inputs differ between crops). To achieve the correct pattern of inputs, it is therefore important to use appropriate relative sizes of plant inputs of each crop with respect to other crops in the rotation.

***Rate of decomposition***

The amount of C lost from each pool in each time-step, $C_{\mathrm{loss}}$ (t ha$^{-1}$), is calculated as

$$C_{\mathrm{loss}} = C_{\mathrm{pool}}\left(1 - \exp\left(-k_{\mathrm{pool}} \times r_{\mathrm{mod}}\right)\right) \qquad \text{(eq.2.1.2)}$$

where $C_{\mathrm{pool}}$ is the amount of C in the pool (t ha$^{-1}$), $k_{\mathrm{pool}}$ is the rate constant for decomposition of the pool (for DPM $k_{\mathrm{pool}}$ = 10/12 = 0.8333 month$^{-1}$, for RPM $k_{\mathrm{pool}}$ = 0.3/12 = 0.025 month$^{-1}$, for BIO $k_{\mathrm{pool}}$ = 0.66/12 = 0.055 month$^{-1}$ and for HUM $k_{\mathrm{pool}}$ = 0.02/12 = 0.0017 month$^{-1}$), and $r_{\mathrm{mod}}$ is the product of rate modifiers that account for changes in temperature ($r_{\mathrm{temp}}$, Coleman and Jenkinson, 1996), soil moisture ($r_{\mathrm{wat}}$, Bradbury et al., 1993), acidity ($r_{\mathrm{pH}}$, Parton et al., 1996) and salinity ($r_{\mathrm{sal}}$, Setia et al., 2012):

$$r_{\mathrm{temp}} = \frac{47.91}{\left(1+\exp\left(106.06/(T_{\mathrm{a}}+18.27)\right)\right)} \qquad \text{(eq.2.1.3)}$$

where $T_{\mathrm{a}}$ is the average monthly air temperature (°C);

$$r_{\mathrm{wat}} = \min\left(1, r_{\mathrm{wat,0}} - \left(1 - r_{\mathrm{wat,0}}\right)\left(\frac{V_{\mathrm{wat}} - V_{\mathrm{PWP}}}{V_{\mathrm{FC}} - V_{\mathrm{PWP}} - D_{-100\mathrm{kPa}}}\right)\right) \qquad \text{(eq.2.1.4)}$$

where $r_{\mathrm{wat,0}}$ is the moisture rate modifier at permanent wilting point (= 0.2), $V_{\mathrm{wat}}$ is the water content of the soil in the given time-step, $V_{\mathrm{PWP}}$ is the water content at the permanent wilting point, $V_{\mathrm{FC}}$ is the water content at field capacity, and $D_{-100\mathrm{kPa}}$ is the deficit in soil water at -100 kPa, calculated as $D_{-100\mathrm{kPa}} = 0.444 \times (V_{\mathrm{FC}} - V_{\mathrm{PWP}})$ after Coleman and Jenkinson (1996) (all given in mm for the depth of soil simulated);

$$r_{\mathrm{pH}} = 0.56 + \frac{\tan^{-1}\left(3.14 \times 0.45 \times (S_{\mathrm{pH}} - 5)\right)}{3.14} \qquad \text{(eq.2.1.5)}$$

where $S_{\mathrm{pH}}$ is the soil pH measured in 0.01M $CaCl_2$ ; and

$$r_{\mathrm{sal}} = \exp(-0.09 \times S_{\mathrm{sal}}) \qquad \text{(eq.2.1.6)}$$

where $S_{\mathrm{sal}}$ is the soil salinity, measured as electrical conductivity in a 1:5 soil/water suspension (dS m$^{-1}$).

***Fate of soil organic carbon after decomposition***

After Coleman and Jenkinson (1996), the C lost from each pool due to aerobic decomposition is partitioned into HUM, BIO and $CO_2$ according to the clay content of the soil, proportions $p_{\mathrm{HUM}}$, $p_{\mathrm{BIO}}$ and $p_{\mathrm{CO2}}$ respectively;

$$p_{\mathrm{HUM}} = \left( \frac{1}{\left(1+1.67\times\left(1.85+1.6\times\exp\left(-0.0786\times P_{\mathrm{clay}}\right)\right)\right)} \right) \Big/ (1+0.85) \qquad \text{(eq.2.1.7)}$$

$$p_{\mathrm{BIO}} = \left( \frac{1}{\left(1+1.67\times\left(1.85+1.6\times\exp\left(-0.0786\times P_{\mathrm{clay}}\right)\right)\right)} \right) - p_{\mathrm{HUM}} \qquad \text{(eq.2.1.8)}$$

$$p_{\mathrm{CO2}} = 1 - p_{\mathrm{BIO}} - p_{\mathrm{HUM}} \qquad \text{(eq.2.1.9)}$$

where $P_{\mathrm{clay}}$ is the percentage clay in the soil.

***Inputs of carbon to the soil***

The default plant inputs of C and any other C inputs specified in the input data are added to the soil in the appropriate month. These inputs are divided between the SOC pools according to the DPM:RPM ratio of plant inputs, and the DPM:HUM ratio and proportion of IOM of organic wastes, (after Smith et al., 2014):

$$C_{\mathrm{PI,DPM}} = C_{\mathrm{PI}} \times \frac{p_{\mathrm{D:R,PI}}}{(1+p_{\mathrm{D:R,PI}})} \qquad \text{(eq.2.1.10)}$$

where $C_{\mathrm{PI,DPM}}$ is the amount of plant inputs passed to the DPM pool in the time-step (t ha$^{-1}$), $C_{\mathrm{PI}}$ is the total amount of C added in plant inputs in the time-step (t ha$^{-1}$), and $p_{\mathrm{D:R,PI}}$ is the ratio of DPM:RPM in the plant inputs (for arable assumed to be 1.44, for grassland, 0.67, and for forest and scrub, 0.25 after Coleman and Jenkinson, 1996);

$$C_{\mathrm{PI,RPM}} = C_{\mathrm{PI}} \times \frac{1}{(1+p_{\mathrm{D:R,PI}})} \qquad \text{(eq.2.1.11)}$$

where $C_{\mathrm{PI,RPM}}$ is the amount of plant inputs passed to the RPM pool in the time-step (t ha$^{-1}$);

$$C_{\mathrm{OW,DPM}} = C_{\mathrm{OW}} \times \frac{p_{\mathrm{D:H,OW}}(1-p_{\mathrm{IOM,OW}})}{(1+p_{\mathrm{D:H,OW}})} \qquad \text{(eq.2.1.12)}$$

where $C_{\mathrm{OW,DPM}}$ is the amount of organic waste passed to the DPM pool in the time-step (t ha$^{-1}$), $C_{\mathrm{OW}}$ is the total amount of C added in organic waste inputs in the time-step (t ha$^{-1}$), $p_{\mathrm{D:H,OW}}$ is the ratio of DPM:HUM in the active organic waste added (assumed to be 31.45 for fresh waste, 0.07 for compost, 0.14 for bioslurry and 0.05 for biochar after Smith et al., 2014), and $p_{\mathrm{IOM,OW}}$ is the proportion of inert organic matter in the added organic waste (assumed to be 0% for fresh waste, compost and bioslurry, and 50% for biochar after Smith et al., 2014); and

$$C_{\mathrm{OW,HUM}} = C_{\mathrm{OW}} \times \frac{(1-p_{\mathrm{IOM,OW}})}{(1+p_{\mathrm{D:H,OW}})} \qquad \text{(eq.2.1.13)}$$

where $C_{\mathrm{OW,HUM}}$ is the amount of organic waste passed to the HUM pool in the time-step (t ha$^{-1}$).

***Distribution of plant inputs***

The plant inputs for annual crops are distributed over the growing season between sowing and harvest using the equation for C inputs provided by Bradbury et al. (1993);

$$\frac{C_{\mathrm{PI,mon}}}{C_{\mathrm{PI}}} = \exp\left(-k_{\mathrm{PI,C}} \times (t_{\mathrm{harv}} - t_{\mathrm{mon}})\right) \Big/ \sum_{(\mathrm{i=sow,harv})} \exp\left(-k_{\mathrm{PI,C}} \times (t_{\mathrm{harv}} - t_{\mathrm{mon}})\right) \qquad \text{(eq.2.1.14)}$$

where $C_{\mathrm{PI,mon}}$ is the plant input of C in month $mon$ (t ha$^{-1}$), $C_{\mathrm{PI}}$ is the total plant input of C over the year (t ha$^{-1}$), $k_{\mathrm{PI,C}}$ is a constant describing the shape of the exponential curve for C input (after the value used for wheat by Bradbury et al. (1993) set to 0.15 week$^{-1}$ ≈ 0.6 month$^{-1}$), $t_{\mathrm{harv}}$ is the harvest month, and $t_{\mathrm{mon}}$ is the current month.

For perennial crops, plant inputs are assumed to be distributed evenly across the growing season, ie $\frac{C_{\mathrm{PI,mon}}}{C_{\mathrm{PI}}}$ = 1 for all months.

***Inert organic carbon***

The C in the IOM pool, $C_{\mathrm{IOM}}$ (t ha$^{-1}$) is initially estimated using the Falloon equation (Falloon et al., 1998) as

$$C_{\mathrm{IOM}} = 0.049 \times \left({C_{\mathrm{meas}}}^{1.139}\right) \qquad \text{(eq.2.1.15)}$$

where $C_{\mathrm{IOM}}$ is the amount of C in the IOM pool (t ha$^{-1}$), and $C_{\mathrm{meas}}$ is the measured C content of the soil (t ha$^{-1}$).

This is assumed to be inert, and does not change unless organic waste containing IOM is added to the soil;

$$C_{\mathrm{OW,IOM}} = p_{\mathrm{IOM,OW}} \times C_{\mathrm{OW}} \qquad \text{(eq.2.1.16)}$$

where $C_{\mathrm{OW,IOM}}$ is the amount of organic waste passed to the IOM pool in the time-step (t ha$^{-1}$).

## 2.2. Soil water

***Available water in a given depth of soil***

For a given depth of soil, $d$ (cm), the available water is calculated as the difference between the water content at field capacity, $V_{\mathrm{FC}}$ (mm), and a lower limit of water content. The lower limit for the water content is calculated from the water content at permanent wilting point, $V_{\mathrm{PWP}}$ (mm), divided by a "drying potential", $r_{\mathrm{dry}}$ (currently set to 2). The values $V_{\mathrm{FC}}$ and $V_{\mathrm{PWP}}$ are calculated as

$$V_{\mathrm{FC}} = \frac{\theta_{FC} \times d}{10} \qquad \text{(eq.2.2.1)}$$

and

$$V_{\mathrm{PWP}} = \frac{\theta_{PWP} \times d}{10 \times r_{\mathrm{dry}}} \qquad \text{(eq.2.2.2)}$$

where $\theta_{FC}$ is the volumetric water content at field capacity (%) and $\theta_{\mathrm{PWP}}$ is the volumetric water content at permanent wilting point (%).

***Volumetric water content at field capacity and permanent wilting point***

*Generic equations*

The values $\theta_{\mathrm{FC}}$ and $\theta_{\mathrm{PWP}}$ are obtained from pedotransfer functions provided by Tóth et al. (2015);

$$\theta_{\mathrm{FC}} = 24.49 - 18.87\left(\frac{1}{1+P_{\mathrm{C}}}\right) + 0.4527\left(P_{\mathrm{clay}}\right) + 0.1535\left(P_{\mathrm{silt}}\right) + 0.1442\left(P_{\mathrm{silt}}\right)\left(\frac{1}{1+P_{\mathrm{C}}}\right) - 0.00511\left(P_{\mathrm{silt}}\right)\left(P_{\mathrm{clay}}\right) + 0.08676\left(P_{\mathrm{clay}}\right)\left(\frac{1}{1+P_{\mathrm{C}}}\right) \quad \text{(eq.2.2.3)}$$

and

$$\theta_{\mathrm{PWP}} = 9.878 + 0.2127\left(P_{\mathrm{clay}}\right) - 0.08366\left(P_{\mathrm{silt}}\right) - 7.67\left(\frac{1}{1+P_{\mathrm{C}}}\right) + 0.003853\left(P_{\mathrm{silt}}\right)\left(P_{\mathrm{clay}}\right) + 0.233\left(P_{\mathrm{clay}}\right)\left(\frac{1}{1+P_{\mathrm{C}}}\right) + 0.09498\left(P_{\mathrm{silt}}\right)\left(\frac{1}{1+P_{\mathrm{C}}}\right) \quad \text{(eq.2.2.4)}$$

where $P_{\mathrm{clay}}$, $P_{\mathrm{silt}}$, $P_{\mathrm{C}}$ are the percentage clay, silt, and C in the soil, respectively.

*Halaba specific equations*

Equations specific to the Halaba area were derived by fitting to measurements for the Halaba area. ** Dali – please give details **

$$\theta_{\mathrm{FC}} = \left((4.442 \times P_{\mathrm{C}}) - (0.061 \times P_{\mathrm{sand}}) + \left(0.34 \times P_{\mathrm{clay}}\right) + 22.821\right) \quad \text{(eq.2.2.5)}$$

$$\theta_{\mathrm{PWP}} = \left((1.963 \times P_{\mathrm{C}}) - (0.029 \times P_{\mathrm{sand}}) + \left(0.166 \times P_{\mathrm{clay}}\right) + 11.746\right) \quad \text{(eq.2.2.6)}$$

where $P_{\mathrm{sand}}$ is the percentage sand in the soil.

***Weather data for steady state simulation***

The weather before the drought can be described using a repeated 12 month input of "typical" weather data; monthly total rainfall (mm) and monthly average air temperature (°C). This could be obtained from the weather data for the year previous to the drought or could be selected as the year that is closest to the average annual rainfall and air temperature over a number of years. It should not be obtained from the averages for a particular month over a number of years as this approach smooths out extreme weather events, which can have a significant impact on SOC turnover.

***Potential evapotranspiration***

The potential evapotranspiration, $V_{\mathrm{PET}}$ (mm month$^{-1}$), is obtained from the Thornthwaite equation (Thornthwaite, 1948).

$$V_{\mathrm{PET}} = 16\left(\frac{n_{\mathrm{days,mon}}}{30}\right)\left(\frac{L}{12}\right)\left(\frac{10 \times T_a}{I_{\mathrm{heat}}}\right)^{\varepsilon} \quad \text{(eq.2.2.7)}$$

where $n_{\mathrm{days,mon}}$ is the number of days in the month, $L$ is the day length (hours), $T_a$ is the average monthly temperature (°C), $I_{\mathrm{heat}}$ is the heat index, and $\varepsilon$ is a dimensionless exponent function.

