

Rangeland Production v0.2.0 Model Documentation

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December 2020

Summary

The Rangeland Production model (RPM) uses gridded climate and soils data to quantify the productivity of a rangeland area to support ruminant livestock and wildlife populations. The model may be run with gridded grazing animal density data, or with the assumption that grazing animals are uniformly distributed across the areas where they occur. With this estimated livestock density and gridded climate inputs, the model predicts the combined impacts of livestock management and climate in controlling rangeland condition and livestock diet sufficiency.

The Model

How it Works

The model uses a gridded adaptation of the Century model (version 4.6, Parton *et al.* 1988) to predict forage growth from climate and soils data, including the impacts of grazing. Coupled with the forage production model, the herbivore diet selection and physiology submodel simulates diet selection and estimates whether the selected diet meets or exceeds maintenance energy needs. The herbivore diet and physiology submodels are adapted from GRAZPLAN, which was developed for ruminant livestock (Freer *et al.* 2012). Full equations for both model adaptations appear in the relevant submodel sections below.

Entities, state variables and scales

The model operates at a monthly time step, over a time period and a fixed area specified by the user. The spatial resolution of the model is dictated by one user input such that all model inputs and outputs are resampled to match this input: if an animal density raster is supplied by the user, other inputs are resampled to the resolution of the animal density raster. If animal density is not supplied by the user, the spatial resolution of the model is given by precipitation inputs. Within the simulated area, each pixel is characterized by a set of state variables and parameters at the level of site, herbaceous plant functional type, and grazing animal. Each pixel is associated with a single site type, zero or one herbivore type, and one or more plant functional types. Site types correspond to broad ecosystem categories and are characterized by state variables describing soil water content, carbon (C), nitrogen (N), and phosphorus (P) in surface litter, and C, N, and P in inorganic and organic pools of the soil (table 1). Following Century,

site state variables include three soil organic matter pools (active, slow, and passive), above and belowground litter pools, and a surface microbial pool. Each of these pools are composed of a stock of C, N, and P. At each model time step, site-level state variables are updated as precipitation flows through soil water layers and is removed by transpiration, and C, N, and P decompose from one pool into another.

Table 1. Site-level state variables of the Rangeland Production model. Each pixel of the simulated area is associated with a single set of site state variables.

State variable	Definition	Units
metabc_1	Surface metabolic C	g/m ²
metabc_2	Belowground metabolic C	g/m ²
som1c_1	Surface microbial C	g/m ²
som1c_2	Active organic C	g/m ²
som2c_1	Surface slow organic C	g/m ²
som2c_2	Soil slow organic C	g/m ²
som3c	Passive organic C	g/m ²
strlig_1	Lignin content of surface structural material	g lignin/ g biomass
strlig_2	Lignin content of soil structural material	g lignin/ g biomass
strucc_1	Surface structural C	g/m ²
strucc_2	Belowground structural C	g/m ²
metabe_1_1	Surface metabolic N	g/m ²
metabe_2_1	Belowground metabolic N	g/m ²
minerl_1_1	Mineral N for soil layer 1	g/m ²
minerl_10_1	Mineral N for soil layer 10	g/m ²
minerl_2_1	Mineral N for soil layer 2	g/m ²
minerl_3_1	Mineral N for soil layer 3	g/m ²
minerl_4_1	Mineral N for soil layer 4	g/m ²

minerl_5_1	Mineral N for soil layer 5	g/m ²
minerl_6_1	Mineral N for soil layer 6	g/m ²
minerl_7_1	Mineral N for soil layer 7	g/m ²
minerl_8_1	Mineral N for soil layer 8	g/m ²
minerl_9_1	Mineral N for soil layer 9	g/m ²
som1e_1_1	Surface microbe N	g/m ²
som1e_2_1	Active organic N	g/m ²
som2e_1_1	Surface slow organic N	g/m ²
som2e_2_1	Soil slow organic N	g/m ²
som3e_1	Passive organic N	g/m ²
struce_1_1	Surface structural N	g/m ²
struce_2_1	Belowground structural N	g/m ²
metabe_1_2	Surface metabolic P	g/m ²
metabe_2_2	Belowground metabolic P	g/m ²
minerl_1_2	Mineral P for soil layer 1	g/m ²
minerl_10_2	Mineral P for soil layer 10	g/m ²
minerl_2_2	Mineral P for soil layer 2	g/m ²
minerl_3_2	Mineral P for soil layer 3	g/m ²
minerl_4_2	Mineral P for soil layer 4	g/m ²
minerl_5_2	Mineral P for soil layer 5	g/m ²
minerl_6_2	Mineral P for soil layer 6	g/m ²
minerl_7_2	Mineral P for soil layer 7	g/m ²
minerl_8_2	Mineral P for soil layer 8	g/m ²
minerl_9_2	Mineral P for soil layer 9	g/m ²

occlud	Occluded P	g/m ²
parent_2	Parent P	g/m ²
plabil	Labile P	g/m ²
secndy_2	Strongly sorbed P	g/m ²
som1e_1_2	Surface microbe P	g/m ²
som1e_2_2	Active organic P	g/m ²
som2e_1_2	Surface slow organic P	g/m ²
som2e_2_2	Soil slow organic P	g/m ²
som3e_2	Passive organic P	g/m ²
struce_1_2	Surface structural P	g/m ²
struce_2_2	Belowground structural P	g/m ²
asmos_1	Moisture in soil layer 1	g/m ²
asmos_2	Moisture in soil layer 2	g/m ²
asmos_3	Moisture in soil layer 3	g/m ²
asmos_4	Moisture in soil layer 4	g/m ²
asmos_5	Moisture in soil layer 5	g/m ²
asmos_6	Moisture in soil layer 6	g/m ²
asmos_7	Moisture in soil layer 7	g/m ²
asmos_8	Moisture in soil layer 8	g/m ²
asmos_9	Moisture in soil layer 9	g/m ²
avh2o_3	Moisture in top two soil layers	g/m ²
snlq	Liquid in snow	g/m ²
snow	Standing snowpack	g/m ²

Plant functional types (PFT) are herbaceous plants with different growth patterns or nutritive quality for herbivores (for example, different types of grass) and are characterized by state variables adapted from Century that describe C, N, and P in live and standing dead biomass (table 2). A PFT may occupy less than 100% of a pixel and multiple PFT may occur on a single pixel. In this case, the PFT do not directly interact but are assumed to have access to soil water and nutrient resources on that pixel in proportion to their fractional cover. At each model time step, PFT-level state variables are updated as new growth, senescence, and grazing by herbivores occur.

Table 2. Plant functional type (PFT) level state variables of the Rangeland Production model. Each pixel of the simulated area may contain one or more PFTs.

State variable	Definition	Units
aglive	Aboveground live C	g/m ²
bglive	Belowground live C	g/m ²
stdedc	Standing dead C	g/m ²
aglive_1	Aboveground live N	g/m ²
bglive_1	Belowground live N	g/m ²
crpstg_1	Retranslocation N storage pool	g/m ²
stdede_1	Standing dead N	g/m ²
aglive_2	Aboveground live P	g/m ²
bglive_2	Belowground live P	g/m ²
crpstg_2	Retranslocation P storage pool	g/m ²
stdede_2	Standing dead P	g/m ²
avh2o_1	Water available for plant growth	g/m ²

While multiple animal types may occur across the study area, a single pixel may be occupied by only one (or zero) grazing animal type. Each animal type is characterized by its type (cattle, sheep, or goat), sex, average age (days), average weight (kg), weight at birth (kg), standard reference weight (kg), and density (animals per pixel; table 3). The standard reference weight (cf. Freer *et al.* 2012) is the weight of a mature female in median condition and varies by

breed. Additional state variables characterizing male animals include castrate status (castrate or entire), and breeding females are characterized by their reproductive stage.

The density of livestock on each simulated pixel may be supplied by the user as a raster. If an animal density raster is not supplied by the user, the model assumes that grazing animals are distributed uniformly across pixels inside areas where they occur. The extent of grazing animals' presence is given by user input in the form of management polygons, which indicate areas grazed by animals over the course of the simulation and the total number of animals in each area.

A modeled livestock herd is characterized in a general way and is static throughout a model run. When breeding females are simulated, animals undergo cycles of conception, pregnancy, and lactation because these reproductive stages have strong influences on energy demands of the herd (IPCC 2006). The model does not estimate allocation of the diet to growth above maintenance requirements, but instead simply records whether maintenance needs were met or exceeded. Therefore most animal state variables, including age and weight, are static; only reproductive status of breeding females and its impact on energy and protein requirements is updated. The model does not simulate herd dynamics. Births and deaths are not tracked, and suckling calves are assumed to receive nutrition only from milk.

Table 3. State variables of the animal submodel.

State variable	Units or allowable values
Type	B. indicus, B. taurus, sheep, goat
Age	days
Weight	kg
Weight at birth	kg
Standard reference weight	kg
Sex	Entire male, castrate male, breeding female, non-breeding female
Reproductive stage (for breeding females)	Pregnant, open, lactating
Disaggregated density	Animals per pixel

Process overview and scheduling

At each monthly time step, the model simulates soil water dynamics and decomposition of surface and soil organic pools. The distribution of grazing animals inside management polygons (areas where grazing animals occur) is estimated once by the model if not supplied by the user. When animal density is estimated by the model, a uniform distribution of animals across pixels within management polygons is assumed.

The user is required to specify a management threshold, representing the minimum required total biomass across PFTs to be left standing after animal diet selection. The management threshold does not describe carrying capacity *per se*, but instead is a modeling artifact that is required for boundary cases where simulated densities are high relative to the productivity of the site. In a case when herbivore demand for forage is greater than the management threshold would allow, intake of forage is restricted to leave residual biomass equal to the management threshold. It is expected that in this case, the restricted diet would be insufficient to meet maintenance requirements.

The diet selection submodel simulates selective feeding by herbivores from the total available forage across PFTs according to the provisional forage production in the absence of grazing. The diet selection submodel predicts the forage intake of an individual animal, then multiplies that predicted intake by the density of animals per pixel to get the total offtake of each PFT consumed by herbivores on each pixel. If the sum of forage biomass selected by herbivores exceeds available forage according to the management threshold, intake is reduced such that forage consumed is equal to available forage. This rule is applied separately to each PFT, meaning that if demand for one PFT exceeds availability, intake of that PFT may be decreased while intake of other PFTs remains unchanged. In this situation, the relative proportions of different PFTs would differ from what was selected according to the diet selection submodel.

After the calculation of offtake selected from provisional biomass in the current month, the model calculates final biomass production, this time incorporating impacts of grazing. This final calculation includes altered root:shoot ratio and altered N content of live shoots and roots according to grazing pressure (Holland *et al.* 1992). Following Century, grazing pressure is expressed as the fraction of live and dead biomass removed following senescence of live material and fall of standing dead, but prior to new growth (i.e., input parameters “flgrem” and “fdgrem” of Century). The absolute offtake of grazing calculated by the diet selection submodel is converted to the fraction of standing live and dead relative to this intermediate point.

Energy and protein contents of the diet are compared to maintenance energy and protein requirements for maintenance, including pregnancy and lactation for breeding females. The ability of the selected diet to satisfy maintenance needs is summarized with the metric of diet sufficiency, which indicates whether the selected diet is adequate for animals to maintain their current condition or size.

All spatial inputs are aligned and resampled by the model to a single bounding box and pixel size. When an animal density raster is supplied by the user, all inputs are resampled to match the resolution of the animal density raster; otherwise, inputs are resampled to match the resolution of the precipitation rasters.

Initialization

Simulations run over a short time frame are dominated by initial condition uncertainty, while those run over a longer period are more likely to be dominated by boundary condition uncertainty (Li *et al.* 2009). For this reason, the Century model is customarily run for a long “spin-up” period, as long as several thousand years, to establish equilibrium soil nutrient pools. The rangeland production model instead requires that initial conditions be supplied by the user, with the expectation that initial conditions may be derived from a similar “spin-up” process or from reasonable prior knowledge of the study area via an external analysis. A series of rasters or a table of values for each state variable covering the study area (tables 1 and 2) must be supplied. If multiple PFT are simulated, a separate value for each PFT-level state variable in table 2 must be supplied for each PFT.

Input

Data inputs for the model consist of site inputs and temporal controls, including climate and soil inputs (table 4). Precipitation and vegetation index rasters must be supplied for each month of the simulation; precipitation inputs must be supplied for at least 12 months to allow the model to calculate annual precipitation.

Another set of spatial inputs are required that give the extent of site types, PFTs, and animal types. These link site, PFT, and animal parameters to each other spatially. For the site spatial index, this input gives broad ecosystem types and indexes parameters controlling site-level processes such as N deposition rate, soil depth, and maximum decomposition rate of each soil organic matter pool (see Appendix 1, table 1 for required site parameters). The site spatial index should be a raster of integers, where the integer value of each pixel is matched to a row in the site parameter table by the field “site_id”.

Parameters describing PFTs such as maximum growth rate, optimum temperature for growth, and senescence month (Appendix 1, table 2) are linked to their spatial extent via fractional cover rasters that give the fraction cover (0 - 1) of one PFT in each pixel of the study area. These rasters are linked to the PFT parameter table via their filename.

The animal types spatial index is a polygon layer indicating the areas over which animals graze. Each feature in this polygon layer is grazed by one animal type, and features may not overlap (thus enforcing the rule that each pixel may be grazed by only one animal type). Features in this polygon layer are indexed to animal parameters (see Appendix 1, table 3) by the field “animal_id”. The layer must also have a field called “num_animal”, which gives the number of animals grazing inside the associated polygon.

All spatial inputs must be in geographic coordinates (i.e., latitude and longitude).

Table 4. Required data inputs for the Rangeland Production model.

Category	Dataset	Format	Units or allowable values
Site	Number of months to run simulation	integer	months
	Starting year	integer	E.g. 2015
	Starting month	integer	E.g. 1, for January
	Area of interest	polygon shapefile	
	Management threshold	float	kg/ha
	Proportion legume	raster	fraction (0 - 1)
Soil	Fraction sand, silt, clay (20 cm depth)	rasters	fraction (0 - 1)
	Bulk density (20 cm depth)	raster	g per cm ³
	pH (20 cm depth)	raster	pH scale
Climate	Monthly average minimum daily temperature	directory of rasters, one per month of the year	degrees C
	Monthly average maximum daily temperature	directory of rasters, one per month of the year	degrees C
	Monthly precipitation	directory of rasters, one per month of the simulation run	cm
Parameter spatial indices	Site spatial index	raster	integer
	Plant functional type fractional cover	rasters, one per PFT	fraction (0 - 1)
	Animal grazing areas	polygon shapefile	
Parameters	Site parameter table	comma separated value table	See Appendix 1, table 1 for required values
	Plant functional type parameter table	comma separated value table	See Appendix 1, table 2 for required values
	Animal parameter table	comma separated value table	See Appendix 1, table 3 for required values
Either tables or rasters:			
Initial conditions			

	Initial conditions directory, containing rasters for site and plant functional type state variables	Path to directory containing initial conditions rasters for site and PFT state variables	See tables 1 and 2 for required values
	Initial conditions table: site state variables	comma separated	See table 1 for value table containing required values initial value for each site state variable
	Initial conditions table: plant functional type state variables	comma separated	See table 2 for value table containing required values initial value for each PFT state variable
Crude protein (optional)	Crude protein concentration of forage	float value	$g * g^{-1}$ (0-1)

For precipitation and temperature rasters, the user must supply a path to a directory containing monthly raster files. Inside the directory, the filename of each raster must allow the model to identify the year and month that the raster pertains to. For temperature rasters, file names must end with the month number (e.g., *max_temperature_1.tif* for January). For precipitation rasters, raster file names must end with the year, followed by an underscore (“_”), followed by the month number. For example, *precipitation_2016_1.tif* for January of 2016.

Similarly, for PFT fractional cover rasters, the filename of each fractional cover raster must indicate the PFT that it pertains to. The user must supply a PFT fractional cover path pattern that includes the substring “<PFT>”, where “<PFT>” can be replaced with an integer value for each simulated plant functional type. Integer values for each plant functional type must match values in the column named “PFT” in the plant functional type parameter table. For example, if the PFT fractional cover pattern is given as “./workspace/pft_<PFT>.tif” and the directory “workspace” contains these files: “pft_1.tif”, “pft_10.tif”, then the “PFT” column of the plant functional type parameter table must contain the values 1 and 10.

Appendix 1, table 3 gives required parameters in the animal parameter table, which must contain an integer field called “animal_id” that corresponds to the field “animal_id” of the grazing areas polygon layer. The parameter “grzeff” controls the relationship between grazing intensity and altered root:shoot ratio and aboveground production, using empirical relationships derived from Holland *et al.* (1992). The levels of grzeff have the following effects: 0: grazing has no direct effect on production; 1: linear impact on aboveground production; 2: quadratic impact on aboveground production and root/shoot ratio; 3: quadratic impact on root/shoot ratio;

4: linear impact on root/shoot ratio; 5: quadratic impact on aboveground production and linear impact on root/shoot ratio; 6: linear impact on agb and root/shoot ratio.

The user must supply initial values for site-level state variables in table 1 and PFT state variables in table 2. These initial values may be supplied in raster form, or as tables. If both are supplied, the rasters will be used; if rasters are not supplied, tables must be supplied.

Using rasters to initialize the model allows for initial conditions to vary across space within the study area and within site and PFT types. If rasters are used to initialize the model, a GeoTIFF raster for each site- and PFT-level state variable in tables 1 and 2 must be supplied. Names of each raster must correspond exactly to the state variable names in tables 1 and 2. For PFT-level state variables, the file name of each state variable raster must include a suffix that identifies the PFT index appearing in the PFT parameter table.

Using tables to initialize the model is appropriate if initial conditions should be uniform across the study area or within site and PFT types. If tables of initial values are used to initialize the model, the site state variable initial value table should be in a similar format to the site parameter table, with a column named “site” containing integers that match integer values in the site spatial index raster. Similarly, the format of the PFT initial value state variables should be similar to the PFT parameter table. The PFT initial value table must contain an integer column named “PFT” with values for each PFT identified by filenames of the PFT fractional cover rasters.

Crude protein content of forage is an optional user input. This value should be between 0 and 1, corresponding to 0 - 100% crude protein concentration. If supplied, this value is substituted for crude protein content of forage when calculating digestibility and ingestibility of forage, and protein content of the diet for grazing animals. It is “animal-facing” only and only impacts diet selection and diet sufficiency for animals. It does not alter ecosystem-level nitrogen flows and is not reflected in plant uptake of nitrogen or nitrogen returned in feces of grazing animals. The user-supplied crude protein value is applied uniformly across live and standing dead fractions of all simulated PFTs.

Model outputs

The model creates a folder in the workspace directory called “output” and there saves raw and summarized descriptors of potential biomass (total biomass in the absence of grazing), standing biomass (biomass left standing after offtake by grazers), and animal diet sufficiency. Summarized outputs are aggregated across time steps and/or pixels and are saved inside a folder called “summary_results” inside the “output” folder. Mean potential biomass, standing biomass, and animal diet sufficiency are summarized in the following fields appended to the animal grazing areas in the shapefile “*grazing_areas_results_rpm_<results suffix>.shp*”:

- *potbiom_m*: mean potential biomass (kg/ha) across time steps across pixels inside the grazing area feature. This is total potential modeled biomass in the absence of grazing, including live and standing dead fractions of all plant functional types.

