CNGRAS

A dynamic simulation model for grassland management and
C and N flows at field scale

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1.   Introduction

Grassland is by far the most extended form of agricultural land use in Europe. In many countries it occupies more than 40% of total agricultural land, even up to 90% in Ireland (Conijn *et al.*, 2002). Farmers use grassland for the production of animal feed, in particular for ruminant species kept for milk or meat production. Because grass is an important fraction of the ration, grass production is an indispensable economic factor in today's animal (ruminant) production sector. On the other hand, due to its large area, grassland also plays a major role in many environmental issues that are related to agricultural activities, such as carbon sequestration, climate change, water balance, nitrate pollution, erosion, biodiversity, etc. The increasing concern over the last few decades about the adverse effects of agricultural activities on the environment increased government interference (local, national and international) with grassland management by imposing various restrictions in order to protect the human population and the environment.

Some examples that apply to grassland in the Netherlands are: restrictions on the use of irrigation water in drought-sensitive areas, regulations on the use of animal manure and total fertilisation, restrictions on timing of management such as manure application and grassland renovation, etc. Many of these restrictions will not only have an effect on the environment, but undoubtedly also on grassland productivity. However, the relation between abiotic conditions, grassland productivity/management and environmental quality is very complex and many questions remain with respect to the (long-term) effects of the restrictions.

A sustainable balance between grass production and the environment requires a thorough understanding of grassland and grass production in relation to water and nutrient cycling (carbon, nitrogen, phosphorus, etc.). This is an ongoing task for farmers, scientists and society in an ever-changing production situation, e.g., due to climate change, technical innovations, or simply by applying new management rules. Grassland models may help with this task because such models can improve our understanding of the system and are a practical tool for establishing effective management rules. Models should be used in addition to experiments, which are needed to provide the basic relationships. However, experiments are always time- and location-specific, whereas models, if sufficiently tested, can be used to increase the scope and applicability of experimental results.

In the past, many experiments and modelling work focused on the harvestable part of grass production, which is only part of the whole grassland ecosystem (see, e.g., Lantinga, 1985; Van Loo, 1993; Deenen, 1994; Hofstede 1995a&b; Hofstede *et al.*, 1995; Ten Berge *et al.*, 2000). The other part, i.e., the non-harvestable production, has received less attention in this research. However, this non-harvestable part is comparable in size to the harvested part of total production or total uptake. Corré & Conijn (2004), e.g., estimated from various sources that the non-harvested nitrogen uptake of productive grasslands amounts to 245-300 kg N ha^{-1} per year. This amount is incorporated into the soil in an organic form through death of plant parts (roots and stubbles) and harvesting losses, and affects many of the environmental issues mentioned above, in particular when the system is not in equilibrium. The notion that the non-harvested part is important has lead to a specifc research project in the 1990s to investigate the role of the non-harvestable parts in the N balance of grassland (carried out by the Grassland Department of CABO, a former research institute in Wageningen, now merged into Plant Research International). Development of a grassland model for the field scale was started in this project; part of this model is described in this report. Unlike many other models on grassland productivity, this model should explicitly incorporate the 'hidden' part of total grass production and nutrient uptake.

The grassland model was aimed to be used for answering questions related to grassland productivity, effects of water shortage or surplus, greenhouse gas dynamics (emissions or immissions of CO_2 and N_2O), short-term and long-term changes in soil fertility and nitrate leaching. The model in its present version should therefore integrate the key processes related to the carbon, nitrogen and water balance in the grassland ecosystem, not only because these processes interact strongly, but also because effects of management, weather and soils must be evaluated simultaneously for all issues to prevent swapping one problem for another. Moreover, the model should be applicable to situations from the past, but also to future scenario analyses when conditions may be different from

today (e.g., different climatic conditions). Special attention is needed for incorporating various management options into the model in order to mimick closely the actual management (as practised today on production grasslands) and possible alternatives. These requirements resulted in a dynamic model, operating with small time steps (e.g., one day) for simulation of the effects of (daily) weather/climate conditions and grassland management. But the model is also suitable for use on a time scale of several decades to simulate long-term effects.

A general description of the five components of the grassland model and their interactions is given in Chapter 2. Possibilities for coupling various components into a grassland model, including some references of applications are given. Chapter 3 contains a detailed description of two of the five components, explaining the basic equations which are used in the grass growth calculations with respect to dry matter (carbon), nitrogen and water. Production/uptake, partitioning and senescence/death of plant parts are the key processes that are simulated. It also includes the equations on harvesting via cutting and grazing. Some examples of applications of the grassland model in recent years are given in Chapter 4.

2. General features

The grassland model consists of five main components, in which the calculations on carbon, nitrogen and water cycling in the grassland ecosystem are performed. These are: (1) grass production, (2) grassland management, (3) soil organic carbon and nitrogen, (4) soil inorganic nitrogen, and (5) soil water balance (Table 2.1).

Table 2.1.   *The five components of the grassland model with their main processes and outputs.*

	Component	Main processes	Main outputs
1.	Grass production	Dry matter, carbon and nitrogen cycling within the grass vegetation	Amount of gross CO_2 fixation, harvestable grass dry matter and grass nitrogen
2.	Grassland management	Fertilisation, harvesting and irrigation on the grass-soil system	Gross and net grass dry matter and nitrogen yields, and nitrogen and water inputs into the soil system
3.	Soil organic carbon and nitrogen	Organic matter decomposition, carbon and nitrogen mineralisation	Amount of CO_2 production, inorganic nitrogen supply through mineralisation and amount of organic carbon and nitrogen in the soil
4.	Soil inorganic nitrogen	Transformations and flows of inorganic nitrogen in the soil and across the boundaries of the soil system	Soil inorganic nitrogen content and nitrogen losses through NO_3 leaching and denitrification, including N_2O emission
5.	Soil water balance	Water flows in the soil and across the boundaries of the soil system	Soil water content and net water supply to groundwater and surface water

General descriptions of the five components are given in Sections 2.1-2.4 and the main interactions between the five components are listed in Appendix II.

2.1   Grass production

CNGRAS calculates the dry matter, carbon and nitrogen dynamics in grass biomass on a daily basis as a function of weather and soil conditions, management and various characteristics of the grass species. Four plant compartments are distinguished: root, stem, leaf and a reserve pool (Figure 2.1). Increase in root, stem and leaf biomass follows from the partitioning of newly produced dry matter among these plant compartments and relocation from the reserve pool. Dry matter production depends on the amount of radiation absorbed by the green leaf area index and is influenced by air temperature, leaf nitrogen content and transpiration status. Relocation of dry matter from the reserve pool may also contribute to the growth of roots, leaves and stems. This is mainly calculated shortly after a harvest, when temperatures favourable for growth coincide with low production rates due to the recent defoliation.
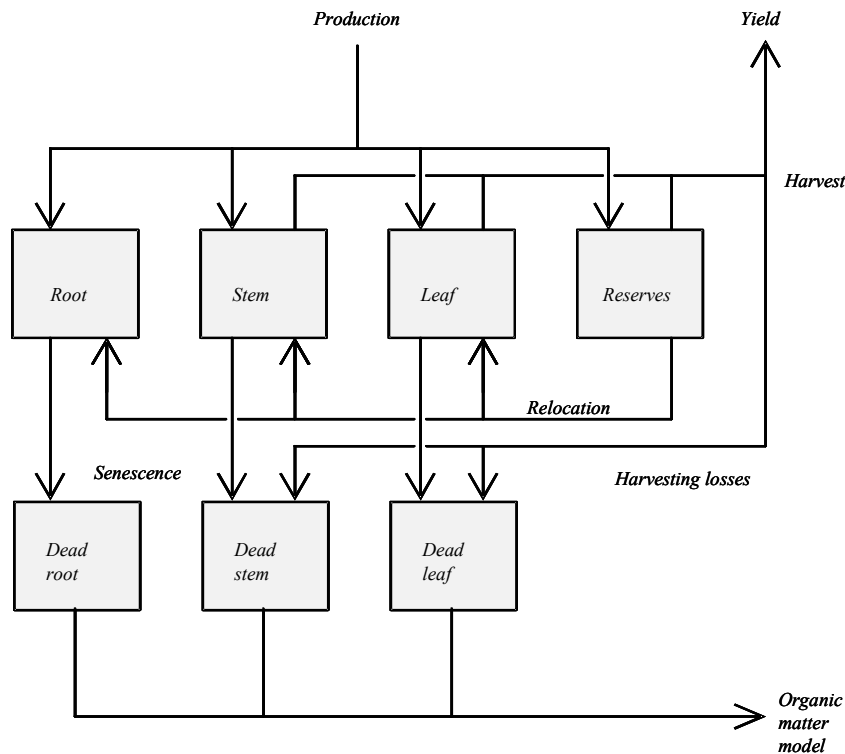
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Figure 2.1.   The four plant biomass compartments (root, stem, leaf and reserves) and their main flows in modelling grass dry matter dynamics in CNGRAS.

Decrease in root, leaf and stem dry matter occurs through senescence and cutting or grazing. Root, stem and leaf death rates due to senescence are calculated continuously as a function of temperature and water stress (root) and temperature, leaf area index, water and nitrogen stress (stem and leaf). The death rates are added to pools of dead root, stem and leaf dry matter, which are input for the soil organic matter model. Due to harvesting activities, a decrease is calculated in the stem, leaf and reserve biomass pools with different functions for determining these decrease rates in case of cutting or grazing. Total decrease is partitioned between (a) offtake (net yield), which is removed from the field in case of cutting or taken in by the grazing animals, and (b) harvesting losses, remaining at the field and which are added to the pools of dead stems and leaves. Carbon dynamics of the grass sward have been correlated to the dry matter dynamics by applying coefficients for the conversion of dry matter units into carbon units. Sections 3.1 and 3.2 of this report contain detailed descriptions of the process equations.

For the partitioning of nitrogen, only three plant compartments have been used, i.e., root, stem and leaf, because nitrogen available for relocation is assumed to be part of the total amount of nitrogen in root, stem and leaf (Figure 2.2). The amount of inorganic nitrogen taken up from the soil has been modelled as a function of nitrogen demand, which depends on the difference between attainable and actual nitrogen contents in each plant compartment. Demand is corrected for the relocation of nitrogen from senescencing plant parts. The total amount of nitrogen available for partitioning among the three plant compartments is given by the sum of the soil nitrogen uptake rate and the nitrogen relocation rates from each plant compartment.
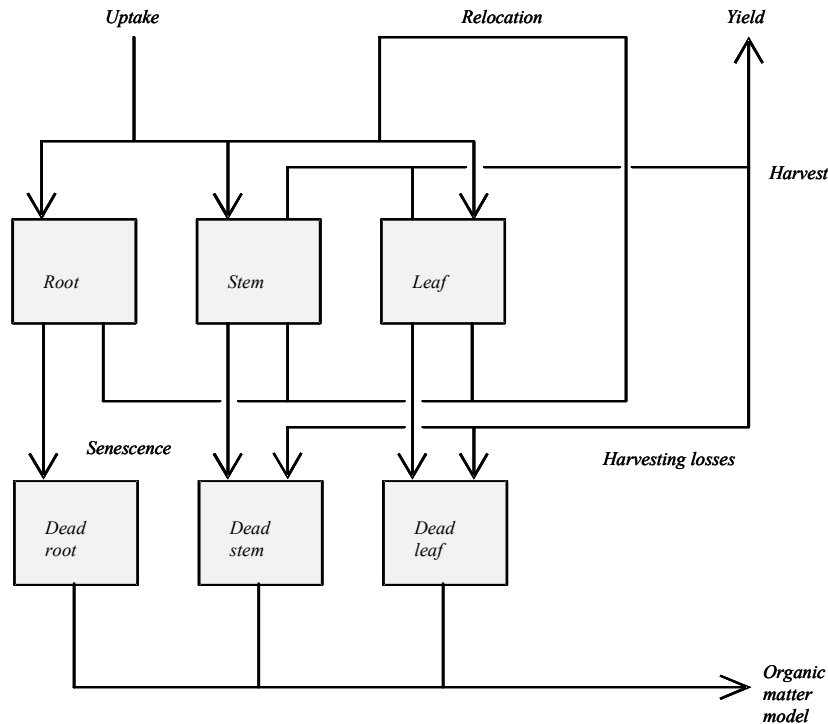
Figure 2.2. The three plant biomass compartments (root, stem and leaf) and their main flows in modelling grass nitrogen dynamics in CNGRAS.

Loss rates of nitrogen due to death of roots, stems and leaves have been modelled parallel to the dry matter decrease rates. They are added to the pools of dead root, stem and leaf nitrogen, which are input for the soil organic matter model. Nitrogen concentrations in senescencing plant parts are generally lower than those in younger tissue, which indicates that nitrogen is withdrawn or relocated before abscission. This process is simulated in CNGRAS and contributes to the internal supply of nitrogen for partitioning within the plant. Harvesting decreases the nitrogen contents in stems and leaves and again a partitioning between net yield and losses is made. Nitrogen concentrations, e.g., amount of leaf nitrogen per unit leaf dry matter, are dynamically computed for all living and dead plant compartments. They are not constant and may vary depending on the growing conditions. In CNGRAS low nitrogen concentrations in leaf tissue negatively affect dry matter production, change the partitioning of dry matter in favour of the roots, and accelerate the senescence of the aboveground plant parts. Section 3.3 of this report contains detailed descriptions of the process equations.

2.2   Grassland management

The effects of grassland management on grass production, soil nitrogen and soil water balance are modelled in CNGRAS. Special feature of production grassland as compared with most other agricultural plant production systems is the frequent defoliation by cutting or grazing within one growing season. On Dutch dairy farms, grassland is harvested 4 to 8 times per year and the same field may be grazed and cut several times within one year. Also other management activities may occur frequently within one year, such as fertilisation and irrigation. In developing CNGRAS considerable attention has been paid to a flexible input system for the model related to these various grassland management options. The model user can (through the management input file) enter a different set of input parameters for each harvest, which ensures maximum flexibility of the model. A set of inputs is used to determine the following management aspects related to periodic harvesting:

a. timing of harvesting (day of the year or at a certain dry matter yield),
b. harvesting method (cutting or grazing),
c. maximum herbage dry matter intake (in case of grazing),
d. number of grazing days or field days (in case of cut grass drying on the field),
e. harvesting losses that remain at the field,
f. timing of fertilisation (day of the year),
g. amount and type of nitrogen fertilisation (as ammonium, nitrate and organic nitrogen), and
h. amount of N input through grazing animals (excretion) and grassland area affected by urine deposition.

These sets of input parameters for all harvests within one year together constitute the management calendar and define the major management activities for one growing season. The actual management choices for a grassland field on a dairy farm can be mimicked very closely by combining the various options, and various systems can be simulated, such as no grazing, continuous grazing and rotational systems with alternating grazing and cutting. CNGRAS can be used for situations with a known past management calendar (e.g., when comparing model results with observed data) as well as for scenario studies where the timing of management events depends on the actual state of the grassland system which may be different from year to year. Examples of input possibilities related to flexible grassland management are: (1) harvesting when the grass biomass yield or the number of growing days since the last harvest exceeds a threshold value, and (2) removing the animals from a field after a predefined number of grazing days or if the amount of grass drops below the adequate level for grazing.

Fertilisation is defined by the amounts of inorganic (NO_3 and NH_4) and organic nitrogen applied through fertilisation and timing of the application in number of days after the last harvest or since 1 January (only for the first fertiliser application in a year). Different fertiliser types can be used in the model. If organic manure is used, the organic nitrogen is distributed among the pools of soil organic nitrogen, from which nitrogen is released in inorganic form through decomposition of organic matter. The input of the amount of nitrogen applied through fertilisation should be corrected for possible losses due to ammonia volatilisation because this process is not simulated by the grassland management model. The management calendar offers different options for harvesting and fertilisation for each harvest. e.g., a field can be grazed twice in spring at a biomass yield of 1700 kg ha^{-1}, followed by two cuts in summer at 3000 kg ha^{-1} and grazed again one or more times in autumn with a target yield of 1500 kg ha^{-1}. Fertilisation can be adjusted for each growing period to supply the adequate amount of nitrogen for the desired yields.

Information on irrigation can be supplied either by an irrigation calendar, consisting of dates and amounts of water applied, to simulate a known situation or by applying a certain amount of water when grass growth is significantly reduced by water stress or at a certain soil water deficit during the calculations. The latter possibility can be used in scenario studies. The irrigation calendar operates independently of the management calendar, which is based on harvest events.

The grassland management component of the model comprises the following subtasks:
a. determining the days within one growing season at which harvesting takes place, which triggers a number of other events;
b. calculating the amount of harvested grass dry matter and nitrogen as function of the total amount of aboveground biomass and as function of the harvesting method (grazing or cutting), and
c. effectuating all other information on fertilisation, irrigation and urine deposition due to grazing animals into the model calculations (mainly by adding the inputs to the appropriate carbon and nitrogen pools in the model).

Section 3.4 of this report contains detailed descriptions of the process equations of subtask b).

2.3   Soil organic carbon and nitrogen

Soil organic matter level, carbon dynamics and nitrogen mineralisation are important aspects of the functioning of a grassland ecosystem with possibly far-reaching consequences for grassland productivity and environmental quality. The model component on soil organic carbon and nitrogen integrates inputs and outputs of organic carbon and nitrogen in soil organic matter at each time step. Inputs are derived from grass residues, organic fertilisers and faeces deposition during animal grazing, outputs are given by carbon and nitrogen mineralisation, i.e. the transformation of organic C and N into inorganic C and N.

Total organic C and N in the soil is subdivided into three different pools, mainly to account for differences in mineralisation rates between various soil organic matter fractions. Soil biomass, such as living microbes, earthworms, etc. (but excluding plant roots), is not simulated separately, but is included in each organic matter pool. Total organic C and N input from grass residues is partitioned among these pools as a function of the N:C ratio of the organic input. Partitioning of organic fertiliser inputs should be directly supplied by the model user through the management input file for each fertiliser application, which enables the simulation of applying various types of organic fertilisers. Because soil organic matter is found at various depths in the soil, inputs are -for reasons of simplicity- directly distributed over soil depth by using constant distribution functions. Movement of organic matter in the soil is thus not explicitly simulated but is included in the soil depth distribution functions. A separate distribution function is given for each organic matter pool because the relative distribution with soil depth differs among the three soil organic matter pools.

The transformation of organic carbon into CO_2 (carbon mineralisation rate M_C (g C m^{-2} d^{-1})) has been described as a process with first order kinetics (see eqn. 2.3.1). In the model the relative carbon mineralisation rate k (d^{-1}) is influenced by (a) soil temperature, (b) water content in the soil, and (c) clay content of the soil. The nitrogen mineralisation rate M_N (g N m^{-2} d^{-1}) is calculated as a function of k and two other parameters, viz. the microbial growth efficiency e (-) and the C:N ratio of the microbes χ_m (g C g^{-1} N), according to eqn. 2.3.2,

$$M_C = kC_{org} \qquad\qquad\qquad (2.3.1)$$

$$M_N = \frac{k}{1-e}(N_{org} - \frac{eC_{org}}{\chi_m}) \qquad\qquad\qquad (2.3.2)$$

with C_{org} and N_{org} representing the amount of organic carbon and nitrogen in a soil organic matter pool (g C or N m^{-2}), respectively. The same process equations are used in all organic matter pools but with different parameter values. The values of both e and χ_m are assumed constant, but (may) differ between the three organic matter pools.

The process equations on soil carbon and nitrogen dynamics are *not* described in more detail in this report. More information on the theory and application of the equations can be found in Conijn (1995), Bloemhof & Berendse (1995) and Berendse *et al.* (1987, 1989). The model component on soil organic carbon and nitrogen described above has been used in a scenario study to investigate the effects of fertilisation strategies on grass yields and N losses (Conijn & Henstra, 2003).