The heat index, $I_{\mathrm{heat}}$, is a function of monthly air temperature, $T_{\mathrm{a,mon}}$, calculated as

$$I_{\mathrm{heat}} = \sum_{\mathrm{mon}=1}^{12} \left(\frac{T_{\mathrm{a,mon}}}{5}\right)^{1.514} \qquad \text{(eq.2.2.8)}$$

and the exponent function, ε, is calculated from the heat index, $I_{\mathrm{heat}}$, as

$$\varepsilon = 6.75 \times 10^{-7} I_{\mathrm{heat}}{}^{3} - 7.71 \times 10^{-3} I_{\mathrm{heat}}{}^{2} + 1.792 \times 10^{-2} I_{\mathrm{heat}} + 4.0239 \times 10^{-1} \qquad \text{(eq.2.2.9)}$$

The day length, $L$, is calculated using a modification of a formula provided by Kirk (2011) as presented by Brand et al. (2016)

$$L = 2\left(\frac{24}{2\pi}\right) \cos^{-1}\left(-\tan(\phi)\tan(\delta)\right) = \left(\frac{24}{\pi}\right) \cos^{-1}\left(-\tan(\phi)\tan(\delta)\right) \qquad \text{(eq.2.2.10)}$$

where ϕ is the latitude in radians (converted from decimal degrees ($\phi°$) to radians (rad), as $\phi = \left(\frac{\pi}{180}\right)\phi°$), and $\delta$ is the declination of the sun, calculated from the date in Julian days as an angle in radians ($\theta_{\mathrm{d}}$):

$$\delta = 0.006918 - 0.399912\cos(\theta_{\mathrm{d}}) + 0.070257\sin(\theta_{\mathrm{d}}) - 0.006758\cos(2\theta_{\mathrm{d}}) + 0.000907\sin(2\theta_{\mathrm{d}}) - 0.002697\cos(3\theta_{\mathrm{d}}) + 0.001480\sin(3\theta_{\mathrm{d}}) \qquad \text{(eq.2.2.11)}$$

The date number in Julian days, $n_{\mathrm{todate}}$, ranges from 0 on January 1st to 364 on December 31st. This can be converted to an angle in radians using

$$\theta_{\mathrm{d}} = 2\pi\left(\frac{n_{\mathrm{todate}}}{365}\right) \qquad \text{(eq.2.2.12)}$$

***Potential evapotranspiration from the selected depth of soil***

The potential evapotranspiration from the selected soil depth, $V_{\mathrm{PET,d}}$ (mm), is estimated from the proportion of the maximum rooting depth, $d_{\mathrm{max}}$ (cm), included in the depth of soil being simulated, $d$ (cm),

$$V_{\mathrm{PET,d}} = \min\left(V_{\mathrm{PET}}, V_{\mathrm{PET}} \times \left(\frac{d}{d_{\mathrm{max}}}\right)\right) \qquad \text{(eq.2.2.13)}$$

The maximum rooting depths for Ethiopian crops are given in Table 2.2.1.

Table 2.2.1. Rooting depths for Ethiopian crops

| Crop | Maximum rooting depth (cm) | Reference | Comment |
|---|---|---|---|
| Maize | 170 | Allen et al. (1998). | |
| Pulses / lentils | 100 | Allen et al. (1998). | |
| Teff | Over 80 (80 used) | Ayele et al. (2001); Kubo et al. (2012). | Many observations |

| | | | |
|---|---|---|---|
| Haricot beans | 100-150<br>(average 125 used) | Beebe et al. (2013). | Water absorption mainly in top 70cm |
| Finger millet | 150 | Beebe et al. (2013). | |
| Pepper | 60 | Alemayehu (2009). | Thesis |
| Coffee | 150 | Siles et al (2010); | |
| | | Defrenet et al. (2016) | 92% root at 150cm depth and only 8% below that. |
| Chat | 300-500<br>(average 400 used) | Lemesa (2001) | |
| Tomatoes | 150 | Allen et al. (1998). | |
| Cabbage | 80 | Allen et al. (1998). | |
| Grassland | 100-200<br>(average 150 used) | Allen et al. (1998). | |
| Shrubland | | | |

***Initialisation of soil water***

The soil water calculation at time $t_0$ is initialised at the average between field capacity and wilting point, $V_{\mathrm{wat,t0}} = \frac{(V_{\mathrm{FC}}+V_{\mathrm{PWP}})}{2}$ (mm). In the next timestep, the rainfall, $V_{\mathrm{rain,t1}}$ (mm) minus the potential evapotranspiration $V_{\mathrm{PET,t1}}$ (mm), plus any irrigation, $V_{\mathrm{irrig,t1}}$ (mm), are added to the soil, and the soil water is allowed to adjust between the range of the water available to the selected depth at field capacity, $V_{\mathrm{FC}}$ (mm), and at permanent wilting point, $V_{\mathrm{PWP}}$ (mm), giving a revised water content at time $t_1$, $V_{\mathrm{wat,t1}}$ (mm);

$$V_{\mathrm{wat,t1}} = \max\left(\min\left(\left(V_{\mathrm{wat,t0}} + V_{\mathrm{rain,t1}} - V_{\mathrm{PET,t1}} + V_{\mathrm{irrig,t1}}\right), V_{\mathrm{FC}}\right) V_{\mathrm{PWP}}\right) \qquad \text{(eq.2.2.14)}$$

Soil water is calculated over the 10 years and checked for steady state (no change).

## 2.3. Changes in soil carbon

The SOC pools are run to steady state, and then the model is run forward with changes in conditions implemented. To simulate the effects of a drought or flood, the typical weather data used for the steady state run is substituted with the weather data for the atypical year. The changes in organic inputs are estimated as far as possible using ratios; this approach is used in order to reduce potential errors associated with a full simulation of organic inputs that is not informed by the previous input values.

The plant input of C in any month ($mon$) of an atypical year, $C_{\mathrm{PI,atyp,mon}}$ (t ha$^{-1}$) is estimated from the ratio of plant production in an atypical year compared to a typical year, $p_{\mathrm{plant,atyp}}$,

$$C_{\mathrm{PI,atyp,mon}} = C_{\mathrm{PI,typ,mon}} \times p_{\mathrm{plant,atyp}} \quad \text{(eq.2.3.1)}$$

where $C_{\mathrm{PI,typ,mon}}$ is the plant input of C in month ($mon$) of a typical year (t ha$^{-1}$). Calculation of the ratio of plant production in an atypical year compared to a typical year is described in section 3.

The organic waste input of C in any month ($mon$) of an atypical year, $C_{\mathrm{OW,atyp,mon}}$ (t ha$^{-1}$) is estimated from the ratio of organic waste production in an atypical year compared to a typical year, $p_{\mathrm{OW,atyp}}$,

$$C_{\mathrm{OW,atyp,mon}} = C_{\mathrm{OW,typ,mon}} \times p_{\mathrm{OW,atyp}} \qquad \text{(eq.2.3.2)}$$

where $C_{\mathrm{OW,typ,mon}}$ is the organic waste input of C in month ($mon$) of a typical year (t ha$^{-1}$). The calculation of the ratio of organic waste produced in an atypical year compared to a typical year is described in section 4.

Other changes in conditions that may be included in future calculations, but have not yet been described include

1. The impact of animals scavenging plant residues as they move through fields (to water in drought years;
2. Impact of floods on erosion.

## 2.4. Soil nitrogen

Nitrogen (N) is assumed to be held in 6 pools in the soil; mineral N (nitrate and ammonium) and organic N (DPM, RPM, BIO and HUM-N). The release or uptake of N by organic matter is adjusted to maintain a stable C:N ratio, as described in section 3.3. The amount of nitrate changes according to inputs from the atmosphere, fertilisers and nitrification, and losses by immobilisation, leaching, denitrification and crop uptake. The amount of ammonium changes according to inputs from the atmosphere, fertilisers and by mineralisation, and losses by immobilisation, nitrification, volatilisation and crop uptake. Because the time step of the model is long (1 month), if the loss processes were calculated sequentially, as is often done in models with a shorter time step, there would be an unrealistically high rate of loss by the processes applied first. Therefore, the potential loss by each process is first calculated assuming no other demands on the mineral N, and then the loss by each process is adjusted using a “loss adjustment ratio” to account for the losses by the other processes. In this, way, all processes are assumed to occur simultaneously.

***Minimum nitrate and ammonium***

Due to the diffuse double layer around clay minerals and other soil particles, Bradbury et al. (1993) proposed that some of the mineral N is so tightly held in the soil that it cannot be accessed by plants, micro-organisms or leaching loss. Therefore, there is a critical minimum level of minimum N, below which, the mineral N cannot fall. This is important for comparison of the mineral N levels against field measurements, but is highly site specific, being dependent on the clay minerals, organic matter particles, and the way that the soil is aggregated. Therefore, in the absence of site specific information, it is assumed that the critical minimum level of mineral N is zero. This assumption means that the mineral N levels calculated provide estimates of changes, but not the absolute amount of mineral N. For comparison against a field experiments, the critical minimum level of mineral N, as observed in the field for that experiment, should first be added to the amount of mineral N estimated here. The nitrate and ammonium pools are initialised at the minimum level, and the model run for 10 years to establish the amount of nitrate or ammonium at the start of the forward run.

***Loss adjustment factor***

The potential losses from the soil are first calculated assuming no demand on mineral N from other loss processes. The actual loss by each process is then adjusted by multiplying by the loss adjustment factor, $f_{\mathrm{NO3,loss}}$ for nitrate and $f_{\mathrm{NH4,loss}}$ for ammonium, calculated as

$$f_{\mathrm{NO3,loss}} = \frac{(N_{\mathrm{NO3,start}} + N_{\mathrm{NO3,in}})}{N_{\mathrm{NO3,loss}}} \qquad \text{(eq.2.4.1)}$$

if $(N_{\mathrm{NO3,loss}} \leq (N_{\mathrm{NO3,start}} + N_{\mathrm{NO3,in}}))$, $f_{\mathrm{NO3,loss}} = 1$

where $N_{\mathrm{NO3,start}}$ is the amount of N available as nitrate at the start of the month, and $N_{\mathrm{NO3,in}}$ is the sum of all nitrate-N inputs and $N_{\mathrm{NO3,loss}}$ is the sum of all nitrate-N losses that occur during the month (all in kg ha$^{-1}$). A similar expression is used to calculate $f_{\mathrm{NH4,loss}}$.

***Inputs of nitrate***

*Atmospheric deposition* - The atmospheric deposition of N to the soil, $N_{\mathrm{atm}}$ (kg ha$^{-1}$), is entered as an input, according to the region where the farm is located, and a proportion is added to the nitrate pool, $p_{\mathrm{NO3,atm}}$, according to the composition of the atmospheric deposition. Therefore, the amount of nitrate added to the soil by atmospheric deposition, $N_{\mathrm{NO3,atm}}$ (kg ha$^{-1}$), is given by

$$N_{\mathrm{NO3,atm}} = p_{\mathrm{NO3,atm}} \times N_{\mathrm{atm}} \qquad \text{(eq.2.4.2)}$$

Here it is assumed that the atmospheric deposition is composed of equal proportions of nitrate and ammonium-N ($p_{\mathrm{NO3,atm}}$ = 0.5). This assumption may differ according to region.

*Fertiliser inputs* - The inputs of N fertiliser, $N_{\mathrm{fert}}$ (kg ha$^{-1}$), is assumed to add different proportions of nitrate to the soil, depending on the fertiliser type. Urea fertiliser (the main form of fertiliser used in Africa and India, decomposes on application to the soil to produce ammonium. Therefore, the proportion of nitrate added in the fertiliser, $p_{\mathrm{NO3,fert}}$, is zero. The fertiliser inputs to the nitrate pool, $N_{\mathrm{NO3,fert}}$ (kg ha$^{-1}$), are therefore set to zero,

$$N_{\mathrm{NO3,fert}} = p_{\mathrm{NO3,fert}} \times N_{\mathrm{fert}} = 0 \qquad \text{(eq.2.4.3)}$$

If different types of fertilisers are to be investigated, this assumption should be changed.

*Nitrification* – Nitrified ammonium, $N_{\mathrm{NH4,nitrif}}$ (kg ha$^{-1}$), is assumed to be added to the nitrate-N pool with no gaseous losses of N as NO or $N_2O$. Therefore, the input of N to nitrate by nitrification, $N_{\mathrm{NO3,nitrif}}$ (kg ha$^{-1}$) is equivalent to $N_{\mathrm{NH4,nitrif}}$,

$$N_{\mathrm{NO3,nitrif}} = N_{\mathrm{NH4,nitrif}} \qquad \text{(eq.2.4.4)}$$

***Losses of nitrate***

*Immobilisation* – The soil N supply is calculated as described in section 3.3. A negative soil N supply represents immobilised N. Immobilisation is assumed to occur first from the ammonium pool. Therefore, the potential loss of N from the nitrate pool by immobilisation, $N_{\mathrm{NO3,immob}}$ (kg ha$^{-1}$) is calculated as

$$N_{\mathrm{NO3,immob}} = \min\left(-\min\left((N_{\mathrm{soil}} - N_{\mathrm{NH4,immob}}), 0\right), N_{\mathrm{NO3}} - N_{\mathrm{NO3,min}}\right) \qquad \text{(eq.2.4.5)}$$

where $N_{\mathrm{soil}}$ is the soil N supply, $N_{\mathrm{NH4,immob}}$ is the N immobilised from the ammonium pool, and $N_{\mathrm{NO3,min}}$ is the minimum possible amount of nitrate-N, all in kg ha$^{-1}$.

*Leaching* – Nitrate-N lost by leaching, $N_{\mathrm{NO3,leach,t1}}$ (kg ha$^{-1}$), is calculated from the concentration of available nitrate in the soil at the start of the time step plus any inputs of nitrate after dilution with rainwater and the water drained from the soil$V_{\mathrm{wat,drained,t1}}$, (mm),

$$N_{\mathrm{NO3,leach,t1}} = \frac{(N_{\mathrm{NO3,start}} + N_{\mathrm{NO3,in}} - N_{\mathrm{NO3,min}})}{(V_{\mathrm{wat,start}} + V_{\mathrm{rain,t1}} - V_{\mathrm{PET,d,t1}})} \times V_{\mathrm{wat,drained,t1}} \qquad \text{(eq.2.4.6)}$$

where $V_{\mathrm{rain,t1}}$ is the rainfall during the time step (mm), $N_{\mathrm{NO3,start}}$ is the amount of nitrate-N at the start of the time step (kg ha$^{-1}$), $N_{\mathrm{NO3,in}}$ is the total N inputs to the nitrate pool (kg ha$^{-1}$), $N_{\mathrm{NO3,min}}$ is the minimum level of nitrate-N, below which no losses will occur (kg ha$^{-1}$), $V_{\mathrm{wat,start}}$ is the amount of water (mm) in the soil at the start of the time step, $V_{\mathrm{PET,d,t1}}$ is the potential evapotranspiration during the time step (mm) and $V_{\mathrm{wat,drained,t1}}$ is the volume of water drained (mm) during the time step, all given to the specified depth of soil.