- *stdbiom_m*: mean standing biomass (kg/ha) across time steps across pixels inside the grazing area feature. This is total modeled biomass after offtake by grazing animals, including live and standing dead fractions of all plant functional types.
- *dietsuff_m*: mean diet sufficiency, the ratio of metabolizable energy intake to maintenance energy requirements, across time steps across pixels inside the grazing area feature.

Raw output rasters for each model time step are produced for the values in table 5. These outputs are located directly in the “output” folder.

Table 5. Raw model outputs. For each of these quantities, the model produces a series of rasters covering the study area, one per monthly time step of the time period simulated.

Quantity	Units	Filename	Notes
Total potential biomass	kg/ha	potential_biomass_ <year>_<month>_ <results suffix>.tif	Total potential modeled biomass in the absence of grazing, including live and standing dead fractions of all plant functional types
Total standing biomass	kg/ha	standing_biomass_ <year>_<month>_ <results suffix>.tif	Total modeled biomass after offtake by grazing animals, including live and standing dead fractions of all plant functional types
Diet sufficiency		diet_sufficiency_ <year>_<month>_ <results suffix>.tif	Ratio of metabolizable energy intake to maintenance energy requirements on pixels where animals grazed

By default, the model does not save other state variables. If you wish to save state variable rasters for each state variable in tables 1 and 2, for each time step of the model, check the “Save State Variable Rasters” checkbox on the user interface. In this case, state variable rasters are saved in a folder named “*state_variables_m<step>*” in the workspace directory for each time step of the model run.

Limitations and Simplifications

The model is designed to be applicable in multiple climatic zones and regions of the world; this generality implies necessary simplifications that distinguish the model from other existing models that are much more complex and site-specific (e.g., SPUR (Foy *et al.* 1999), GrassGro (Moore *et al.* 1997), EcoMod (Johnson *et al.* 2008)).

Although multiple plant functional types may occupy a pixel, direct interactions between functional types such as competition for water and nutrients are not modeled. However, plant types can exhibit indirect facilitation through herbivore diet selection, such that preference for one plant type will free the other from consumption.

We assume that the livestock herd consists of adult animals only and do not model population dynamics such as births or deaths. While energy demand of pregnancy and lactation are accounted, the number of animals in each sex and age class does not change. We assume that all cattle are of beef cattle type, thus ignoring slightly modified parameter values provided in Freer *et al.* (2012) that apply to lactating cows of dairy type. During pregnancy, we do not track the weight of the fetus explicitly, but assume that it is in median condition for its stage of development.

The model does not include importation of supplemental feed above what the simulated forage growth provides. The model is therefore limited to extensive grazing systems where this restriction is acceptable.

Submodels

Plant production submodel

The submodels that predict soil water content, soil organic matter and nutrient content, forage production, and impacts of grazing were adapted from the Century model (Parton *et al.* 1988). Century model equations describing the flow of water, carbon, nitrogen, and phosphorus were transcribed from the Century version 4.6 Users' Manual, from peer reviewed publications describing the model, and from source code when necessary.

Naming conventions

For portions of the rangeland production model that were adapted from Century, state variables and parameters take their names from Century version 4.6. Most Century state variables and parameters include array indices pertaining to an element (i.e., 1 = N, 2 = P) or a soil layer (i.e., 1 = surface, 2 = soil). For example, the state variable `metabc_1` represents metabolic surface C, while `metabc_2` represents metabolic belowground C. Other indices refer to another group of related quantities. For example, the site parameter `pcemic1(1,1)` references a layer index, an element index, and an index to three related quantities (maximum ratio, minimum ratio, and minimum absolute content): `pcemic<layer>(<element>,<max ratio, min ratio, or absolute content>.`

The rangeland production model reproduces these indices by simply replacing parentheses and commas with underscores. For example, the Century site parameter `pcemic1(1,1)` becomes `pcemic1_1_1` in the rangeland production model. In this document, we refer to rangeland production model name versions.

Most of the flow of N and P in Century is identical; the pools, equations, and parameters pertaining to each element are simply indexed by the element. Here, we reproduce that structure by presenting the flow of one generic element indexed by “<iel>”. In state variables and parameters, iel=1 indicates N, and iel=2 indicates P.

Differences between Century and the Rangeland Production model

- The Rangeland Production model can simulate multiple plant functional types, while Century simulates only one community-level vegetation type. The Rangeland Production model therefore contains multiple pools for aboveground and belowground C, N and P in live plant material, one for each PFT, while Century includes only one of each of these pools.
- No support for woody vegetation in the Rangeland Production model: GRAZPLAN, the animal diet and physiology model that was adapted to the animal submodel of the Rangeland Production model, does not support diet selection from woody vegetation.
- No support for modeling annual plants (crops) with the Rangeland Production model: valid values for the PFT parameter frtcindx are 0 or 1 only.
- Sulfur is not modeled by the Rangeland Production model: it is not important for predicting forage growth and quality.
- The Rangeland Production model does not support irrigation.
- The Rangeland Production model does not support simulation of enriched CO₂ on biomass production.
- The Rangeland Production model does not track CO₂ or N released into the atmosphere.
- The Rangeland Production model does not support stable isotope analysis.
- The Rangeland Production model does not support impacts of cultivation.
- The Rangeland Production model calculates non-symbiotic soil N fixation from annual precipitation only, not from annual evapotranspiration.
- The Rangeland Production model does not calculate baseflow, streamflow, or mineral content of water flowing out of the soil as baseflow.
- The Rangeland Production model does not compute soil erosion.
- The following Century parameters were fixed:
 - swflag=1 (use equations from Gupta and Larson 1979 to determine both soil wilting point, awilt (-15 bar) and field capacity, afield (-0.33 bar))
 - ideo=2 (use the ratio of rainfall/PET to calculate effect of soil moisture on decomposition)
 - nsfix=0 (non-symbiotic N fixation is based on annual precipitation)
 - bioflg=1 (new growth is reduced by physical obstruction)
 - texesp_1=0 (the flow of secondary P to occluded P is fixed, not influenced by soil texture or pH)

- $\text{texepp}_1=0$ (the rate of mineralization from parent P is fixed, not influenced by soil texture)

The following derived parameters do not change the course of the simulation and are calculated upon initialization:

- Field capacity (afiel) and wilting point (awilt) for each soil layer are calculated according to the method of Gupta and Larson 1979, ('Estimating soil and water retention characteristics from particle size distribution, organic matter percent and bulk density'. Water Resources Research 15:163), assuming -15 bar for wilting point and -0.33 bar for field capacity.
- wc , water content used to calculate potential production = $\text{afiel} - \text{awilt}$ for the first soil layer
- eftext , the effect of soil texture on soil microbe decomposition rate = $\text{peftxa} + \text{peftxb} * \text{sand}$
- p1co2_2 , the fraction of C lost to CO_2 during decomposition from $\text{som1c_2} = \text{p1co2a_2} + \text{p1co2b_2} * \text{sand}$
- fps1s3 , the effect of clay content on decomposition from $\text{som1c_2} = \text{ps1s3_1} + \text{ps1s3_2} * \text{clay}$
- fps2s3 , the effect of clay content on decomposition from $\text{som2c_2} = \text{ps2s3_1} + \text{ps2s3_2} * \text{clay}$
- orglch , the effect of sand content on organic leaching from soil = $\text{omlech_1} + \text{omlech_2} * \text{sand}$
- vlossg , the percent of gross mineralized N that is volatilized to the atmosphere during decomposition, is calculated from soil clay content:
 - $\text{vlossg} = 0.03$ if $\text{clay} < 0.1$; $\text{vlossg} = 0.01$ if $\text{clay} > 0.3$; else
 - $\text{vlossg} = -0.1 * (\text{clay} - 0.3) + 0.01$
- potential intake for each animal type (equation 1 under diet selection submodel, below)

Where

- adep_<lyr> , peftxa , peftxb , p1co2a_2 , p1co2b_2 , omlech_1 , omlech_2 , ps2s3_1 , ps2s3_2 are fixed parameters
- sand is proportion sand content of soil (0 - 1)
- clay is proportion clay content of soil (0 - 1)

Calculate required maximum C/N and C/P ratios for decomposition of structural material (i.e., material containing lignin): these limit the decomposition of structural material and do not change throughout the simulation. The names of these ratios contain three indices that distinguish them from each other: one index indicating whether above- or belowground material is decomposing; an index indicating the mineral element that the ratio pertains to; and an index

indicating whether the ratio pertains to material decomposing to som1 or som2. These indices are positioned in the ratio names as:

rnew<a or b, indicating above- or belowground material>s_<1 or 2, indicating N or P>_<1 or 2, indicating decomposition to som1 or som2>

For example, the ratio rnewas_1_1 is the required N ratio for aboveground material decomposing into som1; the ratio rnewbs_2_1 is the required P ratio for belowground material decomposing into som1.

First calculate cemicb1 and cemicb2, intermediate parameters:

- $\text{cemicb1}_{\langle iel \rangle} = (\text{pcemic1_2}_{\langle iel \rangle} - \text{pcemic1_1}_{\langle iel \rangle}) / \text{pcemic1_3}_{\langle iel \rangle}$
- $\text{cemicb2}_{\langle iel \rangle} = (\text{pcemic2_2}_{\langle iel \rangle} - \text{pcemic2_1}_{\langle iel \rangle}) / \text{pcemic2_3}_{\langle iel \rangle}$

Then calculate maximum ratios for surface material flowing into som1c_1:

- if $(\text{strucc_1} * 2.5) < 0$
 - $\text{econt}_{\langle iel \rangle} = 0$.
 - else: $\text{econt}_{\langle iel \rangle} = \text{struce_1}_{\langle iel \rangle} / (\text{strucc_1} * 2.5)$
- if $\text{econt}_{\langle iel \rangle} > \text{pcemic1_3}_{\langle iel \rangle}$:
 - $\text{rnewas}_{\langle iel \rangle_1} = \text{pcemic1_2}_{\langle iel \rangle}$
 - else: $\text{rnewas}_{\langle iel \rangle_1} = \text{pcemic1_1}_{\langle iel \rangle} + \text{econt}_{\langle iel \rangle} * \text{cemicb1}_{\langle iel \rangle}$

Then do the same thing for the flow of N and P into som2, using parameters $\text{pcemic2}_{\langle lyr \rangle_ \langle iel \rangle}$:

- if $(\text{strucc_1} * 2.5) < 0.0000000001$:
 - $\text{econt}_{\langle iel \rangle} = 0$
 - else: $\text{econt}_{\langle iel \rangle} = \text{struce_1}_{\langle iel \rangle} / (\text{strucc_1} * 2.5)$
 - if $\text{econt}_{\langle iel \rangle} > \text{pcemic2_3}_{\langle iel \rangle}$:
 - $\text{rnewas}_{\langle iel \rangle_2} = \text{pcemic2_2}_{\langle iel \rangle}$
 - else: $\text{rnewas}_{\langle iel \rangle_2} = \text{pcemic2_1}_{\langle iel \rangle} + \text{econt}_{\langle iel \rangle} * \text{cemicb2}_{\langle iel \rangle}$

The ratios for flow of N and P into som2 are adjusted with the addition of a fraction of the ratios entering som1, calculated with the parameters $\text{radlp}_{\langle \rangle_ \langle iel \rangle}$:

- $\text{radds1}_{\langle iel \rangle} = \text{radlp_1}_{\langle iel \rangle} + \text{radlp_2}_{\langle iel \rangle} * (\text{rnewas}_{\langle iel \rangle_1} - \text{pcemic1_2}_{\langle iel \rangle})$
- $\text{rnewas}_{\langle iel \rangle_2} = \text{rnewas}_{\langle iel \rangle_2} + \text{radds1}_{\langle iel \rangle}$
- $\text{rnewas}_{\langle iel \rangle_2} = \max(\text{rnewas}_{\langle iel \rangle_2}, \text{radlp_3}_{\langle iel \rangle})$

Similarly, the maximum required ratios of C/N and C/P flowing from soil structural C (strucc_2) into soil microbial C (som1c_2) and soil slow organic C (som2c_2) are calculated upon initialization and do not change throughout the simulation. These are simply equal to the input parameters $\text{varat1}_{\langle \rangle_ \langle iel \rangle}$ and $\text{varat22}_{\langle \rangle_ \langle iel \rangle}$.

- $\text{rnewbs}_{\langle iel \rangle_1} = \text{varat1_1}_{\langle iel \rangle}$

- $\text{newbs_} \langle \text{iel} \rangle _2 = \text{varat22_1_} \langle \text{iel} \rangle$

Potential Production Submodel

For each PFT, if plant growth is scheduled to occur this month, calculate potential production. The effect of soil water availability on potential production is calculated from reference evapotranspiration, water content of the top layer of soil, and soil texture:

- h2ogef_1 , the limiting effect of soil water availability on growth = $1 + 1 / (\text{pprpts_3} - (\text{pprpts_1} + (\text{pprpts_2} * \text{wc}))) * (\text{h2ogef_1_prior} - \text{pprpts_3})$, bounded to be between 0.01 and 1

Where

- wc , water content, is calculated during initialization and described above
- $\text{h2ogef_1_prior} = \text{pet}$ if $\text{pet} < 0.01$, else
- $\text{h2ogef_1_prior} = (\text{avh2o_1} + \text{precip}_m) / \text{pet}$
- avh2o_1 , water in soil available for plant growth, is calculated in soil water submodel in previous monthly timestep (or supplied as an initial parameter)
- pet , reference evapotranspiration modified by fwloss parameter = $\text{monpet} * \text{fwloss_4}$
- monpet , reference evapotranspiration for this month calculated with FAO Penman-Monteith method

Average soil surface temperature, ctemp , is calculated from temperature inputs and modified by current live biomass, aglive and the fixed parameter pmxbio :

- $\text{biomass} = \min(\text{aglive} * 2.5, \text{pmxbio})$
- tmxs , maximum temperature = $\text{tmax}_m + (25.4 / 1 + 18 * \exp(-0.2 * \text{tmax}_m)) * (\exp(\text{pmxtmp} * \text{biomass}) - 0.13)$
- tmns , minimum temperature = $\text{tmin}_m + \text{pmntmp} * \text{biomass} - 1.87$
- $\text{ctemp} = (\text{tmxs} + \text{tmns}) / 2$

The limiting effect of temperature on potential production, potprd , is calculated from soil surface temperature and by the PFT parameters describing response to temperature, ppdf_1-4_1 :

- $\text{frac} = (\text{ppdf_2_1} - \text{ctemp}) / (\text{ppdf_2_1} - \text{ppdf_1_1})$
- If $\text{frac} \leq 0$, $\text{potprd} = 0$
- Else $\text{potprd} = \exp(\text{ppdf_2_1} / \text{ppdf_3_1} * _1 - \text{frac}^{\text{ppdf_4_1}}) * \text{frac}^{\text{ppdf_3_1}}$
- If average temperature (calculated from temperature inputs) is < 0 , $\text{potprd} = 0$

The limiting effect of obstruction by standing dead material on potential production, biof , is calculated from current standing dead biomass (stdedc) and litter (strucc_1), the ratio of current live biomass to standing dead biomass, and PFT parameters controlling this effect:

- bioc , maximum potential effect = $\text{stdedc} + 0.1 * \text{strucc_1}$, bounded to be greater than 0 and less than pmxbio

- $\text{bioprd} = 1 - (\text{bioc} / \text{biok5} + \text{bioc})$
- $\text{temp1} = 1 - \text{bioprd}$
- $\text{temp2} = \text{temp1} * 0.75$
- $\text{temp3} = \text{temp1} * 0.25$
- $\text{ratlc} = \text{aglive} / \text{bioc}$
- $\text{biof} = (\text{bioprd} + \text{temp2}) + (\text{temp3} * (\text{ratlc} - 1))$ if $\text{ratlc} \geq 1$.
- $\text{biof} = (\text{bioprd} + \text{temp2}) + \text{temp3} * (\text{ratlc} - 1)$ if $\text{ratlc} > 1$ and $\text{ratlc} \leq 2$
- $\text{biof} = 1$ if $\text{ratlc} > 2$

Solar radiation outside the atmosphere, shwave, is calculated from the site latitude:

- $\text{shwave} = f(\text{month}, \text{latitude})$

Total potential production (tgprod_pot_prod, aboveground and belowground production combined) is calculated from the PFT intrinsic growth capacity, limited by the preceding factors:

- $\text{tgprod_pot_prod} = \text{prdx_1} * \text{shwave} * \text{potprd} * \text{h2ogef_1} * \text{biof}$

Root:shoot Ratio Submodel

Production is allocated to above and belowground fractions according to water and nutrient availability; if the plant experiences water stress or nutrient stress, additional production is allocated to the roots. Because plant demand for N and P depends on potential production, a provisional fraction of C allocated to roots (fracrc_p) must be calculated. Calculation of fracrc_p follows the value of the input parameter frtcindx, which indicates whether the plant should be treated as a perennial plant, or whether the “Great Plains equation” should be used (i.e., the original Century formulation developed for use in the great plains of the US).

- Great Plains:
 - $\text{fracrc_p} = 1 / (1 / \text{rtsh} + 1)$
 - Where $\text{rtsh} = (\text{bgppa} + \text{grwprc} * \text{bgppb}) / (\text{agppa} + \text{grwprc} * \text{agppb})$
 - Where $\text{grwprc} = \text{growing season precipitation}$
- Perennial plant:
 - $\text{fracrc_p} = (\text{cfrtcw_1} + \text{cfrtcw_2} + \text{cfrtcn_1} + \text{cfrtcn_2}) / 4$

Before calculating the availability of soil nutrients, favail_2, the intermediate parameter describing availability of P, must be calculated. Favail_2 is calculated from mineral N in the surface layer and from the site parameters favail(4-7).

The availability of soil available nutrients, eavail_<iel>, depends partly on the site parameter favail_<iel> (fraction of N or P available), rimpct, the impact of current root biomass, and estimated <iel> in crop storage:

- $\text{eavail_<iel>} = (\text{availm_<iel>} * \text{favail_<iel>} * \text{rimpct}) + \text{crpstg_<iel>}$

- $eavail_{<N>} = eavail_{<N>} + maxNfix$

Where

- $availm_{<iel>}$ is the sum of mineral $<iel>$ in soil layers accessible by plant roots (i.e., $sum(minerl_{<layer>_{<iel>}}$ for layer in 1:number of layers for plant growth)
- $favail_{<iel>}$ is a PFT-specific parameter
- $crpstg_{<iel>}$ is retranslocation $<iel>$ storage pool for the PFT
- $rimpct = 1$ if $(rictrl * bglive * 2.5) > 33$
- Else $rimpct = 1 - riint * exp(-rictrl * bglive * 2.5)$
- Where
 - $riint$ and $rictrl$ are PFT-specific parameters
 - $bglive$ is current belowground live biomass
- $maxNfix$, N fixation by the PFT = $snfxmx * (tgprod_pot_prod / 2.5)$
- Where
 - $snfxmx$ is a PFT-specific parameter

The plant demand for N and P is calculated from the minimum allowable C/N and C/P ratios for the PFT:

- $demand_{<iel>} = demand_{above_{<iel>}} + demand_{below_{<iel>}}$
- $demand_{above_{<iel>}} = (agprod / 2.5) * (1 / cercrp_{min_{<iel>}}_{above})$
- $demand_{below_{<iel>}} = (tgprod_pot_prod - agprod) / 2.5 * (1 / cercrp_{min_{<iel>}}_{below})$
- $cercrp_{min_{<iel>}}_{above}$, the minimum C/ $<iel>$ ratio in aboveground biomass = $min(pramn_{<iel>}_1 + (pramn_{<iel>}_2 - pramn_{<iel>}_1) * 2.5 * aglive / biomax, pramn_{<iel>}_2)$
- $cercrp_{min_{<iel>}}_{below}$, the minimum C/ $<iel>$ ratio in belowground biomass = $prbm_{<iel>}_1 + prbm_{<iel>}_2 * grwprc$

Where

- $pramx_{<iel>}_1$, $pramx_{<iel>}_2$, $biomax$, are PFT-specific parameters
- $grwprc$ = growing season precipitation
- $agprod$, provisional aboveground production = $tgprod_pot_prod * (1 - fracrc_p)$

The revised fraction of C allocated to roots, $fracrc$, is recalculated from the effects of nutrient and water stress. If the “Great Plains equation” is used, nutrient and water stress are not considered and $fracrc$ is equal to the provisional fraction calculated above. For perennial plants, the fraction is the maximum of that limited by water stress, and that limited by nutrient stress (where the most limiting nutrient determines nutrient stress).