2.4   Soil inorganic nitrogen and soil water balance

The descriptions of the soil inorganic nitrogen and soil water balance fall outside the scope of this report. It is possible to couple soil models of varying complexity to the other components of the grassland model. Some examples are given below, including some references to more information on those soil models/applications.

Soil inorganic nitrogen

FUSSIM2 (Heinen & De Willigen, 1998, 2001) has been coupled to the first three components of Table 2.1 to calculate the fate of inorganic N in the soil. Four different N forms are distinguished (NH_4, NO_3, N_2O and N_2) and the transformations as well as the flows through the soil and across the soil boundaries are simulated, including plant N uptake. This coupled model has been applied in the study of Conijn & Henstra (2003) and also in a study to investigate the effect of unfertilized buffer strips on the N leaching from grassland to groundwater and surface water (Assinck *et al.*, 2002; Van Beek *et al.*, 2002).

Soil water balance

SWAP (Van Dam *et al.*, 1997) has been combined with the grass production and grassland management components (see Table 2.1) in the Waterpas model (De Vos *et al.*, 2004) and FUSSIM2 (Heinen & De Willigen, 1998; 2001) has been used for the soil water balance in the studies of Conijn & Henstra (2003), Assinck *et al.* (2002) and Van Beek *et al.* (2002). The 2-D version of FUSSIM2 has been used in the buffer strip study, calculating water (and N) flows in two directions: vertically and horizontally in the direction of the buffer strip and the ditch. A simple model on soil water balance has also been coupled; this model uses the 'tipping bucket' concept without explicitly considering capillary rise of soil water.

3. Process modelling

3.1 Grass biomass

State variables

Four compartments are used in describing total grass biomass: leaf laminae (W_{lv}), leaf sheaths and 'true' stems (W_{st}), roots (W_{rt}) and reserves located in leaf sheaths and stems (W_{rs}), all in g dry matter m^{-2}. W_{rs} consists mainly of soluble carbohydrates. Wherever stem biomass is used in this report, it should be read as leaf sheaths and 'true' stems, excluding the reserves in those compartments. The sum of W_{lv}, W_{st} and W_{rs} equals total aboveground biomass. The dry matter content of these plant parts refers to living tissues. Net changes in these compartments are simulated by computing increase, as a result of dry matter production and partitioning, and decrease due to death of plant tissues, relocation and harvesting. Standing dead plant material is not simulated in the present version of the model because dead plant tissues are directly transferred to soil organic matter for reasons of simplicity.

Rate variables

3.1.1 Production

Many researchers have shown that dry matter production is roughly proportional to the amount of radiation absorbed by the crop (e..g, Monteith, 1977; Spitters, 1987; review by Gosse *et al.*, 1986; Nonhebel, 1997). Therefore, net dry matter production rate P (g dry matter m^{-2} d^{-1}) is calculated by

$$P = I_a E_{act} \tag{3.1.1}$$

with I_a the absorbed photosynthetically active radiation at crop level (MJ m^{-2} d^{-1}) and E_{act} the efficiency of using absorbed light for dry matter production (g dry matter MJ^{-1}). Underlying processes, like photosynthesis and respiration, are thus not modelled explicitly, but their net result in terms of dry matter production is given by the variable E_{act} in eqn. 3.1.1. I_a from eqn. 3.1.1 is described by a negative exponential function as a function of leaf area index L (m^2 leaf m^{-2} ground),

$$I_a = (1 - \rho_c) I_p (1 - e^{-k_p L}) \tag{3.1.2}$$

where I_p equals the photosynthetically active radiation PAR (MJ m^{-2} d^{-1}), k_p is the extinction coefficient (m^2 ground m^{-2} leaf) and ρ_c is the canopy reflection coefficient (-). I_p or PAR refers to incoming radiation with wavelengths between 400 and 700 nm, which can be used by the plant in the process of photosynthesis, and equals roughly 50% of the global solar radiation (wavelength range between 300 and 3000 nm; Goudriaan & Van Laar, 1994). Part of I_p (ρ_c) is reflected and cannot be absorbed while another part ($e^{-k_p L}$) is transmitted through the canopy and reaches the soil surface depending on L. Both parts are lost for dry matter production. ρ_c is calculated as a function of the scattering coefficient of individual leaves, σ (-), according to Goudriaan & Van Laar (1994),

$$\rho_c = \frac{1 - \sqrt{1 - \sigma}}{1 + \sqrt{1 - \sigma}} \tag{3.1.3}$$

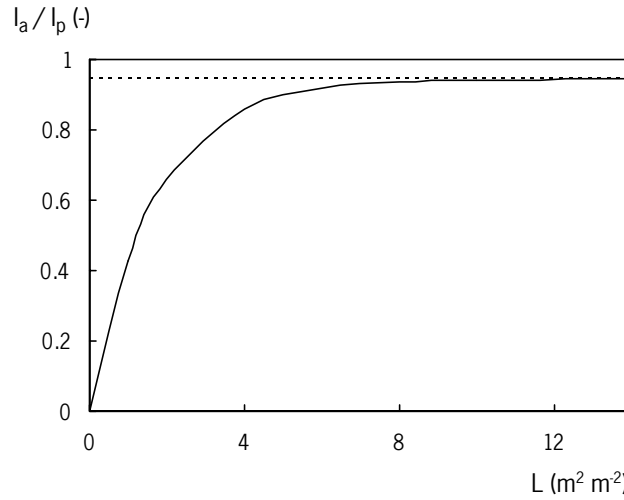Figure 3.1.1 gives a graphical representation of eqn. 3.1.2.

Figure 3.1.1. Fraction absorbed photosynthetically active radiation as function of leaf area index L, according to eqn. 3.1.2 with the parameter values from Table 3.1.1. The dashed horizontal line represents the maximum level that can be absorbed (= 1 − ρ_c).

Light use efficiency E_{act} from eqn. 3.1.1 is calculated in two steps from the maximum light use efficiency E_{max} (g dry matter MJ^{-1}), and the light use efficiency under non-limiting conditions of water and nutrient status in the plant E_{opt} (g dry matter MJ^{-1}). E_{opt} depends on the maximum light use efficiency, day of the year, prevailing temperature and leaf area index L,

$$E_{opt} = f_{d,E} f_{T,E} f_{L,E} E_{max}$$
(3.1.4)

with $f_{d,E}$ (-), $f_{T,E}$ (-) and $f_{L,E}$ (-) factors related to day of the year, temperature and L, respectively. Possible values of each factor range from 0 (E_{opt} = 0) to 1 ($E_{opt} = E_{max}$).

Effect of day of the year

The time course of $f_{d,E}$ (Figure 3.1.2) corresponds with the trend in measured values of light-saturated leaf photosynthesis during the year with high values in spring/early summer and low values in winter, as used by Van Loo (1993), based on Parsons and Robson (1981) and Lantinga (1988). The variation in $f_{d,E}$ is explained by differences in the presence of reproductive versus vegetative tillers and changes in radiation level during the year (Van Loo, 1993). This time trend also holds for the response of leaf photosynthesis at low light intensities (i.e. the initial light use efficiency for leaf photosynthesis according to Lantinga, 1985).

Effect of temperature

The reduction factor due to suboptimal temperature ($f_{T,E}$) does not only comprise the effect of temperature on photosynthesis, but also its effect on respiration and on other growth processes. Therefore, it is modelled as a function of daily average air temperature T_a (°C, see Figure 3.1.3), which is simply computed as the mean of daily minimum and maximum air temperature, T_{min} and T_{max} (°C), by

$$T_a = 0.5(T_{min} + T_{max})$$
(3.1.5)

The response curve of $f_{T,E}$ to air temperature is more or less bell-shaped: $f_{T,E}$ equals zero beyond a lower and a higher threshold value for T_a and between both thresholds $f_{T,E}$ increases from 0 to 1 and decreases again to 0 if T_a approaches the higher threshold value (Figure 3.1.3). This shape is caused by the different responses of photosynthesis and respiration to increasing temperature. Photosynthesis itself also has a bell-shaped response to

temperature, whereas maintenance respiration tends to double for each 10 ^{0}C rise in temperature (Penning de Vries *et al.*, 1989). The overall outcome of both processes is then that beyond the optimum temperature for photosysnthesis, net dry matter production decreases due to increasing respiratory costs. It could be argued that at very high temperatures there will be a net decrease in the amount of dry matter (photosynthesis has stopped, respiration continues), but this is not modelled here because those temperatures do normally not occur in temperate regions, for which the model originally has been developed. $f_{T,E}$ of Figure 3.1.3 reflects a grass species that is adapted to 'cool' temperate regions, where dry matter production is already at its maximum at relatively low temperatures (around 10 ^{0}C for the daily average air temperature).

Figure 3.1.2. Relation between day of the year (1 = January 1st) and $f_{d,E}$ in eqn. 3.1.4. See text for further explanation.

Figure 3.1.3. Relation between daily average air temperature T_a and $f_{T,E}$ in eqn. 3.1.4. See text for further explanation.

Effect of leaf area index

The factor $f_{L,E}$ is introduced in eqn. 3.1.4 to account for the effect of high leaf area indices on dry matter production. At a leaf area index of ca. 4 - 6 (m^2 m^{-2}) the absorption of radiation at canopy level is almost complete (except for the reflected part) and the rate of photosynthesis is at its maximum. Beyond this level, crop

photosynthesis rate is constant but respiration rate still increases with higher L, because maintenance respiration costs are proportional to the amount of biomass (Penning de Vries & Van Laar, 1982; Lövenstein *et al.*, 1992). The result in terms of net dry matter production will therefore decrease with increasing L beyond a threshold level (Figure 3.1.4).
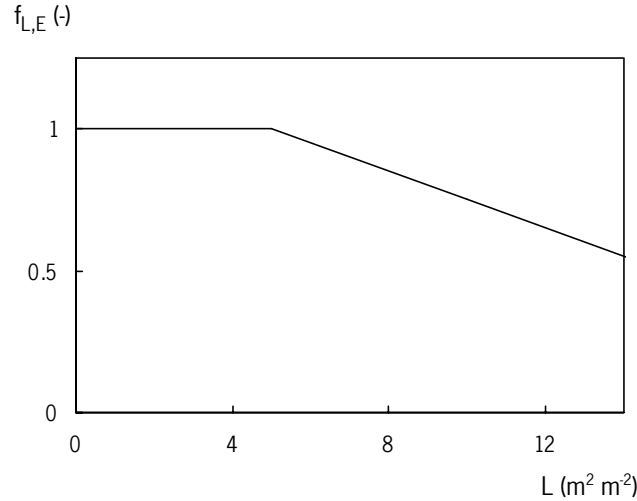

Figure 3.1.4.   Relation between leaf area index L and $f_{L,E}$ in eqn. 3.1.4. See text for further explanation.

E_{opt} from eqn. 3.1.4 refers to light use efficiency at crop level under water and nutrient conditions that are not limiting for plant production. Dry matter production of the grass vegetation is reduced in CNGRAS at water and nutrient conditions that limit plant production. The model calculates effects of water and nitrogen stress on light use efficiency by using two multiplication factors, $f_{w,E}$ (-) for water and $f_{N,E}$ (-) for nitrogen, assuming other nutrients being amply available (see eqn. 3.1.6).

$$E_{act} = f_{w,E} f_{N,E} E_{opt}$$
(3.1.6)

The effects of pests and diseases on E_{act} have not been modelled.

Effect of water

In the process of dry matter production water is lost to the atmosphere via the stomata. Stomata in plants are used for gas exchange: CO_2 is imported from the atmosphere and assimilated into carbohydrates but at the same time water is lost from the plant in the opposite direction. To balance this water loss and thereby maintaining optimal functioning of the plant, water needs to be taken up from the soil. A common reaction of plants to water shortage, i.e. a situation where water loss exceeds water uptake for some time, is to reduce the aperture of the stomata, which raises the resistance to water movement through the stomata. This leads to a lower rate of water loss by the plant, or in other words: the actual transpiration rate drops below the potential transpiration rate that occurs in a situation without water shortage. But a reduced opening of the stomata has also negative consequences for the rate of CO_2 flow into the leaves and thus on photosynthesis and dry matter production. It appears that the ratio between dry matter production and transpiration is fairly constant over a wide range of soil moisture conditions (Lövenstein *et al.*, 1992). Therefore, the effect of water stress on dry matter production, $f_{w,E}$ in eqn. 3.1.6, is calculated as the ratio between actual transpiration Tr_a (mm d^{-1}) and potential transpiration Tr_p (mm d^{-1}),

$$f_{w,E} = \frac{Tr_a}{Tr_p}$$
(3.1.7)

The effect of water shortage on dry matter production is thus simulated instantaneously if actual water uptake falls below potential water uptake. In CNGRAS Tr_p is dynamically calculated as a function of weather characteristics and L, and Tr_a depends on Tr_p (i.e. the maximum value for Tr_a), root functioning and soil water availability.

Effect of nitrogen

$f_{N,E}$ is calculated as function of the prevailing nitrogen concentration in the leaves and two threshold values, $C_{Nlv,mp}$ and $C_{Nlv,op}$ (g N g^{-1} dry matter). $f_{N,E}$ equals zero for leaf nitrogen concentrations below $C_{Nlv,mp}$ and $f_{N,E}$ equals 1 for concentrations above $C_{Nlv,op}$. Between both threshold values $f_{N,E}$ increases linearly from 0 to 1 (Figure 3.1.5). The response of E_{act} to leaf nitrogen concentration is primarily based on the effect of leaf nitrogen on photosynthesis, which decreases to zero if leaf nitrogen level drops to its minimum level. At this minimum level leaf nitrogen concentration is not equal to zero, because some nitrogen remains part of leaf components that are not actively involved in the process of photosynthesis.

Figure 3.1.5. Relation between leaf nitrogen concentration C_{Nlv} and $f_{N,E}$ in eqn. 3.1.6. See text for further explanation.

A zero net dry matter production rate will be calculated if leaf nitrogen concentration equals $C_{Nlv,mp}$. However, at $C_{Nlv,mp}$ there is still some photosynthetic activity because the rate of carbon consumption by respiratory processes is then balanced by the rate of carbon fixation by photosynthesis. The leaf nitrogen concentration at which photosynthesis ceases will be slightly lower than $C_{Nlv,mp}$ and in that case the net rate of dry matter production would be negative. This situation is not simulated by the current version of the model.

Parameter input values

The range of possible parameter values related to the production equations are given in Table 3.1.1.

Table 3.1.1.   Summary of input values related to dry matter production (section 3.1.1).

Parameter	Equation or Figure	Unit	Range of values	Value used[1]	Source
k_p	eqn. 3.1.2	m^2 ground m^2 leaf	0.5-0.7	0.6	b,c,d
σ	eqn. 3.1.3	-	0.1-0.3	0.2	B
E_{max}	eqn. 3.1.4	g dry matter MJ^{-1}	2.3-3.3	2.6	c,e[2]
$C_{Nlv,mp}$	Fig. 3.1.5	g N g^{-1} dry matter	0.005-0.015	0.012	A
$C_{Nlv,op}$	Fig. 3.1.5	g N g^{-1} dry matter	0.02-0.04	0.025	F
$f_{d,E}$	eqn. 3.1.4 & Fig. 3.1.2	-	0.0-1.0	see App. I	f,g
$f_{T,E}$	eqn. 3.1.4 & Fig. 3.1.3	-	0.0-1.0	see App. I	H
$f_{L,E}$	eqn. 3.1.4 & Fig. 3.1.4	-	0.0-1.0	see App. I	A

[1]   *Values as used in a study on the relation between fertilisation strategies and nitrate losses (Conijn & Henstra, 2003). They refer to grass growth under farming conditions.*

[2]   *Values of 3.0 - 3.1 g dry matter MJ^1 from sources c and e used in combination with a reduction of 15% to account for differences between farmers' field and experimental fields (Ten Berge et al., 2000).*

a   =   Estimated by means of a calibration procedure
b   =   Goudriaan & Van Laar (1994; using $\sigma = 0.2$ results in $\rho_c = 0.06$)
c   =   Bouman *et al.* (1996)
d   =   Verberne (1992)
e   =   Nonhebel (1997)
f   =   Lantinga (1985)
g   =   Van Loo (1993)
h   =   Penning de Vries *et al.* (1989; based on optimum temperature for photosynthesis of 10 - 20 °C and doubling of maintenance respiration costs at every 10 °C increase).

3.1.2   Death

Senescence and death of plant parts are important processes in the dynamics of grass biomass. According to Sibma & Ennik (1988), Whitehead (1986) and Van Loo (1993), about 50% of net dry matter production is invested in non-harvested parts, i.e. roots and not harvested aboveground biomass (mainly based on results from experimental fields with low or zero harvesting losses). Assuming total standing grass biomass in equilibrium over a period of one year, this means that roughly half of the net production is lost by death of plant parts (see also Corré & Conijn, 2004). Eventually, dead plant parts are incorporated into the soil, so the modelling of senescence and death of plant parts forms an important input for the simulation of soil organic carbon and nitrogen dynamics. In CNGRAS death rates of leaves, stems and roots are calculated, whereas reserves (W_{rs}) are not subjected to losses via death of plant parts. It is assumed that the reserves are withdrawn and re-used in the plant before abscission of stem parts (see section 3.1.3: Relocation). Senescence and death of plant parts due to 'natural' processes is elaborated below, death related to harvesting activities is treated in section 3.4 (Management).

Leaves

Leaf death is simulated by calculating a decrease in leaf biomass, D_{Wlv} (g dry matter m^{-2} d^{-1}), proportional to the amount of existing living leaf biomass, according to

$$D_{Wlv} = d_{lv}W_{lv}$$ (3.1.8)

where d_{lv} is the relative leaf death rate (d^{-1}). The calculation of d_{lv} comprises two steps.

Effect of leaf area index

First, the relative leaf death rate under non-limiting conditions of water and nitrogen ($d_{lv,L}$) is calculated as a function of leaf area index L (Figure 3.1.6). $d_{lv,L}$ is related to L, because leaf senescence is accelerated at high leaf area indices due to low radiation levels at ground level and relocation of nitrogen from shaded leaves located at the bottom of the canopy (Van Loo, 1993; Van Laar *et al.*, 1992; Bouman *et al.*, 1996).

Figure 3.1.6.   *Relation between leaf area index L and relative leaf death rate under optimal conditions $d_{lv,L}$ in eqn. 3.1.8. See text for further explanation.*

Second, the senescence of leaves can also be accelerated due to suboptimal conditions of water and nitrogen supply. Leaf senescence is strongly affected by the balance between carbon input and output to the leaf. If this balance becomes negative permanently (output > input), the leaf will soon become redundant and shed. Suboptimal conditions of water and nitrogen supply have a negative influence on carbon input (lower photosynthesis rate) and therefore accelerate senescence and leaf death. The effect of water and nitrogen on leaf death can also be explained by assuming that all leaves can be characterised by their age and that a leaf dies if it reaches a certain (maximum) age. Under stress conditions, e.g., caused by water or nitrogen shortage, senescence is accelerated which means that the maximum ages of all leaves that experience stress are reduced. Leaves will then reach their maximum age in a shorter time span as compared to a situation without stress and thus leaf death is enhanced. The effects of water and nitrogen are modelled by calculating an increase in leaf death rate during drought conditions and in case of a low nitrogen status, by

$$d_{lv} = d_{lv,L}(1 + f_{w,D} + f_{N,D})$$ (3.1.9)

where $f_{w,D}$ (-) and $f_{N,D}$ (-) are the relative acceleration effects on leaf death rate due to water stress and nitrogen shortage, respectively. Both effects range from 0 (no acceleration) to 2 (maximum acceleration, corresponding to an increase of 200% in leaf death rate). They are used in an additive way in eqn. 3.1.9 because it is assumed that when the two stress factors occur simultaneously, the effect on leaf death rate is more pronounced than when they occur one at the time.