The volume of water drained in time step t1, $V_{\mathrm{wat,drained,t1}}$ (mm), is calculated as the hydrologically effective rainfall minus the amount of water needed to bring the specified soil depth to field capacity,

$$V_{\mathrm{wat,drained,t1}} = \max\left(\left(\left(V_{\mathrm{rain,t1}} - V_{\mathrm{PET,d,t1}}\right) - \left(V_{\mathrm{FC}} - V_{\mathrm{wat,t0}}\right)\right), 0\right) \qquad \text{(eq.2.4.7)}$$

where $V_{\mathrm{rain,t1}}$ is the rainfall (mm), and $V_{\mathrm{PET,d,t1}}$ is the potential evapotranspiration, $V_{\mathrm{FC}}$ is the field capacity and $V_{\mathrm{wat,t0}}$ is the soil water at time t0, all given in mm to the specified depth of soil $d$ (cm).

*Denitrification* – Following the simple approach used in ECOSSE (Bell et al., 2012), losses of nitrate-N by denitrification, $N_{\mathrm{denit}}$ (kg ha$^{-1}$), are calculated as

$$N_{\mathrm{denit}} = N_{\mathrm{denit,max}} \times m'_{\mathrm{NO3}} \times m'_{\mathrm{wat}} \times m'_{\mathrm{bio}} \qquad \text{(eq.2.4.8)}$$

where $N_{\mathrm{denit,max}}$ is the maximum potential rate of denitrification (kg ha$^{-1}$ month$^{-1}$), and $m'_{\mathrm{NO3}}$, $m'_{\mathrm{wat}}$ and $m'_{\mathrm{bio}}$ are the rate modifiers according to the amount of nitrate in the soil, the soil moisture content and the biological activity of the soil, respectively (dimensionless).

The value of $N_{\mathrm{denit,max}}$ depends on the soil texture and soil biota (Henault and Germon, 2000), but in the absence of a well-established relationship for this, $N_{\mathrm{denit,max}}$ was set to be equivalent to the value derived by Bell et al. (2012) of 1 kg ha$^{-1}$ day$^{-1}$ for a 5 cm soil layer (0.2 $\times\, d$ kg ha$^{-1}$ day$^{-1}$), modified to be limited by the amount of available nitrate-N in the soil layer, $N_{\mathrm{NO3}} = N_{\mathrm{NO3,start}} + N_{\mathrm{NO3,in}} - N_{\mathrm{NO3,min}}$ (kg ha$^{-1}$),

$$N_{\mathrm{denit,max}} = \min\left(N_{\mathrm{NO3}}, 0.2 \times {}^{d}/_{5} \times n_{\mathrm{days,mon}}\right) \qquad \text{(eq.2.4.9)}$$

where $n_{\mathrm{days,mon}}$ is the number of days in the month.

The nitrate rate modifier, $m'_{\mathrm{NO3}}$, reflects the reduced response of denitrification to the increase in the amount of nitrate at higher levels (Henault and Germon, 2000),

$$m'_{\mathrm{NO3}} = \frac{N_{\mathrm{NO3}}}{(N_{\mathrm{d50}} + N_{\mathrm{NO3}})} \qquad \text{(eq.2.4.10)}$$

where $N_{\mathrm{d50}}$ is the soil nitrate-N content at which denitrification is 50% of its full potential (kg ha$^{-1}$). After Henault and Germon (2000), this was set to $N_{\mathrm{d50}} = (3.3 \times d)$ kg ha$^{-1}$.

The soil moisture rate modifier, $m'_{\mathrm{wat}}$, is estimated using the equation derived by Grundmann and Rolston (1987), limited to a maximum value of 1,

$$m'_{\mathrm{wat}} = \min\left(1, \left(\frac{\max\left(0, x^{(V_{\mathrm{wat}} - V_{\mathrm{PWP}})}/_{(V_{\mathrm{FC}} - V_{\mathrm{PWP}})}\right) - 0.62}{0.38}\right)^{1.74}\right) \qquad \text{(eq.2.4.11)}$$

The biological activity rate modifier, $m'_{\mathrm{bio}}$, is limited to a maximum value of 1, and is calculated using the relationship developed by Bradbury et al. (1993) that uses the amount of carbon dioxide C produced by aerobic decomposition, $C_{\mathrm{CO2}}$ (t ha$^{-1}$ month$^{-1}$), as a surrogate for biological activity,

$$m'_{\mathrm{bio}} = \min(1,\ C_{\mathrm{CO2}} \times 0.1) \qquad \text{(eq.2.4.12)}$$

After Bell et al. (2012), the amount of the denitrified N lost as nitrous oxide ($N_2O$), $N_{\mathrm{denit,N2O}}$ (kg ha$^{-1}$ month$^{-1}$) is then estimated from the amount of water and nitrate in the soil,

$$N_{\mathrm{denit,N2O}} = \left(1 - (p_{\mathrm{w}} \times p_{\mathrm{NO3}})\right) \times N_{\mathrm{denit}} \qquad \text{(eq.2.4.13)}$$

where $p_{\mathrm{w}}$ and $p_{\mathrm{NO3}}$ are the proportions of $N_2$ produced according to soil water and nitrate content;

$$p_{\mathrm{w}} = 0.5 \times {}^{(V_{\mathrm{wat}} - V_{\mathrm{PWP}})}/_{(V_{\mathrm{FC}} - V_{\mathrm{PWP}})} \qquad \text{(eq.2.4.14)}$$

and

$$p_{\mathrm{NO3}} = 1 - \left(\frac{N_{\mathrm{NO3}}}{(40d) + N_{\mathrm{NO3}}}\right) \qquad \text{(eq.2.4.15)}$$

*Crop uptake* – The N demand of the crop is calculated from the proportion of the optimum yield estimated assuming no other losses of mineral N, as described in section 3.3 after Reid (2002),

$$p_{\mathrm{yld:opt}} = (1 + c_{\mathrm{N}}) p_{\mathrm{N:opt}}{}^{c_{\mathrm{N}}} - \left(c_{\mathrm{N}} \times p_{\mathrm{N:opt}}{}^{(1 + c_{\mathrm{N}})}\right) \qquad \text{(eq.2.4.16)}$$

where $p_{\mathrm{yld:opt}}$ is the proportion of the optimum yield achieved if the proportion of the optimum supply of N is $p_{\mathrm{N:opt}}$ $\left(0 \leq p_{\mathrm{yld:opt}} \leq 1\right)$, and $c_{\mathrm{N}}$ is the N response coefficient, calculated by fitting to N response curves for the particular crop.

Solving this equation for $p_{\mathrm{N:opt}}$ allows the N demand in each month, $N_{\mathrm{crop}}$ (kg ha$^{-1}$ month$^{-1}$) to be estimated for the value of $p_{\mathrm{yld:opt}}$ in the month,

$$N_{\mathrm{crop}} = {}^{p_{\mathrm{N:opt}} \times N_{\mathrm{opt}}}/_{t_{\mathrm{grow}}} \qquad \text{(eq.2.4.17)}$$

where $N_{\mathrm{opt}}$ is the optimum N supply required for the optimum yield, and $t_{\mathrm{grow}}$ is the number of months in the growing season. This assumes a linear uptake curve (rather than a sigmoid relationship as is usually used (eg Bradbury et al., 1993; Whitmore and Addiscott, 1987)). However, because crops can take up more N than is needed when it is available (luxury uptake), it was decided that the extra complexity and parameters needed to estimate the sigmoid uptake was not worthwhile on a monthly time step.

Because a simple algebraic solution for $p_{\mathrm{N:opt}}$ could not be found, the value of $p_{\mathrm{N:opt}}$ was obtained by calculating a matrix of $p_{\mathrm{yld:opt}}$ for every value of $p_{\mathrm{N:opt}}$ from 0 to 1 with an increment of 0.01, and then finding the closest value to $p_{\text{yld:opt}}$ and then identifying the corresponding value of $p_{\text{N:opt}}$. Therefore, the estimates of $p_{\text{N:opt}}$ are within the nearest 0.01 value. Therefore, the error in the estimates will be $0.01 \times N_{\text{opt}}$ (usually less than 1 kg N ha$^{-1}$).

It was assumed that the crop N demand from the nitrate pool, $N_{\text{NO3,crop}}$ (kg ha$^{-1}$) was shared equally between available nitrate and ammonium,

$$N_{\text{NO3,crop}} = N_{\text{crop}} \times \left( {}^{N_{\text{NO3}}}/_{(N_{\text{NO3}} + N_{\text{NH4}})} \right) \qquad \text{(eq.2.4.18)}$$

where $N_{\text{NO3}}$ is the nitrate and $N_{\text{NH4}}$ is the ammonium available in the soil to the simulated depth (kg ha$^{-1}$).

***Inputs of ammonium***

*Atmospheric deposition* – Similarly to the atmospheric inputs for nitrate, the amount of ammonium-N input by atmospheric deposition, $N_{\text{NH4,atm}}$ (kg ha$^{-1}$) is given by

$$N_{\text{NH4,atm}} = p_{\text{NH4,atm}} \times N_{\text{atm}} \qquad \text{(eq.2.4.19)}$$

where $p_{\text{NH4,atm}}$ is the proportion of ammonium in the atmospheric deposition, assumed to be 0.5.

*Fertiliser inputs* - The inputs of N fertiliser, $N_{\text{fert}}$ (kg ha$^{-1}$), are here assumed to be in the form of urea. This decomposes on application to the soil to produce ammonium. Therefore, the proportion of fertiliser N is added to the ammonium pool, $p_{\text{NH4,fert}}$, is set to 1. The amount of ammonium-N supplied by the fertiliser, $N_{\text{NH4,fert}}$ (kg ha$^{-1}$), is given by

$$N_{\text{NH4,fert}} = p_{\text{NH4,fert}} \times N_{\text{fert}} = N_{\text{fert}} \qquad \text{(eq.2.4.20)}$$

If different types of fertilisers are to be investigated, this assumption should be changed.

*Mineralisation* - Mineralisation of organic N is assumed to release N in the form of ammonium. Therefore, a positive net soil N supply, $N_{\text{soil}}$ (kg ha$^{-1}$) (see section 3.3), is equivalent to the input of ammonium-N due to mineralisation, $N_{\text{NH4,miner}}$ (kg ha$^{-1}$),

$$N_{\text{NH4,miner}} = \max(N_{\text{soil}}, 0) \qquad \text{(eq.2.4.21)}$$

***Losses of ammonium***

*Immobilisation* – A negative soil N supply, $N_{\text{soil}}$ (kg ha$^{-1}$) (see section 3.3), represents immobilised N. Immobilisation is assumed to occur first from the ammonium pool before drawing on nitrate. Therefore, the potential loss of N from the ammonium pool by immobilisation, $N_{\text{NH4,immob}}$ (kg ha$^{-1}$) is calculated as

$$N_{\text{NH4,immob}} = \min\left(-\min(N_{\text{soil}}, 0), N_{\text{NH4}} - N_{\text{NH4,min}}\right) \qquad \text{(eq.2.4.22)}$$

where $N_{\text{soil}}$ is the soil N supply, $N_{\text{NH4,immob}}$ is the N immobilised from the ammonium pool and $N_{\text{NH4,min}}$ is the minimum possible amount of ammonium-N, all in kg ha$^{-1}$.

*Nitrification* – After Bradbury et al. (1993), nitrified ammonium, $N_{\mathrm{NH4,nitrif}}$ is assumed to occur by a first order reaction, using the same environmental rate modifiers as in soil organic matter decomposition ($r_{\mathrm{temp}}$, $r_{\mathrm{wat}}$, $r_{\mathrm{pH}}$ and $r_{\mathrm{sal}}$ as calculated in section 2.1),

$$N_{\mathrm{NH4,nitrif}} = \min\left( N_{\mathrm{NH4}} \times \left(1 - \exp\left(-k_{\mathrm{nitrif}} \times r_{\mathrm{temp}} \times r_{\mathrm{wat}} \times r_{\mathrm{pH}} \times r_{\mathrm{sal}} \times r_{\mathrm{inhibit}}\right)\right), N_{\mathrm{NH4}} - N_{\mathrm{NH4,min}} \right)$$

(eq.2.4.23)

where $k_{\mathrm{nitrif}}$ is the rate constant for nitrification, set to 0.6 week$^{-1}$ = 2.6 month$^{-1}$ (after Bradbury et al., 1993), and $r_{\mathrm{inhibit}}$ is an inhibition rate modifier, set to account for site / treatment specific nitrification inhibition, such as due to coating of urea fertiliser with the nitrification inhibitor, neem (set to 1 if no nitrification inhibition occurs).

After Bell et al. (2012), 2% of the fully nitrified N is assumed to be lost as gas, with 40% lost as NO and 60% s $N_2O$, and 2% of the partially nitrified N is assumed to be lost as gas at field capacity, with a linear decrease in this loss as water declines to wilting point,

$$N_{\mathrm{nitrif,N2O}} = N_{\mathrm{NH4,nitrif}} \times \left(\left(p_{\mathrm{N2O,FC}} \times \frac{V_{\mathrm{wat}}}{V_{\mathrm{FC}}}\right) + \left(p_{\mathrm{nitrif,gas}} \times (1 - p_{\mathrm{NO}})\right)\right) \qquad \text{(eq.2.4.24)}$$

where $N_{\mathrm{nitrif,N2O}}$ is the nitrified N lost as $N_2O$ (kg ha$^{-1}$), $p_{\mathrm{N2O,FC}}$ is the proportion of $N_2O$ produced due to partial nitrification at field capacity (0.02), $p_{\mathrm{nitrif,gas}}$ is the proportion of full nitrification lost as gas (0.02), and $p_{\mathrm{NO}}$ is the proportion of full nitrification gaseous loss that is NO (0.4).

*Volatilisation* – After Bradbury et al. (1993), volatilisation of ammonium or urea-N, $N_{\mathrm{NH4,volat}}$ (kg ha$^{-1}$) is assumed to occur from applied manure and fertiliser only; ammonium that is already integrated into the soil matrix is likely to be held more strongly on surfaces of the soil particles, and so is less likely to be lost by volatilisation. In this simple approach, a fixed proportion ($p_{\mathrm{volat}}$ = 0.15) of the ammonium-N or urea-N in applied manure, $N_{\mathrm{NH4,manure}}$ (kg ha$^{-1}$), and fertilisers, $N_{\mathrm{NH4,fert}}$ (kg ha$^{-1}$) is assumed to be lost in the month of application only, and only if the rainfall in that month, $V_{\mathrm{rain}}$ (mm), is less than a critical level ($V_{\mathrm{rain,crit}}$ < 21 mm),

$$\text{if } (V_{\mathrm{rain}} < V_{\mathrm{rain,crit}}), \quad N_{\mathrm{NH4,volat}} = p_{\mathrm{volat}} \times \left(N_{\mathrm{NH4,manure}} + N_{\mathrm{NH4,fert}}\right) \qquad \text{(eq.2.4.25)}$$

*Crop uptake* – As for nitrate, it was assumed that the crop N demand from the ammonium pool, $N_{\mathrm{NH4,crop}}$ (kg ha$^{-1}$) was shared equally between available nitrate and ammonium,

$$N_{\mathrm{NH4,crop}} = N_{\mathrm{crop}} \times \left({N_{\mathrm{NH4}}}/{(N_{\mathrm{NO3}} + N_{\mathrm{NH4}})}\right) \qquad \text{(eq.2.4.26)}$$

where $N_{\mathrm{NO3}}$ is the nitrate and $N_{\mathrm{NH4}}$ is the ammonium available in the soil to the simulated depth (kg ha$^{-1}$).