- Great Plains:
 - $fracrc = 1 / (1 / rtsh + 1)$
 - Where $rtsh = (bgppa + grwprc * bgppb) / (agppa + grwprc * agppb)$
 - Where $grwprc$ = growing season precipitation

- Perennial plant:
 - $\text{fracrc} = \max(\text{h2oeff}, \text{ntreff})$, bounded to be ≤ 0.99
 - h2oeff , the limiting effect of water, is the y-value lying on the line described by (0, cfrtcw_1) and (1, cfrtcw_2), corresponding to the x-value h2ogef_1 (the limiting effect of soil water availability on growth, calculated above)
 - ntreff , the limiting effect of N and P, is the maximum value across $\langle \text{iel} \rangle$ of the y-value lying on the line described by (0, cfrtcn_1) and (1, cfrtcn_2), corresponding to the x-value $\text{a2drat_}\langle \text{iel} \rangle$

Where

- $\text{a2drat_}\langle \text{iel} \rangle$, the effect of nutrient $\langle \text{iel} \rangle$ demand on root/shoot allocation = $\text{evail_}\langle \text{iel} \rangle / \text{demand_}\langle \text{iel} \rangle$, bounded to be between 0 and 1

Above- and belowground production is then calculated according to tgprod_pot_prod , total production limited by solar radiation, temperature, soil moisture, and obstruction, and the fraction of C allocated to roots:

- bgprod , belowground production = $\text{tgprod_pot_prod} * \text{fracrc}$
- agprod , aboveground production = $\text{tgprod_pot_prod} - \text{bgprod}$
- rtsh , root:shoot ratio = $\text{bgprod} / \text{agprod}$

The final calculation of aboveground production and the root:shoot ratio are modified by the removal of biomass by grazing. If grazing occurred during the previous month. The impact of grazing is controlled by the PFT-specific input parameters grzeff and gremb , which specify the effect of grazing on production and the root-shoot ratio, and by flgrem , the fraction of aboveground live biomass removed by grazing (between 0 and 1).

- If $\text{grzeff} = 0$, aboveground production and root:shoot ratio are unchanged
- If $\text{grzeff} = 1$:
 - $\text{agprod} = (1 - (2.21 * \text{flgrem})) * \text{agprod}$, bounded to be ≥ 0.02
- If $\text{grzeff} = 2$:
 - $\text{agprod} = (1 + 2.6 * \text{flgrem} - (5.83 * \text{flgrem}^2)) * \text{agprod}$, bounded to be ≥ 0.02
 - $\text{rtsh} = \text{rtsh} * 3.05 * \text{flgrem} - 11.78 * \text{flgrem}^2$, bounded to be ≥ 0.01
- If $\text{grzeff} = 3$:
 - $\text{rtsh} = \text{rtsh} * 3.05 * \text{flgrem} - 11.78 * \text{flgrem}^2$, bounded to be ≥ 0.01
- If $\text{grzeff} = 4$:
 - $\text{rtsh} = 1 - (\text{flgrem} * \text{gremb})$
- If $\text{grzeff} = 5$:
 - $\text{agprod} = (1 + 2.6 * \text{flgrem} - (5.83 * \text{flgrem}^2)) * \text{agprod}$, bounded to be ≥ 0.02
 - $\text{rtsh} = 1 - (\text{flgrem} * \text{gremb})$
- If $\text{grzeff} = 6$:
 - $\text{agprod} = (1 - (2.21 * \text{flgrem})) * \text{agprod}$, bounded to be ≥ 0.02

- $rtsh = 1 - (flgrem * gremb)$
- $bgprod = rtsh * agprod$

Total final potential production, $tgprod$, is calculated from the adjusted above- and belowground production. Potential C production, $pcrope$, is calculated from $tgprod$. Note that $pcrope$ is the value that is used to calculate actual (realized) production in the plant growth submodel.

- $tgprod$, total final potential production = $agprod + bgprod$
- $pcrope = tgprod / 2.5$

Soil Water Submodel

The soil water submodel simulates the flow of precipitation through interception by plants, infiltration into the soil, percolation through the soil, and transpiration by plants. Outputs that must be saved from this model are $avh2o(1)$, water available to plants for growth (used in the potential production submodel), $avh2o(3)$, water in the first two soil layers (used in the decomposition submodel to calculate the impact of soil moisture on decomposition), and $amov_2$, an index indicating whether movement of water occurs from the top soil layer (used in the decomposition submodel to determine whether leaching of nutrients occurs). These quantities are calculated by partitioning precipitation among soil layers after accounting for losses to evapotranspiration.

The model simulates precipitation as snow and the effects of lingering snowpack. As the fate of moisture in new snow and existing snowpack is followed, we track moisture inputs after snow, $inputs_after_snow$. This gives the water draining into the soil after snowfall, evaporation from snow, and melting of existing snowpack. If the temperature is below freezing, all precipitation falls as snow and $inputs_after_snow = 0$. If the temperature is above freezing and some previous snowpack exists, $inputs_after_snow$ is calculated as liquid that melts from the snow. If the temperature is above freezing, and there is no existing snowpack to melt, then $inputs_after_snow$ is equal to $precip$.

If the average air temperature is below freezing (i.e., $tave \leq 0$), precipitation occurs in the form of snow.

- $snow, snowpack = snow + precip$
- $inputs_after_snow = 0$

If the temperature is above freezing, but some snowpack exists, the incoming precipitation is added to snowpack liquid ($snlq$).

- $snlq = snlq + precip$
- $inputs_after_snow = 0$

If some snowpack exists, even if the temperature is below freezing, some snow is evaporated with associated consumption of potential energy for evapotranspiration. Evaporation from snow consumes both the ice and liquid portions of snow:

- snowtot , liquid and ice portions of snow = $\text{snow} + \text{snlq}$
- evsnow , evaporation from snowpack = $\text{pet} * 0.87$, bounded to be less than or equal to snowtot
- snow_rem , snow remaining after evaporation = $\max(\text{snow} - \text{evsnow} * (\text{snow} / \text{snowtot}), 0)$
- snlq_rem , liquid in snowpack remaining after evaporation = $\max(\text{snlq} - \text{evsnow} * (\text{snlq} / \text{snowtot}), 0)$
- petrem , PET energy remaining after evaporation of snow = $\text{pet} - \text{evsnow} / 0.87$, bounded to be greater than or equal to 0

Where

- pet , reference evapotranspiration modified by fwloss parameter = $\text{monpet} * \text{fwloss}(4)$
- monpet , reference evapotranspiration for this month calculated with FAO Penman-Monteith method

If snowpack exists following evaporation and the air temperature is sufficient (if $\text{tave} \geq \text{tmelt}(1)$), then some snow melts. The melted snow is moved to snlq , liquid in the snowpack, and the excess liquid above 50% of snowpack is drained into the soil as moisture inputs after snow (inputs_after_snow).

- snowmelt , liquid melted from snow = $\text{tmelt_2} * (\text{tave} - \text{tmelt}(1)) * \text{shwave}$
- snowmelt is bounded to be greater than or equal to zero, and less than or equal to snow
- $\text{snow} = \text{snow} - \text{snowmelt}$
- $\text{snlq} = \text{snlq} + \text{snowmelt}$
- If $\text{snlq} > 0.5 * \text{snow}$:
 - add , additional liquid draining from snow = $\text{snlq} - 0.5 * \text{snow}$
 - $\text{snlq} = \text{snlq} - \text{add}$
 - $\text{inputs_after_snow} = \text{inputs_after_snow} + \text{add}$
 - snowmelt , liquid melted from snow = inputs_after_snow

Where

- tmelt_2 and $\text{tmelt}(1)$ are fixed parameters
- tave is average air temperature
- shwave is solar radiation outside the atmosphere, calculated from current month and site latitude

After accounting for snowfall, evaporation from snow, and water melting from snow, moisture is allocated to runoff, canopy interception and bare soil evaporation. Potential total transpiration

water loss is calculated according to aboveground live biomass, and then water is distributed sequentially to each soil layer.

Moisture is first lost to runoff:

- $\text{runoff} = \text{fracro} * (\text{inputs_after_snow} - \text{precro})$, bounded to be greater than or equal to 0
- winputs , water available for evapotranspiration = $\text{inputs_after_snow} - \text{runoff}$

The loss of precipitation to canopy interception and bare soil evaporation is calculated if there is no snow cover. Loss to canopy interception and bare soil evaporation is a function of live, standing dead, and surface litter biomass. The total loss of moisture to interception and bare soil evaporation is bounded to be less than or equal to 40% of reference evapotranspiration:

- alit , biomass in surface litter = $(\text{strucc}(1) + \text{metabc}(1)) * 2.5$, bounded to be ≤ 400 for the soil water submodel
- aliv , aboveground live biomass = $\text{aglive} * 2.5 + (0.25 * \text{pcrope} * 2.5)$
- adead , aboveground dead biomass = $\text{stdedc} * 2.5$
- sd , standing biomass = $\text{aliv} + \text{adead}$, bounded to be ≤ 800 for the soil water submodel
- aint , moisture lost to canopy interception = $(0.0003 * \text{alit} + 0.0006 * \text{sd}) * \text{fwloss}(1)$
- abs , moisture lost to bare soil evaporation = $0.5 * \exp((-0.002 * \text{alit}) - (0.004 * \text{sd})) * \text{fwloss_2}$
- evap_losses , total surface evaporation = $\min(((\text{abs} + \text{aint}) * \text{winputs}), (0.4 * \text{petrem}))$
- add , moisture available at this step for transpiration = $\text{winputs} - \text{evl}$

Where

- petrem is energy remaining for evaporation after evaporation of snow

The moisture remaining after interception and surface soil evaporation is then allocated to soil layers, where it may be further lost through transpiration by plants and direct evaporation from the top soil layer. Before moisture is passed sequentially through each layer of soil, the total potential transpiration water loss (trap , cm/month) is calculated. Total transpiration (trap) is first calculated as the remainder of reference evapotranspiration after evaporation of snow and surface evaporation. It is then limited by temperature and by live biomass: if the average temperature is less than 2 degrees Celsius, trap is zero. When the temperature is greater than or equal to 2 degrees Celsius, trap is limited by live biomass.

- $\text{trap} = \text{petrem} - \text{evap_losses}$
- If $\text{tave} < 2$: $\text{trap} = 0$ else
- $\text{trap} = \max(\min(\text{trap}, \text{petrem} * 0.65 * (1 - \exp(-0.02 * \text{aliv}))), 0)$

The second potential loss of moisture before allocation among soil layers is through evaporation from the first soil layer (pevp , cm/day). This is calculated prior to transpiration because it is derived from potential transpiration (while actual transpiration (trap) is reduced twice (line 169,

line 241, H2olos.f) according to actual water available to transpire), but is not accounted for in soil moisture summaries until moisture is removed by transpiration.

- $pevp = \max(\text{petrem} - \text{trap} - \text{evl}, 0)$

Before water is allocated to soil layers, transpiration losses are subtracted from water inputs to the soil. “This is necessary for a monthly time step to give plants in wet climates adequate access to water for transpiration. -rm 6/94, Pulliam 9/94”, line 166-167, H2olos.

Simultaneously, total transpiration (trap) is restricted to be less than available water inputs to the soil at this point (add).

- $\text{tran}, \text{evapotranspiration limit} = \min(\text{trap} - 0.01, \text{add})$
- $\text{trap} = \text{trap} - \text{tran}$
- $\text{add}, \text{moisture allocated to soil layers in the next step} = \text{add} - \text{tran}$

Before any water is actually removed by transpiration, water is allocated among soil layers.

Water moves sequentially through each layer of soil according to the field capacity of the layer; if the capacity of a layer is exceeded, the excess is passed to the next layer. The output amov_2 is calculated during this step, indicating whether water flows from the top soil layer. Moisture that remains at the bottom of all modeled soil layers is lost as storm flow.

- $\text{afl}\langle\text{layer}\rangle$, the water holding capacity of this layer = $\text{adep}\langle\text{layer}\rangle * \text{afiel}\langle\text{layer}\rangle$
- $\text{asmos}\langle\text{layer}\rangle = \text{asmos}\langle\text{layer}\rangle + \text{added_from_above}$
- If $\text{asmos}\langle\text{layer}\rangle > \text{afl}$:
 - $\text{amov}\langle\text{layer}\rangle = \text{asmos}\langle\text{layer}\rangle$
 - $\text{asmos}\langle\text{layer}\rangle = \text{afl}\langle\text{layer}\rangle$
- Else, $\text{amov}\langle\text{layer}\rangle = 0$
- $\text{added_to_below} = \text{amov}\langle\text{layer}\rangle$

Where

- added_from_above is the water added to soil layer $\langle\text{layer}\rangle$ from precipitation or the upper adjacent layer
- added_to_below is the water remaining after saturation that moves to the lower adjacent layer

After moisture has been distributed among soil layers according to the field capacity of each layer, transpiration water loss from each layer is calculated. Total transpiration water loss is apportioned from each soil layer according to the fixed parameter $\text{awtl_}\langle\text{lyr}\rangle$, the weighting factor for transpiration loss for the soil layer. This describes the density of roots inside that soil layer and determines the fraction of available water in that layer that can be extracted by roots.

- $\text{avw}\langle\text{layer}\rangle$, water in this layer available for transpiration = $\text{asmos}\langle\text{layer}\rangle - \text{awilt}\langle\text{layer}\rangle * \text{adep}\langle\text{layer}\rangle$

- $awwt<layer>$, available water weighted by transpiration depth distribution factor = $avw<layer> * awtl<layer>$
- tot , total available water = $\text{sum}(avw)$ across layers
- $tot2$, total available water weighted by transpiration depth distribution factors = $\text{sum}(awwt)$ across layers

Total transpiration is restricted to be less than or equal to total water available for transpiration:

- $trap = \min(tot, trap)$

Actual transpiration from each soil layer, $trl<layer>$, is calculated for each soil layer accessible by plant roots (i.e., for $<lyr>$ in $1:nlaypg$):

- $avinj<layer>$, water in this layer available for transpiration = $asmos<layer> - awilt<layer> * adep<layer>$
- $trl<layer> = \min((trap * awwt<layer> / tot2, avinj)$
- $avinj<layer> = avinj<layer> - trl<layer>$
- $asmos<layer> = asmos<layer> - trl$

The relative water content of soil layer 1, $rwcf_1$, is used to calculate evaporative water loss from the top soil layer. It is updated after transpiration from soil layer 1 is removed:

- $rwcf_1 = (asmos_1 / adep_1 - awilt_1) / (afiel_1 - awilt_1)$

After the loss of soil moisture to transpiration is calculated, additional water is removed from the top soil layer due to evaporation. The amount removed, $pevp$, was calculated from potential evapotranspiration before allocation of water to soil layers. It is now removed from the top soil layer.

- $evmt = \max((rwcf_1 - 0.25) / (1 - 0.25), 0.01)$
- $evlos$, evaporative water loss from soil layer 1 = $\min(evmt * pevp * abs * 0.1, \max(asmos_1 - awilt_1 * adep_1, 0))$
- $asmos_1 = asmos_1 - evlos$
- $avinj_1 = avinj_1 - evlos$

Soil moisture available to plants for growth for each plant functional type ($avh2o(1)_{PFT}$) is the sum of $avinj<layer>$ across soil layers accessible by the roots of that plant functional type, weighted by the percent cover of the plant functional type (i.e., $\text{sum}(avinj<layer>$ for layer in $1:nlaypg$, multiplied by % cover of the PFT). Soil moisture impacting decomposition ($avh2o(3)$) is the sum of $avinj<layer>$ in the top 2 layers (i.e., $\text{sum}(avinj<layer>$ for layer in $1:2$).

Decomposition

Decomposition, where C, N and P move from one surface or soil stock to another, is performed four times per month. Some intermediate quantities controlling decomposition are calculated during model initialization (described under Initialization above), while others are calculated once per month.

The flow of C, N and P is generally limited by the availability of N and P in the donating stock (i.e., the stock that material is leaving). Decomposition can only occur if the actual C/N and C/P ratios of the donating stock are smaller than required ratios, or if mineral N or P is available. The required ratios for decomposition from structural material (i.e., material containing lignin) are fixed throughout the simulation; the required ratios for decomposition of other stocks are recalculated at each decomposition step.

If both the C/N and C/P ratios are sufficiently small to allow decomposition, the decomposition event may be associated with some respiration, where some C is released in the form of CO₂ to the atmosphere (the grazing forage model does not track CO₂ released to the atmosphere). Respiration includes some mineralization of N and P. After the C lost to respiration is calculated, the C, N and P moving from the donating to the recipient stock are calculated. The amount of N and P moving to the recipient stock is usually calculated according to the required ratios for decomposition to occur.

The following intermediate quantities influencing decomposition are calculated once per month:

- $agdefac$, the aboveground decomposition factor = $\max(0.0, tfunc * agwfunc)$
- $bgdefac$, the belowground decomposition factor = $\max(0.0, tfunc * bgwfunc)$
- $pheff_struc$, the impact of pH on decomposition for structural material = $0.5 + (1.1 / \pi) * \arctan(\pi * 0.7 * (pH - 4.))$, bounded between 0 and 1
- $pheff_metab$, the impact of pH on decomposition for metabolic material = $0.5 + (1.14 / \text{numpy.pi}) * \arctan(\text{numpy.pi} * 0.7 * (pH - 4.8))$, bounded between 0 and 1

Where $tfunc$, the effect of temperature on decomposition, is calculated according to an arctangent curve from $stemp$, estimated soil surface mean temperature:

- $tfunc = \max(0.01, teff_2 + (teff(3) / \pi) * \arctan(\pi * teff(4) * (stemp - teff(1)))) / temp_normalizer$
- $temp_normalizer = teff_2 + (teff(3) / \pi) * \arctan(\pi * teff(4) * (30.0 - teff(1)))$

and $agwfunc$, the effect of soil moisture on decomposition, is calculated from the ratio of soil water in the top two soil layers ($avh2o(3)$) to reference evapotranspiration:

- if $rprpet > 9$: $agwfunc = 1$. else
- $agwfunc = \min(1., 1./(1. + 30.0 * \exp(-8.5 * rprpet)))$

- If there is water melting from snowpack (if snowmelt > 0), rprpet, the ratio of soil moisture to reference evapotranspiration = (avh2o(3) + snowmelt) / pet
- Else: rprpet = (avh2o(3) + precip) / pet
- pet, reference evapotranspiration modified by fwloss parameter = monpet * fwloss(4)
- monpet, reference evapotranspiration for this month calculated with FAO Penman-Monteith method
- bgwfunc = agwfunc

Soil surface mean temperature is calculated from temperature inputs and modified by estimated impact of shading by biomass and surface litter, and estimated daylength:

- If there is snowpack, stemp= 0; else
- tmxs, maximum temperature with leaf shading = $t_{max} + (25.4 / (1 + 18 * \exp(-0.2 * t_{max}))) * (\exp(p_{mxtmp} * bio) - 0.13)$
- tmns, minimum temperature with leaf shading = $t_{min} + p_{mntmp} * bio - 1.78$
- Where bio = $aglive * 2.5 + stdedc * 2.5 + elitst * (strucc(1) + metabc(1)) * 2.5$
- Estimated daylength = f(month, latitude)
- tmns_mlt, the daylength multiplier for minimum temperature = $((12 - daylength) * 3 + 12) / 24$ if daylength < 12, else $tmns_mlt = ((12 - daylength) * 1.2 + 12) / 24$, bounded to be between 0.05 and 0.95
- tmxs_mlt, daylength multiplier for maximum temperature = $1 - tmns_mlt$
- stemp = $tmxs_mlt * tmxs + tmns_mlt * tmns$

anerb, the effect of soil anaerobic conditions on decomposition, is calculated from rprpet and the aneref(1-3) parameters describing rprpet thresholds:

- If rprpet > aneref(1): $xh2o = (rprpet - aneref(1)) * pet * (1 - drain)$
- else: anerb = 1.
- If $xh2o > 0$:
 - $newrat = aneref_1 + (xh2o / pet)$
 - $slope = (1 - aneref(3)) / (aneref_1 - aneref_2)$
 - $anerb = 1 + slope * (newrat - aneref_1)$
- If $anerb < aneref(3)$: $anerb = aneref(3)$

Prior to decomposition, calculate N fixation for this month: monthly N fixation is calculated from annual N deposition, calculated once per year. Monthly N fixation is calculated according to the ratio of the current month's precipitation to annual precipitation. Total N fixed this month, wdfxm, is added to the mineral N pool.