Effect of water

$f_{w,D}$ is calculated as a function of the transpiration ratio Tr_a / Tr_p (-). The curve of Figure 3.1.7 is characterised by two parameters: a maximum effect ($f_{w,D,mx}$ = 2) if the actual transpiration and thus the transpiration ratio equal zero and a threshold value for the transpiration ratio $Tr_{r,t}$ beyond which no effect is simulated ($f_{w,D}$ = 0). A quadratic function of Tr_a / Tr_p is used to calculate the values between both thresholds. Possible values of Tr_a / Tr_p range between 0 and 1. The effect of water stress is thus modelled instantaneously, but low drought conditions (e.g. $Tr_a >$ 0.9 Tr_p) are assumed to have no effect on leaf death.

Figure 3.1.7. Relation between the transpiration ratio Tr_a / Tr_p and $f_{w,D}$ in eqn. 3.1.9. See text for further explanation.

Effect of nitrogen

$f_{N,D}$ is calculated as a function of the prevailing leaf nitrogen concentration (Figure 3.1.8) and three parameters: (i) a maximum effect ($f_{N,D,mx}$ = 2), (ii) a minimum leaf nitrogen concentration $C_{Nlv,mn}$ (g N g^{-1} dry matter) at which the maximum effect is calculated, and (iii) an optimum leaf nitrogen concentration at which the effect of nitrogen on leaf death is negligible. Between the minimum and optimum concentration, values for $f_{N,D}$ are calculated by means of a quadratic function of C_{Nlv}. In the model $C_{Nlv,mn}$ is a constant and the calculated actual leaf nitrogen concentration cannot drop below this minimum value. The optimum concentration that forms the threshold for calculating an effect is modelled as a constant fraction ($\eta_{N,o}$) of the attainable leaf nitrogen concentration, which in turn is negatively correlated to L (see section 3.3). As a consequence, the optimum concentration decreases with increasing L (Figure 3.1.8). As an example: a leaf nitrogen concentration of 0.02 g N g^{-1} dry matter indicates more stress if L equals 2 m^2 m^{-2} than in a situation where L equals 10 m^2 m^{-2} because the optimum nitrogen concentration is higher at lower L. It assumes that the vertical distribution of nitrogen concentration in the canopy is positively correlated to the vertical distribution of light interception for maximising photosynthesis. More nitrogen is available for distribution at a higher L than at a lower L (at equal nitrogen concentration) and this results in a higher nitrogen concentration in the top of the canopy where most of the photosynthesis occurs. This is reflected in the response curves of Figure 3.1.8.
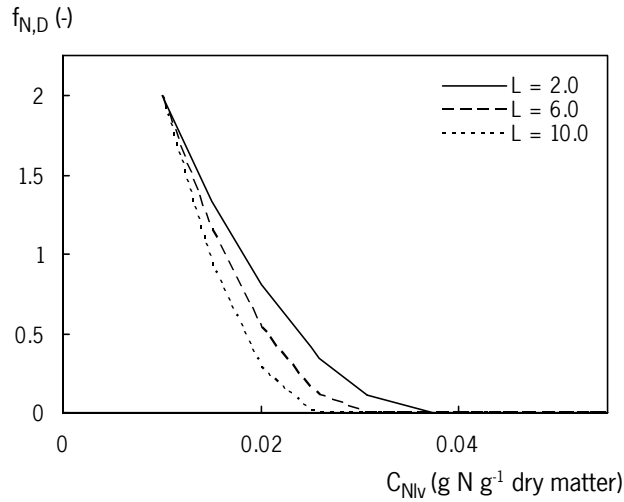
Figure 3.1.8. Relation between leaf nitrogen concentration C_{Nlv} and $f_{N,D}$ in eqn. 3.1.9. See text for further explanation.

Stems

When a leaf dies, both parts of it, lamina and sheath, are involved. Therefore, stem senescence is related to leaf senescence by

$$D_{Wst} = D_{Wlv} \frac{p_{st}}{p_{lv}}$$

(3.1.10a)

where D_{Wst} is the stem death rate (g dry matter m^{-2} d^{-1}) and p_{st} and p_{lv} are the partitioning factors for leaf sheaths and leaf lamina, respectively (-) when leaves are formed (see also section 3.1.4). The ratio p_{st}/p_{lv} corresponds with the ratio in biomass of sheath and lamina of a full-grown leaf and is used in eqn. 3.1.10a to correlate sheath death rate to lamina death rate.

The calculation according to eqn. 3.1.10a will not be valid in two situations: (i) if true stems have been developed during the generative phase, and (ii) during a short period after harvesting when the ratio between sheath and lamina biomass in the stubble is different from p_{st}/p_{lv} due to selective removal of leaf laminae at harvesting. To account for these situations in calculating stem death rate, two intermediate state variables are used: $W_{lv,0}$ and $W_{st,0}$ (g dry matter m^{-2} d^{-1}). They are defined by the amount of biomass in leaf laminae and total stems (true stems + sheaths) of the stubble that has been produced in the growing period preceding the latest harvest event. It thus contains 'old' plant material relative to the biomass that is produced in the present growing period. In W_{lv} and W_{st}, i.e. total biomass in leaf laminae and stems, both 'old' and 'young' aboveground biomass is included and the difference between W_{lv} and $W_{lv,0}$ and W_{st} and $W_{st,0}$ is the newly formed aboveground biomass between two successive harvests. $W_{lv,0}$ and $W_{st,0}$ are only used for the purpose of calculating stem death rate and they are initialised at each harvest with W_{lv} and W_{st}, i.e. the leaves and stems of the stubble that are left directly after harvesting. After initialisation, $W_{lv,0}$ and $W_{st,0}$ decrease with the leaf and stem death rates, where stem death rate is now simulated as

$$D_{Wst} = D_{Wlv} \frac{W_{st,0}}{W_{lv,0}}$$

(3.1.10b)

$W_{lv,0} / W_{st,0}$ corresponds with the ratio in stem and leaf biomass of the 'old' material. Eqn. 3.1.10b is used as long as $W_{lv,0}$ and $W_{st,0} > 0$, which means that in the model first the 'older' material dies, before the more recently produced biomass. Eqn. 3.1.10a becomes valid again if $W_{lv,0}$ and $W_{st,0}$ equal zero and W_{lv} and W_{st} only contain plant biomass produced during the present growing period. In general with growing periods of about 4 weeks, $W_{lv,0}$ and $W_{st,0}$ equal zero before the next harvest, which means that the 'old' material dies completely during a regrowth period. It is assumed that true stems in case of generative development only decrease after decapitation of growing

points has occurred. It will then only involve the stem material that remains in the stubble after harvesting and this is included in $W_{st,0}$.

Roots

Root death is modelled as a fraction of the living root biomass by:

$$D_{Wrt} = d_{rt}W_{rt}$$ (3.1.11)

with D_{Wrt} the root death rate (g dry matter m^{-2} d^{-1}) and d_{rt} the relative root death rate (d^{-1}). d_{rt} is calculated as a function of temperature (Figure 3.1.9) because it is assumed that root senescence is positively related to temperature with low values in winter and high values in summer. In this function T_a is used for reasons of simplicity instead of soil temperature. Root longevity and death is difficult to measure and estimates from literature for the yearly relative death rate range from 1.0 to 2.0 y^{-1} (Whitehead, 1986). The values for d_{rt} from Figure 3.1.9 result in a value of about 1.5 y^{-1} in an average year, which corresponds with an average maximum age for roots of about 8 months.
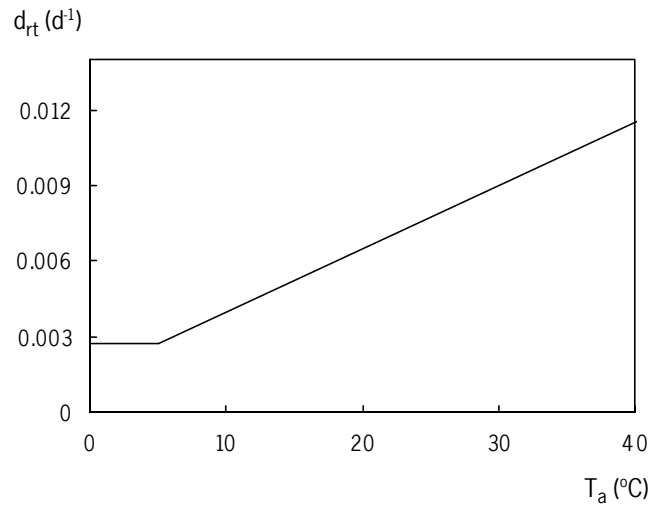

Figure 3.1.9. Relation between average air temperature T_a and relative root death rate d_{rt} in eqn. 3.1.11. For temperatures below 5 °C a constant value for d_{rt} is assumed. See text for further explanation.

Parameter input values

The possible parameter values related to the death equations are given in Table 3.1.2.

Table 3.1.2. Summary of input values related to biomass death (section 3.1.2).

Parameter	Equation or Figure	Unit	Range of values	Value used[1]	Source
$Tr_{r,t}$	Fig. 3.1.7	-	0.3-1.0	0.67	a
$f_{w,D,mx}$	Fig. 3.1.7	-	0.0-5.0	2.0	a,b
$f_{N,D,mx}$	Fig. 3.1.8	-	0.0-5.0	2.0	a
$C_{Nlv,mn}$	Fig. 3.1.8	g N g^{-1} dry matter	0.005-0.015	0.010	c
$\eta_{N,o}$	Fig. 3.1.8	-	0.5-1.0	0.8	a
p_{st}	eqn. 3.1.10a, eqn. 3.4.1	-	1.5-3.5	2.4	d[2]
p_{lv}	eqn. 3.1.10a, eqn. 3.4.1	-	6.0-8.5	7.0	d,e
$d_{lv,L}$	eqn. 3.1.9 & Fig. 3.1.6	d^{-1}	0.0-0.05	see App. I	b,c
d_{rt}	eqn. 3.1.11 & Fig. 3.1.9	d^{-1}	0.0-0.025	see App. I	a,f,g

[1] Values as used in a study on the relation between fertilisation strategies and nitrate losses (Conijn & Henstra, 2003). They refer to grass growth under farming conditions.

[2] According to Robson (1973), ratio of lamina weight to sheath weight (during the vegetative period) is virtually constant and equals 7 : 3, where sheath weight includes the weight of reserves located in the sheaths. If it is assumed that the average weight of the reserves in the sheaths amounts to 25%, the ratio of the partitioning coefficients as used in CNGRAS becomes 7 : 2.4.

a = Estimated by means of a calibration procedure
b = Bouman *et al.* (1996)
c = Van Loo (1993)
d = Robson (1973)
f = Bloemhof (1993)
g = Verberne (1992)
h = Whitehead (1986)

3.1.3   Relocation

The model calculates the rate of reserve relocation before biomass partitioning because the total amount of biomass available for partitioning (section 3.1.4) equals the sum of 'new' biomass produced at the current time (section 3.1.1) and the relocation of reserves (this section). Relocation is defined here as the use of biomass, produced before the current time, for the growth of leaves, stems and roots at the current time. For grass growth, relocation of reserves can be important to support regrowth shortly after defoliation when L and therefore P are low. Without this extra source the rate of formation of new leaves and roots after defoliation may be too low, which frequently occurs at managed swards. Other workers have also used a reserve or substrate pool in their models to simulate grass growth (Verberne, 1992, Van Loo, 1993, Bouman *et al.*, 1996).

The dry matter reserve pool in CNGRAS is modelled explicitly via W_{rs}. It is assumed that W_{rs} consists mainly of carbohydrates and that these reserves are stored in the stems (including leaf sheaths; Van Loo, 1993). After harvesting (by cutting or grazing), the remaining stubble contains a high proportion of stem material from which the reserves can be relocated. Reserve relocation is calculated at two occasions:
(i)   as a simple consequence of stem death and the assumption that part of the reserve pool in the stems is withdrawn before stems actually die off, and
(ii)   in case the demand for carbohydrates due to leaf and root growth exceeds the current net production of carbohydrates.

Related to senescence

The reserve relocation rate due to stem death, $R_{Wrs,s}$ (g dry matter m^{-2} d^{-1}), is modelled proportionally to the stem death rate D_{Wst} and the concentration of reserves in the stems, according to

$$R_{Wrs,s} = D_{Wst} \frac{W_{rs}}{W_{st}} \qquad (3.1.12)$$

This is in agreement with the assumption that reserves are not subjected to death and therefore are not transferred to soil organic matter via death of stems (see section 3.1.2).

Related to low production

The relocation rate due to low production rates, $R_{Wrs,p}$ (g dry matter m^{-2} d^{-1}), is related on the one hand to the current supply of carbohydrates available for growth of new leaves and roots, and on the other hand to conditions that determine the growth rate of new leaves and roots. The latter is important in calculating the relocation rate because it influences the demand for carbohydrates. The relocation of reserves is modelled as function of supply and demand in a rather empirical way due to lack of precise data. Only the effects of water stress $f_{w,R}$ (-) and temperature $f_{T,R}$ (-) on demand and the effect of the supply rate of carbohydrates $f_{S,R}$ (-) are incorporated (with values ranging from 0 to 1). Furthermore, it is assumed that $R_{Wrs,p}$ is limited by W_{rs} multiplied by a maximum relative relocation rate to prevent excessive high depletion rates of the reserve pool. The calculation of $R_{Wrs,p}$ now reads

$$R_{Wrs,p} = f_{w,R} f_{T,R} f_{S,R} r_{rs,mx} W_{rs} \qquad (3.1.13)$$

with $r_{rs,mx}$ the maximum relative relocation rate (d^{-1}) and $f_{w,R}$, $f_{T,R}$, respectively $f_{S,R}$, which may reduce the actual relocation rate $R_{Wrs,p}$ relative to its maximum, given by $r_{rs,mx} W_{rs}$. According to Van Loo (1993), relocation of carbohydrates due to low production rates usually occurs only for a few days after defoliation. Therefore, it has not been considered during four months in winter (November – February), when $R_{Wrs,p}$ is set to zero.

Effect of water

Conditions that are suboptimal for growth processes have a negative effect on demand and will reduce the actual relocation rate. Here, it is assumed that the effect of water on production (see eqn. 3.1.7) can also be used to estimate the effect on growth processes, thus

$$f_{w,R} = f_{w,E} \qquad (3.1.14)$$

Effect of temperature

The effect of temperature on the actual relocation rate is given in Figure 3.1.10. The daily average temperature of the top soil (0 - 5 cm), T_s (ºC), is used to determine $f_{T,R}$, because soil temperature has an important effect on the appearance of new tillers and leaves and therefore on growth and demand for carbohydrates (Van Loo, 1993; Bouman *et al.*, 1996). Below the lower and above the upper threshold (0 and 40 ºC, respectively, in Figure 3.1.10), $f_{T,R}$ equals zero. Optimum growth and relocation rates are assumed to fall between 20 and 25 ºC (Robson *et al.*, 1989 ; Verberne, 1992). Figures 3.1.3 and 3.1.10, which both show a relation depending on temperature, differ mainly in their optimum temperature, where the optimum temperature for photosynthesis (Figure 3.1.3) is lower than the optimum for growth of plant tissues (i.e cell division and extension, Figure 3.1.10).

Figure 3.1.10.   Relation between daily average temperature T_s of the top soil (0-5 cm) and $f_{T,R}$ in eqn. 3.1.13. See text for further explanation.

Effect of supply

If the net supply rate of carbohydrates from current production is very low, relocation may be at its maximum ($f_{S,R}$ = 1). On the other hand, at higher supply levels, relocation rate decreases to zero because the growth of new leaves and roots can be realised at the expense of current production of carbohydrates ($f_{S,R}$ = 0). $f_{S,R}$ is modelled by using two parameters, a lower threshold ($S_{c,L}$) below which $f_{S,R}$ equals 1 and an upper threshold ($S_{c,U}$) beyond which $f_{S,R}$ equals 0. In beween both parameters $f_{S,R}$ decreases linearly from 1 to 0 (Figure 3.1.11).

Figure 3.1.11.   Relation between carbohydrate supply rate S_c and $f_{S,R}$ in eqn. 3.1.13. See text for further explanation.

The net carbohydrate supply S_c (g CH_2O m^{-2} d^{-1}) from Figure 3.1.11 is estimated by

$$S_c = C_{dm}P$$ (3.1.15)

with C_{dm} the amount of carbohydrates consumed per unit of dry matter produced (g CH_2O g^{-1} dry matter). C_{dm} is usually referred to as assimilate or glucose requirement and represents the amount of carbohydrates that is needed for the formation of structural plant material (Penning de Vries *et al.*, 1989 ; Goudriaan & Van Laar, 1994). Its value

depends on the proportions of the components in plant tissue, such as carbohydrates, proteins, fats, etc., because the production of each component requires a different amount of carbohydrates. The value for C_{dm} exceeds 1 in most situations, indicating that weight is lost in the process of converting carbohydrates into average plant material. This weight loss is mainly due to the release of CO_2 and water during the biosynthesis of plant components. The reciproke of C_{dm} is used in growth models that calculate the increase in plant dry matter as a function of the available carbohydrates (e.g., crop growth model SUCROS in Goudriaan & Van Laar, 1994).

Actual relocation rate from the reserve pool R_{Wrs} (g dry matter m^{-2} d^{-1}) is now given by either $R_{Wrs,s}$ or $R_{Wrs,p}$ whichever has the largest value,

$$R_{Wrs} = \max(R_{Wrs,s}; R_{Wrs,p})$$
(3.1.16)

With eqn. 3.1.16 it is implicitly assumed that the extra demand for carbohydrates from the reserve pool, represented by $R_{Wrs,p}$, is first fulfilled by the carbohydrates that become available due to stem death ($R_{Wrs,s}$) and that an additional reserve relocation only occurs if more carbohydrates are needed ($R_{Wrs,p} > R_{Wrs,s}$). On the other hand, if there is no need for extra carbohydrates to support growth ($R_{Wrs,p} = 0$), the actual relocation (R_{Wrs}) is given by the relocation due to stem death ($R_{Wrs,s}$), which is always computed if $D_{Wst} > 0$.

Parameter input values

The possible parameter values related to the relocation equations are given in Table 3.1.3.

Table 3.1.3. Summary of input values related to relocation (section 3.1.3).

Parameter	Equation or Figure	Unit	Range of values	Value used[1]	Source
$r_{rs,mx}$	eqn. 3.1.13	d^{-1}	0.05-0.5	0.15	a
C_{dm}	eqn. 3.1.15 & 3.1.17	g CH_2O g^{-1} dry matter	1.3-1.7	1.45	b,c,d,e
$S_{c,L}$	Fig. 3.1.11	g CH_2O m^{-2} d^{-1}	0.0-15.0	2.5	a,d[2]
$S_{c,U}$	Fig. 3.1.11	g CH_2O m^{-2} d^{-1}	0.0-30.0	7.5	a,d[2]
$f_{T,R}$	eqn. 3.1.13 & Fig. 3.1.10	-	0.0-1.0	see App. I	f,g

[1] Values as used in a study on the relation between fertilisation strategies and nitrate losses (Conijn & Henstra, 2003). They refer to grass growth under farming conditions.