## 3. Crop production

Accurate simulation of yield is notoriously difficult and data hungry, due to the wide range of factors that can inhibit crop growth, such as diseases, pests, nutrients and water. Therefore, the change in crop production is simulated here using a simple ratio approach. This aims to increase accuracy possible with only limited data of predictions of yield by using inputs of "typical yield" to scale the results. The typical yield, $C_{\mathrm{yld,typ}}$ (t ha$^{-1}$) is supplied as an input to the model, and is then modified according to the ratio of plant production in the atypical year compared to that in the typical year, $p_{\mathrm{plant,atyp}}$,

$$C_{\mathrm{yld,atyp}} = C_{\mathrm{yld,typ}} \times p_{\mathrm{plant,atyp}} \qquad \text{(eq.3.0.1)}$$

where $C_{\mathrm{yld,atyp}}$ is the harvested product under atypical environmental conditions, for example drought or floods. The value of $p_{\mathrm{plant,atyp}}$ is obtained from the ratio of net primary production estimated under the typical and the atypical environmental conditions, $C_{\mathrm{npp,typ}}$ and $C_{\mathrm{npp,atyp}}$ (t ha$^{-1}$);

$$p_{\mathrm{plant,atyp}} = \frac{C_{\mathrm{npp,atyp}}}{C_{\mathrm{npp,typ}}} \qquad \text{(eq.3.0.2)}$$

This approach assumes that the factors not explicitly described have a similar impact on yield in both the typical and the altered environmental conditions.

In the simple, one crop, simulation, $C_{\mathrm{npp,typ}}$ and $C_{\mathrm{npp,atyp}}$ are obtained by summing net primary production over the year. In the rotational simulation, $C_{\mathrm{npp,typ}}$ and $C_{\mathrm{npp,atyp}}$ are obtained by summing over the full 10 years of the simulation, dividing the net primary production for each crop by the harvest index.

The calculation of net primary production uses a choice of simple non-process based models as detailed below.

### 3.1. Net primary production from temperature and rainfall during the growing season

The net primary production is calculated using a modification of the well-established Miami model (Leith, 1972). The Miami model calculates net primary production, based on total annual temperature and rainfall. Droughts and floods are not usually sustained throughout the year, and the growing season for some crops is very short, so atypical weather conditions could easily miss the growing season of a particular crop. Using the temperature and rainfall across the whole year may, therefore, misrepresent the impacts of the atypical conditions on some crops. Therefore, temperature and rainfall are only considered during the growing season of the selected crop. Because the model uses the *ratio* of net primary production in typical and atypical years to calculate changes in plant production ($p_{\mathrm{plant,atyp}}$), differences in the absolute values of net primary production estimated by the original Miami model and by this modified approach are not important; it is the *relative* value of net primary production in the two years that is the key driver used in this model. Using this approach, the model estimates the net primary production of C in this year relative to a year with different conditions, $C_{\mathrm{npp}}$ (t ha$^{-1}$), as

$$C_{\mathrm{npp}} = \min\left( 15\left(1 - \exp\left(-0.000664, V_{\mathrm{rain,grow}}\right)\right), \left( {}^{15}\!\Big/\!\left(1 + \exp\left(1.315 - 0.119\, T_{\mathrm{a,grow}}\right)\right)\right)\right) \qquad \text{(eq.3.1.1)}$$

where the first term expresses the rain limited net primary production, using $V_{\mathrm{rain,grow}}$, the rainfall during the growing season (mm), and the second term expresses the temperature limited net primary production, using $T_{\mathrm{a,grow}}$, the average air temperature during the growing season (°C).

## 3.2. Net primary production according to growing degree days and water stress during the growing season

Following a method presented by Zaks et al. (2007), the net primary production was estimated according to the growing degree days and water stress experienced during the growing season,

$$C_{\mathrm{npp.mon}} = 27.20 \times \max\left(0, \left( {0.0396} \Big/ \left(1 + \exp\left(6.33 - 1.5\left(\frac{T_{\mathrm{GDD}}}{11500}\right)\right)\right) \times (39.58\, I_{\mathrm{ws}} - 14.52)\right)\right) \qquad \text{(eq.3.2.1)}$$

where $C_{\mathrm{npp.mon}}$ is the net primary production of C in this month relative to this month in a year with different conditions, modified according to growing degree days and water stress (t ha$^{-1}$), $T_{\mathrm{GDD}}$ is the growing degree days (°C day) and $I_{\mathrm{ws}}$ is the dimensionless water stress index. Equation 3.2.1 differs from the calculation presented by Zaks et al. (2007) in that the net primary production was calculated monthly using the water stress index for the previous month. The change in production compared to the production in a typical year for that month was then summed to give the change in production across the whole year. This approach does not imply accurate estimation of the pattern of production through the year; it is used as a device to calculate the annual change in production without causing a circular calculation, as actual evapotranspiration is dependent on soil water, which is dependent on soil carbon, which is in turn dependent on plant inputs, which are driven by actual evapotranspiration.

***Growing degree days***

The growing degree days ($T_{\mathrm{GDD}}$) indicates the cumulative temperature when plant growth is assumed to be possible (above 5°C), and is calculated as

$$T_{\mathrm{GDD}} = \max\left(0, n_{\mathrm{days,mon}} \times \left(T_{\mathrm{a,mon}} - 5\right)\right) \qquad \text{(eq.3.2.2)}$$

where $mon$ is the month, $n_{\mathrm{days,mon}}$ is the number of days in the month, and $T_{\mathrm{a.mon}}$ is the average air temperature (°C).

***Water stress index***

The water stress index ($I_{\mathrm{ws}}$), indicates the ability of the land surface to meet the atmospheric demand for water, and is calculated as

$$I_{\mathrm{ws}} = {V_{\mathrm{AET(mon-1)}}} \Big/ {V_{\mathrm{PET(mon-1)}}} \qquad \text{(eq.3.2.3)}$$

where $mon$ is the month from sowing to harvest, $V_{\mathrm{AET(mon-1)}}$ is the actual evapotranspiration and $V_{\mathrm{PET(mon-1)}}$ is the potential evapotranspiration from the full rooting zone of the crop in the previous month (both in mm month$^{-1}$). The value of $V_{\mathrm{PET(mon-1)}}$ is calculated in the same way as $V_{\mathrm{PET,d}}$ shown in section 2.2, assuming the maximum rooting depth of the crop, and $V_{\mathrm{AET(mon-1)}}$ is calculated in the same way, but constrained according to the available soil water, and the maximum rate of evapotranspiration (set to 5 mm per day after Zaks et al. (2007)),

$$V_{\mathrm{AET(mon-1)}} = \min\left(V_{\mathrm{PET(mon-1)}}, 5 \times\ n_{\mathrm{days,month}}, (V_{\mathrm{wat}} - V_{\mathrm{PWP}})\right) \quad \text{(eq.3.2.4)}$$

where $V_{\mathrm{wat}}$ is the total soil water (mm), where $n_{\mathrm{days,month}}$ is the number of days in the month and $V_{\mathrm{PWP}}$ is the soil water at permanent wilting point (mm).

This is in contrast to Prentice et al. (1993), who used the ratio of available soil water to available water at field capacity;

$$V_{\mathrm{AET(mon-1)}} = \min\left(V_{\mathrm{PET(mon-1)}}, 5 \times\ n_{\mathrm{days,month}} \times {}^{(V_{\mathrm{wat}} - V_{\mathrm{PWP}})}\!\big/_{(V_{\mathrm{FC}} - V_{\mathrm{PWP}})}\right) \quad \text{(eq.3.2.5)}$$

where $V_{\mathrm{FC}}$ is the soil water at field capacity (mm).

The different form of the equation was used to achieve the correct response to increasing soil organic matter, which increased the water held in the soil, so should have reduced the limitation to evapotranspiration, but with the Prentice equation gave the opposite response.

### 3.3. Nutrient limitation of net primary production

The relative net primary production, as estimated by Zaks et al. (2007), is modified according to nutrient limitation using an approach given by Reid (2002). This simple approach calculates the amount of nutrient available in the soil and compares it to the optimum amount of nutrient for that crop;

$$p_{\mathrm{X:opt}} = \frac{(X_{\mathrm{soil}} + X_{\mathrm{fert}} - X_{\mathrm{min}})}{(X_{\mathrm{opt}} - X_{\mathrm{min}})} \quad \text{(eq.3.3.1)}$$

where $p_{\mathrm{X:opt}}$ is the proportion of nutrient (N, P or K) available compared to the optimum amount of nutrient, $(0\ \leq p_{\mathrm{X:opt}} \leq 1)$, $X_{\mathrm{soil}}$ is the soil supply of the nutrient (kg ha$^{-1}$), $X_{\mathrm{fert}}$ is the fertiliser input of the nutrient (kg ha$^{-1}$), $X_{\mathrm{min}}$ is the minimum amount of nutrient that results in a harvestable yield (kg ha$^{-1}$), and $X_{\mathrm{opt}}$ is the optimum amount of nutrient for the crop which results in crop yield that is not limited by the nutrient (kg ha$^{-1}$). According to Reid (pers.comm.), the value for $X_{\mathrm{min}}$ was set to zero.

The proportion of the yield at the optimum nutrient content that is achieved under these nutrient limited conditions is then calculated as

$$p_{\mathrm{yld:opt}} = (1 + c_{\mathrm{X}}) p_{\mathrm{X:opt}}{}^{c_{\mathrm{X}}} - \left(c_{\mathrm{X}}. p_{\mathrm{X:opt}}{}^{(1+c_{\mathrm{X}})}\right) \quad \text{(eq.3.3.2)}$$

where $p_{\mathrm{yld:opt}}$ is the proportion of the optimum yield achieved if the proportion of the optimum supply of nutrients is $p_{\mathrm{X:opt}}$ $(0\ \leq p_{\mathrm{X:opt}} \leq 1)$, and $c_{\mathrm{X}}$ is the nutrient response coefficient, calculated by fitting to nutrient response curves for the particular crop.

In a typical year, the value of $p_{\mathrm{yld:opt}}$ is then used to adjust the net primary production calculated according to other limitations, $C_{\mathrm{npp}}$ (t ha$^{-1}$),

$$C^{*}{}_{\mathrm{npp}} = p_{\mathrm{yld:opt}} \times C_{\mathrm{npp}} \quad \text{(eq.3.3.3)}$$

where $C^*{}_{\mathrm{npp}}$ is the relative net primary production modified according to nutrient limitation. The change in crop production is limited so that

$$p_{\mathrm{plant,atyp}} < {}^{M_{\mathrm{crop,max}}}\!/_{M_{\mathrm{crop,typ}}} \qquad \text{(eq.3.3.4)}$$

where $p_{\mathrm{plant,atyp}}$ is the ratio of plant production in an atypical year compared to a typical year, $M_{\mathrm{crop,typ}}$ is the entered value for typical yield (t ha$^{-1}$), and $M_{\mathrm{crop,max}}$ is the maximum potential yield for the crop (t ha$^{-1}$). Using Liebig's law of the minimum, the final value of relative net primary production, $C^{**}{}_{\mathrm{npp}}$ (t ha$^{-1}$) is taken to be the minimum value of net primary production calculated for each of the nutrients (X) considered, $C^*{}_{\mathrm{npp,X}}$ (t ha$^{-1}$),

$$C^{**}{}_{\mathrm{npp}} = \min_{\mathrm{X}}\left[C^*{}_{\mathrm{npp,X}}\right] \qquad \text{(eq.3.3.5)}$$

By doing this calculation for each month in the growing season, more than one factor can limit crop production at a time.

A similar approach is used to calculate the change in yield.

In order to simulate the effects of nutrient limitation on the monthly plant inputs to the soil, the above calculation was done for each month separately, assuming the nutrient supply remained at the level calculated in that month over the whole growing season. This was necessary for plant inputs in the following month to be estimated from the proportion of typical crop production achieved in the current month. The plants inputs were used by the soil organic matter components of the model to calculate decomposition (as described in section 2). The decomposition was then used (as described below) to estimate the soil nutrient supply. The monthly calculations of the proportion of typical crop production achieved effectively assume that nutrient requirement is the same at all stages of the growing season. This assumptions is not true, so this should not be taken as an estimate of the pattern of crop growth; it is merely a way of allowing nutrient limitation to be incorporated into the crop growth in the current year. Note, in order to avoid a mathematical loss of plant inputs, for the monthly calculations the proportion of the optimum yield achieved was limited to the range $(0.1 \leq p_{\mathrm{yld:opt}} \leq 1)$. Not allowing this proportion to be zero introduces a small error, but this is likely to be negligible on an annual basis.

***Fertiliser nutrient supply***

The amount of nutrient supply from fertiliser, $X_{\mathrm{fert}}$ (kg ha$^{-1}$) is calculated from the fertiliser added to the soil, $X_{\mathrm{fert,in}}$ (kg ha$^{-1}$) and the efficiency of fertiliser use, $p_{\mathrm{eff,fertX}}$ (dimensionless), as

$$X_{\mathrm{fert}} = p_{\mathrm{eff,fertX}} \times X_{\mathrm{fert,in}} \qquad \text{(eq.3.3.6)}$$

After Reid (2002), the value for $p_{\mathrm{eff,fertX}}$ is set to 0.33 for broadcast application and 0.61 for band application of N. The values of $p_{\mathrm{eff,fertX}}$ for P and K were set to 1.0.

***Soil nutrient supply***

The soil nutrient supply in each month, $X_{\mathrm{soil}}$ (kg ha$^{-1}$), is calculated from the release of nutrient associated with the loss of $CO_2$-C on decomposition, $X_{\mathrm{release}}$ (kg ha$^{-1}$), and the subsequent capture or further release of nutrients to adjust the C:nutrient ratio of the soil organic matter to the stable ratio of the nutrient, $X_{\mathrm{adjust}}$ (kg ha$^{-1}$),

$$X_{\mathrm{soil}} = X_{\mathrm{release}} - X_{\mathrm{adjust}} \qquad \text{(eq.3.3.7)}$$

Note, if the material has a higher C:nutrient ratio than stable soil organic matter, then $X_{\mathrm{release}}$ and $X_{\mathrm{adjust}}$ equate to mineralisation and immobilisation of nutrient, respectively. However, if a material with a lower C:N ratio than the stable soil is added, then $X_{\mathrm{adjust}}$ becomes negative and equates to additional mineralisation.