- $wdfxm, \text{ total N fixed this month} = baseNdep * (precip / annual_precip) + epnfs_2 * \min(annual_precip, 100) * (precip / annual_precip)$

Where baseNdep is calculated from annual precipitation during yearly tasks.

Four times per month, calculate decomposition from each surface and soil pool.

Decomposition of surface structural material

If there is material in surface structural material to decompose (if $\text{strucc_1} > 0.0000001$), calculate tcflow , the total flow from strucc_1 :

- $\text{tcflow} = \min(\text{strucc_1}, \text{strmax_1}) * \text{agdefac} * \text{dec1_1} * \exp(-\text{pligst_1} * \text{strlig_1}) * \text{dtm} * \text{pheff_struc}$

Where

- agdefac , the aboveground decomposition factor, is defined above
- strlig_1 is the state variable representing the lignin content of surface structural residue (grams of lignin / grams biomass)
- dtm is the time step in years (i.e., because this is done 4 times per month, $\text{dtm} = 0.020833$)
- pheff_struc is defined above

Test whether N and P are sufficient to allow C to decompose from strucc_1 . The C/N and C/P ratios of the decomposing stock (strucc_1) are compared to the required ratios for aboveground material decomposing into som1 . If the ratios are sufficient to allow decomposition to som1 , the material will also decompose to som2 . If the ratios are insufficient, the material will not decompose at all.

- if $\text{aminrl_<iel>} < 0.0000001$:
 - if $(\text{strucc_1} / \text{struce_1_<iel>} > \text{rnewas_<iel>_1})$: the material cannot decompose
- else: the material can decompose

Both the C/N and C/P ratios must be sufficiently small to allow decomposition.

Where

- aminrl_<iel> = mineral <iel> in the surface layer averaged across decomposition timesteps
- rnewas_<iel>_1 , the maximum required ratio for aboveground material decomposing to som1 , is calculated upon initialization

If C can decompose from strucc_1 , C first flows from strucc_1 into som2c_1 . The proportion of total flow from strucc_1 that flows into som2c_1 is calculated according to its lignin content.

- tosom2 , the C that flows from strucc_1 into $\text{som2c_1} = \text{tcflow} * \text{strlig_1}$
- co2los_2 , the loss of CO_2 through respiration = $\text{tosom2} * \text{rsplig}$
- $\text{strucc_1} = \text{strucc_1} - \text{co2los_2}$
- $\text{tosom2} = \text{tosom2} - \text{co2los_2}$

The respiration associated with the decomposition event also includes some mineralization of N and P, where N and P flow from the surface pool to the mineral pool. The amount of N and P mineralized from the surface pool is calculated according to their ratios in respired material:

- mnrflo_iel , the amount of iel moving from struce_1_iel to minerl_1_iel = $\text{co2los_2} * \text{struce_1_iel} / \text{strucc_1}$

Gross mineralization of N (the sum only of mineralization), which is used to calculate volatilization loss of N after decomposition, is updated with this amount:

- $\text{gromin_1} = \text{gromin_1} + \text{mnrflo_1}$

As C flows from strucc_1 into som2c_1 , N and P move from the surface structural pool (struce_1_iel) into the slow surface organic matter pool (som2e_1_iel). With the flow of elements between pools, immobilization or mineralization may occur, depending on whether the C/ iel ratio of decomposing material is more or less than the required ratios for new material (i.e., agrat_iel_som2 or rnewas_iel_2 , described under initialization).

- outofa_iel , the iel flowing out of struce_1_iel = $\text{struce_1_iel} * (\text{tosom2} / \text{strucc_1})$
- If $(\text{tosom2} / \text{outofa_iel}) > \text{rnewas_iel_2}$:
 - Immobilization occurs, if there is enough labile iel to supply it
 - $\text{immflo_iel} = \text{tosom2} / \text{rnewas_iel_2} - \text{outofa_iel}$
 - If $(\text{minerl_1_iel} - \text{immflo_iel}) < 0$:
 - mnrflo_iel , the mineral flow of $\text{iel} = 0$
 - else: outofa flows from struce_1_iel to som2e_1_iel and
 - immflo_iel flows from minerl_1_iel to som2e_1_iel
 - $\text{mnrflo_iel} = -\text{immflo_iel}$
- else (the C/ iel ratio of decomposing material is less than rnewas_iel_2):
 - Mineralization occurs
 - atob , the fraction of iel moving to $\text{som2e_1_iel} = \text{tosom2} / \text{rnewas_iel_2}$
 - atob flows from struce_1_iel to som2e_1_iel and
 - $\text{mnrflo_iel} = \text{outofa} - \text{atob}$
 - mnrflo_iel flows from struce_1_iel to minerl_1_iel

Where

- minerl_1_iel is current mineral iel in surface pool, i.e. pertaining to the current four-times-per-month decomposition timestep.
- tosom2 is the C flowing from strucc_1 to som2c_1
- rnewas_iel_2 is the maximum required C/ iel ratio for material flowing to som2c_1 , calculated during initialization

Gross mineralization (gromin_iel , the sum only of mineralization) is updated with the calculated mineral flow:

- If $\text{mnrflo_iel} > 0$: $\text{gromin_iel} = \text{gromin_iel} + \text{mnrflo_iel}$

The remainder of total C flow from strucc_1 flows to som1c_1 , and is again associated with some loss of CO_2 through respiration:

- tosom1 , the C that flows from strucc_1 into $\text{som1c_1} = \text{tcflow} - \text{tosom2} - \text{co2los_2}$
- co2los_1 , additional CO_2 associated with respiration to $\text{som1c_1} = \text{tosom1} * \text{pslco2_1}$
- $\text{strucc_1} = \text{strucc_1} - \text{co2los_1}$
- $\text{tosom1} = \text{tosom1} - \text{co2los_1}$

Again, the respiration associated with decomposition of soil from strucc_1 into som1c_1 includes some mineralization of N and P. Again, the amount of mineralized N and P is according to their ratios in respired material, as described above.

As C flows from strucc_1 into som1c_1 , N and P move from the surface structural pool (strucc_1_iel) into the surface microbial pool (som1e_1_iel). With the flow of elements between pools, immobilization or mineralization may occur, depending on whether the C/<iel> ratio of decomposing material is more or less than the required ratios for new material entering som1 (i.e., agrat_iel_som1 , described under initialization). Importantly, flows of N and P into som2e_1_iel must be reconciled before proceeding with movement of N and P into som1e_1_iel because the supply of labile N and P determines whether immobilization or mineralization occurs during the flow into som1e_1_iel .

Decomposition of soil structural material

If there is soil structural material to decompose (if $\text{strucc_2} > 0.0000001$), calculate tcflow , the total potential flow from strucc_2 :

- $\text{tcflow} = \min(\text{strucc_2}, \text{strmax_2}) * \text{bgdefac} * \text{dec1_2} * \exp(-\text{pligst_2} * \text{strlig_2}) * \text{anerb} * \text{dtm} * \text{pheff_struc}$

Where

- bgdefac , the belowground decomposition factor, is defined above
- strlig_2 is the lignin content of soil structural residue (grams of lignin / grams biomass)
- dtm is the time step in years (i.e., because this is done 4 times per month, $\text{dtm} = 0.020833$)
- pheff_struc is defined above
- anerb , the effect of soil anaerobic conditions on decomposition, is defined above

Test for the maximum required C/N and C/P ratios in strucc_2 before decomposing material into som1c_2 and som2c_2 :

- if $\text{aminrl_iel} < 0.0000001$:
 - if $(\text{strucc_2} / \text{strucc_2_iel}) > \text{nnewbs_iel_1}$: the material cannot decompose to som1 or som2

- else: the material can decompose to som1c_2 and som2c_2

Both the C/N and C/P ratios must be sufficiently small to allow decomposition.

Where

aminrl_<iel> = mineral <iel> in the surface layer averaged across decomposition timesteps

If C can decompose from strucc_2 into som1c_2, it can also decompose into som2c_2.

Structural C first decomposes into som2c_2. The decomposition event is associated with some respiration.

- tosom2, the C that flows from strucc_2 into som2c_2 = tcflow * strlig_2
- co2los_2, the loss of CO₂ associated with this decomposition event = tosom2 * rsplig
- strucc_2 = strucc_2 - co2los_2
- tosom2 = tosom2 - co2los_2

The respiration associated with the decomposition event also includes some mineralization of N and P. These calculations are identical to those performed for respiration during decomposition from surface structural pools (struce_1_<iel> described above.

N and P flow from struce_2_<iel> into som2e_2_<iel> according to according to the proportion of strucc_2 that is moving into som2c_2, if their availability in struce_2 or mineral availability is high enough to supply their movement. This flow is identical to the movement of N and P from surface structural pools (struce_1_<iel> into the surface slow pool (som2e_1_<iel> as described above.

The C flowing from strucc_2 into som1c_2 is the remainder of what was already calculated to flow to som2c_2, and is again associated with some loss of CO₂ through respiration:

- tosom1, the C that flows from strucc_2 into som1c_2 = tcflow - tosom2 - co2los_2
- co2los_1, additional CO₂ associated with respiration to som1c_1 = tosom1 * ps1co2_2
- strucc_2 = strucc_2 - co2los_1
- tosom1 = tosom1 - co2los_1

Again, the respiration associated with decomposition of soil from strucc_2 into som1c_2 includes some mineralization of N and P.

As C flows from strucc_2 into som1c_2, N and P flow from struce_2_<iel> into som1e_2_<iel> according to the proportion of strucc_2 that is moving into som1c_2, if their availability in struce_2 or mineral availability is high enough to supply their movement. This flow is identical to the movement of N and P from surface structural pools (struce_1_<iel> into the surface slow pool (som2e_1_<iel> as described above.

Decomposition of surface metabolic material

If there is material in the surface metabolic pool (metabc_1) to decompose into surface som1c, first compute the required C/N and C/P ratios for decomposition to occur:

- if (metabc_1 * 2.5) < 0.0000000001:
 - econt_<iel> = 0.
 - else: econt_<iel> = metabe_1_<iel> / (metabc_1 * 2.5)
- if econt_<iel> > pcemic1_3_<iel>:
 - agdrat_<iel> = pcemic1_2_<iel>
 - else: agdrat_<iel> = pcemic1_1_<iel> + econt_<iel> * cemicb1_<iel>

Where

cemicb1 = intermediate parameter calculated upon Initialization, described above

Calculate tcflow, the total flow from metabc_1:

- tcflow = metabc_1 * agdefac * dec2_1 * dtm * pheff_metab, bounded to be smaller than or equal to metabc_1

Where

- agdefac, the aboveground decomposition factor, is defined above
- dec2_1 is an input parameter
- dtm is the time step in years (i.e., because this is done 4 times per month, dtm = 0.020833)
- pheff_metab is defined above

Compare current C/N and C/P ratios in surface metabolic material to the maximum ratios to test whether decomposition can occur:

- If animrl_<iel> < 0.0000001:
 - If (metabc_1 / metabe_1_<iel>) > agdrat_<iel>: the material cannot decompose
- else: the material can decompose

Both the C/N and C/P ratios must be sufficiently small to allow decomposition.

Where

- animrl_<iel> is the sum of positive layers of the mineral element (N or P) before uptake by plants
- agdrat_<iel>, the required ratio for decomposition to occur, is calculated above

If decomposition can occur, the decomposition event is associated with some respiration, where some C is lost to CO₂.

- co2los, the loss of CO₂ during respiration = tcflow * pmco2_1

- $tosom1$, the C that flows from $metabc_1$ into $som1c_1 = tcflow - co2los$

The respiration associated with the decomposition event also includes some mineralization of N and P. Again, as C flows from $metabc_1$ into $som1c_1$, N and P flow from $metabe_1_<iel>$ into $som1e_1_<iel>$ according to their ratios in surface metabolic material (i.e., $metabe_1_<iel> * (tosom1 / metabc_1)$).

Decomposition of soil metabolic material

If there is material in the soil metabolic pool ($metabc_2$) to decompose, first compute the required C/N and C/P ratios for belowground decomposition to occur:

- If $animrl_<iel>$, mineral $<iel>$ in the surface layer averaged across decomposition timesteps, < 0 :
 - $bgdrat_<iel> = varat1_1_<iel>$
- else if $aminrl_<iel> > varat1_3_<iel>$:
 - $bgdrat_<iel> = varat1_2_<iel>$
- else $bgdrat_<iel> = (1 - aminrl_<iel> / varat1_3_<iel>) * (varat1_1_<iel> - varat1_2_<iel> + varat1_2_<iel>)$

Calculate $tcflow$, the total flow from $metabc_2$:

- $tcflow = metabc_2 * bgdefac * dec2_2 * dtm * pheff_metab * anerb$, bounded to be greater than or equal to $metabc_2$

Where

- $bgdefac$, the belowground decomposition factor, is defined above
- $dec2_2$ is an input parameter
- dtm is the time step in years (i.e., because this is done 4 times per month, $dtm = 0.020833$)
- $pheff_metab$ is defined above
- $anerb$, the impact of soil anaerobic conditions on decomposition, is defined above

Compare current C/N and C/P ratios in soil metabolic material to the maximum ratios to test whether decomposition can occur:

- If $animrl_<iel> < 0.0000001$:
 - If $(metabc_2 / metabe_2_<iel>) > bgdrat_<iel>$: the material cannot decompose
- else: the material can decompose

Both the C/N and C/P ratios must be sufficiently small to allow decomposition.

Where

- $animrl_<iel>$ is the sum of positive layers of the mineral element (N or P) before uptake by plants

- $bgdrat_{<iel>}$, the required ratio for belowground decomposition to occur, is calculated above

If decomposition can occur, the decomposition event is associated with some respiration, where some C is lost to CO_2 and some mineralization of N and P occurs.

- $co2los$, the loss of CO_2 during respiration = $tcf_{flow} * pmco2_2$
- $tosom1$, the C that flows from $metabc_2$ into $som1c_2$ = $tcf_{flow} - co2los$

If decomposition occurs, N and P move from metabolic pools ($metabe_2_{<iel>}$) into active organic N or P ($som1e_2_{<iel>}$) according to their ratios in soil metabolic material (i.e., $metabe_2_{<iel>} * (tosom1 / metabc_2)$).

Decomposition of surface organic matter

If there is material in surface SOM to decompose ($som1c_1 > 0.0000001$), calculate the maximum C/ $<iel>$ ratios that allow decomposition to occur:

- $radds1 = rad1p_1_{<iel>} + rad1p_2_{<iel>} * ((som1c_1 / som1e_1_{<iel>} - pcemic1_2_{<iel>})$
- $rceto2_{<iel>} = som1c_1 / som1e_1_{<iel>} + radds1$
- $rceto2_{<iel>}$ is bounded to be less than $rad1p_3_{<iel>}$

Compute tcf_{flow} , the total flow from $som1c_1$:

- $tcf_{flow} = som1c_1 * agdefac * dec3_1 * dtm * pheff$

Where

- $agdefac$, the aboveground decomposition factor, is calculated prior to decomposition and described above
- $dec3_1$ is a fixed parameter
- dtm is the time step in years (i.e., because this is done 4 times per month, $dtm = 0.020833$)
- $pheff$, the effect of soil pH on decomposition = $0.5 + (1.1 / \pi) * \arctangent(\pi * 0.7 * (pH - 4.0))$, bounded between 0 and 1

Test if C/N and C/P ratios are sufficiently small to allow decomposition:

- if $aminrl_{<iel>} < 0.0000001$:
 - if $(som1c_1 / som1e_1_{<iel>} > rceto2_{<iel>})$: the material cannot decompose to $som2c_1$
- else: the material can decompose into $som2c_1$

Both the C/N and C/P ratios must be sufficiently small to allow decomposition.

Where

$aminrl_{<iel>} = \text{mineral } <iel> \text{ in the surface layer averaged across decomposition timesteps}$

If C can decompose from som1c_1 into som2c_1, there is some associated respiration where CO₂ is released into the atmosphere.

- $\text{co2los, C lost to CO}_2 = \text{tcflow} * \text{p1co2a_1}$
- $\text{tosom2, the C that flows from som1c_1 to som2c_1} = \text{tcflow} - \text{co2los}$

The respiration associated with the decomposition event includes some mineralization of N and P. Again, if C flows from som1c_1 to som2c_1, N and P move from surface microbial pools (som1e_1_<iel> into surface slow organic N or P (som2e_1_<iel> according to their ratios in surface organic matter (i.e., som1e_1_<iel> * (tosom2 / som1c_1).

Decomposition of soil active organic C

If there is material in soil active organic C to decompose ($\text{som1c_2} > 0.0000001$), calculate the maximum C/<iel> ratios that allow decomposition to occur:

- If animrl_<iel> , mineral <iel> in the surface layer averaged across decomposition timesteps, < 0 :
 - $\text{bgdrat_<iel>} = \text{varat22_1_<iel>}$
- else if $\text{aminrl_<iel>} > \text{varat22_3_<iel>}$:
 - $\text{bgdrat_<iel>} = \text{varat22_2_<iel>}$
- else $\text{bgdrat_<iel>} = (1 - \text{aminrl_<iel>} / \text{varat22_3_<iel>} * (\text{varat22_1_<iel>} - \text{varat22_2_<iel>} + \text{varat22_2_<iel>}))$

Calculate tcflow, the total flow of C from som1c_2:

- $\text{tcflow} = \text{som1c_2} * \text{bgdefac} * \text{dec3_2} * \text{eftext} * \text{anerb} * \text{dtm} * \text{pheff}$

Where

- bgdefac, the belowground decomposition factor, is defined above
- dec3_2 is a fixed parameter
- eftext, the effect of soil texture on soil microbe decomposition rate, is described in “Initialization” above
- anerb, the impact of soil anaerobic conditions on decomposition, is defined above
- dtm is the time step in years (i.e., because this is done 4 times per month, $\text{dtm} = 0.020833$)
- pheff, the effect of soil pH on decomposition of som1 = $0.5 + (1.14 / \pi) * \arctangent(\pi * 0.7 * (\text{pH} - 4.8))$, bounded between 0 and 1

Test if C/N and C/P ratios are sufficiently small to allow decomposition from som1c_2:

- if $\text{aminrl_<iel>} < 0.0000001$:
 - if $(\text{som1c_2} / \text{som1e_2<iel>} > \text{bgdrat_<iel>})$: the material cannot decompose from som1c_2
- else: the material can decompose from som1c_2

Both the C/N and C/P ratios must be sufficiently small to allow decomposition.