[2] The values are chosen such that the relocation related to low production ceases a few days after defoliation under optimal growing conditions, which is in agreement with the findings of Van Loo (1993).

a = Estimated by means of a calibration procedure
b = Penning de Vries *et al.* (1989)
c = Goudriaan & Van Laar (1994)
d = Van Loo (1993)
e = Lantinga (1985)
f = Verberne (1992)
g = Robson *et al.* (1989)

3.1.4   Partitioning

Total biomass growth G_t (g dry matter m^{-2} d^{-1}) from current production and relocation from the reserve pool in the stems is now calculated by

$$G_t = P + \frac{R_{Wrs}}{C_{dm}}$$
(3.1.17)

The partitioning of G_t among the four plant compartments is modelled according to

$$G_{Wrt} = f_{rt}G_t$$
(3.1.18a)

$$G_{Wlv} = f_{lv}G_t$$
(3.1.18b)

$$G_{Wst} = f_{st}G_t$$
(3.1.18c)

$$G_{Wrs} = f_{rs}G_t$$
(3.1.18d)

with G_{Wrt}, G_{Wlv}, G_{Wst} and G_{Wrs} the biomass growth rates of roots, leaves, stems and reserves, respectively (g dry matter m^{-2} d^{-1}) and f_{rt}, f_{lv}, f_{st}, and f_{rs} the corresponding partitioning factors (-). The sum of the four partitioning factors equals 1. The values of two partitioning factors (f_{rt} and f_{rs}) are determined as a function of the specific leaf area of leaves grown during the current time step, λ_n (m^2 leaf g^{-1} leaf dry matter). The relation between f_{rt}, f_{rs} and λ_n (see Figure 3.1.12) does not reflect a direct causal link between the partitioning factors and the specific leaf area, but both are related to other processes. λ_n represents the balance between leaf area growth and leaf biomass growth of newly grown leaves. A low value for λ_n combines a relatively low area growth with a high biomass partitioning to the leaves. This situation occurs, e.g., during stress of low temperature or shortage of water and nutrients (Van Loo, 1993, Jones *et al.*, 1980) and also when biomass production is high at high values of L. The result will be that thick leaves are formed. The high supply / low demand combination causes a low sink strength of the leaves in consuming carbohydrates, leaving a relatively high proportion of the available carbohydrates for investment in the roots or set aside as reserves. For a high value of λ_n the opposite holds. Thin leaves are formed when biomass production is low and the potential for leaf area is relatively high, e.g., in low light conditions or shortly after defoliation if temperatures are favourable for leaf growth (Van Loo, 1993, Sheehy *et al.*, 1980). Then, less carbohydrates will be left over for the roots and the reserves, because the leaves have a higher demand for carbohydrates and will consume relatively more. Therefore, in the model a function is used that correlates low values of λ_n with high values for the biomass partitioning factors to roots and reserves and vice versa (see Figure 3.1.12). Calculation of λ_n is described is section 3.2 (Leaf area). A lower value for λ_n is simulated in case of water and nitrogen stress, which results in higher values for f_{rt} and f_{rs} (see Figure 3.1.12). This agrees with the well-known response of plants, where root growth is favoured at the expense of shoot growth at suboptimal supply rates of water and nutrients from the soil (Brouwer, 1962).
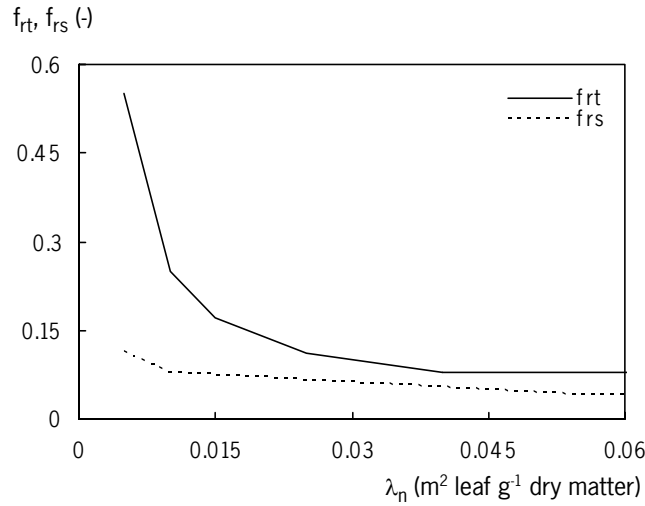
Figure 3.1.12. Relation between the specific leaf area of newly grown leaves, λ_n, and the partitioning factors for root and reserve biomass growth. See text for further explanation.

If W_{rs} exceeds a predefined maximum level, f_{rs} is set to zero to prevent accumulation of excessive high reserve levels in the stems. In that situation equation 3.1.19 is used instead of the relation from Figure 3.1.12,

$$f_{rs} = 0, \qquad \text{if } W_{rs} > f_{rs,x} W_{st} \tag{3.1.19}$$

with $f_{rs,x}$ defined as the maximum fraction of reserve biomass in the stems (g reserve dry matter g^{-1} stem dry matter). The partitioning factors for stems and leaves are now calculated by

$$f_{st} = (1 - f_{rt} - f_{rs}) \frac{p_{st}}{p_{lv} + p_{st}} \tag{3.1.20}$$

$$f_{lv} = (1 - f_{rt} - f_{rs} - f_{st}) \tag{3.1.21}$$

Two specific situations exist where the above equations for f_{rt} as function of λ_n (Figure 3.1.12) and for f_{st} (eqn. 3.1.20) are not valid and other calculations are made to determine the partitioning factors:

(i) Shortly after harvesting, the ratio between lamina and total leaf (sheath + lamina) in the stubble differs from $p_{lv} / (p_{st} + p_{lv})$ due to the selective removal of leaf laminae at harvesting. In the remaining stubble W_{lv} is temporarily decreased relative to W_{st}. During the initial regrowth of the sward, growth of the lamina is enhanced, which partly restores the original ratio between lamina and total leaf. This is simulated by decreasing f_{st} relative to its value as calculated by eqn. 3.1.20, as long as the ratio $W_{lv} / (W_{st} + W_{lv})$ is below $p_{lv} / (p_{st} + p_{lv})$. A decrease in f_{st} will result in an increase in f_{lv} via eqn. 3.1.21. The relation between $W_{lv} / (W_{st} + W_{lv})$ and f_{st}, which is used in the model, is given in Figure 3.1.13, where the maximum decrease in f_{st} is restricted to half of the value calculated with eqn. 3.1.20 (see value of f_{st} for $W_{lv} / (W_{st} + W_{lv}) = 0$). This restriction is applied because part of the total growth in lamina and sheath is realised by the formation of new leaves. For those leaves the ratio between lamina and total leaf equals $p_{lv} / (p_{st} + p_{lv})$, which was already calculated via f_{lv} and f_{st} from eqn. 3.1.20 and 3.1.21.

Figure 3.1.13. Relation between the ratio $W_{lv}/(W_{st} + W_{lv})$ and the partitioning factor f_{st}. This relation is used in addition to eqn. 3.1.20. On the Y-axis $f_{st}(\lambda_n)$ refers to the value for f_{st} as calculated with eqn. 3.1.20, on the X-axis p^* equals $p_{lv}/(p_{st} + p_{lv})$. See text for further explanation.

(ii) If 'true' stem formation occurs due to generative development in spring, f_{st} will be higher than the value calculated with eqn. 3.1.20/Figure 3.1.13 because this value only represents the sheath part of leaves. The extra biomass partitioning towards the stem, $f_{st,f}(-)$, when 'true' stems are formed, is described as a function of the temperature sum (see Figure 3.1.14). The temperature sum is calculated by daily accumulation of T_a with a base temperature of $0\ ^{0}C$ and is set to zero at the beginning of each regrowth period. Normally, generative development is only found during spring, but its effect on partitioning can be pronounced, especially in case of long growing periods. Via the input file of the model it is possible to limit the calculations for the 'true' stem development to the first (few) growing period(s) in spring. Moreover, these calculations can also be skipped, if 'true' stem development is insignificant, e.g. due to frequent defoliation.

The model uses the sum of $f_{st,f}$ and f_{st}, as calculated above by eqn. 3.1.20 and the relation in Figure 3.1.13 for the total biomass partitioning factor towards stem growth in eqn. 3.1.18c. It is assumed that the extra (true) stems grow at the expense of roots. Thus, the partitioning factor for the roots according to Figure 3.1.12, $f_{rt}(\lambda_n)$, is decreased by $f_{st,f}$ by

$$f_{rt} = f_{rt}(\lambda_n) - f_{st,f} \tag{3.1.22}$$

Figure 3.1.14. Relation between the temperature sum T_{sum} and the extra biomass partitioning factor for the growth of 'true' stems during the generative phase, $f_{st,f}$. See text for further explanation.

Parameter input values

The possible parameter values related to the biomass partitioning equations are given in Table 3.1.4.

Table 3.1.4. Summary of input values related to biomass partitioning (section 3.1.4).

Parameter	Equation or Figure	Unit	Range of values	Value used[1]	Source
$f_{rs,x}$	eqn. 3.1.19	g reserve dry matter g^{-1} stem dry matter	0.01-0.5	0.30[2]	b
f_{rt}	eqn. 3.1.18, 3.1.20, 3.1.21, 3.1.22 & Fig. 3.1.12	-	0.0-1.0	see App. I	a,b-f
f_{rs}	eqn. 3.1.18, 3.1.19, 3.1.20, 3.1.21 & Fig. 3.1.12	-	0.0-1.0	see App. I	a
$f_{st,f}$	eqn. 3.1.22 & Fig. 3.1.14	-	0.0-0.5	see App. I	[3]

[1] Values as used in a study on the relation between fertilisation strategies and nitrate losses (Conijn & Henstra, 2003). They refer to grass growth under farming conditions.

[2] Highest value in Van Loo (1993) with respect to water-soluble carbohydrates equals 0.28.

[3] The values in Appendix I for $f_{st,f}$ as function of T_{sum} have not yet been checked with literature sources, but they were arbitrarily chosen (this option was not used in the study of Conijn & Henstra (2003).

a = Estimated by means of a calibration procedure
b = Van Loo (1993)
c = Lantinga (1985)
d = Sibma & Ennik (1988)
e = Van de Pol-van Dasselaar & Lantinga (1995)
f = Bouman *et al.* (1996)

3.1.5   Net change

Net changes in the biomass of each compartment are calculated as the difference between biomass growth (eqn. 3.1.18a-d) and decrease (eqn. 3.1.11 for roots, eqn. 3.1.8 for leaves, eqn. 3.1.10a,b for stems and

eqn. 3.1.16 for reserves). These net changes are integrated in time to determine the new amounts of biomass after each time step. An additional decrease in leaf, stem and reserve biomass is calculated in case of harvesting (see section 3.4).

The possible initial values for the state variables related to grass biomass are given in Table 3.1.5.

Table 3.1.5.   Input values for the state variables, related to grass biomass.

State variable	Description	Unit	Range of values[1]	Value used[2]
W_{lv}	Amount of leaf biomass	g dry matter m^{-2}	1-250	84
W_{st}	Amount of sheath and stem biomass	g dry matter m^{-2}	1-120	27
W_{rs}	Amount of reserve biomass	g dry matter m^{-2}	0.2-30	9
W_{rt}	Amount of root biomass	g dry matter m^{-2}	100-1500	450

[1]   *Possible values refer to a situation shortly after harvesting or during winter.*
[2]   *Values as used in a study on the relation between fertilisation strategies and nitrate losses (Conijn & Henstra, 2003). They refer to the state of the grass sward on January 1st (under 100% cutting regime).*

3.2   Leaf area

State variable

Total leaf area of the grass sward is described by its leaf area index L (m^2 leaf m^{-2} ground), which refers to the area of laminae only. The dynamics in L are simulated by calculating increase and decrease, separately, and integrating the net change in leaf area in time.

Rate variables

3.2.1   Increase and decrease

Leaf area and leaf biomass are strongly correlated because both L and W_{lv} refer to the same morphological unit of the plant, i.e. the leaf laminae. Therefore, the increase and decrease in L are simulated by using G_{Wlv} (eqn. 3.1.18b) and d_{lv} (eqn. 3.1.9), respectively,

$$G_L = G_{Wlv}\lambda_n \tag{3.2.1}$$

$$D_L = d_{lv}L \tag{3.2.2}$$

where G_L and D_L are the increase and decrease in leaf area index (m^2 leaf m^{-2} ground d^{-1}), respectively. The specific leaf area of leaves, grown during the current time step, λ_n depends on a potential specific leaf area, λ_p (m^2 leaf g^{-1} leaf dry matter), and on temperature, water and nitrogen status, by

$$\lambda_n = \min(f_{w,\lambda}; f_{N,\lambda})f_{T,\lambda}\lambda_p \tag{3.2.3}$$

with $f_{T,\lambda}$ (-), $f_{w,\lambda}$ (-) and $f_{N,\lambda}$ (-) factors related to temperature, transpiration of water and leaf nitrogen concentration, respectively. A minimum function is used to integrate the factors for water and nitrogen, where possible values of each factor range from 0 ($\lambda_n = 0$) to 1 ($\lambda_n = \lambda_p$). The potential specific leaf area, λ_p, reflects therefore the maximum value for λ_n and is calculated as a function of leaf area index L.

Effect of leaf area index

In general a low leaf area index is correlated with a high specific leaf area of newly formed leaves (thin leaves) and vice versa (see Figure 3.2.1). The reason for this is that biomass production is low at low L, whereas the growth potential for leaves is high. The latter is caused by the high irradiance at ground level due to the low L which stimulates new tiller and leaf formation (Van Loo 1993, Bouman *et al.*, 1996). This situation causes a high demand / low supply balance in the plant, which results in a low carbohydrate level in the plant and consequently in a high specific leaf area (see e.g. Johnsson & Thornley, 1985, Verberne, 1992 and Van Loo, 1993). By using the relation of Figure 3.2.1, the model calculations also correspond with the trend in the specific leaf area development after a harvesting event, with higher values at the beginning of a regrowth period and lower values later on (Sheehy *et al.*, 1980, unpublished data of A.J.C. de Visser).

λ_p (m^2 leaf g^{-1} leaf dry matter)

Figure 3.2.1.   Relation between leaf area index L and the potential specific leaf area λ_p of newly produced leaf biomass. See text for further explanation.

Effect of temperature

For estimating the effect of temperature on specific leaf area, $f_{T,\lambda}$ in eqn. 3.2.3, $f_{T,R}$ is used,

$$f_{T,\lambda} = f_{T,R}$$

(3.2.4)

The effect of temperature on λ_p can be explained by different responses of leaf biomass accumulation and leaf area growth to prevailing temperatures. The optimum temperature for photosynthesis is lower than that for cell division and cell extension (cf. Figures 3.1.3 and 3.1.10). This causes a stronger decrease in leaf area expansion at decreasing temperatures relative to the net production of carbohydrates. The result is that the pool of carbohydrates increases at decreasing temperatures because the rate of consumption decreases relatively more than the net production rate. The increasing carbohydrate level has a lowering effect on the specific leaf area of newly formed leaf biomass (cf. effect of high L on λ_p), thus resulting in thicker leaves. So, at decreasing temperatures the value of $f_{T,\lambda}$ is below one and a reduction in λ_n is calculated relative to its potential value of λ_p (see Figure 3.2.1). The temperature effect on specific leaf area has been estimated by using $f_{T,R}$, because both factors ($f_{T,\lambda}$ and $f_{T,R}$) are related to the same process of leaf area growth.

Effect of water

The effect of increasing water stress on the specific leaf area is comparable to that of decreasing temperatures (see above) because the key processes that are involved are affected in a similar way. If the actual transpiration rate drops below the potential transpiration rate of water, leaf area growth is affected more strongly than the processes

directly related to net biomass accumulation. The consequences will be that the carbohydrate level increases under drought conditions (Van Loo, 1993) and that the specific leaf area decreases (e.g., Jones *et al.*, 1980). In the model these processes are simulated by $f_{w,E}$ and $f_{w,\lambda}$, which are the factors for the effect of water stress on net biomass production and the specific leaf area, respectively. In Figure 3.2.2 both factors are related to the transpiration ratio Tr_a/Tr_p (-), i.e. the ratio between actual and potential transpiration, which is used as a measure for water stress. According to the different responses of leaf area growth and net biomass accumulation to water stress, $f_{w,\lambda}$ is in most situations below $f_{w,E}$ at equal values of Tr_a/Tr_p.

In the model the relation between Tr_a/Tr_p and $f_{w,\lambda}$ is characterised by three threshold values: (a) $Tr_{\lambda 1}$ below which $f_{w,\lambda}$ equals 0, (b) $Tr_{\lambda 2}$ at which $f_{w,\lambda}$ equals 0.5 and (c) $Tr_{\lambda 3}$ beyond which $f_{w,\lambda}$ equals 1. Linear interpolation is used to determine the values for $f_{w,\lambda}$ if the ratio between actual and potential transpiration falls between these threshold values (see Figure 3.2.2).

Figure 3.2.2. Relation between the transpiration ratio Tr_a/Tr_p and the reduction factor on specific leaf area due to water stress conditions $f_{w,\lambda}$ in eqn. 3.2.3. The dotted line represents the relation between Tr_a/Tr_p and $f_{w,E}$ (eqn. 3.1.7). See text for further explanation.

Effect of nitrogen

For calculating the effect of nitrogen status on specific leaf area the same holds as for temperature and water effects: low nitrogen concentrations have a similar effect on leaf area growth, carbohydrate level and specific leaf area as low temperature and transpiration ratios. In the model $f_{N,\lambda}$ is related to the leaf nitrogen concentration, C_{Nlv} (see Figure 3.2.3) for which an intermediate variable C^* (-) is calculated to determine $f_{N,\lambda}$ as function of C_{Nlv},

$$C^* = \frac{C_{Nlv} - C_{Nlv,mn}}{\eta_{N,ol} C_{Nlv,a} - C_{Nlv,mn}}$$

(3.2.5)

C^* has been defined as the ratio between the difference in actual and minimum leaf nitrogen concentration (numerator) and the difference in the optimum and minimum leaf nitrogen concentration (denominator). C^* ranges from zero ($C_{Nlv} = C_{Nlv,mn}$) to values of one ($C_{Nlv} = \eta_{N,o} C_{Nlv,a}$) and higher ($C_{Nlv} > \eta_{N,o} C_{Nlv,a}$) and is a relative measure of the leaf nitrogen concentration with respect to its optimum value. The optimum concentration, which equals the threshold value for C_{Nlv} beyond which no effect is calculated ($f_{N,\lambda} = 1$), is a function of L because it is determined as a constant fraction ($\eta_{N,o}$) of the attainable leaf nitrogen concentration, which decreases at increasing L (see section 3.3). It is thus assumed that at a higher L a lower leaf nitrogen concentration is sufficient to realise optimum conditions for leaf area growth, which can be explained by the larger amount of nitrogen available for remobilisation from older leaves towards the newly grown leaves. The thresholds in Figure 3.2.3 equal those of section 3.1.2 (cf. Figure 3.1.8), where they are used to calculate the additional leaf death in case actual leaf nitrogen concentration drops below these optimum values.

A reduction of the specific leaf area is calculated ($f_{N,\lambda} < 1$) for values of C_{Nlv} below the optimum concentration, for which two extra threshold parameters are used to determine the response of $f_{N,\lambda}$ to C_{Nlv}: (a) for C^* below $C_{\lambda 1}$ the value for $f_{N,\lambda}$ equals zero and $f_{N,\lambda}$ equals 0.5 if C^* equals $C_{\lambda 2}$. For values of C^* that fall between the three threshold values ($C_{\lambda 1}$, $C_{\lambda 2}$ and 1), linear interpolation is used to find the corresponding values for $f_{N,\lambda}$ (see Figure 3.2.3).

Figure 3.2.3. Relation between leaf nitrogen concentration C_{Nlv} and the reduction factor on specific leaf area due to nitrogen stress conditions $f_{N,\lambda}$ in eqn. 3.2.3. See text for further explanation.

All variables, $f_{T,\lambda}$, $f_{w,\lambda}$ and $f_{N,\lambda}$, including λ_p as function of L, refer to the specific leaf area of newly grown leaf biomass. The ratio between L and W_{lv} gives the specific leaf area of all existing leaves. Under normal field conditions the respons of L / W_{lv} is less pronounced compared to changes in λ_n because usually the amount of new leaf material is only a small portion of total leaf biomass.