The release of nutrient associated with $CO_2$-C loss is given by the loss of C from the soil and the C:nutrient ratio of the material being lost,

$$X_{\mathrm{release}} = p_{\mathrm{CO2}}\left(\left(\frac{1000}{p_{\mathrm{C:X,DPM}}}\right)C_{\mathrm{loss,DPM}} + \left(\frac{1000}{p_{\mathrm{C:X,RPM}}}\right)C_{\mathrm{loss,RPM}} + \left(\frac{1000}{p_{\mathrm{C:X,soil}}}\right)C_{\mathrm{loss,BIO}} + \left(\frac{1000}{p_{\mathrm{C:X,HUM}}}\right)C_{\mathrm{loss,HUM}}\right) \qquad \text{(eq.3.3.8)}$$

and adjustment of nutrient content is given by the difference in the stable C:nutrient ratio of the soil and the material being transformed into BIO and HUM from the DPM and RPM pools,

$$\begin{aligned} X_{\mathrm{adjust}} = {} & p_{\mathrm{BIO}}\left(\left(\left(\frac{1000}{p_{\mathrm{C:X,soil}}}\right) - \left(\frac{1000}{p_{\mathrm{C:X,DPM}}}\right)\right)C_{\mathrm{loss,DPM}} + \left(\left(\frac{1000}{p_{\mathrm{C:X,soil}}}\right) - \left(\frac{1000}{p_{\mathrm{C:X,RPM}}}\right)\right)C_{\mathrm{loss,RPM}}\right) + \\ & p_{\mathrm{HUM}}\left(\left(\left(\frac{1000}{p_{\mathrm{C:X,soil}}}\right) - \left(\frac{1000}{p_{\mathrm{C:X,DPM}}}\right)\right)C_{\mathrm{loss,DPM}} + \left(\left(\frac{1000}{p_{\mathrm{C:X,soil}}}\right) - \left(\frac{1000}{p_{\mathrm{C:X,RPM}}}\right)\right)C_{\mathrm{loss,RPM}}\right) + \\ & \left(\left(\frac{1000}{p_{\mathrm{C:X,soil}}}\right) - \left(\frac{1000}{p_{\mathrm{C:X,HUM}}}\right)\right)C_{\mathrm{HUM}} \end{aligned} \qquad \text{(eq.3.3.9)}$$

where $p_{\mathrm{C:X,DPM}}$, $p_{\mathrm{C:X,RPM}}$ and $p_{\mathrm{C:X,HUM}}$ are the C:nutrient ratio of the DPM, RPM and HUM pools respectively (X is N, P or K); $p_{\mathrm{C:X,soil}}$ is the stable C:X ratio of the soil (for N set to 8.5 after Bradbury et al., 1993; for P set to ****; and for K set to ****); $p_{\mathrm{CO2}}$, $p_{\mathrm{BIO}}$ and $p_{\mathrm{HUM}}$ are the proportions of $CO_2$, BIO and HUM produced on decomposition respectively; and $C_{\mathrm{loss,DPM}}$, $C_{\mathrm{loss,RPM}}$, $C_{\mathrm{loss,BIO}}$ and $C_{\mathrm{loss,HUM}}$ are the C lost from the DPM, RPM, BIO and HUM pools respectively. These are calculated as described in section 2.1.

The C:X ratio of the DPM changes from the C:X ratio of the plant inputs with extra applications of organic wastes to the pool. This is tracked throughout the simulation,

$$p_{\mathrm{C:X,DPM}} = \frac{\left(C_{\mathrm{DPM,last}} + C_{\mathrm{PI,DPM}} + C_{\mathrm{OW,DPM}}\right)}{\left(\left({C_{\mathrm{DPM,last}}}/{p_{\mathrm{C:X,DPM,last}}}\right) + \left({C_{\mathrm{PI,DPM}}}/{p_{\mathrm{C:X,plant}}}\right) + \left({C_{\mathrm{OW,DPM}}}/{p_{\mathrm{C:X,OW}}}\right)\right)} \qquad \text{(eq.3.3.10)}$$

where $C_{\mathrm{DPM,last}}$ is the stock of C in the DPM pool in the last time step (t ha$^{-1}$), $C_{\mathrm{PI,DPM}}$ and $C_{\mathrm{OW,DPM}}$ are the inputs of C to the DPM pool from plant inputs and extra inputs (e.g. as applied organic wastes) (t ha$^{-1}$), and $p_{\mathrm{C:X,DPM,last}}$, $p_{\mathrm{C:X,plant}}$ and $p_{\mathrm{C:X,OW}}$ are the C:nutrient ratios of the DPM pool in the last time step, the plant inputs and the organic wastes, respectively.

Because extra organic inputs are described using only the DPM:HUM ratio and IOM content (after Smith et al., 2014b), the C:X ratio of the RPM pool can be ore simply calculated from the C:X ratio of the plant inputs only ($p_{\mathrm{C:X,plant}}$),

$$p_{\mathrm{C:X,RPM}} = \frac{\left(C_{\mathrm{RPM,last}}+C_{\mathrm{PI,RPM}}\right)}{\left(\left(C_{\mathrm{RPM,last}}/p_{\mathrm{C:X,RPM,last}}\right)+\left(C_{\mathrm{PI,RPM}}/p_{\mathrm{C:X,plant}}\right)\right)} \qquad \text{(eq.3.3.11)}$$

Whereas the C : nutrient ratio of the BIO pool remains at the steady state for the soil ($p_{\mathrm{C:X,soil}}$), the HUM pool receives nutrient inputs from the applied organic wastes. It is assumed that the nutrients are partitioned between the DPM, HUM and IOM pools of added organic waste in the same way as the carbon (ie all pools have the same C:X ratio), so the changing value $p_{\mathrm{C:X,HUM}}$ is given by

$$p_{\mathrm{C:X,HUM}} = \frac{\left(C_{\mathrm{HUM,last}}+C_{\mathrm{OW,HUM}}\right)}{\left(\left(C_{\mathrm{HUM,last}}/p_{\mathrm{C:X,HUM,last}}\right)+\left(C_{\mathrm{OW,HUM}}/p_{\mathrm{C:X,OW}}\right)\right)} + \left(\left(p_{\mathrm{C:X,soil}} - p_{\mathrm{C:X,HUM,last}}\right) \times \frac{X_{\mathrm{soil,last,act}}}{X_{\mathrm{soil,last}}}\right)$$

(eq.3.3.12)

where $C_{\mathrm{HUM,last}}$ is the stock of C in the HUM pool in the last time step (t ha$^{-1}$), $C_{\mathrm{OW,HUM}}$ is the input of C to the HUM pool from organic wastes (t ha$^{-1}$), $p_{\mathrm{C:X,HUM,last}}$ is C:nutrient ratio of the HUM pool in the last timestep, $X_{\mathrm{soil,last\_act}}$ is the actual soil nutrient supply in the last time step after adjustment for available nutrient (kg ha$^{-1}$) and $X_{\mathrm{soil,last}}$ is the soil nutrient supply if nutrient is not limiting (kg ha$^{-1}$). The amount of C partitioned to the HUM pool ($C_{\mathrm{OW,HUM}}$) is calculated from the DPM:HUM ratio of the organic waste ($p_{\mathrm{D:H,OW}}$),

$$C_{\mathrm{OW,HUM}} = C_{\mathrm{OW}} \times \frac{\left(1-p_{\mathrm{IOM,OW}}\right)}{\left(1+p_{\mathrm{D:H,OW}}\right)} \qquad \text{(eq.3.3.13)}$$

where default values of $p_{\mathrm{D:H,OW}}$ are obtained from Smith et al. (2014a).

The C to nutrient ratios for the different crops and land uses ($p_{\mathrm{C:X,plant}}$) are given in Table 3.2.1.

Table 3.2.1. Carbon to nutrient ratios for different crops and land uses

| Crop / Land use | C:N ratio | | C:P ratio | | C:K ratio | |
|---|---|---|---|---|---|---|
| | Value | Data sources | Value | Data sources | Value | Data sources |
| Grassland | 100 | | | | | |
| Shrubland | 34 | | | | | |
| Maize | 50 | Abera et al., 2013 | | | | |
| Haricot beans | 50 | Abera et al., 2013 | | | | |
| Teff | 50 | Giday et al., 2014; Rimhanen and | | | | |

| | | |
|---|---|---|
| | | Kahiluoto, 2014 |
| Finger millet | 20 | Kushwah et al., 2014 |
| Pepper | 50 | Kulcu, R 2015 |
| Coffee | 50 | Paula et al., 2010 |
| Chat | 20 | |
| Tomatoes | 20 | Kulcu, R 2014 |
| Cabbage | 50 | Youssef and Lashein, 2013 |
| Wheat | 80 | |
| Sorghum | 85 | |
| Rice IR36 | 86 | |
| Rice Mahamay | 86 | |
| Rice Kranti | 86 | |
| Rice Khitish | 86 | |
| Rice Lalat | 86 | |
| Rice Swarma | 86 | |
| Rice Ranjit | 86 | |
| Rice Mahsuri | 86 | |
| Rice Madhuri | 86 | |
| Rice Rajshree | 86 | |
| Rice Sashi | 86 | |
| Rice Gayatri | 86 | |

***Description of nutrient response***

The nutrient response of the different land uses and crops is calculated using the optimum nutrient levels ($X_{\mathrm{opt}}$) and nutrient response coefficients ($c_{\mathrm{X}}$) as shown in Table 3.2.2. These parameters were derived by fitting a quadratic equation to yield response experiments that measure the yield with respect to the amount of the particular nutrient applied when all other nutrients and growth factors are non-limiting (see for example Figure 1).

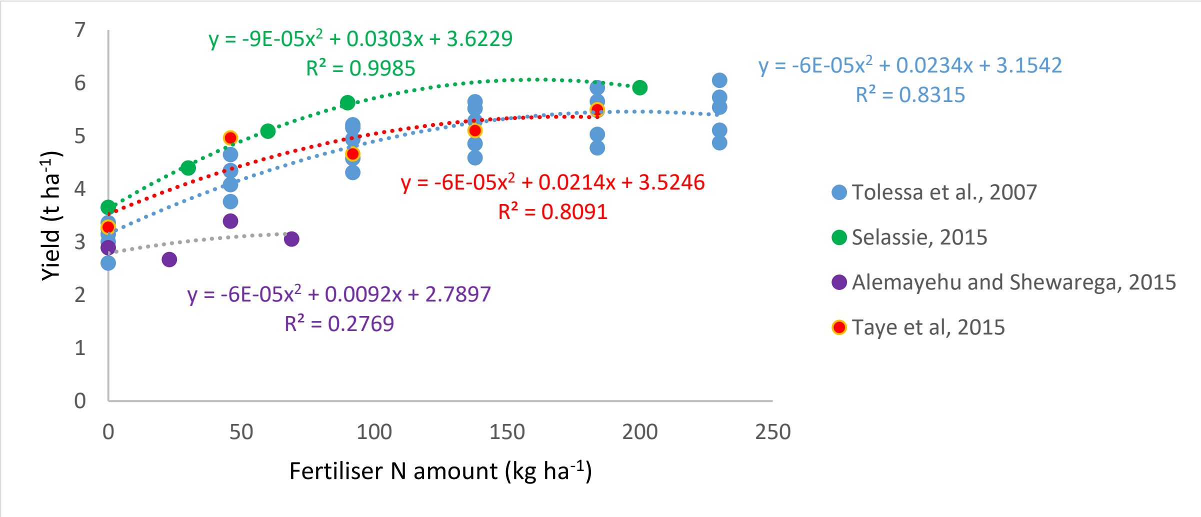



Figure 1. Examples of quadratic equations fitted to nitrogen response experiment for maize.

The derived quadratic equation for yield was extrapolated to a yield of zero,

$$aX_{\mathrm{fert}}{}^{2} + bX_{\mathrm{fert}} + c = 0 \qquad \text{(eq.3.3.14)}$$

where $X_{\mathrm{fert}}$ is the applied nutrient and $a$, $b$ and $c$ are fitted constants. This was done using the quadratic formula,

$$X_{\mathrm{fert,0}} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \qquad \text{(eq.3.3.15)}$$

The value of $X_{\mathrm{fert,0}}$ was taken to be the soil nutrient supply at the particular site ($X_{\mathrm{soil}}$), and added to the amount of nutrient applied as fertiliser to give the yield response to total nutrient supply. This then provided a unified set of data that could be used to derive the values of $X_{\mathrm{opt}}$ and $c_{\mathrm{X}}$ across all experiments (see for example Figure 2).

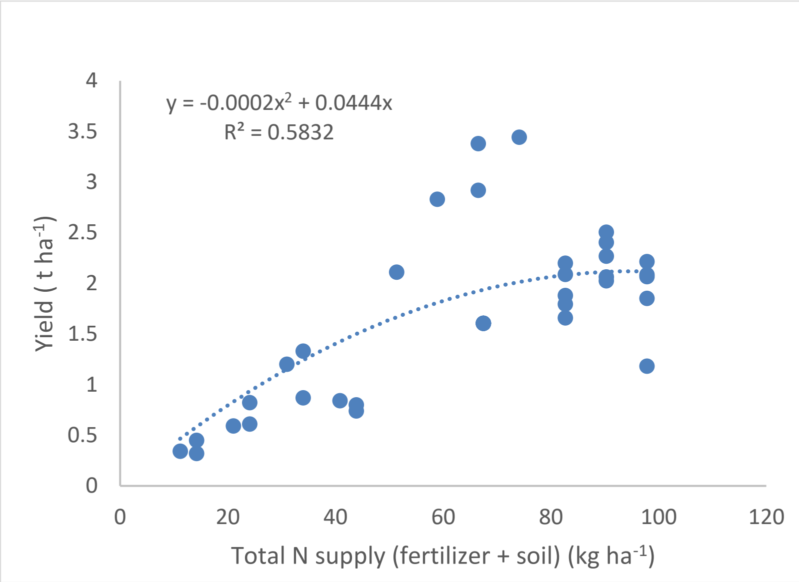



Figure 2. Example of a unified set of data across a number of different experiments used to derive the optimum nutrient level and the nutrient response coefficient (source: *****)

The value of $X_{\mathrm{opt}}$ was taken to be the nutrient supply when the fitted quadratic equation reaches its maximum turning point (the first derivative = 0), $2a(X_{\mathrm{soil}}+X_{\mathrm{fert}})+b=0$, so

$X_{\mathrm{opt}}=\frac{-b}{2a}$ (eq.3.3.16)

In the above example, the value of $X_{\mathrm{opt}}=\frac{-0.0002}{2\times 0.0444}=111$ kg ha$^{-1}$.

The values of $X_{\mathrm{opt}}$, $X_{\mathrm{soil}}$ and $X_{\mathrm{fert}}$ were used to calculate $p_{\mathrm{X:opt}}$ at each point, allowing the value of $c_{\mathrm{X}}$ to be obtained by iteratively fitting to maximise the goodness-of-fit between the measure points and the fitted equation.