If C/<iel> ratios are sufficiently small to decompose from som1c_2, the flow to som3 is calculated first. Some respiration is associated with this decomposition event:

- co2los , the loss of C to $\text{CO}_2 = \text{tcflow} * \text{p1co2_2}$

Where p1co2_2 is computed at initialization, described above

The respiration associated with the decomposition event also includes some mineralization of N and P.

som1c_2 decomposes first into som3:

- tosom3 , the C flowing from som1c_2 to som3 = $\text{tcflow} * \text{fps1s3} * (1 + \text{animpt} * (1 - \text{anerb}))$

Where

- fps1s3 , the effect of clay content on decomposition from som1c_2, is calculated in Initialization above
- animpt is a fixed parameter
- anerb , the effect of soil anaerobic conditions on decomposition, is defined above

If C decomposes from som1c_2 into som3, N and P flow from som1e_2_<iel> into som3e_<iel>. The C/<iel> ratios of decomposing material are different from the maximum ratios allowing decomposition from som1c_2 to occur, and are calculated as:

- If animrl_<iel> , mineral <iel> in the surface layer averaged across decomposition timesteps, < 0:
 - $\text{bgdrat_<iel>} = \text{varat3_1_<iel>}$
- else if $\text{aminrl_<iel>} > \text{varat3_3_<iel>}$:
 - $\text{bgdrat_<iel>} = \text{varat3_2_<iel>}$
- else $\text{bgdrat_<iel>} = (1 - \text{aminrl_<iel>} / \text{varat3_3_<iel>} * (\text{varat3_1_<iel>} - \text{varat3_2_<iel>} + \text{varat3_2_<iel>}))$

If there is a positive flow of water out of the soil layer (if $\text{amov_2} > 0$, calculated in soil water submodel above), organic nutrients may leach into streamflow. The C leached into streamflow is a portion of tcflow , the total flow from som1c_2:

- cleach , the C flowing from som1c_2 to stream(5) = $\text{tcflow} * \text{orglch} * \text{linton}$

Where

- orglch is computed during initialization, described above
- $\text{linton} = \min(1 - (\text{omlech}(3) - \text{amov_2}) / \text{omlech}(3), 1)$
- $\text{omlech}(3)$ is a fixed parameter

If water flows out of the soil layer, N and P also undergo leaching. The amount of N and P leaching into streamflow is proportional to leaching of C:

- orgflow, the <iel> leaching from som1e_2 into streamflow = cleach / rceofl

Where

- cleach, the C leaching from som1c_2 to stream(5), is described under soil C submodel above
- rceofl = (som1c_2 / som1e(2, 1)) * 2
- rceofl = (som1c_2 / som1e(2, 2)) * 35

The C decomposing from som1c_2 into som2_2 is the remainder of total C flow from som1c_2:

- tosom2, the C flowing from som1c_2 into som2_2 = tcflow - co2los - tosom3 - cleach

If C flows from som1c_2 into som2_2, N and P decompose from som1e_2_<iel> into som2e_2_<iel>. The C/<iel> ratios of material flowing from som1e_2 into som2e_2 are the same as the maximum ratios that allow decomposition of som1c_2 to occur, and their calculation is described above (i.e., bgdrat_<iel> calculated from varat22).

Decomposition of soil slow organic material

If there is material in the soil slow organic pool to decompose (if som2c_2 > 0.0000001), calculate the maximum C/<iel> ratios that allow decomposition to occur:

- If animrl_<iel>, mineral <iel> in the surface layer averaged across decomposition timesteps, < 0:
 - bgdrat_<iel> = varat1_1_<iel>
- else if aminrl_<iel> > varat1_3_<iel>:
 - bgdrat_<iel> = varat1_2_<iel>
- else bgdrat_<iel> = (1 - aminrl_<iel> / varat1_3_<iel>) * (varat1_1_<iel> - varat1_2_<iel> + varat1_2_<iel>)

Calculate tcflow, the total flow of C from som2c_2:

- tcflow = som2c_2 * bgdefac * dec5_2 * anerb * dtm * pheff

Where

- bgdefac, the belowground decomposition factor, is defined above
- dec5_2 is a fixed parameter
- anerb, the impact of soil anaerobic conditions on decomposition, is defined above
- dtm is the time step in years (i.e., because this is done 4 times per month, dtm = 0.020833)
- pheff, the effect of soil pH on decomposition = 0.5 + (1.14 / pi) * arctan(pi * 0.7 * (pH - 4.8)), bounded between 0 and 1

Test if C/N and C/P ratios are sufficiently small to allow decomposition from som2c_2 by comparing to the maximum ratios calculated above (i.e., bgdrat_<iel> calculated from varat1):

- if $\text{aminrl_iel} < 0.0000001$:
 - if $(\text{som2c_2} / \text{som2e_2_iel}) > \text{bgdrat_iel}$: the material cannot decompose from som2c_2
- else: the material can decompose from som2c_2

Both the C/N and C/P ratios must be sufficiently small to allow decomposition.

If C/<iel> ratios are sufficiently small to decompose from som2c_2 , the flow to som3c is calculated first. Some respiration and loss of CO_2 is associated with this decomposition event:

- co2los , the loss of C to $\text{CO}_2 = \text{tcflow} * \text{p2co2_2}$

Where p2co2_2 is a fixed parameter.

The respiration associated with the decomposition event also includes some mineralization of N and P.

- tosom3 , the C flowing from som2c_2 to $\text{som3c} = \text{tcflow} * \text{fps2s3} * (1 + \text{animpt} * (1 - \text{anerb}))$

Where

- fps2s3 , the effect of clay content on decomposition from som2c_2 , is calculated in Initialization above
- animpt is a fixed parameter
- anerb , the impact of soil anaerobic conditions on decomposition, is defined above

If decomposition occurs from som2c_2 to som3c , N and P move from som2e_2_iel to som3e_iel according to the following ratios (here called “ bgdrat_iel ”):

- If animrl_iel , mineral <iel> in the surface layer averaged across decomposition timesteps, < 0 :
 - $\text{bgdrat_iel} = \text{varat3_1_iel}$
- else if $\text{aminrl_iel} > \text{varat3_3_iel}$:
 - $\text{bgdrat_iel} = \text{varat3_2_iel}$
- else $\text{bgdrat_iel} = (1 - \text{aminrl_iel} / \text{varat3_3_iel}) * (\text{varat3_1_iel} - \text{varat3_2_iel}) + \text{varat3_2_iel}$

The remainder of total flow from som2c_2 moves to som1c_2 :

- tosom1 , the C flowing from som2c_2 to $\text{som1c_2} = \text{tcflow} - \text{co2los} - \text{tosom3}$

N and P move from som2e_2_iel to som1e_2_iel during this decomposition event, according to the maximum C/<iel> ratios that were used to test whether decomposition from som2c_2 could occur (i.e., bgdrat_iel calculated with varat1).

Decomposition of surface slow organic C

If there is material in surface slow organic C to decompose (if $\text{som2c_1} > 0.0000001$), calculate the maximum required C/<iel> ratios for decomposition to occur:

- If aminrl_<iel> , mineral <iel> in the surface layer averaged across decomposition timesteps, < 0 :
 - $\text{bgdrat_<iel>} = \text{varat1_1_<iel>}$
- else if $\text{aminrl_<iel>} > \text{varat1_3_<iel>}$:
 - $\text{bgdrat_<iel>} = \text{varat1_2_<iel>}$
- else $\text{bgdrat_<iel>} = (1 - \text{aminrl_<iel>} / \text{varat1_3_<iel>} * (\text{varat1_1_<iel>} - \text{varat1_2_<iel>} + \text{varat1_2_<iel>}))$

Calculate tcflow , the total flow of C from som2c_1 :

- $\text{tcflow} = \text{som2c_1} * \text{agdefac} * \text{dec5_1} * \text{dtm} * \text{pheff}$

Where

- agdefac , the aboveground decomposition factor, is calculated prior to decomposition and described above
- dec5_1 is a fixed parameter
- dtm is the time step in years (i.e., because this is done 4 times per month, $\text{dtm} = 0.020833$)
- pheff , the effect of soil pH on decomposition $= 0.5 + (1.1 / \pi) * \arctangent(\pi * 0.7 * (\text{pH} - 4))$, bounded between 0 and 1

Test if C/N and C/P ratios are sufficiently small to allow decomposition:

- if $\text{aminrl_<iel>} < 0.0000001$:
 - if $(\text{som2c_1} / \text{som2e_1_<iel>} > \text{bgdrat_<iel>})$: the material cannot decompose
- else: the material can decompose

Both the C/N and C/P ratios must be sufficiently small to allow decomposition.

Where

- $\text{aminrl_<iel>} = \text{mineral <iel> in the surface layer averaged across decomposition timesteps}$

If the material can decompose, first calculate the loss of C to CO_2 during respiration:

- co2los , the C that flows from som2c_1 during respiration $= \text{tcflow} * \text{p2co2_1}$

Where p2co2_1 is a fixed parameter.

Respiration is associated with some mineralization of N and P, calculated according to their proportions in surface som2 .

- tosom1 , C that flows from som2c_1 to $\text{som1c_1} = \text{tcflow} - \text{co2los}$

If decomposition occurs from som2c_1 into som1c_1, N and P move from som2e_1_<iel> to som1e_1_<iel> according to the ratios calculated to test whether decomposition could occur (i.e., bgdrat calculated with varatl).

Flow from passive organic C

If there is material in passive organic C to decompose (if som3c > 0.0000001), it decomposes to som1c_2 with some associated CO₂ loss during respiration. The maximum C/<iel> ratios for material flowing to som1c_2 are the same as those calculated for material flowing from metabc_2 to som1c_2 (i.e., bgdrat_<iel> calculated with varatl).

- tcflow, the total flow of C from som3c = som3c * bgdefac * dec4 * anerb * detm * pheff

Where

- bgdefac, the belowground decomposition factor, is defined above
- dec4 is an input parameter
- dtm is the time step in years (i.e., because this is done 4 times per month, dtm = 0.020833)
- pheff, the effect of soil pH on decomposition = $0.5 + (1.1 / \pi) * \arctan(\pi * 0.7 * (\text{pH} - 3))$, bounded between 0 and 1
- anerb, the impact of soil anaerobic conditions on decomposition, is defined above

Compare current C/N and C/P ratios in soil metabolic material to the maximum ratios to test whether decomposition can occur:

- If animrl_<iel> < 0.0000001:
 - If (som3c / som3e_<iel>) > bgdrat_<iel>: the material cannot decompose
- else: the material can decompose

Both the C/N and C/P ratios must be sufficiently small to allow decomposition.

Where

- animrl_<iel> is the sum of positive layers of the mineral element (N or P) before uptake by plants
- bgdrat_<iel>, the required ratio for decomposition to occur, is calculated above from varatl

If decomposition can occur, the decomposition event is associated with some respiration, where some C is lost to CO₂. The respiration associated with the decomposition event also includes some mineralization of N and P.

- co2los, the C flowing to CO₂ during respiration = tcflow * p3co2 * anerb
- tosom1, the C that flows from som3c to som1c_2 = tcflow - co2los

If decomposition occurs from som3c into som1c_2, N and P move from som3e_<iel> to som1e_2_<iel> according to the ratios calculated to test whether decomposition could occur (i.e., bgdrat calculated with varatl).

Flow from surface slow organic C to soil slow organic C

If there is material in surface slow organic C (if $\text{som2c_1} > 0.0000001$), some of som2c_1 flows into som2c_2 via mixing. This mixing flow, unlike all other decomposition flows, is not limited by C/N and C/P ratios and does not imply any respiration.

- tcflow , the C that flows from som2c_1 to $\text{som2c_2} = \text{som2c_1} * \text{cmix} * \text{agdefac} * \text{dtm}$

Where

- cmix is a fixed parameter
- agdefac , the aboveground decomposition factor, is defined above
- dtm is the time step in years (i.e., because this is done 4 times per month, $\text{dtm} = 0.020833$)

During mixing, N and P move from som2e_1_<iel> to som2e_2_<iel> according to their current ratios in som2 (i.e., $\text{som2c_1} / \text{som2e_1_<iel>}$). Note that any mineralization of N that occurs during mixing is not added to gross mineralization of N during decomposition.

Mineral P flows among parent, secondary, and occluded P

Unlike the N submodel, which contains only one mineral pool, the P submodel contains additional pools (labile P (plabil), sorbed P, strongly sorbed P (secndy_2), parent P (parent_2), and occluded P (occlud)). At each 1/4-month decomposition timestep, after organic flows have been calculated, there is additional flow of P among these pools.

Some P may flow from parent material to the mineral compartment:

- fparnt , P weathered from parent material and flowing to surface mineral P = $\text{pparmn_2} * \text{parent_2} * \text{defac} * 0.020833$

Some P flows from secondary P to the mineral compartment in the surface soil layer:

- fsecnd , P flowing from secondary P to surface mineral P = $\text{psecmn_2} * \text{secndy_2} * \text{defac} * 0.020833$

Some P flows back from mineral compartment of each soil layer to secondary P:

- fmnsec_<lyr> , the P flowing from mineral P in this soil layer to secondary P = $\text{pmnsec_2} * \text{minerl_<lyr>_2} * (1 - \text{fsol}) * \text{defac} * 0.020833$

Where

- fsol , the amount of P in solution, is calculated from mineral P as:
- $c = \text{sorpmx} * (2 - \text{pslsrb}) / 2$
- $b = \text{sorpmx} - \text{minerl_2} + c$
- $\text{Labile} = (-b + \sqrt{b * b + 4. * c * \text{minerl_1_2}}) / 2$
- $\text{fsol} = \text{labile} / \text{minerl_1_2}$

Some P flows from the secondary pool (secndy_2) to occluded P (occlud):

- $fsecoc$, flow from secondary to occluded = $psecoc1 * secndy_2 * defac * 0.020833$

Some P flows from occluded to secondary P:

- $focsec$, flow from occluded to secondary = $psecoc2 * occlud * defac * 0.020833$

*** end of decomposition ***

After flows between all state variables have been calculated, pools are updated by performing the flow in the same sequence in which they were calculated. Average mineral content of N and P is updated at each four-times-per-month decomposition timestep:

- $aminrl_<iel>$, the average mineral $<iel>$ in surface pool = $(aminrl_<iel> + minerl_1_<iel>) / 2$

Where

- $minerl_1_<iel>$ is current mineral $<iel>$ in surface pool, i.e. pertaining to the current four-times-per-month decomposition timestep.

Volatilization loss of N is calculated according to gross mineralization of N during decomposition, and the derived parameter $vlossg$ (calculated from the fixed parameter $vlossg$ at initialization):

- $volgm = vlossg * gromin_1$
- $minerl_1_1 = minerl_1_1 - volgm$

Although the Rangeland Production model does not track total volatilized N released to the atmosphere as an output variable, this volatilization loss is calculated because it modifies the N in state variable $minerl_1_1$.

Plant Growth Submodel

Calculate the fall of material from standing dead biomass to litter, both $fsdc$ (C that falls from standing dead to litter), and $epart_<iel>$ (N and P that flow from standing dead to litter):

- $fsdc = stdedc * fallrt$
- $epart_<iel> = (stdede_<iel> / stdedc) * fsdc$

Where

- $fallrt$ is a PFT-specific parameter

The material that falls from standing dead biomass to litter is partitioned into structural ($strucc_1$) and metabolic ($metabc_1$) surface pools according to current levels of mineral N and P in the surface pool, and lignin content of $stdedc$. The flow of partitioned C, N and P is described below under “Partitioning of organic residue”.

Calculate $rdeath$, the C that flows from $bglive$ upon the death of roots, and $epart_<iel>$, the N and P that flows from $bglive_<iel>$ upon the death of roots. Root death only occurs if $stemp$,

average temperature for this month, is greater than or equal to $rtdtmp$, the minimum temperature required for root death to occur.

- $rdeath = root_death_rate * bglivc$ if $stemp \geq rtdtmp$, otherwise $rdeath = 0$
- $root_death_rate = rdr * (1 - avh2o_1 / (deck5 + avh2o_1))$, bounded to be ≤ 0.95
- $epart_iel = (bglivc_iel / bglivc) * rdeath$

The material that flows from belowground live material is partitioned into structural and metabolic soil layers according to current mineral N and P in the soil pools, and lignin content of $bglivc$. The flow of partitioned C, N and P is described below under “Partitioning of organic residue”.

The death of aboveground live biomass results from senescence, which is scheduled by the user to happen in one or more specific months of the year. In other months of the year, some shoot death may occur because of water stress or shading. Calculate $sdethc$, the C that flows from $aglivc$ upon the death of shoots, and $sdethe_iel$, the iel that flows from $aglive_iel$ during shoot death:

- $sdethc = fdeth * aglivc$
- $sdethe = fdeth * aglive_iel$

Where

- If senescence is scheduled this month:
 - $fdeth = fsdeth_2$
- Else: $fdeth = fsdeth_1 * (1 - bgwfunc)$
- If $aglivc > fsdeth_4$ and senescence is not scheduled this month, death due to shading is added to death due to soil water restriction:
 - $fdeth = fdeth + fsdeth_3$

The material leaving $aglivc$ due to shoot death flows to $stdedc$.

N and P flow from $aglive_iel$ in proportion to their ratio to $aglivc$:

- $stdethe_iel$, N or P flowing from $aglive_iel = fdeth * aglive_iel$

A portion of the N and P flowing from $aglive_iel$ goes to the retranslocation storage pool, according to the fixed parameter $crprtf_iel$:

- $tostore$, N or P flowing from $aglive_iel$ to $crpstg_iel = sdethe * crprtf_iel$
- $tostdede$, N or P flowing from $aglive_iel$ to $stdede_iel = stdethe_iel - tostore$

Some N is also volatilized, according to the input parameter $vlossp$.

The growth of new biomass is then calculated from potential production, calculated above, and nutrient limitation. Actual growth is calculated relative to $pcopc$, the potential production of C. Note that this is linearly related to $tgprod$, calculated by the potential production submodel. No

growth occurs in months when senescence is scheduled to occur. Also, no growth occurs if one of either N or P is not available (i.e., if $\text{avail}\langle\text{N}\rangle + \text{snfxmx_1} = 0$, or if $\text{avail}\langle\text{P}\rangle = 0$).