Parameter input values

The possible parameter values related to the leaf area equations are given in Table 3.2.1.

Table 3.2.1. Summary of input values related to leaf area (section 3.2).

Parameter	Equation or Figure	Unit	Range of values	Value used[1]	Source
$Tr_{\lambda 1}$	Fig. 3.2.2	-	0.0-0.5	0.35	a
$Tr_{\lambda 2}$	Fig. 3.2.2	-	0.2-0.8	0.75	a
$Tr_{\lambda 3}$	Fig. 3.2.2	-	0.7-1.0	0.95	a
$C_{\lambda 1}$	Fig. 3.2.3	-	0.0-0.5	0.2	a
$C_{\lambda 2}$	Fig. 3.2.3	-	0.2-0.8	0.7	a
λ_p	eqn. 3.2.3 & Fig. 3.2.1	m^2 leaf g^{-1} leaf dry matter	0.01-0.08	see App. I	a,b-d

[1] *Values as used in a study on the relation between fertilisation strategies and nitrate losses (Conijn & Henstra, 2003). They refer to grass growth under farming conditions.*

a   = Estimated by means of a calibration procedure
b   = Van Loo (1993)
c   = Verberne (1992)
d   = Bouman *et al.* (1996)

3.2.2   Net change

Net change in leaf area index is given by G_L minus D_L, which is integrated in time to determine the new L after each time step. An additional decrease in L is calculated in case of harvesting (see section 3.4).

The possible initial values for L are given in Table 3.2.2.

Table 3.2.2.   Input values related to leaf area index.

State variable	Description	Unit	Range of values[1]	Value used[2]
L	leaf area index	m^2 leaf m^{-2} ground	0.01-3.0	1.2

[1]   Possible values refer to a situation shortly after harvesting or during winter.

[2]   Value as used in a study on the relation between fertilisation strategies and nitrate losses (Conijn & Henstra, 2003). The value refers to the state of the grass sward on January 1st (under 100% cutting regime).

3.3   Grass nitrogen

State variables

Contrary to the use of four compartments in describing grass biomass, grass nitrogen in the model comprises only three compartments: nitrogen in the leaf laminae (N_{lv}), in the leaf sheaths and 'true' stems (N_{st}) and in the roots (N_{rt}), all in g N m^{-2}. Thus, the amount of nitrogen associated with the reserve biomass in the sheath/stem is not explicitly simulated but is included in N_{st}. Total aboveground nitrogen equals the sum of N_{lv} and N_{st}. Similar to the dry matter state variables in the model, the nitrogen content of these plant parts also refers to living tissues. Net changes in these compartments are simulated by computing increase, as a result of nitrogen uptake from the soil and partitioning, and decrease due to death of plant tissues, relocation and harvesting. Nitrogen in dead plant material is directly transferred to soil organic nitrogen for reasons of simplicity.

All nitrogen concentrations used in the model are defined as the amount of nitrogen per unit of biomass (g N g^{-1} dry matter). The actual nitrogen concentrations in plant biomass are given by

$$C_{Nlv} = \frac{N_{lv}}{W_{lv}} \tag{3.3.1a}$$

$$C_{Nst} = \frac{N_{st}}{W_{st} + W_{rs}} \tag{3.3.1b}$$

$$C_{Nrt} = \frac{N_{rt}}{W_{rt}} \tag{3.3.1c}$$

with C_{Nlv}, C_{Nst} and C_{Nrt} the actual nitrogen concentrations in leaves, stems and roots, respectively.

Rate variables

3.3.1   Uptake

The uptake of nitrogen from the soil depends on many factors, such as the availability of inorganic nitrogen in the soil and root uptake characteristics. It is known that even at ample soil nitrogen availability, plant nitrogen concentrations are below species-specific values. Apparently, the nitrogen uptake rate is influenced by the capacity

of the plant to store nitrogen in its tissue. In the nitrogen uptake calculations the nitrogen storage capacity is used in a rather empirical way to calculate a limit to the amount of nitrogen actually taken up from the soil. The minimum between this limit and a potential uptake rate based on soil nitrogen availability gives the actual uptake rate, U_N (g N m^{-2} d^{-1}),

$$U_N = \min(U_{Np}; U_{Nx})$$
(3.3.2)

where U_{Np} refers to the potential uptake from the soil (g N m^{-2} d^{-1}) and U_{Nx} is the maximum uptake calculated from the storage capacity of the plant (g N m^{-2} d^{-1}). U_{Np} is based on the possible flux of nitrogen towards the roots as function of the nitrogen transport characteristics in the soil and root length density. A very simple approach in determining U_{Np} is to assume that a constant fraction of the total amount of inorganic nitrogen in the rooted zone of the soil is available for uptake. Transport of nitrogen through the soil is then not explicitly calculated. A more detailed approach is used in FUSSIM2, a simulation model for soil water flow and solute transport, which has been coupled to CNGRAS. This combined model was used in the simulation of nitrate loss by leaching and denitrification from grassland under mowing (Conijn & Henstra, 2003). See Heinen & De Willigen (1998, 2001) for further information on the calculation of U_{Np} in FUSSIM2.

Contrary to U_{Np}, which is a function of soil processes, U_{Nx} depends only on plant characteristics and is therefore explained here. U_{Nx} is calculated from the nitrogen demands of all plant parts. Nitrogen demand is defined as the difference between attainable and actual nitrogen content. Attainable refers to the situation with ample supply from the soil, where the uptake of nitrogen is not limited by the availability of nitrogen in the soil. The attainable nitrogen concentrations have been calculated by

$$C_{Nlv,a} = f_{s,N} C_{Nlv,x}$$
(3.3.3a)

$$C_{Nst,a} = f_{s,N} C_{Nst,x}$$
(3.3.3b)

$$C_{Nrt,a} = C_{Nrt,x}$$
(3.3.3c)

where $C_{Nlv,x}$, $C_{Nst,x}$ and $C_{Nrt,x}$ are the maximum nitrogen concentrations of leaves, stems and roots (g N g^{-1} dry matter), respectively, and $f_{s,N}$ (-) is a reduction factor, which is modelled as a function of leaf area index (see Figure 3.3.1). A decreasing $f_{s,N}$ at increasing L reflects the situation of decreasing shoot nitrogen concentrations during regrowth, even at ample soil nitrogen supply. It has been assumed that the decreasing sink strength of shoot biomass to hold nitrogen is related to the physiological activity of the shoot, which declines with increasing age of the shoot and decreasing irradiation at lower parts of the canopy, if expressed per unit of biomass or per unit of leaf area index. In the model $f_{s,N}$ is related to leaf area index because in general both shoot age and irradiance at ground level are positively correlated with leaf area index. At $L = 0$ the attainable nitrogen concentrations of leaves and sheaths/stems are equal to their maximum values, $C_{Nlv,x}$ and $C_{Nst,x}$ respectively. For the roots a constant value has been used for the attainable concentration (see eqn 3.3.3c) because changes in total root age are likely to be less pronounced than those of the shoot.

Now, nitrogen demands are determined as the difference between attainable and actual nitrogen contents of each plant compartment,

$$X_{Nlv} = C_{Nlv,a} W_{lv} - N_{lv}$$
(3.3.4a)

$$X_{Nst} = C_{Nst,a} (W_{st} + W_{rs}) - N_{st}$$
(3.3.4b)

$$X_{Nrt} = C_{Nrt,a} W_{rt} - N_{rt}$$
(3.3.4c)

with X_{Nlv}, X_{Nst} and X_{Nrt} the nitrogen demands of leaves, stems and roots (g N m^{-2}), respectively. If the actual nitrogen content exceeds the attainable content of a plant compartment, a negative value would be calculated with

eqn. 3.3.4a-c. In that situation a zero value is used for that nitrogen demand instead of the result from eqn. 3.3.4a-c. Situations where this might occur are described in section 3.3.2. The sum of X_{Nlv}, X_{Nst} and X_{Nrt} (each having a zero or positive value) equals the amount of nitrogen that is needed to realise the attainable nitrogen concentrations in all plant parts.

Figure 3.3.1.   Relation between leaf area index L and the sink strength factor of shoot biomass for nitrogen $f_{s,N}$.

In calculating U_{Nx}, time coefficients are used to allow for a time lag between the demand in plant tissues and the actual uptake of nitrogen from the soil,

$$U_{Nx} = \frac{(X_{Nlv} + X_{Nst})}{tc_{sh}} + \frac{X_{Nrt}}{tc_{rt}}$$

(3.3.5)

with tc_{sh} and tc_{rt} (d) the time coefficients for the shoot and root parts, respectively. In a situation where actual nitrogen concentrations are below the attainable concentrations in combination with values of tc_{sh} and tc_{rt} exceeding the time step of integration, a delay is calculated in achieving the attainable concentrations when the nitrogen directly taken up from the soil (U_N) is the only source. As an example: if both tc_{sh} and tc_{rt} equal two days and the time step of integration is one day, the uptake of nitrogen from the soil cannot be more than only half of the amount needed to realise the attainable concentrations in the plant. However, in this situation CNGRAS may calculate actual concentrations equal to attainable concentrations due to the relocation of nitrogen, which represents an internal source for the partitioning of nitrogen to living plant tissues (see section 3.3.2).

Parameter input values

The possible parameter values related to the nitrogen uptake equations are given in Table 3.3.1. These values only refer to the calculation of U_{Nx}, whereas the calculation of U_{Np} is described in Heinen & De Willigen, 1998 and 2001 (applicable for the coupling of CNGRAS with FUSSIM).

Table 3.3.1.   Summary of input values related to nitrogen uptake.

Parameter	Equation or Figure	Unit	Range of values	Value used[1]	Source
$C_{Nlv,x}$	eqn. 3.3.3a	g N g^{-1} dry matter	0.04-0.08	0.055	b-g
$C_{Nst,x}$	eqn. 3.3.3b	g N g^{-1} dry matter	0.02-0.05	0.03	b-g
$C_{Nrt,x}$	eqn. 3.3.3c	g N g^{-1} dry matter	0.015-0.03	0.02	h,i
tc_{sh}	eqn. 3.3.5	D	1-10	3	a
tc_{rt}	eqn. 3.3.5	D	1-10	3	a
$f_{s,N}$	eqn. 3.3.3 & Fig. 3.3.1	-	0.2-1.0	see App. I	a,c

[1]   *Values as used in a study on the relation between fertilisation strategies and nitrate losses (Conijn & Henstra, 2003). These values refer to grass growth under farming conditions.*

a   = Estimated by means of a calibration procedure
b   = Ten Berge *et al.* (2000)
c   = Lövenstein *et al.* (1992)
d   = Van Loo (1993)
e   = Smid *et al.* (1998)
f   = Deenen (1994)
g   = review of a number of models by Conijn (1997)
h   = Whitehead (1986)
i   = Hassink *et al.* (1996)

3.3.2   Relocation and decrease

The demand for nitrogen (X_{Nlv}, X_{Nst} and X_{Nrt}) can be satisfied by uptake of nitrogen from the soil (external supply) but also by relocation of nitrogen already present in plant biomass (internal supply). To calculate the partitioning of nitrogen towards living plant tissues, both the external and internal nitrogen supply should be determined. The external nitrogen supply is given by U_N and is partly described in section 3.3.1. The internal supply due to relocation of nitrogen from existing biomass has been modelled as a function of (1) relative differences in the biomass and nitrogen decrease rates due to senescence (see: *Related to biomass decrease*), and (2) actual concentration exceeding attainable concentration (see: *Related to surplus*).

Related to biomass decrease

Biomass decrease rates have been calculated as a result of the loss of biomass in dead plant material and reserve relocation (see sections 3.1.2 & 3.1.3). It is assumed that these processes affect an amount of nitrogen, which is proportional to the calculated biomass decrease rates, according to

$$D_{Nlv} = C_{Nlv} D_{Wlv} \tag{3.3.6a}$$

$$D_{Nst} = C_{Nst}(D_{Wst} + R_{Wrs}) \tag{3.3.6b}$$

$$D_{Nrt} = C_{Nrt} D_{Wrt} \tag{3.3.6c}$$

where D_{Nlv}, D_{Nst} and D_{Nrt} are the nitrogen decrease rates of leaves, stems and roots (g N m^{-2} d^{-1}), respectively. Due to withdrawal of nitrogen during senescence, the concentration of nitrogen in dead plant material is usually lower than that of living tissues. This implies that only part of the nitrogen decrease rates from eqn. 3.3.6a-c is lost to dead plant material and that the other part is relocated and reused in the plant. The loss rates of nitrogen to dead leaves, stems and roots, L_{Nlv}, L_{Nst} and L_{Nrt} (g N m^{-2} d^{-1}), are obtained from

$$L_{Nlv} = C_{Nlv,d} D_{Wlv} \qquad\qquad (3.3.7a)$$

$$L_{Nst} = C_{Nst,d} D_{Wst} \qquad\qquad (3.3.7b)$$

$$L_{Nrt} = C_{Nrt,d} D_{Wrt} \qquad\qquad (3.3.7c)$$

with $C_{Nlv,d}$, $C_{Nst,d}$ and $C_{Nrt,d}$ the nitrogen concentrations in dead leaves, stems and roots (g N g^{-1} dry matter). The nitrogen concentrations in dead plant material are not constant but depend on the total nitrogen demand of living plant tissues. A high nitrogen demand causes an efficient withdrawal of nitrogen during senescence, which results in a low concentration of nitrogen in dead leaves, stems and roots and vice versa. This has been modelled by relating the nitrogen concentration in dead plant material to the extent of nitrogen deficiency in plant biomass. The quotient of total actual nitrogen content in the biomass and total attainable nitrogen content (Q_N, -) is used as a measure for nitrogen deficiency. The nitrogen concentrations in dead plant material have been simulated by

$$C_{Nlv,d} = C_{Nlv,mn} + f_{Q,N}(C_{Nlv,dx} - C_{Nlv,mn}) \qquad\qquad (3.3.8a)$$

$$C_{Nst,d} = C_{Nst,mn} + f_{Q,N}(C_{Nst,dx} - C_{Nst,mn}) \qquad\qquad (3.3.8b)$$

$$C_{Nrt,d} = C_{Nrt,mn} + f_{Q,N}(C_{Nrt,dx} - C_{Nrt,mn}) \qquad\qquad (3.3.8c)$$

where $C_{Nlv,mn}$, $C_{Nst,mn}$ and $C_{Nrt,mn}$ are the minimum nitrogen concentrations in dead leaves, stems and roots (g N g^{-1} dry matter), respectively, $C_{Nlv,dx}$, $C_{Nst,dx}$ and $C_{Nrt,dx}$ are the maximum nitrogen concentrations in dead plant material (g N g^{-1} dry matter), respectively, and $f_{Q,N}$ is a factor accounting for the effect of Q_N on the withdrawal efficiency (-). The minimum nitrogen concentrations relate to the amount of nitrogen that cannot be withdrawn because it is bound to non-degradable structures. The maximum nitrogen concentrations in dead plant material correspond to the amount of nitrogen that is bound to structures that are not easily degraded and that can only be withdrawn if a nitrogen deficiency occurs. $f_{Q,N}$, with a value ranging from 0 to 1, is calculated as a linear function of Q_N and two threshold values for nitrogen deficiency, q_{N1} and q_{N2} (see Figure 3.3.2). If nitrogen deficiency is relatively high ($Q_N <$ q_{N1}), $f_{Q,N}$ equals zero and the nitrogen concentrations in dead plant material are set at their minimum values. On the other hand, if $Q_N > q_{N2}$, $f_{Q,N}$ equals 1 and maximum values are used for the nitrogen concentrations in dead plant material.
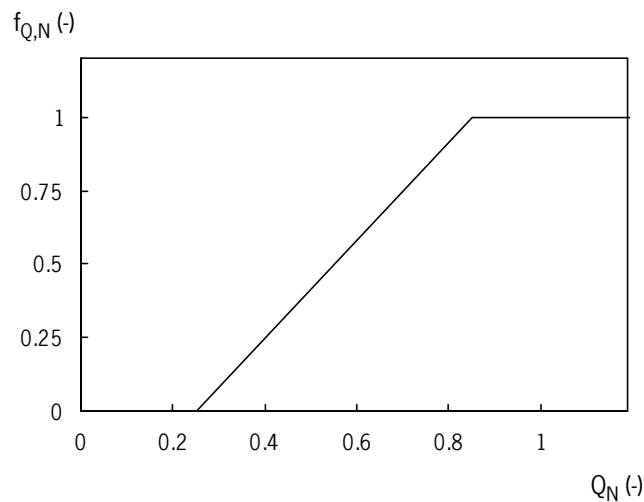

Figure 3.3.2.   *Relation between the quotient of actual and attainable total nitrogen content Q_N and the withdrawal efficiency factor $f_{Q,N}$. See text for further explanation.*

The relocation rates of nitrogen from leaves, stems (including reserves) and roots due to a decrease in biomass, $R_{Nlv,1}$, $R_{Nst,1}$ and $R_{Nrt,1}$ (g N m^{-2} d^{-1}), are now simply calculated by determining the difference in decrease and loss rates,

$$R_{Nlv,1} = D_{Nlv} - L_{Nlv} \qquad\qquad (3.3.9a)$$

$$R_{Nst,1} = D_{Nst} - L_{Nst} \qquad\qquad (3.3.9b)$$

$$R_{Nrt,1} = D_{Nrt} - L_{Nrt} \qquad\qquad (3.3.9c)$$

Related to surplus

A situation of surplus in the existing biomass occurs at increasing L if the actual concentration in a plant compartment is equal or close to the attainable concentration. Due to the decreasing sink strength $f_{s,N}$ at increasing L (see Figure 3.3.1), the attainable concentration may drop below the actual concentration. This causes a surplus above the attainable concentration which is relocated mainly from older plant parts to younger (growing) tissues. The relocation rates of nitrogen from leaves, stems and roots due to this surplus situation, $R_{Nlv,2}$, $R_{Nst,2}$ and $R_{Nrt,2}$ (g N m^{-2} d^{-1}), are calculated by

$$R_{Nlv,2} = \frac{(C_{Nlv} - C_{Nlv,a})W_{lv,e}}{\Delta t}; \qquad \text{for } C_{Nlv} > C_{Nlv,a} \qquad (3.3.10a)$$

$$R_{Nst,2} = \frac{(C_{Nst} - C_{Nst,a})(W_{st,e} + W_{rs,e})}{\Delta t}; \qquad \text{for } C_{Nst} > C_{Nst,a} \qquad (3.3.10b)$$

$$R_{Nrt,2} = \frac{(C_{Nrt} - C_{Nrt,a})W_{rt,e}}{\Delta t}; \qquad \text{for } C_{Nrt} > C_{Nrt,a} \qquad (3.3.10c)$$

with $W_{lv,e}$, $W_{st,e}$, $W_{rs,e}$ and $W_{rt,e}$ the amounts of existing biomass of leaves, stems, reserves and roots (g dry matter m^{-2}), respectively, and Δt the time step of integration (d). It is thus assumed that any nitrogen surplus of equation 3.3.10a-c (actual > attainable) is relocated within the time step of integration. If the actual concentration is below the attainable concentration (actual < attainable), there is no surplus and a zero value is used for this relocation rate instead of the result of eqn. 3.3.10.

The amounts of existing biomass in eqn. 3.3.10 have been corrected for the biomass decrease rates, i.e. they are calculated from the actual biomass at the beginning of each time step minus the decrease due to senescence, relocation or harvesting during this time step. Therefore, $W_{lv,e}$, $W_{st,e}$, $W_{rs,e}$ and $W_{rt,e}$ represent the biomass of the existing plant parts that 'survive' from one moment to the next during the time step of integration. The effect of biomass decrease due to senescence and relocation on the partitioning of nitrogen within the plant has already been described in the above section (*Related to biomass decrease*) and the effect of biomass increase due to growth of plant parts (G_{Wlv}, G_{Wst}, G_{Wrs} and G_{Wrt}) has been modelled separately and is described in section 3.3.3.