Table 3.2.2. Minimum and optimum nutrient levels and nutrient response coefficients for different nutrients, crops and land uses

| Crop / Land use | Optimum nutrient levels $X_{\mathrm{opt}}$ (kg ha$^{-1}$) | | Nutrient response coefficients ($c_{\mathrm{X}}$) | |
|---|---|---|---|---|
| | Value | Data sources | Value | Data sources |
| Nitrogen | | | | |
| Grassland | 100 | | 0.3 | |
| Shrubland | 177 | | 0.9 | |
| Maize | 154 | | 0.3 | |
| Haricot beans | 154 | | 0.3 | |

| | | |
|---|---|---|
| Teff | 154 | 0.3 |
| Finger millet | 154 | 0.3 |
| Pepper | 154 | 0.3 |
| Coffee | 154 | 0.3 |
| Chat | 154 | 0.3 |
| Tomatoes | 154 | 0.3 |
| Cabbage | 154 | 0.3 |
| Wheat | 230 | 0.6 |
| Sorghum | 126 | 1 |
| Rice IR36 | 88 | 1 |
| Rice Mahamay | 102 | 1 |
| Rice Kranti | 94 | 1 |
| Rice Khitish | 79 | 1 |
| Rice Lalat | 105 | 1 |
| Rice Swarma | 123 | 1 |
| Rice Ranjit | 113 | 1 |
| Rice Mahsuri | 75 | 1 |
| Rice Madhuri | 67 | 1 |
| Rice Rajshree | 96 | 1 |
| Rice Sashi | 99 | 1 |
| Rice Gayatri | 96 | 1 |
| **Phosphorus** | | |
| Grassland | | |

| |
|---|
| Shrubland |
| Maize |
| Haricot beans |
| Teff |
| Finger millet |
| Pepper |
| Coffee |
| Chat |
| Tomatoes |
| Cabbage |
| **Potassium** |
| Grassland |
| Shrubland |
| Maize |
| Haricot beans |
| Teff |
| Finger millet |
| Pepper |
| Coffee |
| Chat |
| Tomatoes |
| Cabbage |

## 4. Animal production

The proportion of animal production in an atypical (drought or flood) year compared to a typical year, $p_{\mathrm{livestock,atyp}}$, is very simply estimated by assuming it is proportional to the amount of food available to the animals. Depending on the strategy selected, animal production is either (1) maintained by buying or selling the difference in the production of crops between a typical and atypical year, or (2) allowed to change in proportion to the change in crop production from the previous harvest. Other strategies may be added according to observed behaviour.

If the strategy (1) is selected, then

$$p_{\mathrm{livestock,atyp}} = 1,$$

and the shortfall in produce feed is accommodated in the expenditure of the household.

If the strategy (2) is selected, then animal production changes according to the production of the crops used to feed the animals compared to the production in a typical year, $p_{\mathrm{plant,atyp,crop}}$ (as described in section 3). It is assumed that the crop used to feed the animal is from the previous harvest. The percentages of calorific feed value supplied to animals from the different crops, $P_{\mathrm{feed,crop}}$ (%), are given as inputs to the model. The proportion of animal production achieved in an atypical year, $p_{\mathrm{livestock,atyp}}$ (dimensionless), is then calculated as

$$p_{\mathrm{livestock,atyp}} = \sum_{\mathrm{crop}} \left( \frac{p_{\mathrm{plant,atyp,crop}} \times P_{\mathrm{feed,crop}}}{100} \right) + \frac{P_{\mathrm{feed,buy}}}{100} \qquad \text{(eq.4.0.1)}$$

where $P_{\mathrm{feed,buy}}$ is the percentage of animal feed bought from outside sources.

The typical per head animal production values for milk, $M_{\mathrm{milk,head}}$ (kg y$^{-1}$), meat, $M_{\mathrm{meat,head}}$ (kg y$^{-1}$), manure, $M_{\mathrm{manure,head}}$ (kg y$^{-1}$), and excreted N, $N_{\mathrm{excreted,head}}$ (kg y$^{-1}$), are provided in lookup tables for different grazing systems and regions of SSA by Herrero et al. (2013).

The total production in a typical year for the farm is calculated by multiplying by the number of head of different types of animals, $n_{\mathrm{head}}$, as

$$M_{\mathrm{milk,tot,typ}} = n_{\mathrm{head}} \times M_{\mathrm{milk,head}} \qquad \text{(eq.4.0.2)}$$

$$M_{\mathrm{meat,tot,typ}} = n_{\mathrm{head}} \times M_{\mathrm{meat,head}} \qquad \text{(eq.4.0.3)}$$

$$M_{\mathrm{manure,tot,typ}} = n_{\mathrm{head}} \times M_{\mathrm{manure,head}} \qquad \text{(eq.4.0.4)}$$

$$N_{\mathrm{excreted,tot,typ}} = n_{\mathrm{head}} \times N_{\mathrm{excreted,head}} \qquad \text{(eq.4.0.5)}$$

where $M_{\mathrm{milk,tot,typ}}$, $M_{\mathrm{meat,tot,typ}}$, $M_{\mathrm{manure,tot,typ}}$ and $N_{\mathrm{excreted,tot,typ}}$ are the total milk, meat, manure and N excreted in a typical year (kg y$^{-1}$), respectively.

The total production for an atypical year ($M_{\text{milk,tot,atyp}}$, $M_{\text{meat,tot,atyp}}$, $M_{\text{manure,tot,atyp}}$ and $N_{\text{excreted,tot,atyp}}$ in kg ha$^{-1}$) are then calculated by multiplying by $p_{\text{livestock,atyp}}$,

$$M_{\text{milk,tot,atyp}} = p_{\text{livestock,atyp}} \times M_{\text{milk,tot,typ}} \qquad \text{(eq.4.0.6)}$$

$$M_{\text{meat,tot,atyp}} = p_{\text{livestock,atyp}} \times M_{\text{meat,tot,typ}} \qquad \text{(eq.4.0.7)}$$

$$M_{\text{manure,tot,atyp}} = p_{\text{livestock,atyp}} \times M_{\text{manure,tot,typ}} \qquad \text{(eq.4.0.8)}$$

$$N_{\text{excreted,tot,atyp}} = p_{\text{livestock,atyp}} \times N_{\text{excreted,tot,typ}} \qquad \text{(eq.4.0.9)}$$

## 5. Water use

The total irrigation that is needed in an atypical (drought or flood) year is estimated by assuming that irrigation compensates for any shortfall in soil water compared to a typical year, such that

$$V_{\text{wat,atyp}} + V_{\text{irrig,atyp}} = V_{\text{wat,typ}} + V_{\text{irrig,typ}} \qquad \text{(eq.5.0.1)}$$

where $V_{\text{wat,atyp}}$ and $V_{\text{wat,typ}}$ are the soil water contents, and $V_{\text{irrig,atyp}}$ and $V_{\text{irrig,typ}}$ are the amounts of irrigation in atypical and typical years respectively (mm). This can be rearranged to give the irrigation needed when $(V_{\text{wat,atyp}} < V_{\text{wat,typ}})$;

$$V_{\text{irrig,atyp}} = V_{\text{wat,typ}} + V_{\text{irrig,typ}} - V_{\text{wat,atyp}} \qquad \text{(eq.5.0.2)}$$

The irrigation is constrained so that it cannot exceed the maximum rate of irrigation specified for the site, $V_{\text{irrig,atyp,max}}$ (dm$^3$ m$^{-2}$)

$$0 \le V_{\text{irrig,atyp}} \le {V_{\text{irrig,atyp,max}}}\Big/{(A \times 10^4)} \qquad \text{(eq.5.0.3)}$$

where $A$ is the area of the piece of land (ha).

In a typical year, it is assumed that irrigation is distributed evenly across the growing season.

## 6. Energy use

The inputs to the model specify the percentages of cooking and lighting fuels obtained from wood, charcoal, crop residues, dung, kerosene and electricity, $P_{\text{cook,fuel}}$ and $P_{\text{light,fuel}}$ (%), respectively, where $fuel$ refers to the fuel type. The proportion of fuel available in atypical compared to typical years, $p_{\text{fuel,atyp}}$, provides an estimate for the change in organic resources available for use in cooking,

$$E_{\text{cook,atyp}} = E_{\text{cook,typ}} \times {\sum_{\text{fuel}}\left(P_{\text{cook,fuel}} \times p_{\text{fuel,atyp}}\right)}\Big/{10^2} \qquad \text{(eq.6.0.1)}$$

where $E_{\text{cook,atyp}}$ and $E_{\text{cook,typ}}$ are the energy available for cooking in atypical and typical years respectively (MJ y$^{-1}$), and $fuel$ is the fuel type; wood, charcoal, crop residues, dung, kerosene or electricity.

Similarly, the change in organic resources available for lighting can be written as

$$E_{\text{light,atyp}} = E_{\text{light,typ}} \times \sum_{\text{fuel}}\left(P_{\text{light,fuel}} \times p_{\text{fuel,atyp}}\right) / 10^2 \qquad \text{(eq.6.0.2)}$$

where $E_{\text{light,atyp}}$ and $E_{\text{light,typ}}$ are the energy available for lighting in atypical and typical years respectively (MJ $y^{-1}$).

## 6.1. The proportion of fuel available in atypical compared to typical years

The proportion of fuel available in atypical compared to typical years, $p_{\text{atyp,fuel}}$, is assumed to be 1 for wood, charcoal, kerosene and electricity, as it is not likely that the availability of these fuels will change due to droughts or floods.

For crop residues, $p_{\text{fuel,atyp}}$ is calculated across all areas of the farm using the input values specified for the percentage of the crop type grown in that area that is used for fuel, $P_{\text{use,fuel}}$ (%),

$$p_{\text{fuel,atyp}} = \sum_{\text{area}}\left(\left(p_{\text{plant,atyp,area}} \times P_{\text{area}} \times P_{\text{use,fuel}}\right) \Big/ \sum_{\text{area}}\left(P_{\text{area}} \times P_{\text{use,fuel}}\right)\right) \qquad \text{(eq.6.1.1)}$$

where $p_{\text{plant,atyp,area}}$ is the proportion of plant production in an atypical compared to a typical year (described in section 3), and $P_{\text{area}}$ is the percentage of the farm in this area. Note, $P_{\text{use,fuel}}$ only specifies percent teff, percent maize and percent other crops used for fuel in order to keep the inputs simple for the user.

For dung, $p_{\text{fuel,atyp}}$ is calculated across all animals kept on the farm,

$$p_{\text{fuel,atyp}} = \sum_{\text{animal}}\left(\left(p_{\text{livestock,atyp}} \times n_{\text{head,animal}}\right) \Big/ \sum_{\text{animal}} n_{\text{head,animal}}\right) \qquad \text{(eq.6.1.2)}$$

where $p_{\text{livestock,atyp}}$ is the proportion of animal production in an atypical (drought or flood) year compared to a typical year (described in section 4) and $n_{\text{head,animal}}$ is the number of animals of the given type ($animal$).

## 6.2. Energy use in a typical year

The energy use in a typical year for cooking ($E_{\text{cook,typ}}$) and lighting ($E_{\text{light,typ}}$) can be estimated either from national statistics or the energy use in a typical year specified by the user.

**More needed**
Dali – please put together a database for energy use in a typical year from online sources:

Bailis R, Drigo R, Ghilardi A, Masera O, 2015. The carbon footprint of traditional woodfuels. Nature Climate Change. DOI: 10.1038/NCLIMATE2491
FAOSTAT Forestry Production and Trade (UN FAO, 2013); http://faostat3.fao.org/faostat-gateway/go/to/download/F/*/E
IEAWorld Energy Statistics and Balances (International Energy Agency, 2013); http://www.oecd-ilibrary.org/statistics"

UN Statistics Division Energy Statistics Database (United Nations, 2013); http://data.un.org/Explorer.aspx"

## 7. Labour

Labour is calculated from entered values specifying time spent by different members of the household on collecting water and wood each week, on tending livestock and crops each day, and on other essential activities (such as cooking, cleaning the home etc) each day. The household members are divided into male adults, female adults, male children and female children. This information is then used to estimate the time available for non-essential activities, such as leisure, education, petty trading, off-farm work), and how this changes throughout the year.

### 7.1. Time spent collecting woodfuel

The average time each person spends collecting woodfuel each day, $t_{\mathrm{wood}}$ (hrs d$^{-1}$), is calculated from information provided on the total number of trips made by all people in this group each week to collect woodfuel, $n_{\mathrm{trip,wood}}$, the number of people in the group, $n_{\mathrm{people}}$, the average time spent in each trip travelling to and from the place where wood is collected, $t_{\mathrm{travel,wood}}$ (hrs), and the average time spent in each trip gathering wood, $t_{\mathrm{gather,wood}}$ (hrs);

$$t_{\mathrm{wood}} = \left(n_{\mathrm{trip,wood}} \times \left(t_{\mathrm{travel,wood}} + t_{\mathrm{gather,wood}}\right)\right) \Big/ \left(7 \times n_{\mathrm{people}}\right) \qquad \text{(eq.7.1.1)}$$

This uses the assumptions that wood fuel collection is spread evenly throughout the year. Use of other energy sources, such as crop residues, could change the pattern of wood collection at some times of year. This could be accounted for by assessing the annual patterns of availability of other energy sources and subtracting the energy value from the amount of wood collected. This also assumes that there is no impact of droughts or floods on woodfuel collection. Wet conditions might increase the time spent processing wood; further evidence is needed to include these changes in the model.

### 7.2. Time spent collecting water

The total amount of water collected for the household and animals each month, $V_{\mathrm{water,house}}$ (dm$^3$ mnth$^{-1}$) is calculated from information provided on the total number of trips made by people in each group to collect water for household use and animals (not for irrigation), $n_{\mathrm{trip,water}}$, and the volume of water carried in each trip, $V_{\mathrm{water,trip}}$(dm$^3$),

$$V_{\mathrm{water,house}} = \sum_{\mathrm{i}} \left(\frac{n_{\mathrm{days,month}}}{7} \times n_{\mathrm{trip,water,i}} \times V_{\mathrm{water,trip,i}}\right) \qquad \text{(eq.7.2.1)}$$

where $n_{\mathrm{days,month}}$ is the number of days in the month and the subscript $\mathrm{i}$ indicates the different groups of people in the household.

It is assumed that the water collection for household use and for animals remains constant throughout the year. This may change in dry weather conditions, either with more water collected because animals / people are thirsty, or with less water collected because water is used more sparingly. Further evidence is needed on the impact of dry weather conditions on water use. Therefore, in this first instance, it is assumed that water use is unchanged through the year.

The volume of water collected for irrigation, $V_{\mathrm{irrig}}$ (dm$^3$ mnth$^{-1}$), calculated as described in section 5, is added to this to give the total volume of water required each month, $V_{\mathrm{water,total}}$ (dm$^3$ mnth$^{-1}$),

$$V_{\mathrm{water,total}} = V_{\mathrm{water,house}} + V_{\mathrm{irrig}} \qquad \text{(eq.7.2.2)}$$

The total time spent by each person collecting water for household and animal use, $t_{\mathrm{water,house}}$ (hrs d$^{-1}$) is given by the number of trips made by people in this group to collect water, $n_{\mathrm{trip,water}}$, the average time spent in each trip travelling to and from the place where water is collected, $t_{\mathrm{travel,water}}$ (hrs), the average time spent queuing for water in each trip, $t_{\mathrm{queue,water}}$ (hrs),

$$t_{\mathrm{water,house}} = \left( \left( n_{\mathrm{trip,water}} \times \left( t_{\mathrm{travel,water}} + t_{\mathrm{queue,water}} \right) \right) \Big/ \left( 7 \times n_{\mathrm{people}} \right) \right) \qquad \text{(eq.7.2.3)}$$

Assuming the source of water is the same for irrigation as for animal and household use, and the labour required for collecting this water is divided amongst the members of the household in the same proportions as the collection of water for the household and animals, the total time spent by each person collecting water for household and animal use, $t_{\mathrm{water}}$ (hrs d$^{-1}$) is given by

$$t_{\mathrm{water}} = t_{\mathrm{water,house}} \times \frac{V_{\mathrm{water,total}}}{V_{\mathrm{water,house}}} \qquad \text{(eq.7.2.4)}$$

Assuming the source of water and the responsibility for water collection remains unchanged in a drought year, the extra labour required for water collection in a drought year is given by the increase in irrigation. Survey evidence in Halaba suggests that the water source and responsibility for water collection changes in drought years. Therefore, time spent collecting water in drought years was estimated using different entered values for the time spent travelling and queuing for water. In a flood year, it was assumed that the water source and responsibility for water collection is the same as in a drought year.