Calculate the potential C production limited by each mineral nutrient, accounting for potential N fixation by the plant. First calculate nutrients available. The impact of root biomass on nutrient availability, rimpct , is the same as is calculated above during the calculation of potential production. As calculated above for potential production, the availability of soil available nutrients, avail_iel , depends partly on the site parameter favail_iel , rimpct , and estimated $\langle\text{iel}\rangle$ in plant storage:

- $\text{avail_iel} = (\text{avail}\langle\text{iel}\rangle * \text{favail_iel} * \text{rimpct}) + \text{crpstg_iel}$
- $\text{avail}\langle\text{N}\rangle = \text{avail}\langle\text{N}\rangle + \text{maxNfix}$

Where

- $\text{avail}\langle\text{iel}\rangle$ is the sum of mineral $\langle\text{iel}\rangle$ in soil layers accessible by plant roots (i.e., $\text{sum}(\text{minerl_layer_iel}$ for layer in 1:number of layers for plant growth)
- favail_iel is a PFT-specific parameter
- crpstg_iel is retranslocation $\langle\text{iel}\rangle$ storage pool for the PFT
- $\text{rimpct} = 1$ if $(\text{rictrl} * \text{bglive} * 2.5) > 33$
- Else $\text{rimpct} = 1 - \text{riint} * \exp(-\text{rictrl} * \text{bglive} * 2.5)$
- $\text{maxNfix} = \text{snfxmx} * \text{pcrope}$

Where

- snfxmx is a PFT-specific parameter
- pcrope is potential production calculated by potential production submodel

Calculate the demand for each nutrient from potential production and from the minimum C/ $\langle\text{iel}\rangle$ ratios calculated above in the potential production submodel.

- The original Century formulation has $\text{demand_iel} = \text{pcrope} * \text{maxec_iel}$ on line 65, `Nutrlm.f`. This is identical to the calculation of demand in CropDynC (the root:shoot ratio submodel), except that the conversion of tgprod (total biomass production) to pcrope (C production) and the conversion of $\text{cercrp_min_above-and-below}$ to $\text{maxec_above-and-below}$ are accomplished in different order. In the Rangeland Production model these two calculations are replaced by a single method of calculating demand:
- $\text{demand_iel} = \text{demand_above_iel} + \text{demand_below_iel}$
- $\text{demand_above_iel} = (\text{agprod} / 2.5) * (1 / \text{cercrp_min_iel_above})$
- $\text{demand_below_iel} = (\text{tgprod} - \text{agprod}) / 2.5 * (1 / \text{cercrp_min_iel_below})$
- bgprod , belowground production = $\text{tgprod} * \text{fracrc}$
- agprod , aboveground production = $\text{tgprod} - \text{pgprod}$

Then calculate the C production limited by the availability of each mineral element: actual C production is that which is possible given the most limiting element:

- $cpbe_iel$, the C production limited by $iel = eval_iel / iel$ content of new production

Where

- The iel content of new production is equal to $maxec_iel$, the maximum iel concentration, if $eval_iel$ is greater than $demand_iel$, and is equal to an adjusted content according to the ratio of $eval_iel$ to $demand_iel$ and the difference between $minec_iel$ and $maxec_iel$, the minimum and maximum iel/C ratios in new production.

Actual C production limited by nutrient availability is the C production which is possible given the most limiting element, i.e. the minimum of $cpbe_iel$ across iel values:

- $cprodl$, C production limited by nutrient availability = $\min(cpbe_iel \text{ for } iel \text{ in } N, P)$
- $eprodl_iel$, the iel in new production = $(cprodl * cfrac_{above} * efor_{above_iel} + (cprodl * cfrac_{below} * efor_{below_iel})$
- $plantNfix$, the N fixation that actually occurs = $\max(eprodl_N - eval_N, 0)$

Where

- $cfrac$ is the fraction of C in above- or belowground portions
- $efor_iel$ is the final iel/C ratio in new production

The aboveground fraction of actual C production, $mcprd_{above}$, is calculated from $cprodl$ and the root:shoot ratio calculated in the potential production submodel. This amount flows from atmospheric C to $aglive$. The belowground fraction of actual C production, $mcprd_{below}$, is calculated similarly; this amount flows from atmospheric C to $bglive$.

After total N and P in new production is calculated, the source from which the N and P will be taken up is calculated. If there is sufficient iel in the crop storage pool ($crpstg_iel$) to supply $eprodl_iel$, all uptake is taken from crop storage. Otherwise, the full amount of $crpstg_iel$ is taken up, and the remainder of $eprodl_iel$ is taken up from the soil. For N, the portion of $eprodl_N$ satisfied by uptake from N fixation ($plantNfix$) is accounted before calculating uptake from the soil.

Flows of N and P from the mineral crop storage pool, soil, and N fixation to $aglive_iel$ and $bglive_iel$ are performed. Allocation of uptake to above- vs belowground stocks (i.e., to $aglive_iel$ vs $bglive_iel$) follows eup_1_iel and eup_2_iel , the fraction of iel allocated to above- and below-ground stocks. It is necessary to track these fractions explicitly, rather than simply calculating allocation according to total N or P in new production and the root:shoot ratio as was done for C, because the C/ iel ratios of above- vs belowground stocks differ.

- Uptake from crop storage (crpstg_<iel>) moves to aglive_<iel> and bglive_<iel>
- Uptake from soil mineral pools in the layers of soil available for plant growth proceeds according to the proportion of total mineral <iel> represented by that soil layer
- Uptake from N fixation moves to aglive_<N> and bglive_<N>

Biomass Removal by Grazing

After diet selection by grazing animals is computed, the removal of biomass by grazing and associated return of C, N and P in feces in urine is calculated. Here we follow Century naming conventions by specifying the biomass removal for each PFT in terms of the fraction live biomass removed (flgrem, 0-1), and fraction of standing dead biomass removed (fdgrem, 0-1). The absolute C removed from live biomass by grazing, shremc, flows from aglive, and nutrients in live biomass removed by grazing flow from aglive_<iel>:

- $shreme_<iel>, <iel> \text{ in live biomass removed by grazing} = shremc * aglive_<iel> / aglive$

Sdremc, the C removed from standing dead, flows from stdedc, and nutrients in standing dead flow from stdede_<iel>:

- $sdreme_<iel> = sdremc * stdede_<iel> / stdedc$

The return of C and nutrients in feces and urine is described by input parameters gfcret, the fraction of consumed C that is returned, and gret_<iel>, the fraction of consumed N and P returned.

- $cret, \text{ C returned in feces} = gfcret * (shremc + sdremc)$
- $eret_<iel>, <iel> \text{ return in feces and urine} = gret_<iel> * shreme_<iel> + gret_<iel> * sdreme<ie>$
- $feces_<iel>, <iel> \text{ returned in feces} = fecf_<iel> * eret_<iel>$
- $urine_<iel>, <iel> \text{ returned in urine} = (1 - fecf_<iel>) * eret_<iel>$

Where

- $fecf_<iel>$ is a fixed input parameter
- $gret_<iel>$ is a fixed input parameter, except for N:
 - $gret_<N> = 0.7$ if clay < 0;
 - $gret_<N> = 0.85$ if clay > 0.3;
 - $gret_<N> =$ the y-value lying on the line described by (0, 0.7) and (0.3, 0.85) corresponding to the x-value clay

The C, N and P returned in feces are partitioned into surface structural and metabolic material according to current levels of mineral N and P in the surface pool, and lignin content of the feces. The flow of partitioned C, N and P is described below under “Partitioning of organic residue”. N and P returned in urine flow into minerl_1_<iel>.

Leaching

At each model time step, after plant growth and any removal of biomass by grazing, saturated water flow moving between layers carries leached N and P down through soil layers. The amount

of N or P leached from one layer to the next adjacent layer is calculated from the amount of water moving between layers (amov_<lyr>, calculated in soil water submodel) and the mineral content of the donating layer:

$$\text{Amount_leached} = \text{frlech_iel} * \text{minerl_lyr_iel} * \text{linton}$$

Where

- linton, leaching intensity = $1 - (\text{minlch} - \text{amov_lyr}) / \text{minlch}$, bounded to be between 0 and 1
- frlech, the leaching fraction for the nutrient, is calculated from soil sand content, fixed parameters, and for P, the fraction of P in solution:
- frlech for N = $(\text{fleach_1} + \text{fleach_2} * \text{sand}) * \text{fleach_3}$
- frlech for P = $(\text{fleach_1} + \text{fleach_2} * \text{sand}) * \text{fleach_4} * \text{fsol}$
- fsol, the fraction of mineral P in solution, is calculated from fixed parameters as described above under “Mineral P flows among parent, secondary, and occluded P”
- minlch, fleach_1, fleach_2, fleach_3, fleach_4 are fixed parameters

The mineral element flowing from the current layer is subtracted from that layer’s mineral content, and added to the following adjacent layer:

- $\text{minerl_lyr_iel} = \text{minerl_lyr_iel} - \text{amount_leached}$
- $\text{minerl_lyr+1_iel} = \text{minerl_lyr+1_iel} + \text{amount_leached}$

Partitioning of organic residue

When organic residue is added to the soil, it is partitioned into structural and metabolic pools according to the ratio of lignin to N in the residue. This organic residue may be incoming from the fall of standing dead biomass (where residue from standing dead biomass is partitioned into surface structural and metabolic pools), the death of roots (where residue from dead roots is partitioned into soil structural and metabolic pools), or the addition of organic matter from animal feces (where feces are partitioned into surface structural and metabolic pools).

As incoming material is partitioned, some N or P may be absorbed from the surface mineral N or P pool into the incoming material. The amount transferred, dirabs_<iel>, depends on the N or P in the incoming material and is calculated in two steps. First, dirabs_<iel> is calculated from minerl_1_<iel> and the parameters damr_<lyr>_<iel> and pabres:

$$\begin{aligned} \text{dirabs_iel} &= 0 \quad \text{if } \text{minerl_1_iel} < 0, \text{ else} \\ \text{dirabs_iel} &= \text{damr_lyr_iel} * \text{minerl_1_iel} * \max(\text{cpart} / \text{pabres}, 1.) \end{aligned}$$

where cpart is the C content of incoming material

In the second step, the C/<iel> ratio of incoming material, including direct absorption, is compared to the parameter damrmn_<iel>. If the C/<iel> ratio is too low, dirabs_<iel> is modified to raise the C/<iel> ratio to damrmn_<iel>.

r_{cetot} , the C/<iel> ratio if incoming material = 0 if $(e_{part_<iel>} + d_{irabs_<iel>} \leq 0)$, else
 $r_{cetot} = c_{part} / (e_{part_<iel>} + d_{irabs_<iel>})$

If $r_{cetot} < d_{amrmn_<iel>}$, then $d_{irabs_<iel>}$ is recalculated.

$d_{irabs_<iel>}$, the final amount of <iel> directly absorbed from mineral <iel> to incoming material = $c_{part} / d_{amrmn_<iel>} - e_{part_<iel>}$, restricted to be greater than or equal to zero

where

$e_{part_<iel>}$ is the <iel> content of incoming material

The fraction of C flowing from organic residue into the metabolic pool (m_{etabc_2} for the death of roots, m_{etabc_1} for fall of standing dead and addition of organic matter from animal feces), is calculated from the parameters s_{pl_1} and s_{pl_2} , and r_{lnres} , the ratio of lignin to N in the incoming residue. The ratio of lignin to N in the residue is calculated after any direct absorption of N from the mineral layer is transferred to the residue.

f_{rmet} , the fraction of C in incoming material that is transferred to the metabolic pool = $s_{pl_1} - s_{pl_2} * r_{lnres}$

Where

r_{lnres} , the ratio of lignin to N in incoming material = $f_{rlign} / ((e_{part_1} + d_{irabs_1}) / (c_{part} * 2.5))$

Once calculated, f_{rmet} is restricted by the fraction of lignin in the incoming material, and restricted to be greater than or equal to 0.2:

If $f_{rign} > (1 - f_{rmet})$: $f_{rmet} = (1 - f_{rign})$

$f_{rmet} = \max(f_{rmet}, 0.2)$

The C flowing into $m_{etabc_<lyr>}$ (where $lyr = 1$ for the fall of standing dead and the addition of organic material from animal feces, and $lyr = 2$ for the death of roots) is calculated according to c_{part} and f_{rmet} :

$m_{etabc_<lyr>} = m_{etabc_<lyr>} + (c_{part} * f_{rmet})$

$c_{adds} = c_{part} * (1 - f_{rmet})$

$s_{rucc_<lyr>} = s_{rucc_<lyr>} + c_{adds}$

The N and P flowing into struce_<lyr>_<iel>, eadds_<iel>, are fixed according to the parameter rcestr_<iel>:

$$eadds_iel = cadds / rcestr_iel$$

$$struce_lyr_iel = struce_lyr_iel + eadds_iel$$

The remainder of N and P in incoming material, including direct absorption from the mineral layer, flows into metabe_<lyr>_<iel>:

$$eaddm = epart_iel + dirabs_iel - eadds$$

$$metabe_lyr_iel = metabe_lyr_iel + eaddm$$

The fraction of lignin in incoming material added to the structural pool is calculated from the fraction of lignin in incoming material, and restricted to be less than or equal to 1. This fraction is used to update the state variable strlig_<lyr>, lignin in structural pool in the given layer.

$$fligst = \min((frlign / (cadds / cpart), 1.)$$

$$strlig_lyr = ((strlig_lyr * strucc_lyr + (fligst * cadds)) / (strucc_lyr + cadds))$$

Animal diet selection and physiology submodel

The animal diet selection and physiology submodel calculates the intake of forage by grazing animals from biomass and digestibility of the forage as estimated by the plant production submodel. Given traits of the animals such as age, weight, and reproductive status, the model estimates maintenance energy requirements. The degree to which the selected diet meets maintenance energy requirements is calculated with the metric of diet sufficiency. Livestock physiology submodel parameters are fixed according to the animal's type (specified by the user in the animal parameter table; Appendix 1, table 3) and are prefixed here by "C", following Freer *et al.* (2012). Table 6 contains all fixed animal physiology parameter values. Because these parameter values are indexed by animal type, they are not required to be supplied by the user as input.

Table 6. Fixed parameter values for the livestock physiology submodel, adapted from Freer *et al.* (2012).

Parameter	Description	Units	Value (<i>B. indicus</i>)	Value (<i>B. taurus</i>)	Value (<i>B. indicus</i> x <i>taurus</i>)	Value (sheep and goats)
CA1	UDP digestibility		0.05	0.05	0.05	0.05
CA2	UDP digestibility		0.85	0.85	0.85	0.85
CA3	UDP digestibility		5.5	5.5	5.5	5.5
CA4	UDP digestibility		0.178	0.178	0.178	0.178
CA6	DPLS in MCP		1	1	1	1

CA7	DPLS in MCP		0.6	0.6	0.6	0.6
CI1	Relative size	kg kg ⁻¹	0.025	0.025	0.025	0.04
CI2	Rumen development	d ⁻¹	1.7	1.7	1.7	1.7
CI8	Lactation: peak intake time	d ⁻¹	62	62	62	28
CI9	Intake curvature		1.7	1.7	1.7	1.4
CI12	Lactation: body condition loss					0.15
CI13	Lactation: body condition loss	d ⁻¹				0.02
CI14	Lactation: body condition loss	d ⁻¹				0.002
CI15	Lactation: condition at parturition		0.5	0.5	0.5	
CI19	peak intake level: 1 young		0.416	0.416	0.416	
CI20	Effect of body condition		1.5	1.5	1.5	1.5
CK1	km: M/D in solid diet		0.5	0.5	0.5	0.5
CK2	km: M/D in solid diet	kg MJ ⁻¹	0.02	0.02	0.02	0.02
CK3	km: milk intake		0.85	0.85	0.85	0.85
CK5	kl: M/D in solid diet		0.4	0.4	0.4	0.4
CK6	kl: M/D in solid diet		0.02	0.02	0.02	0.02
CK8	kc	0-1	0.133	0.133	0.133	0.133
CL0	Peak yield scalar if suckling	MJ kg ^{-3/4}	0.375	0.375	0.375	0.486
CL1	Lactation curve: offset	d	4	4	4	2
CL2	Lactation curve: peak time	d	30	30	30	22

CL3	Lactation curve: shape, with young		0.6	0.6	0.6	1
CL5	Milk: metabolizability	0-1	0.94	0.94	0.94	0.94
CL6	Milk: energy content	MJ kg ⁻¹	3.1	3.1	3.1	4.7
CL15	Protein content of milk	kg kg ⁻¹	0.032	0.032	0.032	0.045
CM1	Energy for maintenance: liveweight gain		0.09	0.09	0.09	0.09
CM2	Basal metabolism: weight scalar	MJ kg ^{-3/4}	0.31	0.36	0.335	0.26
CM3	Basal metabolism: effect of age	d ⁻¹	8.00E-05	8.00E-05	8.00E-05	8.00E-05
CM4	Basal metabolism: effect of age		0.84	0.84	0.84	0.84
CM6	Egraze: chewing cost	MJ kg ⁻¹	0.0025	0.0025	0.0025	0.02
CM7	Egraze: chewing cost	0-1	0.9	0.9	0.9	0.9
CM16	Energy cost of horizontal walking	MJ km ⁻¹ kg ⁻¹	0.0026	0.0026	0.0026	0.0026
CN1	Growth rate constant	kg ^{0.27} d ⁻¹	0.0115	0.0115	0.0115	0.0157
CN2	Allometric scalar for growth rate		2.70E-01	2.70E-01	0.27	0.27
CN3	Weighting factor for slow growth		0.4	0.4	0.4	0.4
CP1	Gestation length	d	285	285	285	150
CP4	Effect of relative size on birth weight		0.33	0.33	0.33	0.33

CP5	Final conceptus weight:fetus weight	kg kg ⁻¹	1.8	1.8	1.8	1.43
CP6	Conceptus weight		2.42	2.42	2.42	3.38
CP7	Conceptus weight		1.16	1.16	1.16	0.91
CP8	Final conceptus energy content	MJ kg ⁻¹	4.11	4.11	4.11	4.33
CP9	Conceptus energy		343.5	343.5	343.5	4.37
CP10	Conceptus energy		0.0164	0.0164	0.0164	0.965
CP15	Normal birth weight:SRW, 1 young		7.00E-02	7.00E-02	0.07	0.1
CR1	Digestibility: peak	0-1	0.8	0.8	0.8	0.8
CR2	Digestibility: legume effect		0.17	0.17	0.17	0.17
CR3	Digestibility: slope		1.7	1.7	1.7	1.7
CR4	Availability: grazing rate	kg ⁻¹	0.00078	0.00078	0.00078	0.00112
CR5	Availability: grazing time		0.6	0.6	0.6	0.6
CR6	Availability: grazing time	kg ⁻¹	0.00074	0.00074	0.00074	0.00112
CR7	Relative size on time and rate		0.5	0.5	0.5	0
CR12	Digestibility: effect of pasture height		0.8	0.8	0.8	0.8
CR13	Digestibility: effect of proportion in class		0.35	0.35	0.35	0.35
CRD1	Degradability: feeding level		0.3	0.3	0.3	0.3

CRD2	Degradability: feeding level		0.25	0.25	0.25	0.25
CRD4	RDPR: feeding level	kg ⁻¹	0.007	0.007	0.007	0.007
CRD5	RDPR: feeding level	kg ⁻¹	0.005	0.005	0.005	0.005
CRD6	RDPR: feeding level		0.35	0.35	0.35	0.35
CRD7	time of year (forage)		0.1	0.1	0.1	0.1
CW1	Energy content of clean wool	MJ kg ⁻¹				24
CW2	Basal clean wool growth	kg				0.004
CW3	Clean:greasy ratio	0-1				0.7
CW5	Wool growth: proportion at growth	d ⁻¹				0.25
CW6	Wool growth: photoperiod	h ⁻¹				0.072
CW7	Wool growth: limitation by protein intake	kg kg ⁻¹				1.35
CW8	Wool growth: limitation by energy intake	kg MJ ⁻¹				0.016
CW9	Pregnancy and lactation adjustment	0-1				1
CW12	Age factor exponent					0.025

Diet selection

The diet selection submodel was adopted from the GRAZPLAN model (Freer *et al.* 2012) and describes the diet selected by a ruminant animal from available forage. The diet is selected on the basis of relative ingestibility and relative availability of each feed type, until the maximum intake for that herbivore class is reached. Maximum intake (I_{max} , kg dry matter eaten per day; equation 1) is calculated primarily from the animal's standard reference weight (SRW) and current size relative to SRW , Z (equation 2). Relative size (Z) is calculated from the normal

weight (N), which is defined by the animal's current weight (W) and age (A ; equations 3, 4). The maximum intake is also impacted by a correction factor for animals in high relative condition (CF ; equation 5), and by a lactation factor (LF) for lactating females. The correction factor is calculated from body condition (BC ; equation 6), the ratio of the animal's current weight to its normal weight.