Parameter input values

The possible parameter values related to the nitrogen relocation are given in Table 3.3.2.

Table 3.3.2.   Summary of input values related to nitrogen relocation and decrease.

Parameter	Equation or Figure	Unit	Range of values	Value used[1]	Source
$C_{Nlv,mn}$	eqn. 3.3.8a	g N g^{-1} dry matter	0.005-0.015	see Table 3.1.2	
$C_{Nst,mn}$	eqn. 3.3.8b	g N g^{-1} dry matter	0.002-0.015	0.005	a,b-f
$C_{Nrt,mn}$	eqn. 3.3.8c	g N g^{-1} dry matter	0.002-0.015	0.005	a,b-f
$C_{Nlvd,x}$	eqn. 3.3.8a	g N g^{-1} dry matter	0.02-0.04	0.03	a,b-f
$C_{Nst,dx}$	eqn. 3.3.8b	g N g^{-1} dry matter	0.015-0.3	0.02	a,b-f
$C_{Nrt,dx}$	eqn. 3.3.8c	g N g^{-1} dry matter	0.015-0.025	0.018	a,b-f
q_{N1}	Fig. 3.3.2	-	0.0-0.50	0.25	a,b-f
q_{N2}	Fig. 3.3.2	-	0.50-1.0	0.85	a,b-f

[1]   *Values as used in a study on the relation between fertilisation strategies and nitrate losses (Conijn & Henstra, 2003). These values refer to grass growth under farming conditions.*

a   = Estimated by means of a calibration procedure
b   = Ten Berge *et al.* (2000)
c   = Whitehead (1986)
d   = Van den Pol-Dasselaar & Lantinga (1995)
e   = Conijn (unpublished results from 'Droevendaal')
f   = Baan Hofman (unpublished results from 'Cranendonck')

3.3.3   Partitioning

Total supply of nitrogen for partitioning among plant compartments, K_N (g N m^{-2} d^{-1}), is given by the sum of internal and external sources, according to

$$K_N = U_N + \Sigma R_N \tag{3.3.11}$$

with ΣR_N the total nitrogen relocation rate. ΣR_N has been calculated as the sum of the relocation rates from leaves, stems and roots related to surplus (eqn. 3.3.10a-c) and biomass decrease (eqn. 3.3.9a-c; see section 3.3.2). Calculation of U_N is described in section 3.3.1. Partitioning of K_N is calculated as a function of supply U_N and nitrogen demands, which are determined as function of existing and newly produced biomass and the actual and attainable nitrogen concentrations of each plant part. A difference is made between demand from growing plant parts and demand from existing biomass. Demand from growing plant parts comes from the nitrogen that is needed for the growth of new plant parts during the current time step, whereas the demand from existing biomass is related to suboptimal concentrations (i.e. actual < attainable) of plant parts that were already present at the beginning of a time step. The nitrogen demands of currently growing leaves, stems and roots, $S_{Nlv,g}$, $S_{Nst,g}$ and $S_{Nrt,g}$ (g N m^{-2} d^{-1}) are obtained from the biomass growth rates and the attainable nitrogen concentrations,

$$S_{Nlv,g} = C_{Nlv,a} G_{Wlv} \tag{3.3.12a}$$

$$S_{Nst,g} = C_{Nst,a} (G_{Wst} + G_{Wrs}) \tag{3.3.12b}$$

$$S_{Nrt,g} = C_{Nrt,a} G_{Wrt} \tag{3.3.12c}$$

The nitrogen demands of existing biomass, $S_{Nlv,e}$, $S_{Nst,e}$ and $S_{Nrt,e}$ (g N m^{-2} d^{-1}), have been calculated by determining the amount of nitrogen needed to bring existing biomass at attainable concentrations,

$$S_{Nlv,e} = \frac{(C_{Nlv,a} - C_{Nlv})W_{lv,e}}{\Delta t};$$
for $C_{Nlv,a} > C_{Nlv}$
(3.3.13a)

$$S_{Nst,e} = \frac{(C_{Nst,a} - C_{Nst})(W_{st,e} + W_{rs,e})}{\Delta t};$$
for $C_{Nst,a} > C_{Nst}$
(3.3.13b)

$$S_{Nrt,e} = \frac{(C_{Nrt,a} - C_{Nrt})W_{rt,e}}{\Delta t};$$
for $C_{Nrt,a} > C_{Nrt}$
(3.3.13c)

There is no demand if the actual concentration is above the attainable concentration (actual > attainable) and a zero value is then used instead of the result of eqn. 3.3.13. Eqn. 3.3.13a-c is almost identical to eqn. 3.3.10a-c because the absolute values of the results of both equations are equal. Two opposite situations can be distinguished: there is a demand for nitrogen if the actual nitrogen concentration is below the attainable concentration or there is a surplus if the actual concentration exceeds the attainable concentration. In case of demand, eqn. 3.3.13 will yield a positive value and the same value but with a negative sign will be calculated with eqn. 3.3.10. In this situation a zero value is then used for the relocation rate, as explained in section 3.3.2. Vice versa, if there is a surplus situation, eqn. 3.3.13 will give a negative value and demand is set at zero, whereas a positive value is calculated with eqn. 3.3.10 for the relocation rate.

In the calculations growing plant parts have a first priority in nitrogen partitioning because it is assumed that growth activity is a more important factor in determining the sink strength for nitrogen. This means that the demand of 'newly grown' biomass is satisfied first and that the demands of existing biomass can be fulfilled thereafter if total N supply is adequate. It reflects therefore that total sink strength of any plant organ is highest early in its life time and declines during ageing. The nitrogen uptake rates of each plant compartment, as part of the newly produced biomass during the current time step, $G_{Nlv,g}$, $G_{Nst,g}$ and $G_{Nrt,g}$ (g N m^{-2} d^{-1}), are modelled as function of the nitrogen demands of currently growing plant tissues by

$$G_{Nlv,g} = \min(S_{Nlv,g}, (K_N \frac{S_{Nlv,g}}{\Sigma S_{Ng}}))$$
(3.3.14a)

$$G_{Nst,g} = \min(S_{Nst,g}, (K_N \frac{S_{Nst,g}}{\Sigma S_{Ng}}))$$
(3.3.14b)

$$G_{Nrt,g} = \min(S_{Nrt,g}, (K_N \frac{S_{Nrt,g}}{\Sigma S_{Ng}}))$$
(3.3.14c)

where ΣS_{Ng} equals the sum of all nitrogen demands due to current biomass growth ($S_{Nlv,g}$, $S_{Nst,g}$ and $S_{Nrt,g}$). According to eqn. 3.3.14, the uptake of nitrogen by any plant part will be proportional to its demand from new growth relative to the total demand from new growth, if $\Sigma S_{N,g}$ exceeds K_N. On the other hand, if K_N exceeds $\Sigma S_{N,g}$, the uptake rate by any plant part is at least equal to its demand from new growth. In this situation the remaining part of K_N after partitioning of nitrogen to growing tissues, i.e. $K_N - \Sigma S_{N,g}$, is distributed proportional to the demands of existing biomass of all plant parts relative to the total demand of existing biomass (= $\Sigma S_{N,e}$) by

$$G_{Nlv,e} = \min(S_{Nlv,e}, ((K_N - \Sigma S_{Ng}) \frac{S_{Nlv,e}}{\Sigma S_{Ne}}));$$
for $(K_N - \Sigma S_{N,g}) > 0$
(3.3.15a)

$$G_{Nst,e} = \min(S_{Nst,e}, ((K_N - \Sigma S_{Ng}) \frac{S_{Nst,e}}{\Sigma S_{Ne}}));$$
for $(K_N - \Sigma S_{N,g}) > 0$
(3.3.15b)

$$G_{Nrt,e} = \min(S_{Nrt,e}, ((K_N - \Sigma S_{Ng}) \frac{S_{Nrt,e}}{\Sigma S_{Ne}}));$$
for $(K_N - \Sigma S_{N,g}) > 0$
(3.3.15c)

with $G_{Nlv,e}$, $G_{Nst,e}$ and $G_{Nrt,e}$ (g N m^{-2} d^{-1}) the uptake rates of nitrogen related to suboptimal nitrogen concentrations in existing biomass, respectively. If $\Sigma S_{N,g}$ exceeds K_N, these rates are set to zero. Total uptake per plant part, G_{Nlv}, G_{Nst} and G_{Nrt} (g N m^{-2} d^{-1}), equals the sum of both uptake rates for each plant compartment by

$$G_{Nlv} = G_{Nlv,g} + G_{Nlv,e} \tag{3.3.16a}$$

$$G_{Nst} = G_{Nst,g} + G_{Nst,e} \tag{3.3.16b}$$

$$G_{Nrt} = G_{Nrt,g} + G_{Nrt,e} + (K_N - \Sigma S_{Ng} - \Sigma S_{Ne}) \tag{3.3.16c}$$

It has been assumed that any occurring surplus (K_N - ΣS_{Ng} - ΣS_{Ne}) is partitioned towards the roots. This situation mainly occurs during winter as a result of nitrogen relocation due to senescence in combination with (very) low production levels if the actual concentrations are equal or close to their attainable levels. The sum of existing biomass and biomass of newly grown plant parts will be the new 'total' biomass of each plant compartment after integration. If the demands of both can be satisfied from the total supply K_N, then attainable nitrogen concentrations will be realised in the whole plant.

3.3.4   Net change

Net changes in the nitrogen content of each compartment are calculated as the difference between nitrogen uptake rates (eqn. 3.3.16a-c), losses (eqn. 3.3.6a-c), and the sum of the two relocation rates (eqn. 3.3.9a-c and 3.3.10a-c). These net changes are integrated in time to determine the new amounts of nitrogen after each time step. An additional decrease in leaf and stem nitrogen is calculated in case of harvesting (see section 3.4).

The possible initial values for the state variables related to grass nitrogen are given in Table 3.3.3.

Table 3.3.3.   Input values for the state variables, related to grass nitrogen.

State variable	Description	Unit	Range of values[1]	Value used[2]
N_{lv}	amount of leaf nitrogen	g N m^{-2}	0.01-15	4.2
N_{st}	amount of sheath and stem nitrogen	g N m^{-2}	0.01-4.0	0.98
N_{rt}	amount of root nitrogen	g N m^{-2}	1-30	9.0

[1]   *Possible values refer to a situation shortly after harvesting or during winter.*
[2]   *Values as used in a study on the relation between fertilisation strategies and nitrate losses (Conijn & Henstra, 2003). These values refer to the state of the grass sward on January 1st (under 100% cutting regime).*

3.4   Management

3.4.1   Cutting

In the model a direct effect of cutting is described for the amounts of biomass and nitrogen in living tissues of leaves, stems and reserves and for the leaf area index (W_{lv}, W_{st}, W_{rs}, N_{lv}, N_{st} and L). It is assumed that the grass is cut at the beginning of the day with immediate effect, which means that the 'new' values for these state variables after cutting are valid from the beginning of this day. At the day of cutting the equations related to this cutting event (see below) are thus executed first leading to the values that represent the situation directly after cutting.

Biomass

The calculation of the amount of cut biomass starts with the determination of the amount of aboveground biomass left in the layer beneath cutting height. In CNGRAS a cutting height of approximately 5 - 6 cm is assumed

(Lantinga, 1985; Van Loo, 1993). Three different distribution functions are used to divide total aboveground biomass at the cutting date between the harvestable layer and the layer beneath cutting height. Each function relates total biomass to the amount of biomass beneath cutting height and a different function is applied for leaf laminae, leaf sheaths and true stems. The total amount of biomass above cutting height is then simply computed as the difference between total aboveground biomass (sum of W_{lv}, W_{st} and W_{rs}) and the amounts of these three categories beneath cutting height. In calculating the biomass beneath cutting height, a separate function is used for true stems because the distribution of biomass above and below cutting height is different for true stems as compared to leaf sheaths (see Figure 3.4.1 and 3.4.2 at high values for the x-variable).

True stem beneath cutting height

The amount of true stem biomass is estimated by first calculating the biomass of leaf sheaths, including the reserves in those leaf sheaths, W_{sr} (g dry matter m^{-2}), according to

$$W_{sr} = (1 + \frac{W_{rs}}{W_{st}}) \frac{p_{st}}{p_{lv}} W_{lv} \qquad (3.4.1)$$

In eqn. 3.4.1 it is assumed that at the cutting date the ratio between sheath and lamina biomass is given by p_{st}/p_{lv} and that the amount of reserves in the sheaths is proportional to W_{rs}/W_{st}. Now, the amount of true stem biomass including its share of the reserves, W_{ts} (g dry matter m^{-2}) equals

$$W_{ts} = W_{st} + W_{rs} - W_{sr} \qquad (3.4.2)$$

With the data presented in Figure 3.4.1 (after Bloemhof, 1993) the amount of true stem biomass beneath cutting height, $W_{ts,b}$ (g dry matter m^{-2}) is determined as function of W_{ts}. At low values for W_{ts} all true stem material is located beneath cutting height and $W_{ts,b}$ equals W_{ts}. This situation occurs, e.g., early in the development of true stems. At higher values for W_{ts} true stem biomass starts to develop above cutting height, which is illustrated in Figure 3.4.1 by the deviation of the dashed line from the continuous line, indicating that W_{ts} exceeds $W_{ts,b}$. An increase in $W_{ts,b}$ is assumed at these higher levels of W_{ts}, until a threshold value is realised beyond which $W_{ts,b}$ remains constant. The increase in $W_{ts,b}$ is caused by an increase in the number of true stems as well as in the amount of biomass per stem which are positively correlated with total true stem biomass at intermediate levels of W_{ts}.
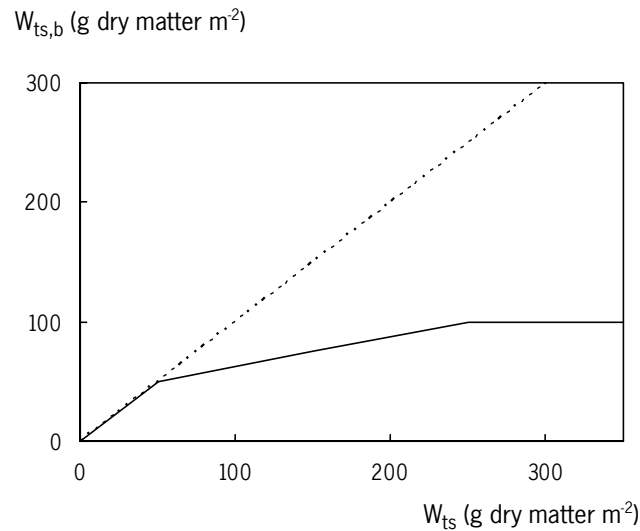
$W_{ts,b}$ (g dry matter m^{-2})

W_{ts} (g dry matter m^{-2})

Figure 3.4.1.   Amount of true stem biomass beneath cutting height $W_{ts,b}$ as function of total true stem biomass W_{ts} (continuous line). The dashed line represents y = x. Difference between both lines gives the amount of biomass above cutting height. See text for further explanation.

The calculations of eqn. 3.4.1 & 3.4.2 will only be performed if the option to simulate the development of true stems during the generative phase in spring is used. For situations without true stem development, W_{ts} is set to zero and the value of W_{sr} is made equal to the sum of W_{st} and W_{rs}.

Lamina and sheath beneath cutting height

The two distribution functions for laminae and sheaths, which are input for the model (see Appendix I), have been derived by combining data on total aboveground biomass (excluding true stems) and the fraction of laminae in cut biomass. This derivation is not part of CNGRAS but has been performed in preparing the input for the model. Here, an explanation is given of these underlying data.

First, a distribution function is used for the total aboveground biomass ω_{ls} (g dry matter m^{-2}), excluding true stems, based on data of Bloemhof (1993, see Figure 3.4.2). This function separates the biomass into two fractions: above and below cutting height. Again, at low values all biomass is located beneath cutting height, which occurs, e.g., shortly after a cutting event. Beyond a lower threshold value, the biomass beneath cutting height $\omega_{ls,b}$ remains approximately constant for a wide range of values for ω_{ls}, until it starts to decrease. $\omega_{ls,b}$ decreases to nearly zero at a predefined value for ω_{ls} and beyond this value it remains nearly zero (Van Loo, 1993). This reflects the situation where the laminae and sheaths beneath cutting height consist only of dead plant material and all living tissues are located above cutting height. Cutting in this stage will result in a high yield (equal to ω_{ls}) but also in a sward after cutting without photosynthetically active leaves and therefore a very low regrowth rate.
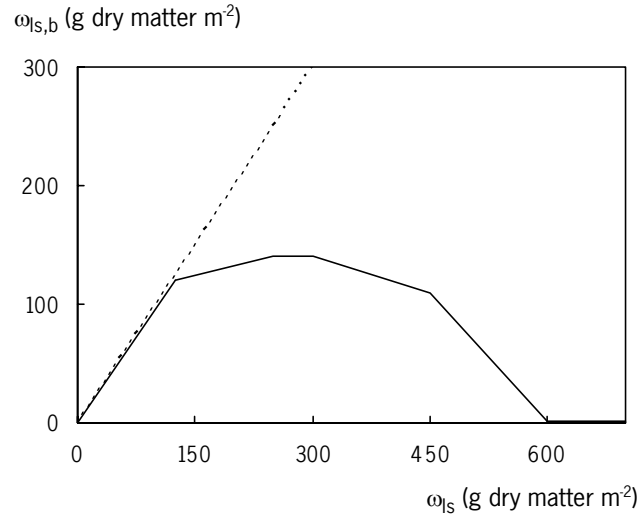
$\omega_{ls,b}$ (g dry matter m^{-2})

Figure 3.4.2.   Amount of lamina and sheath biomass beneath cutting height $\omega_{ls,b}$ as function of total lamina and sheath biomass ω_{ls} (continuous line). The dashed line represents y = x. Difference between both lines gives the amount of biomass above cutting height. See text for further explanation.

Second, it is assumed that for all levels of ω_{ls} the fraction of leaves in total aboveground biomass can be estimated by *0.1 p_{lv}* and thus the fraction of leaf sheaths including the reserves in these sheaths by *1 - 0.1 p_{lv}* (according to Robson, 1973; see also Table 3.1.2). ω_{ls} of Figure 3.4.2 can now be divided into a leaf part and a sheath part, including the reserves in the sheath. This division is needed to be able to translate ω_{ls} into the state variables for the aboveground biomass in CNGRAS, i.e. W_{lv}, W_{st} and W_{rs}. W_{lv} then correlates with *0.1 p_{lv} ω_{ls}* and the sum of W_{st} and W_{rs} minus W_{ts} with $\omega_{\lambda s}$ *- 0.1 p_{lv} ω_{ls}*.