### 7.3. Time spent managing livestock

The time spent managing livestock, $t_{\mathrm{livestock}}$(hrs d$^{-1}$), is calculated from entered values of the total time spent each day by people in this group feeding, watering and herding animals, $t_{\mathrm{animal}}$(hrs d$^{-1}$), and managing dung, $t_{\mathrm{dung}}$(hrs d$^{-1}$),

$$t_{\mathrm{livestock}} = \left( t_{\mathrm{animal}} + t_{\mathrm{dung}} \right) \Big/ n_{\mathrm{people}} \qquad \text{(eq.7.3.1)}$$

This assumes that the total time spent on these activities remains unchanged throughout the year. Drought conditions may result in extra labour as animals need to be herded longer distances to water, or additional water is collected for animals to drink. Further information is needed to decide what triggers additional herding or watering of animals and how long this takes.

### 7.4. Time spent managing crops

The time spent managing crops, $t_{\mathrm{crop}}$ (hrs d$^{-1}$), was calculated from entered values for time spent by people in the different groups within the household sowing, $t_{\mathrm{sow}}$ (hrs d$^{-1}$), tending, $t_{\mathrm{weed}}$ (hrs d$^{-1}$), and harvesting crops, $t_{\mathrm{harv}}$ (hrs d$^{-1}$),

$t_{\text{crop}} = {(t_{\text{sow}} + t_{\text{weed}} + t_{\text{harv}})}/{n_{\text{people}}}$ (eq.7.4.1)

This is accumulated across all areas of the farm, assuming that sowing and harvest days are split equally between different crops in the month of sowing or harvest, and that tending crops continues throughout the growing season and is split equally between the crops growing at that time. Different crops may require different amounts of sowing, tending or harvest, but this is used as a first approximation. No account has yet been taken of the potential need to replant crops following periods of flooding.

### 7.5. Time spent on other activities

The time spent on other essential activities (such as cooking and cleaning the home), $t_{\text{essential}}$ (hrs $d^{-1}$), was calculated from entered values for time spent on these activities, $t_{\text{essential,group}}$ (hrs $d^{-1}$),

$t_{\text{essential}} = {t_{\text{essential,group}}}/{n_{\text{people}}}$ (eq.7.5.1)

The time remaining for non-essential activities, such as leisure (education, petty trading and off-farm work), $t_{\text{non-essential}}$ (hrs $d^{-1}$), was then calculated by difference from the average time each person in that group spends awake each day, $t_{\text{awake}}$ (hrs $d^{-1}$),

$t_{\text{non-essential}} = t_{\text{awake}} - t_{\text{essential}}$ (eq.7.5.2)

The assumes that essential activities are spread evenly throughout the year; some essential activities may in fact be seasonal.

## 8. Purchases and Sales

Purchases and sales are budgeted from data entered on purchases and sales in wet and dry seasons in a typical year, detailing the price of products and the amount purchased or sold. Input values for sales are checked against the amount of products available within the household. The sales and purchases are then distributed through the year according to the rainfall in the month (specifying wet or dry season), and the according to the availability of products for sale (eg harvest time).

### 8.1. Check of products available for sale

***Dung***

The availability of dung for sale, $M_{\text{dung,sale}}$ (kg $y^{-1}$) is calculated from the dung produced by dairy cattle and beef livestock in a typical year, $M_{\text{manure,tot,typ}}$ (kg $y^{-1}$), calculated as described in section 4, and the percentage of dung that is used for sale, $P_{\text{use,sale}}$ (%), i.e.

$M_{\text{dung,sale}} = \sum_{dairy\ \&\ beef\ cattle} \left( M_{\text{manure,tot,typ}} \times {P_{\text{use,sale}}}/{100} \right)$ (eq.8.1.1)

### 8.2. Determination of wet and dry seasons

Months are classified as being in the wet or dry season according to the specified rainfall. For Halaba, it is assumed that a wet month has a rainfall over 100 mm $\text{month}^{-1}$, whereas a dry month has rainfall below 100 mm $\text{month}^{-1}$; this was set for the region by considering the months usually considered to be in the wet and dry seasons, and then determining the boundary condition that would correctly subdivide months between seasons (Legesse et al., 2003; Belete et al., 2017) For different regions, wet and dry months may be classified differently.

### 8.3. Purchases

***Energy, water and food***

The amount of money spent on energy, water, food, $B_{\mathrm{item}}$ (Ethiopian Birr (ETB) week$^{-1}$), is partitioned according to the purchases specified in the wet and dry seasons, and the classification of the month as wet or dry season.

$$B_{\mathrm{item}} = Q_{\mathrm{item}} \times b_{\mathrm{item}} \qquad \text{(eq.8.3.1)}$$

where $Q_{\mathrm{item}}$ is the quantity of the item purchased each week, and $b_{\mathrm{item}}$ is the price of the item per specified unit quantity. Quantities are expressed in units that are convenient for the farmer: for energy purchases, dung cakes are in sacks, wood is in bundles, crop residues are in bundles, charcoal is in sacks and kerosene is in $dm^3$; water is specified in litres ($dm^3$); food is specified in kg; and because all these purchases are assumed to be bought weekly, the time step given is per week.

The expenditure per week is assumed to remain constant across all months of the season. This assumption is only likely to hold for products that are bought weekly rather than being purchased in bulk at a particular time of year. In the absence of further information about bulk buying, an equal distribution of expenditure is the best assumption to use.

Money spent on equipment and other items is calculated as a one off purchase in the year.

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# Appendix A – Symbols used in equations

Note: ordered lower case before uppercase and Roman lettering before Greek. Punctuation and numbering ordered above lettering.

**Up to 7.4**

| Symbol | Definition | Units |
|---|---|---|
| $A$ | Area of the piece of land | ha |
| $c_{\mathrm{N}}$ | N response coefficient | No units |
| $c_{\mathrm{X}}$ | Nutrient (N, P or K) response coefficient | No units |
| $C^{*}{}_{\mathrm{npp}}$ | Relative net primary production modified according to nutrient limitation | t ha$^{-1}$ |
| $C^{*}{}_{\mathrm{npp,X}}$ | Relative net primary production modified according to limitation of nutrient X | t ha$^{-1}$ |
| $C_{\mathrm{CO2}}$ | Amount of carbon dioxide C produced by aerobic decomposition in given month | t ha$^{-1}$ |
| $C_{\mathrm{DPM,last}}$ | Stock of C in the DPM pool in the last time step | t ha$^{-1}$ |
| $C_{\mathrm{HUM,last}}$ | Stock of C in the HUM pool in the last time step | t ha$^{-1}$ |
| $C_{\mathrm{RPM,last}}$ | Stock of C in the RPM pool in the last time step | t ha$^{-1}$ |
| $C_{\mathrm{IOM}}$ | Amount of C in the IOM pool | t ha$^{-1}$ |
| $C_{\mathrm{loss}}$ | Amount of C lost from each pool in each time-step | t ha$^{-1}$ |
| $C_{\mathrm{meas}}$ | Measured total soil C | t ha$^{-1}$ |
| $C_{\mathrm{npp}}$ | Net primary of C production calculated according to environmental limitations | t ha$^{-1}$ |
| $C^{**}{}_{\mathrm{npp}}$ | Net primary of C production calculated according to both water and nutrient limitations | t ha$^{-1}$ |
| $C_{\mathrm{npp,atyp}}$ | Net primary production of C estimated under the atypical conditions | t ha$^{-1}$ |
| $C_{\mathrm{npp.mon}}$ | Net primary production of C for a given month | t ha$^{-1}$ |
| $C_{\mathrm{npp,typ}}$ | Net primary production of C estimated under the typical conditions | t ha$^{-1}$ |
| $C_{\mathrm{OW}}$ | Input of C from organic waste | t ha$^{-1}$ |
| $C_{\mathrm{OW,DPM}}$ | Inputs of C to the DPM pool from organic wastes | t ha$^{-1}$ |
| $C_{\mathrm{OW,HUM}}$ | Inputs of C to the HUM pool from organic wastes | t ha$^{-1}$ |
| $C_{\mathrm{OW,IOM}}$ | Amount of organic waste passed to the IOM pool in the time-step | t ha$^{-1}$ |
| $C_{\mathrm{OW,pool}}$ | Amount of C from organic waste passed to the specified pool in the time-step | t ha$^{-1}$ |
| $C_{\mathrm{OW,atyp,mon}}$ | Input of C from organic waste in month $mon$ in an atypical year | t ha$^{-1}$ |
| $C_{\mathrm{OW,typ,mon}}$ | Input of C from organic waste in month $mon$ in a typical year | t ha$^{-1}$ |
| $C_{\mathrm{PI}}{}^{*}$ | Adjusted plant inputs of C to the soil in growing season | t ha$^{-1}$ |
| $C_{\mathrm{PI}}$ | Plant inputs of C to the soil in growing season | t ha$^{-1}$ |
| $C_{\mathrm{PI,DPM}}$ | Inputs of C to the DPM pool from plant inputs | t ha$^{-1}$ |
| $C_{\mathrm{PI,RPM}}$ | Inputs of C to the RPM pool from plant inputs | t ha$^{-1}$ |
| $C_{\mathrm{PI,mon}}$ | Plant input of C in month | t ha$^{-1}$ |

| Symbol | Definition | Units |
|---|---|---|
| $C_{\text{PI,atyp,mon}}$ | Plant input of C in month in an atypical year | t ha$^{-1}$ |
| $C_{\text{PI,typ,mon}}$ | Plant input of C in month in an typical year | t ha$^{-1}$ |
| $C_{\text{PI,pool}}$ | Amount of C from plant inputs passed to the specified pool in the time-step | t ha$^{-1}$ |
| $C_{\text{pool}}$ | Amount of C in a specific pool | t ha$^{-1}$ |
| $C_{\text{sim}}$ | Simulated total soil carbon | t ha$^{-1}$ |
| $C_{\text{yld,atyp}}$ | Yield of C in an atypical year | t ha$^{-1}$ |
| $C_{\text{yld,typ}}$ | Yield of C in a typical year | t ha$^{-1}$ |
| $d$ | Depth of soil | cm |
| $d_{\text{max}}$ | Maximum rooting depth | cm |
| $D_{-100\text{kPa}}$ | Deficit in soil water at -100 kPa | mm |
| $E_{\text{cook,atyp}}$ | Energy available for cooking in atypical year | MJ |
| $E_{\text{cook,typ}}$ | Energy available for cooking in typical year | MJ |
| $E_{\text{light,atyp}}$ | Energy available for lighting in atypical year | MJ |
| $E_{\text{light,typ}}$ | Energy available for lighting in typical year | MJ |
| $f_{\text{NH4,loss}}$ | Loss adjustment factor for ammonium | No units |
| $f_{\text{NO3,loss}}$ | Loss adjustment factor for nitrate | No units |
| $I_{\text{heat}}$ | Heat index used in Thornthwaite equation | No units |
| $I_{\text{ws}}$ | Water stress index | No units |
| $k_{\text{PI,C}}$ | Constant describing the shape of the exponential curve for C input | month$^{-1}$ |
| $k_{\text{nitrif}}$ | Rate constant for nitrification | month$^{-1}$ |
| $k_{\text{pool}}$ | Rate constant for decomposition of specified C pool | month$^{-1}$ |
| $L$ | Day length | hours |
| $m'_{\text{bio}}$ | Rate modifier for denitrification according to the biological activity of the soil | No units |
| $m'_{\text{NO3}}$ | Rate modifier for denitrification according to the amount of nitrate in the soil | No units |
| $m'_{\text{wat}}$ | Rate modifier for denitrification according to the soil moisture content | No units |
| $M_{\text{crop,max}}$ | Maximum potential yield of a crop | t ha$^{-1}$ |
| $M_{\text{crop,typ}}$ | Entered crop production for a typical year | t ha$^{-1}$ |
| $M_{\text{manure,head}}$ | Typical per head animal production value for manure | kg y$^{-1}$ |
| $M_{\text{manure,tot,atyp}}$ | Total manure produced in an atypical year | kg y$^{-1}$ |
| $M_{\text{manure,tot,typ}}$ | Total manure produced in a typical year | kg y$^{-1}$ |
| $M_{\text{meat,head}}$ | Typical per head animal production value for meat | kg y$^{-1}$ |
| $M_{\text{meat,tot,atyp}}$ | Total meat produced in an atypical year | kg y$^{-1}$ |
| $M_{\text{meat,tot,typ}}$ | Total meat produced in a typical year | kg y$^{-1}$ |
| $M_{\text{milk,head}}$ | Typical per head animal production value for milk | kg y$^{-1}$ |
| $M_{\text{milk,tot,atyp}}$ | Total milk produced in an atypical year | kg y$^{-1}$ |
| $M_{\text{milk,tot,typ}}$ | Total milk produced in a typical year | kg y$^{-1}$ |