The lactation factor (equations 7-9) describes the increased maximum intake of a lactating female and is based on a lactation curve driven by the age of the calf (A_{young}). The factor LA is related to the animal body condition (equation 9); in the original GRAZPLAN formulation, this was related to body condition at parturition (cf. equation 10 in Freer *et al.* 2012), but we have simplified this factor to depend on a static body condition score. It is assumed that all lactating females are suckling one calf.

$$I_{max} = CI_1 \times SRW \times Z \times (CI_2 - Z) \times CF \times LF \quad (1)$$

where

$$Z = \frac{N}{SRW} \quad (2)$$

$$N = CN_3 \times N_{max} + (1 - CN_3) \times W \quad (3)$$

$$N_{max} = SRW - (SRW - W_{birth}) \times \exp\left(\frac{-CN_1 \times A}{SRW^{CN_2}}\right) \quad (4)$$

$$CF = BC \times \frac{CI_{20} - BC}{CI_{20} - 1} \quad (5)$$

$$BC = \frac{W}{N} \quad (6)$$

$$LF = 1 + CI_{19} \times M_i^{CI_9} \times \exp(CI_9 \times (1 - M_i)) \times LA \quad (7)$$

where

$$M_i = \frac{A_{young}}{CI_i} \quad (8)$$

$$LA = 1 - CI_{15} + CI_{15} \times BC \quad (9)$$

Following the calculation of maximum potential intake, the diet selection routine predicts what proportion of the potential intake is selected from each available feed type. In a model run where one plant functional type is simulated, two feed types will always be available: the live fraction, and the standing dead fraction of that grass type. When two or more plant functional types are simulated, the number of available feed types is equal to two times the number of grass types simulated. In the equations below, the subscript "d" indicates one feed type.

Unlike the GRAZPLAN model, which divides available forage into 6 fixed-digestibility classes (cf. Freer *et al.* 2012, p. 6), the Rangeland model calculates availability and digestibility directly from biomass and crude protein content of the live and dead fractions of each plant functional type. Each feed type is characterized by its biomass (B ; kg/ha), crude protein content (P ; g * g⁻¹), digestibility (DMD ; 0 - 1), species factor ($SF = 0$ for C3 grasses, $SF = 0.16$ for C4 grasses), and the proportion of available biomass that is represented by this forage type (ϕ , 0 - 1). The proportion of total forage represented by legumes, by weight (ϕ_{legume} , 0 - 1), influences intake of all feed types.

The diet selection and physiology submodel (adapted from GRAZPLAN) operates on biomass in units of kg of dry matter per ha, while state variables in the plant production submodel (adapted from CENTURY) are tracked in units of grams of carbon per square meter. Before estimating intake of each feed type selected by grazing animals, biomass of each feed type (d) and each plant functional type (pft) is calculated in kg per ha from the carbon state variable in grams per square meter:

$$B_d = cstatv_d \times 2.5 \times 10 \times cover_d \quad (10)$$

where $cstatv_d$ is the state variable representing carbon in feed type d (aglvc if d pertains to live biomass, stdcdc if d pertains to standing dead biomass), and $cover_d$ is the fractional cover of the plant functional type to which feed type d belongs.

The Rangeland model calculates dry matter digestibility of each feed type from its crude protein content, according to the slope and intercept of a linear regression specified in the plant functional type parameter table. When crude protein concentration of forage is supplied by the user, that value is substituted for CP across all feed types. Otherwise, crude protein content of each feed type is calculated from the nitrogen:carbon ratio of state variables making up that feed type:

$$CP_d = \frac{nstatv_d \times 6.25}{cstatv_d \times 2.5} \quad (11)$$

where $nstatv_d$ is the state variable representing nitrogen in feed type d (aglvc_<N> for live biomass, stdede_<N> for standing dead biomass), and $cstatv_d$ is the state variable representing carbon in feed type d (aglvc for live biomass, stdcdc for standing dead biomass).

Prior to beginning diet selection, the feed types are sorted according to their digestibility; the calculation of the proportion of potential intake that is selected from each feed type (equations 12-19) is applied first to the most digestible feed type, and then to the next most digestible, etc. At each application of equations 12-19 to a feed type, the unsatisfied capacity (UC_d) tracks the proportion of potential intake that is not yet satisfied by selection of previous, more digestible, feed types. This simulates the preferential selection of high-digestibility feed types before feed types of lower digestibility.

For each feed type, the proportion of potential intake selected from this feed type (R_d , equation 12) is a product of its “relative availability” and its “relative ingestibility”. Relative availability (F_d , equation 13) is a product of the unsatisfied capacity according to selection of more digestible feed types, the predicted rate of eating this feed type (RR_d , equation 15) and the relative time spent eating this feed type (RT_d , equation 19). RR_d and RT_d are impacted by the relative height of the feed type, HR_d (equation 17) which is calculated with the assumption that

complete cover of one feed type corresponds to a forage height of 3 cm. The rate of eating and time spent eating are also impacted by the size of the animal, reflected in the size factor, ZF_d (equation 18; see equation 2 for the calculation of the animal's current relative size, Z).

$$R_d = F_d \times RQ_d \times (1 + CR_2 \times (\sum_{d=1}^N F_d) \times \phi_{legume}) \quad (12)$$

where

$$F_d = UC_d \times RR_d \times RT_d \quad (13)$$

$$UC_d = \max(0, 1 - \sum_{d=1}^{d-1} F_d) \quad (14)$$

$$RR_d = 1 - \exp(-(1 + CR_{13} \times \phi_d) \times CR_4 \times HF_d \times ZF \times B_d) \quad (15)$$

$$HF_d = 1 - CR_{12} + CR_{12} \times HR_d \quad (16)$$

$$HR_d = 0.003 \times \frac{(\Sigma B)^2}{\Sigma(B^2)} \times B_d \quad (17)$$

$$ZF = 1 + (CR_7 - Z) \text{ if } Z < CR_7, \text{ else}$$

$$ZF = 1 \quad (18)$$

$$RT_d = 1 + CR_5 \times \exp(-(1 + CR_{13} \times \phi_d) \times (CR_6 \times HF_d \times ZF \times B_d)^2) \quad (19)$$

The “relative ingestibility” of a feed type (RQ_d) is calculated primarily from its digestibility (equation 18). The species factor (SF_d) reflects higher predicted intake of C4 grasses than C3 grasses of similar digestibility (Freer *et al.* 2012).

$$RQ_d = 1 - CR_3 \times (CR_1 - (1 - \phi_{legume}) \times SF_d - DMD_d) \quad (20)$$

The actual intake of each feed type, I_d (kg per day), is calculated from the proportion of maximum intake selected from each feed type (equation 21), and the total intake of forage is calculated as the sum across types. The average digestibility of the diet, DMD_f , is calculated from the digestibility of each feed type and its proportion of the diet (equation 23); similarly, the total crude protein intake of the diet, CPI_f , is calculated from crude protein content of each feed type (equation 24). If crude protein concentration in forage is supplied by the user, that value is substituted for CP here across all feed types.

$$I_d = I_{max} \times R_d \quad (21)$$

$$I_f = \sum_{d=1}^N I_d \quad (22)$$

$$DMD_f = \frac{\sum_{d=1}^N (I_d \times DMD_d)}{I_f} \quad (23)$$

$$CPI_f = \sum_{d=1}^N (I_d \times CP_d) \quad (24)$$

Once diet selection completes, if protein content of the diet is low, maximum intake is reduced and diet selection is recalculated once according to the adjusted maximum intake. The reduction factor for maximum intake is calculated from the total intake of rumen degradable protein, $RDPI$, and the requirement for rumen degradable protein, $RDPR$ (equation 28). For cattle of *B. indicus* breeds, this reduction factor is multiplied by 0.5; for cattle of *B. indicus* cross breeds, the reduction factor is multiplied by 0.75.

The intake of rumen degradable protein ($RDPI$; equation 26) depends on L , feeding level. This is calculated from the ratio of energy intake to maintenance energy requirements: see equation 34, below.

$$I_{max, reduced} = I_{max} \times \frac{RDPI}{RDPR} \quad (25)$$

where

$$RDPI = RDPI_f \times (1 - (CRD_1 - CRD_2 \times DMD_f) \times L) \quad (26)$$

$$RDPI_f = CPI_f \times \min(0.84 \times DMD_f + 0.33, 1) \quad (27)$$

$$RDPR = (CRD_4 + CRD_5 \times (1 - \exp(-CRD_6 \times (L + 1)))) \times (RF \times MEI_f) \quad (28)$$

$$RF = 1 + CRD_7 \times \frac{latitude}{40} \times \sin(\frac{2\pi DOY}{365}) \quad (29)$$

Restriction of offtake by management threshold

The intake of each feed type selected by animals is converted to demand for forage by grazing animals, and this is compared to the management threshold to determine the final fraction of biomass removed. The maximum fraction of biomass removed is calculated according to the management threshold, or the total biomass required to be left standing after animal offtake, relative to total biomass across live and standing dead fractions of each plant functional type (equation 30).

The final fraction of biomass removed is $flgrem$ for live biomass, and $fdgrem$ for standing dead biomass; these are the relevant quantities adapted from CENTURY that dictate the impact of grazing intensity on plant growth and nutrient cycling (see “Biomass Removal by Grazing” submodel description, above).

Monthly demand for forage is calculated for each feed type from daily intake of that feed type by an individual animal, assuming 30.4 days per month (equation 30). Here the density of grazing animals (SD) on each pixel is used to convert the intake of an individual animal to total forage demand per pixel.

$$max\ fraction\ removed = \max(\frac{biomass_{total} - management\ threshold}{biomass_{total}}, 0) \quad (30)$$

$$biomass_{total} = \sum_{d=1}^N (cstatv_d \times cover_d) \times 2.5 \times 10 \quad (31)$$

$$demand_d = I_d \times SD \times 30.4$$

$$fraction\ removed_d = \min(\frac{demand_d}{cstatv_d \times 2.5 \times 10 \times cover_d}, max\ fraction\ removed) \quad (32)$$

If the fraction of biomass removed is restricted by the management threshold, daily intake of that feed type is recalculated according to the fraction removed. The calculation of diet sufficiency depends on the actual intake limited by the management threshold.

Diet sufficiency

After completion of a maximum of two iterations of diet selection and restriction of offtake by the management threshold, the diet sufficiency metric is calculated as the ratio of total metabolizable energy intake to maintenance energy requirements:

$$\text{diet sufficiency} = \frac{MEI_{total}}{ME_{total}} \quad (33)$$

Total metabolizable energy content of the diet, MEI_{total} , is calculated from the total digestibility of forage in the diet.

$$MEI_{total} = (17 \times DMD_f - 2) \times I_f \quad (34)$$

Total maintenance metabolizable energy requirement (ME_{total} , equation 35) is calculated as the sum of energy requirements for maintenance, energy requirements for wool production (NE_w , for sheep and goats), and for breeding females, maintenance requirements for pregnancy (ME_c) or lactation (ME_l). The requirement of energy for maintenance is the sum of basal metabolic energy requirements and the energy requirements of grazing (equation 36). The energy requirements of grazing include a constant estimation of the distance walked per day (D), which was fixed at 4 km during preliminary model testing. The efficiency of energy use for maintenance, k_m , is calculated from the energy content of forage in the diet (M/D_f , equations 40-41). For male animals, ME_m is multiplied by 1.15.

$$ME_{total} = ME_m + NE_w + ME_c + ME_l \quad (35)$$

$$ME_m = \frac{E_{metab} + E_{graze}}{k_m} + CM_1 \times MEI_{total} \quad (36)$$

$$L = \frac{MEI_{total}}{ME_m} - 1 \quad (37)$$

where

$$E_{metab} = CM_2 \times W^{0.75} \times \max(\exp(CM_3 \times A), CM_4) \quad (38)$$

$$E_{graze} = CM_6 \times W \times I_f \times (CM_7 - DMD_f) + E_{move} \quad (39)$$

$$E_{move} = CM_{16} \times D \times W \quad (40)$$

$$D = 4 \quad (41)$$

$$k_m = CK_1 + CK_2 \times M/D_f \quad (42)$$

$$M/D_f = \frac{MEI_f}{I_f} \quad (43)$$

Energy requirements of pregnancy are derived from the body weight of the animal for pregnancy purposes, BW , and the relative age of the fetus, RA (equation 44). The energy requirements of pregnancy are simplified from the implementation of Freer *et al.* (2012) in two ways: first, the body condition of the fetus (BC_{foet}) is assumed to be 1; that is, the fetus is

assumed to be in median condition. Second, we also assume that each pregnant animal is pregnant with one fetus.

$$ME_c = \frac{CP_8 \times CP_5 \times BW \times \frac{CP_9 \times CP_{10}}{CP_1} \times \exp(CP_{10} \times (1 - RA) + CP_9 \times 1 - \exp(CP_{10} \times (1 - RA)))}{CK_8} \quad (44)$$

where

$$BW = (1 - CP_4 + CP_4 \times Z) \times CP_{15} \times SRW \quad (45)$$

$$RA = \frac{A_{foet}}{CP_1} \quad (46)$$

Energy requirements of lactation (equation 47) are related to the body condition of the mother and the age of the calf; they have been simplified from Freer *et al.* (2012) in the following two ways. All lactating animals are assumed to be suckling one calf; while maximum milk production is calculated (MP_{max} , equation 48), the actual production of milk is not limited by intake of ME or by the suckling young's ability to consume milk.

$$ME_l = \frac{MP_{max}}{CL_5 \times k_l} \quad (47)$$

$$MP_{max} = CL_0 \times SRW^{0.75} \times Z \times BC \times M_m^{CL_3} \times \exp(CL_3 \times (1 - M_m)) \quad (48)$$

$$M_m = \frac{A_{young} + CL_1}{CL_2} \quad (49)$$

Energy requirements of wool production (NE_w ; equation 50) are calculated from predicted daily wool growth (equation 51), accounting for the effect of age (AF, equation 52), and assuming a constant daylength of 12 hours. Daily wool growth is limited by digestible protein leaving the stomach ($DPLS$, equation 54) and by metabolizable energy available for wool, which is simply the remainder of energy available after accounting for costs of lactation and pregnancy (equation 53).

$$NE_w = CW_1 \times \frac{P_w - CW_2 \times Z}{CW_3} \quad (50)$$

where

$$P_w = \min(CW_7 \times \frac{SEW}{SRW} \times AF \times (1 + CW_6) \times DPLS, CW_8 \times \frac{SEW}{SRW} \times AF \times (1 + CW_6) \times ME_w) \quad (49)$$

$$AF = CW_5 + (1 - CW_5) \times (1 - \exp(-CW_{12} \times age)) \quad (51)$$

$$ME_w = \max(0, MEI_{total} - (ME_l + ME_c)) \quad (52)$$

$$DPLS = D_{udp} \times UDPI + DPLS_{mcp} \quad (53)$$

where

$$D_{udp} = \max(CA_1, \min(CA_3 \times CPI_f - CA_4, CA_2)) \quad (54)$$

$$UDPI = CPI_f - RDPI_f \quad (55)$$

$$DPLS_{mcp} = CA_6 \times CA_7 \times RDPR \quad (56)$$

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Appendix 1. Required model parameters and definitions

Table 1. Required parameters in the site parameter table, giving parameters that are characteristic of a site. The site parameter table is linked spatially to the site spatial index raster through the integer field called “site”.

Parameter	Definition	Valid values
site	Site label matching value in site spatial index raster	integer
adep_10	depth of soil layer 10 (cm)	
adep_2	depth of soil layer 2 (cm)	
adep_3	depth of soil layer 3 (cm)	
adep_4	depth of soil layer 4 (cm)	
adep_5	depth of soil layer 5 (cm)	
adep_6	depth of soil layer 6 (cm)	
adep_7	depth of soil layer 7 (cm)	
adep_8	depth of soil layer 8 (cm)	
adep_9	depth of soil layer 9 (cm)	
agppa	intercept parameter in the equation estimating potential aboveground biomass production for calculation of root/shoot ratio (g/m ² /y)	
agppb	slope parameter in the equation estimating potential above ground biomass production for calculation of root/shoot ratio (g/m ² /y/cm) NOTE - agppb is multiplied by annual precipitation (cm)	
aneref_1	ratio of rain/potential evapotranspiration below which there is no negative impact of soil anaerobic conditions on decomposition	
aneref_2	ratio of rain/potential evapotranspiration above which there is maximum negative impact of soil anaerobic conditions on decomposition	
aneref_3	minimum value of the impact of soil anaerobic conditions on decomposition; functions as a multiplier for the maximum decomposition rate	
animpt	slope term used to vary the impact of soil anaerobic conditions on decomposition flows to the passive soil organic matter pool	
awtl_1	weighting factor for transpiration loss for layer 1; indicates which fraction of the available water can be extracted by the roots	
awtl_10	weighting factor for transpiration loss for layer 10; indicates which fraction of the available water can be extracted by the roots	

awtl_2	weighting factor for transpiration loss for layer 2; indicates which fraction of the available water can be extracted by the roots	
awtl_3	weighting factor for transpiration loss for layer 3; indicates which fraction of the available water can be extracted by the roots	
awtl_4	weighting factor for transpiration loss for layer 4; indicates which fraction of the available water can be extracted by the roots	
awtl_5	weighting factor for transpiration loss for layer 5; indicates which fraction of the available water can be extracted by the roots	
awtl_6	weighting factor for transpiration loss for layer 6; indicates which fraction of the available water can be extracted by the roots	
awtl_7	weighting factor for transpiration loss for layer 7; indicates which fraction of the available water can be extracted by the roots	
awtl_8	weighting factor for transpiration loss for layer 8; indicates which fraction of the available water can be extracted by the roots	
awtl_9	weighting factor for transpiration loss for layer 9; indicates which fraction of the available water can be extracted by the roots	
bgppa	intercept parameter in the equation estimating potential below ground biomass production for calculation of root/shoot ratio (g/m ² /y)	
bgppb	slope parameter in the equation estimating potential below ground biomass production for calculation of root/shoot ratio (g/m ² /y) NOTE - bgppb is multiplied by annual precipitation (cm)	
damr_1_1	fraction of surface N absorbed by residue	0 - 1
damr_1_2	fraction of surface P absorbed by residue	0 - 1
damr_2_1	fraction of soil N absorbed by residue	0 - 1
damr_2_2	fraction of soil P absorbed by residue	0 - 1
damrmn_1	minimum C/N ratio allowed in residue after direct absorption	
damrmn_2	minimum C/P ratio allowed in residue after direct absorption	
dec1_1	maximum surface structural decomposition rate, the fraction of the pool that turns over each year	
dec1_2	maximum soil structural decomposition rate, the fraction of the pool that turns over each year	
dec2_1	maximum surface metabolic decomposition rate, the fraction of the pool that turns over each year	
dec2_2	maximum soil metabolic decomposition rate, the fraction of the pool that turns over each year	
dec3_1	maximum decomposition rate of surface organic matter with active turnover, the fraction of the pool that turns over each year	