Third, information is used with respect to the amount of leaf lamina biomass in the cut biomass relative to the total amount of cut biomass (Figure 3.4.3). According to unpublished data of Rutgers *et al.*, the fraction of leaf laminae in cut biomass, f_{LH}(-), equals 1 at low values for the total amount of cut biomass, indicating that no leaf sheaths are harvested. At higher values for the total biomass this fraction decreases when part of the available leaf sheaths are located above cutting height and appear in the cut biomass. The lowest possible value for f_{LH} is given by *0.1 p_{lv}*, because in that situation all living tissues of laminae and sheaths are cut (see Figures 3.4.2 and 3.4.3) with an estimated fraction of the laminae in total biomass of *0.1 p_{lv}*.
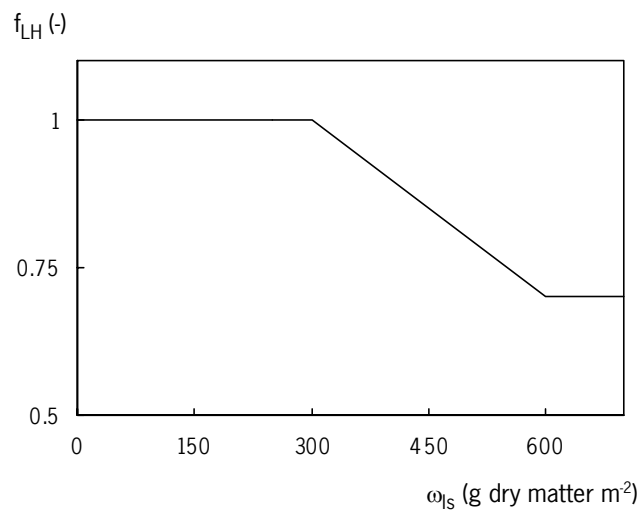
f_{LH} (-)

Figure 3.4.3.   Fraction of leaf lamina biomass yield in total cut biomass f_{LH} as function of total aboveground biomass ω_{ls} (only valid for situations without true stems).

The two distribution functions for leaf laminae and leaf sheaths (including their reserves) have been determined with the above-mentioned data (see Table I.1 in Appendix I for the input data). CNGRAS now calculates the amount of lamina biomass and sheath biomass beneath cutting height, $W_{lv,b}$ and $W_{sr,b}$, as function of W_{lv} and W_{sr} respectively, by

$$W_{lv,b} = Function(W_{lv})f_{w,Y} \qquad (3.4.3a)$$

$$W_{sr,b} = Function(W_{sr})f_{w,Y} \qquad (3.4.3b)$$

In eqn. 3.4.3a&b the "Function" refers to the distribution functions for leaf laminae and sheath, respectively, as explained above. An effect of water stress, $f_{w,Y}(-)$, is added to the equation because prolonged water stress accelerates senescence (see section 3.1.2) and decreases the amount of living tissues beneath cutting height.

Effect of water

The value of $f_{w,Y}$ ranges from nearly zero (maximum effect) to 1 (no effect). $f_{w,Y}$ is calculated as a quadratic function of the cumulative transpiration deficit, Td_C (d), and a threshold value $Td_{C,t}$ beyond which the minimum value for $f_{w,Y}$ is determined (see Figure 3.4.4). This minimum value is set close, but not equal to zero to prevent the situation where no living tissue is left after cutting. This is done because in the calculations of CNGRAS regrowth will not take place if the value of the simulated leaf biomass has dropped to zero.

Figure 3.4.4. *Relation between the effect of water stress on the biomass left after cutting $f_{w,Y}$ and the cumulative transpiration deficit Td_C. Td_C is a measure for the accumulated number of water stress days during the growth period up to the moment of cutting.*

Cumulative transpiration deficit

The cumulative transpiration deficit is a measure for the amount of water stress experienced during the growth period up to the moment of cutting. Td_C is a state variable in CNGRAS and its value is found by integrating the rate of change in the cumulative transpiration deficit in time. This rate of change can be negative, indicating a decrease in Td_C, or positive in which case Td_C increases. The rate of change, $dTd_C(-)$, is computed as a linear function of the transpiration ratio Tr_a / Tr_p (-) and a threshold value $Tr_{r,d}(-)$ at which dTd_C equals zero (see Figure 3.4.5). The threshold value divides the reponse of dTd_C to the transpiration ratio in two sections of increasing and decreasing Td_C. Unfavourable conditions with respect to the transpiration by the grass vegetation, e.g., Tr_a close to zero, increase the value for Td_C. However, favourable transpiration conditions, such as $Tr_a = Tr_p$, can restore a cumulative transpiration deficit (if $Td_C > 0$) until the value for Td_C after integration becomes negative. In that situation

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Td_C is set to zero (= its lowest possible value in the model) in which case the favourable transpiration conditions no longer affect Td_C. Therefore, Td_C represents the number of days with water stress minus the days without or with only minor water stress. It thus describes the state of water stress of the sward by integrating both positive and negative conditions of water supply as accumulated in the recent past.

Figure 3.4.5. *Rate of change in cumulative transpiration deficit as function of the transpiration ratio. A positive value for dTd$_C$ indicates an increase in the cumulative transpiration deficit, whereas a negative value decreases this deficit.*

The possible initial values for the cumulative transpiration deficit Td_C are given in Table 3.4.1.

Table 3.4.1. *Input values for state variable Td$_C$, related to calculation of the amount of grass biomass left after cuttting.*

State variable	Description	Unit	Range of values	Value used[1]
Td_C	cumulative transpiration deficit	d	0-90	0

[1]   *Value as used in a study on the relation between fertilisation strategies and nitrate losses (Conijn & Henstra, 2003). The value refers to the state of the grass sward on January 1st (under 100% cutting regime).*

The amount of cut biomass of leaves, stems and reserves, $W_{lv,h}$, $W_{st,h}$ and $W_{rs,h}$ (g dry matter m^{-2}), respectively, are now found with the determined values for the biomass beneath cutting height,

$$W_{lv,h} = W_{lv} - W_{lv,b}$$ (3.4.4a)

$$W_{st,h} = (W_{st} + W_{rs} - W_{sr,b} - W_{ts,b}) \frac{W_{st}}{W_{st} + W_{rs}}$$ (3.4.4b)

$$W_{rs,h} = (W_{st} + W_{rs} - W_{sr,b} - W_{ts,b}) \frac{W_{rs}}{W_{st} + W_{rs}}$$ (3.4.4c)

The new values of the aboveground biomass after cutting are simply computed as the difference between the amounts before cutting (W_{lv}, W_{st} and W_{rs}) and the harvested amounts obtained from eqn. 3.4.4a-c.

Total amount of cut biomass $W_{sh,h}$ (g dry matter m^{-2}) is given by the sum of $W_{lv,h}$, $W_{st,h}$ and $W_{rs,h}$ (eqn. 3.4.5), which is also equal to W_{sh} minus the sum of the biomass left beneath cutting height.

$$W_{sh,h} = W_{lv,h} + W_{st,h} + W_{rs,h}$$
(3.4.5)

Part of this cut biomass may remain at the field instead of being removed from the field. To account for these 'harvesting losses', the model user should supply a fraction lost, $f_{H,l}$ (-), for each harvest via an input file. Different values can be used for different harvest events. This fraction is then used for all parts of the cut biomass, according to

$$W_{lv,l} = f_{H,l} W_{lv,h}$$
(3.4.6a)

$$W_{st,l} = f_{H,l} W_{st,h}$$
(3.4.6b)

$$W_{rs,l} = f_{H,l} W_{rs,h}$$
(3.4.6c)

The value of $f_{H,l}$ ranges from zero (no losses, 100% of cut biomass removed) to one (no yield, 100% of cut biomass is lost). The latter situation can be used for simulating a cleaning cut. The amount of biomass that is lost at harvesting, $W_{lv,l}$, $W_{st,l}$ and $W_{rs,l}$ (g dry matter m^{-2}), is added to the soil organic matter pool. The other part of the cut biomass ($W_{sh,h}$ minus the sum of $W_{lv,l}$, $W_{st,l}$ and $W_{rs,l}$) is removed from the field and is referred to as net biomass yield or biomass offtake.

Nitrogen

The calculation of the amount of cut nitrogen is closely linked to that of cut biomass. The amount of cut stem nitrogen is simply determined as the product of the sum of the cut biomass of stems and reserves and the overall nitrogen concentration in the stems, C_{Nst} (eqn. 3.4.7b). For the leaves a lower nitrogen concentration in the biomass left after cutting is assumed at higher leaf area index relative to the concentration in total leaf biomass (according to data of Meijs, 1981 and Sibma & Ennik, 1988). In particular at low light intensities in the lower layers of the canopy (as a result of high L), nitrogen is redistributed towards layers higher in the canopy where light intensity is higher. Due to this lower concentration in the leaf parts that are left after cutting a higher proportion of leaf N can be harvested in comparison with the situation of cut biomass. The amount of cut leaf nitrogen is calculated by

$$N_{lv,h} = N_{lv} - (W_{lv,b} C_{Nlv} f_{L,c})$$
(3.4.7a)

$$N_{st,h} = (W_{st,h} + W_{rs,h}) C_{Nst}$$
(3.4.7b)

with $f_{L,c}$ (-) the effect of leaf area index L on the ratio between stubble and total leaf nitrogen concentration (Figure 3.4.6).

Figure 3.4.6. *Effect of leaf area index L on the nitrogen concentration of the leaves left after cutting. See text for further explanation.*

The new values of the amounts of aboveground nitrogen after cutting are simply computed as the difference between the amounts before cutting (N_{lv} and N_{st}) and the harvested amounts obtained from eqn. 3.4.7a-b. Harvesting losses with respect to nitrogen, $N_{lv,l}$ and $N_{st,l}$ (g N m^{-2}), are calculated according to

$$N_{lv,l} = f_{H,l} N_{lv,h} \tag{3.4.8a}$$

$$N_{st,l} = f_{H,l} N_{st,h} \tag{3.4.8b}$$

and are transferred directly to the soil organic nitrogen pool. The other part of the cut amount of nitrogen (sum of $N_{lv,h}$ and $N_{st,h}$ minus sum of $N_{lv,l}$ and $N_{st,l}$) is removed from the field and is referred to as net nitrogen yield or nitrogen offtake.

Leaf area index

The new leaf area index after cutting, L_b (m^2 m^{-2}), is found by

$$L_b = W_{lv,b} \frac{L}{W_{lv}} f_{\lambda} \tag{3.4.9}$$

with f_{λ} (-) a factor to account for differences in the specific leaf area of the leaf part left after cutting relative to overall specific leaf area. If the value of f_{λ} equals one, the specific leaf areas below and above cutting height are equal, whereas if $f_{\lambda} < 1$, a lower specific leaf area in the stubble is assumed.

Parameter input values

The possible parameter values related to the 'cutting' equations are given in Table 3.4.2.

Table 3.4.2.   Summary of input values related to cutting (section 3.4.1).

Parameter	Equation or Figure	Unit	Range of values	Value used[1]	Source
$Td_{C,t}$	Fig. 3.4.4	d	5 – 45	28	a
$Tr_{r,d}$	Fig. 3.4.5	-	0.2 – 0.9	0.67	b
$f_{H,l}$	eqn. 3.4.6a-c, eqn. 3.4.8a-b, eqn. 3.4.13a-c	-	0.0 – 1.0	0.075	c
f_λ	eqn. 3.4.9	-	0.5 – 1.0	0.85	a
$W_{lv,b}$	eqn. 3.4.3a & Fig. 3.4.2	g dry matter m^{-2}	0-W_{lv}	see App. I	d
$W_{ts,b}$	Fig. 3.4.1	g dry matter m^{-2}	0-W_{ts}	see App. I	d
$W_{sr,b}$	eqn. 3.4.3a & Fig. 3.4.2	g dry matter m^{-2}	0-W_{sr}	see App. I	d
$f_{L,c}$	eqn. 3.4.7a & Fig. 3.4.6	-	0.33 – 1.0	see App. I	a,e

[1]   *Values as used in a study on the relation between fertilisation strategies and nitrate losses (Conijn & Henstra, 2003). These values refer to grass growth under farming conditions.*

a   = Estimated by means of a calibration procedure
b   = Value equal to $Tr_{r,t}$ in Table 3.1.2.
c   = Anonymous (1997; value corresponding with cutting, but depends on management; one value needed for each harvest event; a value of 0.15 can be used for grazing)
d   = After Bloemhof (1993) and Van Loo (1993)
e   = After Sibma & Ennik (1988)

3.4.2   Grazing

The direct effects of grazing on the amounts of aboveground biomass and nitrogen in living tissues and on the leaf area index are determined by calculating rates of change in these state variables for each grazing day. These changes are treated as 'normal' rate variables in the same way as growth and decrease rates and are thus integrated in time, together with the other rates of change (contrary to the situation with cutting). The net rate of change of the relevant state variables (see sections 3.1.5, 3.2.2 and 3.3.4) will then directly be affected during the grazing period(s) of the animals in the field.

Biomass

On average, the main effect of grazing on the state variables of the grass vegetation is caused by the removal of biomass through animal intake. Daily dry matter intake per animal, I_d (kg dry matter (animal)$^{-1}$ d^{-1}, is computed by using the formula of Zemmelink (1980, as referred to in Lantinga, 1985). I_d is described as an exponential function of the amount of biomass available for consumption by the animals, I_s (kg dry matter (animal)$^{-1}$ d^{-1}), according to

$$I_s = \frac{10 W_{sh,h}}{D_a \Delta t} \tag{3.4.10}$$

$$I_d = I_m (1 - e^{-(\frac{I_s}{I_m})^{f_I}})^{\frac{1}{f_I}} \tag{3.4.11}$$

with D_a the density of the grazing animals (ha^{-1}), Δt the time step of integration, I_m the maximum dry matter intake (kg dry matter (animal)$^{-1}$ d^{-1}) and f_I(-) a shape parameter of the response curve. Figure 3.4.7 gives a graphical representation of eqn. 3.4.11.

I_d (kg dry matter (animal)$^{-1}$ d^{-1})
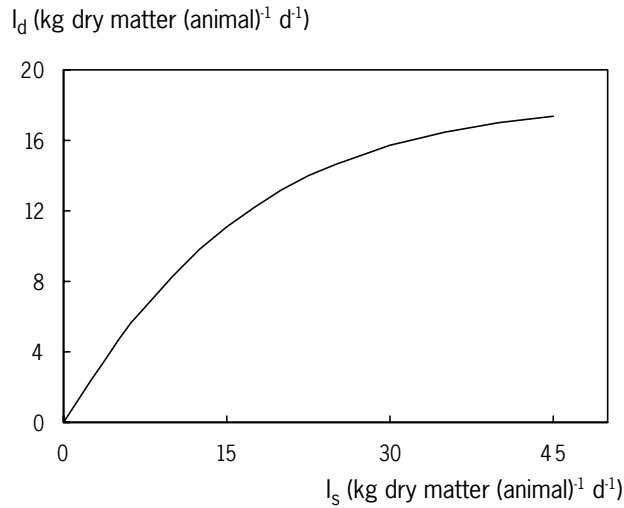
I_s (kg dry matter (animal)$^{-1}$ d^{-1})

Figure 3.4.7. Response of actual dry matter intake I_d on available dry matter per animal I_s with an assumed maximum dry matter intake of 18 kg dry matter (animal)$^{-1}$ d^{-1}.

I_d can also be supplied by the model user via the input file as an alternative option for calculating I_d with eqn. 3.4.11. In that situation I_d equals I_m, where I_m represents the mean intake per grazing period. For each grazing period a different value for I_m can be given.

Daily dry matter intake by the animals is used to compute the decrease in leaf, stem and reserve biomass due to grazing in two steps by eqn. 3.4.12a-c and eqn. 3.4.13a-c. First, the amounts of leaf, stem and reserve biomass that are consumed by the animals, $H_{Wlv,y}$, $H_{Wst,y}$ and $H_{Wrs,y}$ (g dry matter m^{-2} d^{-1}), respectively, are calculated by distributing total intake $0.1\,I_d D_a$ (g dry matter m^{-2} d^{-1}). In eqn. 3.4.12a-c a preferred leaf intake, relative to stems and reserves, is possible by using a leaf grazing preference factor f_{pg} (-). If a value of one is chosen for f_{pg}, the proportion of consumed leaf biomass is equal to the proportion of leaf biomass in total aboveground standing biomass (i.e. no preference). Higher values will increase the leaf biomass intake proportion relative to that of standing biomass.

$$H_{Wlv,y} = 0.1 I_d D_a \frac{f_{pg} W_{lv}}{f_{pg} W_{lv} + W_{st} + W_{rs}} \qquad (3.4.12a)$$

$$H_{Wst,y} = 0.1 I_d D_a \frac{W_{st}}{f_{pg} W_{lv} + W_{st} + W_{rs}} \qquad (3.4.12b)$$

$$H_{Wrs,y} = 0.1 I_d D_a \frac{W_{rs}}{f_{pg} W_{lv} + W_{st} + W_{rs}} \qquad (3.4.12c)$$

The second step in calculating the decrease rates in leaf, stems and reserve biomass due to grazing animals is by taking into account the harvesting or grazing losses. The decrease rates, H_{Wlv}, H_{Wst} and H_{Wrs} (g dry matter m^{-2} d^{-1}), respectively, can be found by dividing the intake rates of eqn. 3.4.12a-c by $1 - f_{H,l}$. The same variable ($f_{H,l}$) is used in eqn. 3.4.13a-c as in the situation with cutting as harvesting method (see eqn. 3.4.6a-c). In general, the fraction harvesting loss differs between cutting or grazing and this can be simulated by supplying different values for $f_{H,l}$ at different harvesting events.

$$H_{Wlv} = \frac{H_{Wlv,y}}{1 - f_{H,l}} \qquad (3.4.13a)$$

$$H_{Wst} = \frac{H_{Wst,y}}{1 - f_{H,l}}$$ (3.4.13b)

$$H_{Wrs} = \frac{H_{Wrs,y}}{1 - f_{H,l}}$$ (3.4.13c)

The decrease rates due to grazing, H_{Wlv}, H_{Wst} and H_{Wrs}, are used to compute the net change in the aboveground state variables for biomass, W_{lv}, W_{st} and W_{rs} (see section 3.1.5), respectively. The differences between the calculated rates of eqn. 3.4.13a-c and their corresponding values of eqn. 3.4.12a-c give the amounts of biomass lost to soil organic matter which is input for the soil organic matter model.

Nitrogen

Nitrogen intake, decrease and loss rates due to grazing are simply determined by multiplying the corresponding biomass rates by the nitrogen concentrations in the aboveground tissues, C_{Nlv} for the leaf biomass and C_{Nst} for stem and reserve biomass together. Net nitrogen yield is given by the sum of the nitrogen intake rates from leaves ($H_{Nlv,y}$ in g N m^{-2} d^{-1}) and stems and reserves ($H_{Nst,y}$ in g N m^{-2} d^{-1}). The net changes in the aboveground nitrogen state variables (see section 3.3.4) are found by determining the result of growth, decrease due to death and decrease due to grazing, H_{Nlv} and H_{Nst} (g N m^{-2} d^{-1}). The amount of nitrogen lost due to grazing, $H_{Nlv,l}$ and $H_{Nst,l}$ (g N m^{-2} d^{-1}), is input for the organic nitrogen pool in the soil.

Leaf area index

The decrease in leaf area index as a result of grazing, H_l (m^2 m^{-2} d^{-1}), is calculated by assuming that it is in proportion to the leaf biomass decrease rate, according to

$$H_L = \frac{L}{W_{lv}} H_{Wlv,y}$$ (3.4.14)

H_l is used to determine the net change in L (see section 3.1.2).

Parameter input values

The possible parameter values related to the 'grazing' equations are given in Table 3.4.3.

Table 3.4.3.   Summary of input values related to grazing (section 3.4.2).