| Symbol | Definition | Units |
|---|---|---|
| $n_{\mathrm{days,mon}}$ | Number of days in the month | No units |
| $n_{\mathrm{head,animal}}$ | Number of animals of the given type | No units |
| $n_{\mathrm{people}}$ | Number of people in the group | No units |
| $n_{\mathrm{todate}}$ | Number of Julian days from January 01 to current date | No units |
| $n_{\mathrm{trip,water}}$ | Total number of trips made by people in each group to collect water for household use and animals (not for irrigation) | No units |
| $n_{\mathrm{trip,water,i}}$ | Total number of trips made by people in each group to collect water for household use and animals (not for irrigation) in group i | No units |
| $n_{\mathrm{trip,wood}}$ | Total number of trips made by all people in this group each week to collect woodfuel | No units |
| $N_{\mathrm{atm}}$ | Atmospheric deposition of N to the soil | kg ha$^{-1}$ |
| $N_{\mathrm{crop}}$ | N demand of the crop in each month | kg ha$^{-1}$ |
| $N_{\mathrm{d50}}$ | Soil nitrate-N content at which denitrification is 50% of its full potential | kg ha$^{-1}$ |
| $N_{\mathrm{denit}}$ | Losses of nitrate-N by denitrification in the given month | kg ha$^{-1}$ |
| $N_{\mathrm{denit,max}}$ | Maximum potential amount of denitrification in a given month | kg ha$^{-1}$ |
| $N_{\mathrm{denit,N2O}}$ | Amount of the denitrified N lost as nitrous oxide | kg ha$^{-1}$ |
| $N_{\mathrm{excreted,head}}$ | Typical per head animal production values for excreted N | kg y$^{-1}$ |
| $N_{\mathrm{excreted,tot,typ}}$ | Total N excreted by an animal in an atypical year | kg y$^{-1}$ |
| $N_{\mathrm{excreted,tot,typ}}$ | Total N excreted by an animal in a typical year | kg y$^{-1}$ |
| $N_{\mathrm{fert}}$ | Inputs of N fertiliser to the soil in the month | kg ha$^{-1}$ |
| $N_{\mathrm{NH4}}$ | Ammonium-N available in the soil to simulated depth | kg ha$^{-1}$ |
| $N_{\mathrm{NH4,atm}}$ | Amount of ammonium-N input by atmospheric deposition | kg ha$^{-1}$ |
| $N_{\mathrm{NH4,crop}}$ | Crop N demand from the ammonium pool | kg ha$^{-1}$ |
| $N_{\mathrm{NH4,fert}}$ | Fertiliser inputs to the ammonium pool this month | kg ha$^{-1}$ |
| $N_{\mathrm{NH4,immob}}$ | N immobilised from the ammonium pool this month | kg ha$^{-1}$ |
| $N_{\mathrm{NH4,min}}$ | Minimum possible amount of ammonium-N on soil to specified depth | kg ha$^{-1}$ |
| $N_{\mathrm{NH4,miner}}$ | Input of ammonium-N due to mineralisation | kg ha$^{-1}$ |
| $N_{\mathrm{NH4,nitrif}}$ | N lost from ammonium pool by nitrification this month | kg ha$^{-1}$ |
| $N_{\mathrm{NH4,volat}}$ | Volatilisation of ammonium or urea-N | kg ha$^{-1}$ |
| $N_{\mathrm{nitrif,N2O}}$ | Nitrified N lost as $N_2O$ | kg ha$^{-1}$ |
| $N_{\mathrm{NO3}}$ | Nitrate-N available in the soil to simulated depth | kg ha$^{-1}$ |
| $N_{\mathrm{NO3,atm}}$ | Atmospheric deposition of nitrate-N to the soil | kg ha$^{-1}$ |
| $N_{\mathrm{NO3,crop}}$ | Crop N demand from the nitrate pool | kg ha$^{-1}$ |
| $N_{\mathrm{NO3,fert}}$ | Fertiliser inputs to the nitrate pool this month | kg ha$^{-1}$ |
| $N_{\mathrm{NO3,immob}}$ | N immobilised from the nitrate pool this month | kg ha$^{-1}$ |
| $N_{\mathrm{NO3,in}}$ | Sum of all nitrate-N inputs during the month | kg ha$^{-1}$ |
| $N_{\mathrm{NO3,leach,t1}}$ | Nitrate-N lost by leaving in this timestep | kg ha$^{-1}$ |
| $N_{\mathrm{NO3,loss}}$ | Sum of all nitrate-N losses during the month | kg ha$^{-1}$ |
| $N_{\mathrm{NO3,min}}$ | Minimum possible amount of nitrate-N in the soil to specified depth | kg ha$^{-1}$ |

| Symbol | Definition | Units |
|---|---|---|
| $N_{NO3,nitrif}$ | Input of N to nitrate by nitrification | kg ha$^{-1}$ |
| $N_{NO3,start}$ | Amount of N available as nitrate at the start of the month | kg ha$^{-1}$ |
| $N_{opt}$ | Optimum N supply for the crop | kg ha$^{-1}$ |
| $N_{soil}$ | Soil N supply | kg ha$^{-1}$ |
| $p_{BIO}$ | Proportion of biomass produced on aerobic decomposition of soil C | No units |
| $p_{C:X,DPM}$ | C:nutrient ratio of the DPM pool | No units |
| $p_{C:X,DPM,last}$ | C:nutrient ratio of the DPM pool in the last timestep | No units |
| $p_{C:X,HUM}$ | C:nutrient ratio of the HUM pool | No units |
| $p_{C:X,HUM,last}$ | C:nutrient ratio of the HUM pool in the last timestep | No units |
| $p_{C:X,RPM}$ | C:nutrient ratio of the RPM pool | No units |
| $p_{C:X,RPM,last}$ | C:nutrient ratio of the RPM pool in the last timestep | No units |
| $p_{C:X,plant}$ | C:nutrient ratio of the plant inputs | No units |
| $p_{C:X,OW}$ | C:nutrient ratio of the organic wastes | No units |
| $p_{C:X,soil}$ | Stable C:nutrient ratio of the soil | No units |
| $p_{CO2}$ | Proportion of $CO_2$ produced on aerobic decomposition of soil C | No units |
| $p_{D:R,PI}$ | Ratio of DPM:RPM in the plant inputs | No units |
| $p_{D:H,OW}$ | Ratio of DPM:HUM in the active organic waste added | No units |
| $p_{eff,fertX}$ | Efficiency of use of nutrient X added as fertiliser | No units |
| $p_{fuel,atyp}$ | Proportion of fuel available in atypical year compared to typical year | No units |
| $p_{HUM}$ | Proportion of humus produced on aerobic decomposition of soil C | No units |
| $p_{IOM,OW}$ | Proportion of inert organic matter in the added organic waste | No units |
| $p_{livestock,atyp}$ | Proportion of animal production in an atypical (drought or flood) year compared to a typical year | No units |
| $p_{nitrif,gas}$ | Proportion of full nitrification lost as gas | No units |
| $p_{N:opt}$ | Proportion of the optimum supply of N in the soil | No units |
| $p_{N2O,FC}$ | Proportion of $N_2O$ produced due to partial nitrification at field capacity | No units |
| $p_{NH4,atm}$ | Proportion of atmospheric deposition added to the ammonium pool | No units |
| $p_{NO}$ | Proportion of full nitrification gaseous loss that is NO | No units |
| $p_{NO3}$ | Proportion of $N_2$ produced by denitrification according to soil nitrate-N | No units |
| $p_{NO3,atm}$ | Proportion of atmospheric deposition added to the nitrate pool | No units |
| $p_{NO3,fert}$ | Proportion of nitrate added in fertiliser | No units |
| $p_{OW,atyp}$ | Ratio of organic waste production in an atypical year compared to a typical year | No units |
| $p_{plant,atyp}$ | Ratio of plant production in an atypical year compared to a typical year | No units |
| $p_{plant,atyp,area}$ | Proportion of plant production in an atypical compared to a typical year | No units |
| $p_{volat}$ | Proportion of ammonium-N or urea-N that can be volatilised | No units |
| $p_{w}$ | Proportion of $N_2$ produced by denitrification according to soil water | No units |

| Symbol | Definition | Units |
|---|---|---|
| $p_{\mathrm{yld:opt}}$ | Proportion of the optimum yield achieved according to nutrients | No units |
| $p_{\mathrm{X:opt}}$ | Proportion of nutrient (N, P or K) available compared to the optimum amount of nutrient | No units |
| $P_{\mathrm{area}}$ | Percentage of the farm in this area | % by area |
| $P_{\mathrm{clay}}$ | Percentage of clay in the soil | % by vol. |
| $P_{\mathrm{cook,fuel}}$ | Percentage of cooking fuel obtained from specified fuel type | % by energy |
| $P_{\mathrm{C}}$ | Percentage of C in the soil | % by vol. |
| $P_{\mathrm{feed,buy}}$ | Percentage of animal feed bought from outside sources | % by vol. |
| $P_{\mathrm{feed,crop}}$ | Percentage of calorific feed value supplied to animal from the crop | % by vol. |
| $P_{\mathrm{light,fuel}}$ | Percentage of lighting fuel obtained from specified fuel type | % by energy |
| $P_{\mathrm{sand}}$ | Percentage of sand in the soil | % by vol. |
| $P_{\mathrm{silt}}$ | Percentage of silt in the soil | % by vol. |
| $P_{\mathrm{use,fuel}}$ | Percentage of the crop type grown in that area that is used for fuel | % by weight |
| $r_{\mathrm{inhibit}}$ | Inhibition rate modifier for nitrification | No units |
| $r_{\mathrm{mod}}$ | Product of rate modifiers for aerobic decomposition of soil C that account for changes different environmental factors | No units |
| $r_{\mathrm{pH}}$ | pH rate modifier for aerobic decomposition of soil C | No units |
| $r_{\mathrm{sal}}$ | Salinity rate modifier for aerobic decomposition of soil C | No units |
| $r_{\mathrm{temp}}$ | Temperature rate modifier for aerobic decomposition of soil C | No units |
| $r_{\mathrm{wat}}$ | Soil moisture rate modifier for aerobic decomposition of soil C | No units |
| $S_{\mathrm{pH}}$ | Soil pH measured in 0.01M $CaCl_2$ | No units |
| $S_{\mathrm{sal}}$ | Soil salinity, measured as electrical conductivity in a 1:5 soil/water suspension | dS $m^{-1}$ |
| $t_{\mathrm{animal}}$ | Total time spent each day by people in this group feeding, watering and herding animals | hrs $d^{-1}$ |
| $t_{\mathrm{dung}}$ | Total time spent each day managing dung | hrs $d^{-1}$ |
| $t_{\mathrm{gather,wood}}$ | Average time spent in each trip gathering wood | hrs |
| $t_{\mathrm{grow}}$ | Number of months in the growing season | No units |
| $t_{\mathrm{harv}}$ | Harvest month | No units |
| $t_{\mathrm{livestock}}$ | Time spent managing livestock | hrs $d^{-1}$ |
| $t_{\mathrm{mon}}$ | Current month | No units |
| $t_{\mathrm{queue,water}}$ | Average time spent queuing for water in each trip | hrs |
| $t_{\mathrm{travel,water}}$ | Average time spent in each trip travelling to and from the place where water is collected | hrs |
| $t_{\mathrm{travel,wood}}$ | Average time spent in each trip travelling to and from the place where wood is collected | hrs |
| $t_{\mathrm{water}}$ | Total time spent by each person collecting water for household and animal use | hrs $d^{-1}$ |
| $t_{\mathrm{water,house}}$ | Total time spent by each person collecting water for household and animal use | hrs $d^{-1}$ |

| Symbol | Definition | Units |
| --- | --- | --- |
| $t_{\mathrm{wood}}$ | Average time each person spends collecting woodfuel each day | hrs $d^{-1}$ |
| $T_{\mathrm{a}}$ | Average monthly air temperature | °C |
| $T_{\mathrm{a,grow}}$ | Average air temperature during the growing season | °C |
| $T_{\mathrm{a,mon}}$ | Average monthly air temperature | °C |
| $T_{\mathrm{GDD}}$ | Growing degree days | °C |
| $V_{\mathrm{AET(mon-1)}}$ | Actual evapotranspiration last month | mm |
| $V_{\mathrm{FC}}$ | Water content at field capacity of soil to given depth | mm |
| $V_{\mathrm{PET}}$ | Potential evapotranspiration of water from the plant in the month | mm |
| $V_{\mathrm{PET,d,t1}}$ | Potential evapotranspiration to given depth during the time step | mm |
| $V_{\mathrm{PET(mon-1)}}$ | Potential evapotranspiration last month | mm |
| $V_{\mathrm{PWP}}$ | Water content at the permanent wilting point of soil to given depth | mm |
| $V_{\mathrm{rain,crit}}$ | Critical level of rainfall, below which volatilisation can occur | mm |
| $V_{\mathrm{rain,grow}}$ | Rainfall during the growing season | mm |
| $V_{\mathrm{irrig}}$ | Volume of water collected for irrigation | $dm^3$ $mnth^{-1}$ |
| $V_{\mathrm{irrig,atyp}}$ | Amount of irrigation applied in an atypical year | mm |
| $V_{\mathrm{irrig,typ}}$ | Amount of irrigation applied in an typical year | mm |
| $V_{\mathrm{rain,t1}}$ | Rainfall during the time step | mm |
| $V_{\mathrm{wat}}$ | Water content of the soil of soil to given depth in the specified time-step | mm |
| $V_{\mathrm{wat,atyp}}$ | Soil water content in the growing season of an atypical year | mm |
| $V_{\mathrm{wat,typ}}$ | Soil water content in the growing season of an typical year | mm |
| $V_{\mathrm{wat,drained,t1}}$ | Water drained from the soil depth in time step | mm |
| $V_{\mathrm{wat,start}}$ | Amount of water in the soil at the start of the time step | mm |
| $V_{\mathrm{wat,t0}}$ | Initial water content of the soil of soil to given depth | mm |
| $V_{\mathrm{water,house}}$ | Total amount of water collected for the household and animals each month | $dm^3$ |
| $V_{\mathrm{water,total}}$ | Total volume of water required each month | $dm^3$ $mnth^{-1}$ |
| $V_{\mathrm{water,trip}}$ | Volume of water carried in each trip | $dm^3$ |
| $V_{\mathrm{water,trip,i}}$ | Volume of water carried in each trip by people in group i | $dm^3$ |
| $X_{\mathrm{adjust}}$ | Capture or release of nutrients to adjust the C:nutrient ratio of the soil organic matter to the stable ratio of the nutrient | kg $ha^{-1}$ |
| $X_{\mathrm{fert}}$ | Nutrient supply to crop from fertiliser added to the soil | kg $ha^{-1}$ |
| $X_{\mathrm{fert,in}}$ | Nutrient added to the soil in fertiliser | kg $ha^{-1}$ |
| $X_{\mathrm{min}}$ | Minimum amount of nutrient that results in a harvestable yield | kg $ha^{-1}$ |
| $X_{\mathrm{opt}}$ | Optimum amount of nutrient for the crop which results in crop yield that is not limited by the nutrient | kg $ha^{-1}$ |
| $X_{\mathrm{OW,DPM}}$ | Nutrient, X, in DPM pool in the organic waste | kg $ha^{-1}$ |
| $X_{\mathrm{OW,HUM}}$ | Nutrient, X, in HUM pool in the organic waste | kg $ha^{-1}$ |
| $X_{\mathrm{release}}$ | Release of nutrient associated with the loss of $CO_2$-C on decomposition | kg $ha^{-1}$ |

| Symbol | Definition | Units |
|---|---|---|
| $X_{\mathrm{soil}}$ | Soil supply of the nutrient to given depth | kg ha$^{-1}$ |
| $X_{\mathrm{soil,last}}$ | Soil supply of the nutrient to given depth in the last timestep (assuming no nutrient limitation) | kg ha$^{-1}$ |
| $X_{\mathrm{soil,last,act}}$ | Soil supply of the nutrient to given depth in the last timestep (actual accounting for nutrient limitation) | kg ha$^{-1}$ |
| $\delta$ | Declination of the sun | radians |
| $\varepsilon$ | Exponent function, used in Thornthwaite equation | No Units |
| $\theta_{\mathrm{d}}$ | Date in Julian days, expressed as an angle | radians |
| $\theta_{\mathrm{FC}}$ | Volumetric water content at field capacity | % |
| $\theta_{\mathrm{PWP}}$ | Volumetric water content at permanent wilting point | % |
| $\phi$ | Latitude | radians |