dec3_2	maximum decomposition rate of soil organic matter with active turnover, the fraction of the pool that turns over each year	
dec_4	maximum decomposition rate of soil organic matter with slow turnover, the fraction of the pool that turns over each year	
dec5_1	maximum decomposition rate of surface organic matter with intermediate turnover, the fraction of the pool that turns over each year	
dec5_2	maximum decomposition rate of soil organic matter with intermediate turnover, the fraction of the pool that turns over each year	
deck5	available soil water content at which shoot and root death rates are half maximum (cm)	
drain	the fraction of excess water lost by drainage; indicates whether a soil is sensitive for anaerobiosis (drain = 0) or not (drain = 1)	0 - 1
edepth	depth of the single soil layer where C, N, and P are calculated	
elitst	effect of litter on soil temperature relative to live and standing dead biomass	
epnfa_1	intercept value for determining the effect of annual precipitation on atmospheric N fixation (wet and dry deposition) (g/m ² /y/cm precip)	0 - 9999
epnfa_2	slope value for determining the effect of annual precipitation on atmospheric N fixation (wet and dry deposition) (g/m ² /yr/cm precip)	0 - 1
epnfs_1	minimum AET value used for determining the effect of annual evapotranspiration on non-symbiotic soil N fixation (cm)	0 - 9999
epnfs_2	intercept value for determining the effect of annual evapotranspiration non-symbiotic soil N fixation (g/m ² /yr/cm aet)	0 - 9999
favail_1	fraction of N available per month to plants	0 - 1
favail_4	minimum fraction of P available per month to plants	0 - 1
favail_5	maximum fraction of P available per month to plants	0 - 1
favail_6	mineral N in surface layer corresponding to maximum fraction of P available (g/m ²)	0 - 1
fleach_1	intercept value for a normal month to compute the fraction of mineral N and P which will leach to the next layer there is a saturated water flow; normal leaching is a function of sand content	
fleach_2	slope value for a normal month to compute the fraction of mineral N and P which will leach to the next layer there is a saturated water flow; normal leaching is a function of sand content	
fleach_3	leaching fraction multiplier for N to compute the fraction of mineral N which will leach to the next layer when there is saturated water flow; normal leaching is a function of sand content	0 - 1

fleach_4	leaching fraction multiplier for P to compute the fraction of mineral P which will leach to the next layer when there is saturated water flow; normal leaching is a function of sand content	0 - 1
fracro	the fraction of the monthly rainfall, over PRECRO, which is lost via runoff	0 - 1
fwloss_1	scaling factor for interception and evaporation of precipitation by live and standing dead biomass	0 - 1
fwloss_2	scaling factor for bare soil evaporation of precipitation	0 - 1
fwloss_3	scaling factor for transpiration water loss	
fwloss_4	scaling factor for potential evapotranspiration	
gremb	grazing effect multiplier for grzeff types 4, 5, 6	
minlch	critical water flow for leaching of minerals (cm of H2O leached below 30 cm soil depth)	
nlayer	number of soil layers in water model (maximum of 9); used only to calculate the amount of water available for survival of the plant	1 - 9
omlech_1	intercept for the effect of sand on leaching of organic compounds	
omlech_2	slope for the effect of sand on leaching of organic compounds	
omlech_3	the amount of water that needs to flow out of water layer to leach organic C at the maximum rate (cm/month)	
p1co2a_1	intercept parameter which controls flow from surface organic matter with fast turnover to CO2 (fraction of C lost to CO2 when there is no sand in the soil)	
p1co2a_2	intercept parameter which controls flow from soil organic matter with fast turnover to CO2 (fraction of C lost to CO2 when there is no sand in the soil)	
p1co2b_1	slope parameter which controls flow from surface organic matter with fast turnover to CO2 (slope is multiplied by the fraction sand content of the soil)	
p1co2b_2	slope parameter which controls flow from soil organic matter with fast turnover to CO2 (slope is multiplied by the fraction sand content of the soil)	
p2co2_1	controls flow from surface organic matter with intermediate turnover to CO2 (fraction of C lost as CO2 during decomposition)	
p2co2_2	controls flow from soil organic matter with intermediate turnover to CO2 (fraction of C lost as CO2 during decomposition)	
p3co2	controls flow from soil organic matter with slow turnover rate to CO2 (fraction of C lost as CO2 during decomposition)	
pabres	amount of residue which will give maximum direct absorption of N (gC/m2)	

pcemic1_1_1	maximum C/N ratio for surface microbial pool
pcemic1_1_2	maximum C/P ratio for surface microbial pool
pcemic1_2_1	minimum C/N ratio for surface microbial pool
pcemic1_2_2	minimum C/P ratio for surface microbial pool
pcemic1_3_1	minimum N content of decomposing aboveground material, above which the C/N ratio of the surface microbes equals pcemic1(2,*)
pcemic1_3_2	minimum P content of decomposing aboveground material, above which the C/P ratio of the surface microbes equals pcemic1(2,*)
pcemic2_1_1	maximum C/N ratio for surface intermediate pool
pcemic2_1_2	maximum C/P ratio for surface intermediate pool
pcemic2_2_1	minimum C/N ratio for surface intermediate pool
pcemic2_2_2	minimum C/P ratio for surface intermediate pool
pcemic2_3_1	minimum N content of decomposing aboveground material, above which the C/N ratio of the surface intermediate pool equals pcemic2(2,*)
pcemic2_3_2	minimum P content of decomposing aboveground material, above which the C/P ratio of the surface intermediate pool equals pcemic2(2,*)
peftxa	intercept parameter for regression equation to compute the effect of soil texture on the microbe decomposition rate (the effect of texture when there is no sand in the soil)
peftxb	slope parameter for the regression equation to compute the effect of soil texture on the microbe decomposition rate; the slope is multiplied by the sand content fraction
pligst_1	effect of lignin on surface structural or fine branch and large wood decomposition
pligst_2	effect of lignin on soil structural or coarse root decomposition
pmco2_1	surface; controls flow from surface metabolic to CO ₂ (fraction of C lost as CO ₂ during decomposition)
pmco2_2	soil; controls flow from soil metabolic to CO ₂ (fraction of C lost as CO ₂ during decomposition)

pmnsec_1	slope for N; controls the flow from mineral to secondary N (/yr)	
pmnsec_2	slope for P; controls the flow from mineral to secondary P (/yr)	
pmntmp	effect of biomass on minimum surface temperature	
	maximum dead biomass (standing dead + 10% litter) level for soil temperature calculation and for calculation of the potential negative effect on plant growth of physical obstruction by standing dead and litter	
pmxbio		
pmxtmp	effect of biomass on maximum surface temperature	
pparmn_1	fraction of parent material that flows to mineral N	
pparmn_2	fraction of parent material that flows to mineral P	
pprpts_1	the minimum ratio of available water to PET which would completely limit production assuming WC = 0	0 - 1
pprpts_2	the effect of WC on the intercept, allows the user to increase the value of the intercept and thereby increase the slope of the line	
pprpts_3	the lowest ratio of available water to PET at which there is no restriction on production	0 - 1
precro	the amount of monthly rainfall required in order for runoff to occur	
pslco2_1	surface; controls amount of CO2 loss when structural decomposes to som1	
pslco2_2	soil; controls amount of CO2 loss when structural decomposes to som1	
psls3_1	intercept for the effect of clay on the control for the flow from soil organic matter with fast turnover to som with slow turnover (fraction of C from som1c to som3c)	
psls3_2	slope for the effect of clay on the control for the flow soil organic matter with fast turnover to som with slow turnover (fraction of C from som1c to som3c)	
ps2s3_1	intercept value which controls flow from soil organic matter with intermediate turnover to soil organic matter with slow turnover (fraction of C from som2c to som3c)	
ps2s3_2	slope value which controls flow from soil organic matter with intermediate turnover to soil organic matter with slow turnover (fraction of C from som2c to som3c)	
psecmn_1	controls the flow from secondary to mineral N	
psecmn_2	controls the flow from secondary to mineral P	
psecoc1	controls the flow from secondary to occluded P	
psecoc2	controls the back flow from occluded to secondary P	
pslsrb	slope term which controls the fraction of mineral P that is labile	1 - 1

rad1p_1_1	intercept used to calculate addition term for C/N ratio of slow SOM formed from surface active pool	
rad1p_1_2	intercept used to calculate addition term for C/P ratio of slow SOM formed from surface active pool	
rad1p_2_1	slope used to calculate addition term for C/N ratio of slow SOM formed from surface active pool	
rad1p_2_2	slope used to calculate addition term for C/P ratio of slow SOM formed from surface active pool	
rad1p_3_1	minimum allowable C/N used to calculate addition term for C/N ratio of slow SOM formed from surface active pool	
rad1p_3_2	minimum allowable C/P used to calculate addition term for C/P ratio of slow SOM formed from surface active pool	
rcestr_1	C/N ratio for structural material (fixed parameter value)	
rcestr_2	C/P ratio for structural material (fixed parameter value)	
rictrl	root impact control term; used for calculating the impact of root biomass on nutrient availability	
riint	root impact intercept; used for calculating the impact of root biomass on nutrient availability	
rsplig	fraction of lignin flow (in structural decomposition) lost as CO ₂	0 - 1
sorpmx	maximum P sorption potential for a soil	100 - 100
spl_1	intercept parameter for metabolic (vs. structural) split	0 - 1
spl_2	slope parameter for metabolic split (fraction metabolic is a function of lignin to N ratio)	0 - 1
strmax_1	maximum amount of structural material in surface layer that will decompose (gC/m ²)	
strmax_2	maximum amount of structural material belowground that will decompose (gC/m ²)	
teff_1	x location of inflection point, for determining the temperature component of DEFAC, the decomposition factor	
teff_2	y location of inflection point, for determining the temperature component of DEFAC, the decomposition factor	
teff_3	step size (distance from the maximum point to the minimum point), for determining the temperature component of DEFAC, the decomposition factor	
teff_4	slope of line at inflection point, for determining the temperature component of DEFAC, the decomposition factor	
tmelt_1	minimum temperature above which at least some snow will melt	

tmelt_2	ratio between degrees above the minimum and cm of snow that will melt
varat1_1_1	maximum C/N ratio for material entering som1
varat1_1_2	maximum C/P ratio for material entering som1
varat1_2_1	minimum C/N ratio for material entering som1
varat1_2_2	minimum C/P ratio for material entering som1
varat1_3_1	amount N present when minimum ratio applies
varat1_3_2	amount P present when minimum ratio applies
varat21_1_1	maximum C/N ratio for material entering surface som2
varat21_1_2	maximum C/P ratio for material entering surface som2
varat21_2_1	minimum C/N ratio for material entering surface som2
varat21_2_2	minimum C/P ratio for material entering surface som2
varat21_3_1	amount N present when minimum ratio applies
varat21_3_2	amount P present when minimum ratio applies
varat22_1_1	maximum C/N ratio for material entering soil som2
varat22_1_2	maximum C/P ratio for material entering soil som2
varat22_2_1	minimum C/N ratio for material entering soil som2
varat22_2_2	minimum C/P ratio for material entering soil som2
varat22_3_1	amount N present when minimum ratio applies
varat22_3_2	amount P present when minimum ratio applies
varat3_1_1	maximum C/N ratio for material entering som3
varat3_1_2	maximum C/P ratio for material entering som3
varat3_2_1	minimum C/N ratio for material entering som3
varat3_2_2	minimum C/P ratio for material entering som3
varat3_3_1	amount N present when minimum ratio applies
varat3_3_2	amount P present when minimum ratio applies
vlossg	multiplier for equation to compute volatilization loss that occurs as a function of gross mineralization

Table 2. Required parameters in the plant functional type (PFT) parameter table, giving parameters that are characteristic of a PFT. This table must contain an integer field called “PFT” that corresponds to PFT identifiers in the filenames of PFT fractional cover rasters.

Parameter	Definition	Valid values
PFT	PFT label matched to filename of fractional cover raster	integer 0 (C3 grass), 0.16 (C4 grass)
species_factor	Coefficient distinguishing C3 from C4 grasses	
digestibility_slope	Slope of linear regression predicting dry matter digestibility (%) from crude protein content (%)	
digestibility_intercept	Intercept of linear regression predicting dry matter digestibility (%) from crude protein content (%)	0 - 1
biok5	level of aboveground standing dead + 10% strucc_1 C at which production is reduced to half maximum due to physical obstruction by the dead material (gC/m ²)	0 - 2000
biomax	biomass level above which the minimum and maximum C/iel ratios of the new shoot increments equal pramn_<iel>_2 and pramx_<iel>_2 respectively (g biomass/m ²)	0 - 1000
cfrtcn_1	maximum fraction of C allocated to roots under maximum nutrient stress	0 - 1
cfrtcn_2	minimum fraction of C allocated to roots with no nutrient stress	0 - 1
cfrtcw_1	maximum fraction of C allocated to roots under maximum water stress	0 - 1
cfrtcw_2	minimum fraction of C allocated to roots with no water stress	0 - 1
claypg	number of soil layers used to determine water and mineral N and P that are available for crop growth	1 - 9
cmix	number of soil layers used to determine water and mineral N and P that are available for crop growth	0 - 1
crprtf_1	fraction of N transferred to a vegetation storage pool from grass/crop leaves at death	0 - 1
crprtf_2	fraction of P transferred to a vegetation storage pool from grass/crop leaves at death	0 - 1
fallrt	fall rate (fraction of standing dead which falls each month)	0 - 1

fligni_1_1	intercept for equation to predict lignin content fraction based on annual rainfall for aboveground material	0 - 1
fligni_1_2	intercept for equation to predict lignin content fraction based on annual rainfall for belowground material	0 - 1
fligni_2_1	slope for equation to predict lignin content fraction based on annual rainfall for aboveground material	0 - 1
fligni_2_2	slope for equation to predict lignin content fraction based on annual rainfall for belowground material	0 - 1
frtcindx	plant growth type = 0 use Great Plains equation = 1 perennial plant	0; 1; 2
fsdeth_1	maximum shoot death rate at very dry soil conditions (fraction/month); for getting the monthly shoot death rate, this fraction is multiplied times a reduction factor depending on the soil water status	0 - 1
fsdeth_2	fraction of shoots which die during senescence month	0.4 - 1
fsdeth_3	additional fraction of shoots which die when aboveground live C is greater than fsdeth_4	0 - 1
fsdeth_4	the level of aboveground C above which shading occurs and shoot senescence increases	0 - 500
nlaypg	number of soil layers in the top level of the water model; determines avh2o_1, used for growth and root death	1 - 10
ppdf_1	optimum temperature for production for parameterization of a Poisson Density Function curve to simulate temperature effect on growth	10 - 40
ppdf_2	maximum temperature for production for parameterization of a Poisson Density Function curve to simulate temperature effect on growth	20 - 50
ppdf_3	left curve shape for parameterization of a Poisson Density Function curve to simulate temperature effect on growth	0 - 1
ppdf_4	right curve shape for parameterization of a Poisson Density Function curve to simulate temperature effect on growth	0 - 10
pramn_1_1	minimum C/N ratio with zero biomass	1 - 100
pramn_1_2	minimum C/N ratio with biomass greater than or equal to biomax	1 - 200
pramn_2_1	minimum C/P ratio with zero biomass	1 - 9999
pramn_2_2	minimum C/P ratio with biomass greater than or equal to biomax	1 - 9999
pramx_1_1	maximum C/N ratio with zero biomass	1 - 200

pramx_1_2	maximum C/N ratio with biomass greater than or equal to biomax	1 - 400
pramx_2_1	maximum C/P ratio with zero biomass	1 - 9999
pramx_2_2	maximum C/P ratio with biomass greater than or equal to biomax	1 - 9999
prbmn_1_1	intercept parameter for computing minimum C/N ratio for below ground matter as a linear function of annual precipitation	0 - 150
prbmn_1_2	slope parameter for computing minimum C/N ratio for below ground matter as a linear function of annual precipitation	0 - 1
prbmn_2_1	intercept parameter for computing minimum C/P ratio for below ground matter as a linear function of annual precipitation	0 - 9999
prbmn_2_2	slope parameter for computing minimum C/P ratio for below ground matter as a linear function of annual precipitation	0 - 1
prbmx_1_1	intercept parameter for computing maximum C/N ratios for below ground matter as a linear function of annual precipitation	0 - 300
prbmx_1_2	slope parameter for computing maximum C/N ratios for below ground matter as a linear function of annual precipitation	0 - 1
prbmx_2_1	intercept parameter for computing maximum C/P ratios for below ground matter as a linear function of annual precipitation	0 - 9999
prbmx_2_2	slope parameter for computing maximum C/P ratios for below ground matter as a linear function of annual precipitation	0 - 1
prdx_1	coefficient for calculating potential aboveground monthly production as a function of solar radiation outside the atmosphere	? - ?
rdr	maximum root death rate at very dry soil conditions (fraction/month); for getting the monthly root death rate, this fraction is multiplied times a reduction factor depending on the soil water status	0 - 1
rtdtmp	physiological shutdown temperature for root death and change in shoot/root ratio	-5 - 5
snfxmx_1	symbiotic N fixation maximum for grassland/crop (g N fixed/g C new growth)	0 - 1

vlossp	fraction of aboveground plant N which is volatilized at senescence	0 - 1
senescence_month	month in which senescence occurs	1 - 12
		integers in [1 - 12], in the format
growth_months	months in which growth occurs	[1, 2, 3]

Table 3. Required input parameters in the animal parameter table. Values in this table are linked to the spatial location of grazing animals by the integer field called “animal_id” that should match values in the field “animal_id” of the grazing areas polygon layer. See main text for explanation of the “grzeff” parameter, which controls the relationship between grazing intensity and altered root:shoot ratio and aboveground production.

Parameter	Definition	Valid values
animal_id	Integer animal label matched to “animal_id” field in management polygon layer	integer Bos indicus ('b_indicus', default), Bos taurus ('b_taurus'), Bos indicus * taurus cross ('indicus_x_taurus'), sheep or goat ('sheep'), camelid ('camelid'), hindgut fermenter ('hindgut_fermenter')
type	General breed / animal type	
birth_weight	Weight at birth (kg)	
sex	Sex	Entire male ('entire_m'), castrate male ('castrate'), breeding female ('breeding_female'), non-breeding female (default)
age	Current age (days)	
weight	Current weight (kg)	
SRW	Standard reference weight: weight of mature female in median condition (kg)	
SFW	Standard fleece weight (for sheep and goats): average weight of fleece (kg)	
conception_month	Conception month (for breeding females)	Month relative to model starting month (may be negative; must be smaller than calving interval)
calving_interval	Calving interval (for breeding females) (months)	
lactation_duration	Lactation duration (for breeding females) (months)	
fecf_1	fraction of excreted N which goes into feces (rest goes into urine)	0 - 1
fecf_2	fraction of excreted P which goes into feces (rest goes into urine)	0 - 1
feclig	lignin content of feces	0 - 1

gfcret	fraction of consumed C which is excreted in feces and urine	0 - 1
gret_1	fraction of consumed N which is excreted in feces and urine (should take into account N losses due to leaching or volatilization from the manure)	0 - 1
gret_2	fraction of consumed P which is excreted in feces and urine (should take into account P losses due to leaching or volatilization from the manure)	0 - 1
grzeff	effect of grazing on production (see text)	0; 1; 2; 3; 4; 5