Parameter	Equation or Figure	Unit	Range of values	Value used[1]	Source
D_a	eqn. 3.4.10	ha^{-1}	0-100	35	b
I_m	eqn. 3.4.11 & Fig. 3.4.7	kg dry matter (animal)$^{-1}$ d^{-1}	0-20	18	c
f_l	eqn. 3.4.11 & Fig. 3.4.7	-	0.5-15	1.23	d
f_{pg}	eqn. 3.4.12a-c	-	1.0-100	2	a

[1]   Values as used in a study on the relation between fertilisation strategies and nitrate losses (Conijn & Henstra, 2003). These values refer to grass growth under farming conditions.

a   = Estimated by means of a calibration procedure
b   = Value depends on farm intensity and management (one value needed for each grazing period)
c   = Lantinga (1985) and Anonymous (1997); value depends on supplemental feeding level (one value needed for each grazing period)
d   = Lantinga (1985) and Meijs (1981, 1983)

4. Case studies

4.1 FAO database on grassland production

Data

CNGRAS has been evaluated by comparing calculated yield (dry matter) production rates with data obtained from the project "Predicting production from grassland" of the FAO Subnetwork of lowland grassland. These data have been gathered in the eighties of the last century in a number of European countries. From the FAO database a selection has been made that was suitable for the purpose of evaluating CNGRAS; this selection contained data from six North European countries (Norway, Ireland, United Kingdom, The Netherlands, Belgium and Germany). The selected data comprise measured harvestable dry matter and meteorological data, both on a weekly basis. All data refer to young grasslands with *Lolium perenne (L.)* as dominant species and all fields received fertilisation aimed at preventing growth limitation by nutrient shortage. In a subset of the experiments from which the data have been used, two treatments were applied with respect to water supply: irrigated and non-irrigated. The other subset contained only data from non-irrigated fields. More information and references on the experiments and the measured data can be found in Bouman *et al.* (1996).

Model

One of the input files of CNGRAS contains a switch parameter (IPS) which enables selection of three different grass production situations. If IPS = 0, grass growth will be calculated without being influenced by water and nitrogen stress. In that situation the model will skip a large number of formulas that deal with the effects of water and nitrogen stress. If IPS =1, water limitation may occur (depending on weather, soil and plant characteristics) and may affect grass growth but nitrogen limitation is still prevented in the calculations. Finally, if IPS = 2, both water and nitrogen stress may influence the model results. For the evaluation with the FAO data, the switch parameter IPS is set to zero in case of an irrigated treatment and to one in case of a non-irrigated treatment. If IPS = 0, soil water and soil nitrogen modules are not used by CNGRAS, which means that only the first two model components of Table 2.1 were needed. For IPS =1 a simple soil water balance ('tipping bucket' concept) was added to the two model components of CNGRAS for use in this evaluation with the FAO data.

Calibration

An independent calibration has not been performed. Instead, the parameter values that resulted from a calibration procedure of LINGRA against the same data set (Bouman *et al.*, 1996) were used as much as possible. Only small changes in these values have been applied if a better result was obtained when comparing calculated and observed data from only one experiment in Wageningen (1983) that was part of the FAO database. The final result of this 'calibration' is given in Figure 4.1 and it was concluded that the results were satisfactory.

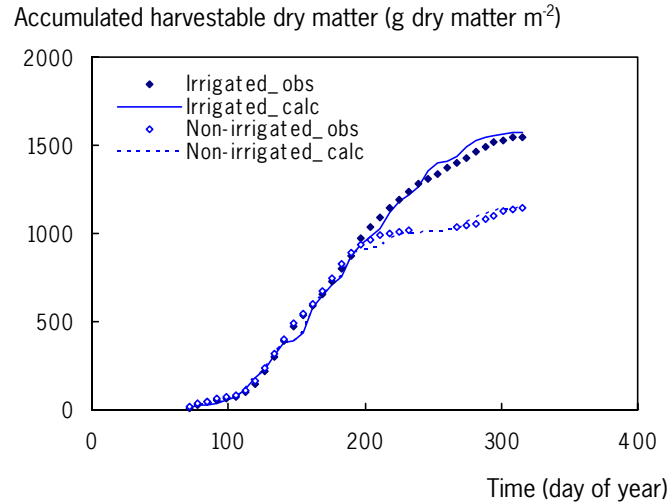Accumulated harvestable dry matter (g dry matter m^{-2})

Figure 4.1   Observed (dots) and calculated (lines) harvestable dry matter of Lolium perenne (L.), accumulated during the 1983 growing season in Wageningen. The experimental data in this figure were used for calibration (see text).

Evaluation

The results of the calculations with CNGRAS were evaluated against (i) weekly observations of accumulated dry matter yields and (ii) final dry matter yields at the end of the growing season of all selected experiments (including the 'data set' used for calibration, see Figure 4.1). By comparing the weekly observations with the corresponding simulated values, an absolute average error ε (g dry matter m^{-2}) has been calculated for each experiment in the database according to

$$\varepsilon = \frac{\sum \left| Y_{t,calc} - Y_{t,obs} \right|}{n}$$
(4.1)

where $Y_{t,calc}$ and $Y_{t,obs}$ are the calculated and observed harvestable dry matter (g dry matter m^{-2}) at time t and n is the number of weekly observations within a growing season (compare the dots and corresponding points of the lines in Figure 4.1). A total of 45 experiments (12 irrigated and 33 non-irrigated) were available for the evaluation and ε ranged from 29 to 289 g dry matter m^{-2}. The average value of ε for all experiments equals 125 g dry matter m^{-2} (115 for the irrigated subset and 129 for the non-irrigated subset). These results are similar to those obtained by LINGRA (121 and 133 for the irrigated and non-irrigated subsets respectively, see Table 3.5 in Bouman *et al.*, 1996). A relative average error has also been calculated by dividing ε by the average value of $Y_{t,obs}$. For the whole data set the average observed yield (based on the weekly observations) was equal to 778 g dry matter m^{-2} and the relative average error is now equal to 0.16 (0.14 for the irrigated experiments and 0.17 for the non-irrigated experiments). Bouman *et al.* (1996) concluded that these results indicate a very good performance for crop growth simulation models and that the model performed well in predicting observed grassland production of perennial ryegrass experiments throughout North Europe.

Results of an evaluation of observed and calculated harvestable dry matter yields against time for Wageningen (two years) and Zegveld (two years) are given in Appendix III. Figure 4.1 and Figure III.1a, which both refer to Wageningen 1983, are slightly different because for the calibration daily weather data from Wageningen have been used, whereas weekly weather recordings were used for the evaluation the FAO database (similar to all other experiments). The result of the weekly input is slightly worse than that of the daily input, in particular for the irrigated treatment.

End-of-season dry matter yields of calculated and observed values have also been compared (Figure 4.2). The average values for the observed and calculated dry matter yields are 1377 and 1354 g dry matter m^{-2}, respectively. On average, the model underestimates the observed end-of-season yields by only 23 g dry matter m^{-2}. Absolute average differences between calculated and observed values equal 200 g dry matter m^{-2}, which is equivalent to 14.5% of the average observed dry matter yield. This relative difference between observed and calculated yield is similar to the relative errors obtained from the weekly observations (see above).

Figure 4.2. *Observed against calculated harvestable dry matter yield at the end of the growing season of all experiments in the selected subset of the FAO database (12 irrigated and 33 non-irrigated experiments).*

4.2 Other case studies

Results of other case studies that have been undertaken with CNGRAS can be found in Oenema (1999, 2000), Conijn & Henstra (2003), Assinck *et al.* (2002) and Van Beek *et al.* (2002). In these cases CNGRAS was coupled with FUSSIM2 (Heinen & De Willigen, 1998, 2001) for soil water and nitrogen calculations.

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Appendix I.
Interpolation tables

Some input values for the model are supplied in the form of an interpolation table, which consists of a number of data pairs (x,y). Each data pair gives the value of a dependent variable (y) and the corresponding independent variable (x). During a simulation run, the model calculates y as function of x. For x values that are not supplied in the interpolation table, the y value is found by linear interpolation between the y values of the two nearest corresponding x values in the interpolation table. Many figures in this report that depict the relation between two variables are based on this procedure.

The input for these interpolation tables, as used in Conijn & Henstra (2003), are given below. Most tables contain extreme minimum or maximum values for the x range to ensure that every possible x value is included and therefore the corresponding y value can be calculated (e.g., –50 and 50 for daily average temperature in calculating $f_{T,E}$ or day number 367 to find $f_{d,E}$ for the last day in a leap year by interpolation between day number 365 and 367).

Table I.1. Input values for linear interpolation function.

Figure	3.1.2		3.1.3		3.1.4		3.1.6		3.1.9	
x,y pair	x	y	x	y	x	y	x	y	x	y
	1	0.8	-50	0	0	1	0	0.0075	-50	0.0027
	15	0.8	0	0	5	1	4	0.0075	5	0.0027
	46	0.85	5	0.4	15	0.5	8	0.012	50	0.014
	105	1.0	10	1			12	0.024		
	227	1.0	15	1			16	0.050		
	288	0.85	20	0.9						
	319	0.8	25	0.5						
	367	0.8	35	0						
			50	0						
	Day	$f_{d,E}$	T_a	$f_{T,E}$	L	$f_{L,E}$	L	$d_{lv,L}$	T_a	d_{rt}

Table I.1. (Continued)

Figure	3.1.10		3.1.12		3.1.12		3.1.14		3.2.1	
x,y pair	x	y	x	y	x	y	x	y	x	y
	-50	0	0	0.85	0	0.15	0	0	0	0.06
	0	0	0.01	0.25	0.01	0.08	200	0	2	0.04
	5	0.1	0.015	0.17	0.055	0.04	400	0.02	4	0.0325
	10	0.4	0.025	0.11	0.09	0.04	600	0.05	8	0.025
	15	0.9	0.04	0.08			4000	0.05	16	0.02
	20	1.0	0.09	0.08						
	25	1.0								
	30	0.9								
	40	0								
	50	0								
	T_s	$f_{T,R}$	λ_n	f_{rt}	λ_n	f_{rs}	T_{sum}	$f_{st,f}$	L	λ_p

Figure	3.3.1		3.4.1		3.4.2		3.4.2		3.4.6	
x,y pair	x	y	x	y	x	y	x	y	x	y
	0	1.0	0	0	0	0	0	0	0	1
	2	0.85	50	50	84	84	36	36	2	1
	4	0.77	150	75	175	65	75	75	4	1
	6	0.7	250	100	210	50	90	90	6	0.93
	8	0.64	2500	100	315	26	135	84	8	0.9
	10	0.59			420	1	180	1	10	0.88
	12	0.54			4200	1	1800	1	12	0.87
	16	0.5							16	0.85
	L	$f_{s,N}$	W_{ts}	$W_{ts,b}$	W_{lv}	$W_{lv,b}$	W_{sr}	$W_{sr,b}$	L	$f_{L,c}$

Appendix II.
Main interactions between the five model components

Model components	1. Grass production	2. Grassland management	3. Soil organic carbon and nitrogen	4. Soil inorganic nitrogen	5. Soil water balance
1. Grass production		information on harvestable dry matter used for timing of management (1 → 2)	transfer of organic matter from plant to soil (1 → 3)	information on nitrogen demand used for calculating nitrogen uptake (1 → 4)	information on leaf area index used for calculating water uptake (1 → 5)
2. Grassland management	amount of cut or grazed grass dry matter and nitrogen (2 → 1)		input of organic nitrogen via fertilisation and grazing (2 → 3)	input of inorganic nitrogen via fertilisation and grazing (2 → 4)	input of water into the soil via irrigation (2 → 5)
3. Soil organic carbon and nitrogen				mineralisation of organic nitrogen into inorganic nitrogen (3 → 4)	
4. Soil inorganic nitrogen	nitrogen uptake from the soil by plant roots (4 → 1)		immobilisation of inorganic nitrogen into organic nitrogen (4 → 3)		
5. Soil water balance	actual and potential water uptake from the soil by plant roots (5 → 1)		information on soil water content used for calculating organic carbon and nitrogen transformations (5 → 3)	information on soil water content used for calculating inorganic nitrogen transformations (5 → 4)	

Appendix III.

Results of an evaluation of CNGRAS against data from experiments in the Netherlands

Accumulated harvestable dry matter (g m^{-2})

Figure III.1a.   Observed (dots) and calculated (lines) harvestable dry matter of Lolium perenne (L.), accumulated during the growing season of 1983 in Wageningen. Results of an evaluation of CNGRAS against a FAO database.
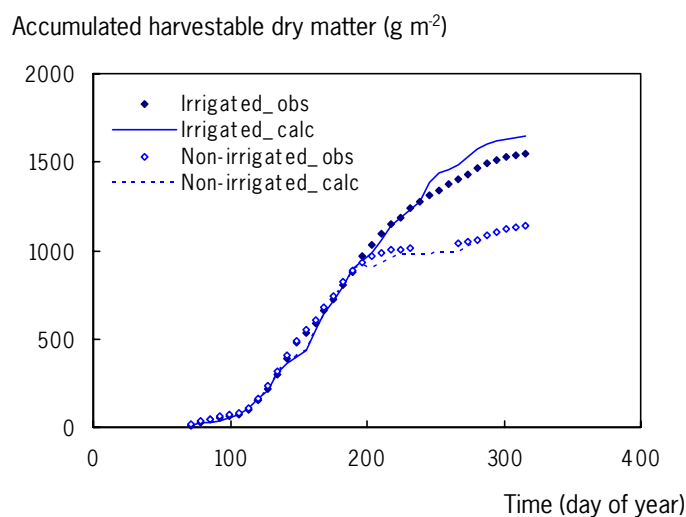
Accumulated harvestable dry matter (g m^{-2})

Figure III.1b.   Observed (dots) and calculated (lines) harvestable dry matter of Lolium perenne (L.), accumulated during the growing season of 1984 in Wageningen. Results of an evaluation of CNGRAS against a FAO database.
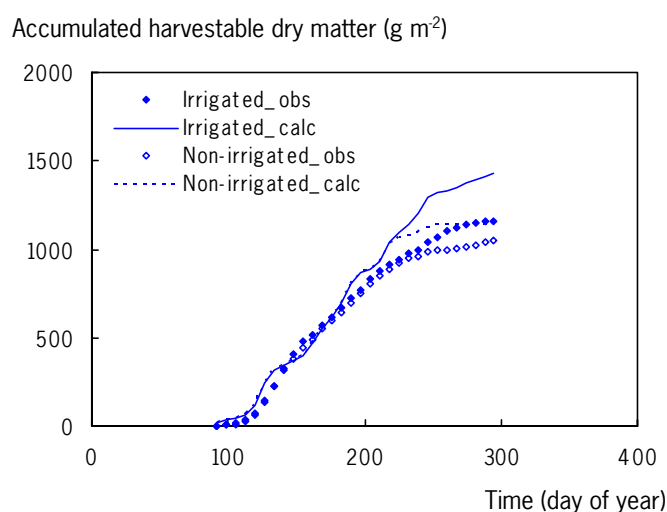
Accumulated harvestable dry matter (g m^{-2})

Figure III.2a.   Observed (dots) and calculated (lines) harvestable dry matter of Lolium perenne (L.), accumulated during the growing season of 1984 in Zegveld. Results of an evaluation of CNGRAS against a FAO database.
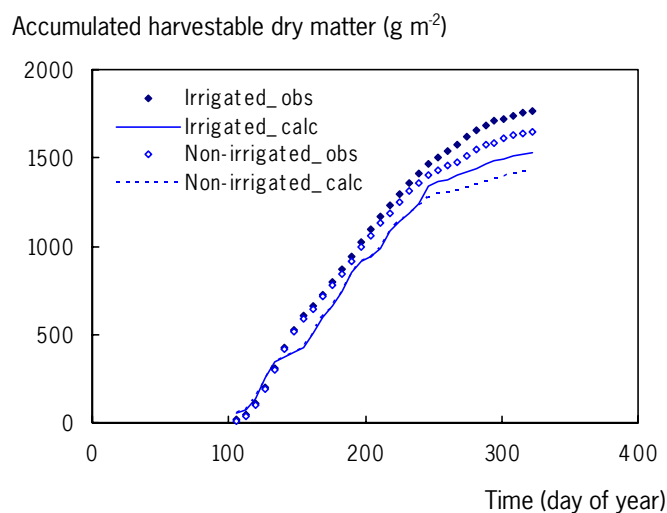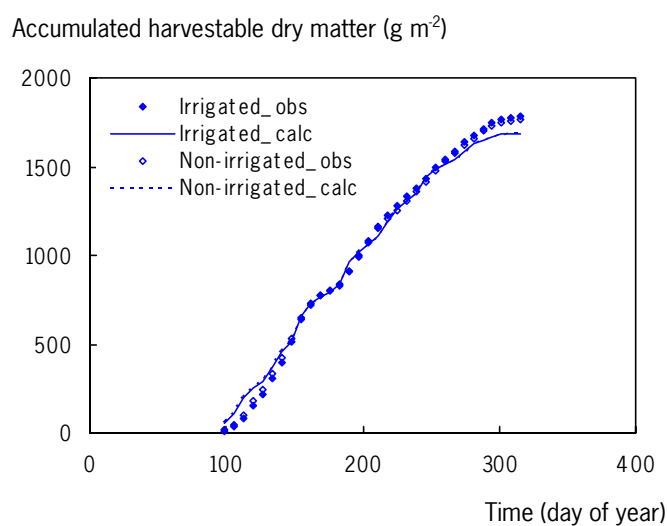
Accumulated harvestable dry matter (g m^{-2})

Figure III.2b.   Observed (dots) and calculated (lines) harvestable dry matter of Lolium perenne (L.), accumulated during the growing season of 1985 in Zegveld. Results of an evaluation of CNGRAS against a FAO database.

Appendix IV.
Description of input variables of CNGRAS

Table IV.1.   Description of input variables of CNGRAS.

State variable	Description	Unit
L	leaf area index	m^2 leaf m^{-2} ground
N_{lv}	amount of leaf nitrogen	g N m^{-2}
N_{rt}	amount of root nitrogen	g N m^{-2}
N_{st}	amount of sheath and true stem nitrogen	g N m^{-2}
Td_C	cumulative transpiration deficit	d
W_{lv}	amount of leaf biomass	g dry matter m^{-2}
W_{rs}	amount of reserve biomass	g dry matter m^{-2}
W_{rt}	amount of root biomass	g dry matter m^{-2}
W_{st}	amount of sheath and true stem biomass	g dry matter m^{-2}

Parameter	Description	Unit
C_{dm}	Amount of carbohydrates consumed per unit of dry matter produced	g CH_2O g^{-1} dry matter
$C_{Nlv,dx}$	maximum nitrogen concentration in dead leaves	g N g^{-1} dry matter
$C_{Nlv,mn}$	minimum nitrogen concentration in dead leaves that is also used as threshold at which the maximum effect of nitrogen stress conditions on leaf death rate is calculated ($f_{N,D,mx}$)	g N g^{-1} dry matter
$C_{Nlv,mp}$	threshold for leaf nitrogen concentration at which grass dry matter production equals zero	g N g^{-1} dry matter
$C_{Nlv,op}$	threshold for leaf nitrogen concentration at which grass dry matter production is not limited by nitrogen conditions	g N g^{-1} dry matter
$C_{Nlv,x}$	maximum leaf nitrogen concentration	g N g^{-1} dry matter
$C_{Nrt,dx}$	maximum nitrogen concentration in dead roots	g N g^{-1} dry matter
$C_{Nrt,mn}$	minimum nitrogen concentration in dead roots	g N g^{-1} dry matter
$C_{Nrt,x}$	maximum root nitrogen concentration	g N g^{-1} dry matter
$C_{Nst,dx}$	maximum nitrogen concentration in dead sheaths and true stems	g N g^{-1} dry matter
$C_{Nst,mn}$	minimum nitrogen concentration in dead sheaths and true stems	g N g^{-1} dry matter
$C_{Nst,x}$	maximum stem nitrogen concentration	g N g^{-1} dry matter
$C_{\lambda 1}$	threshold for relative leaf nitrogen concentration at which the specific leaf area of currently growing leaves equals zero	-
$C_{\lambda 2}$	threshold for relative leaf nitrogen concentration at which the specific leaf area of currently growing leaves is halved due to nitrogen stress conditions	-

Table IV.1. (Continued)

Parameter	Description	Unit
D_a	density of grazing animals	ha^{-1}
$d_{lv,L}$	relative leaf death rate under optimal conditions of water and nitrogen	d^{-1}
d_{rt}	relative root death rate	d^{-1}
E_{max}	maximum light use efficiency	g dry matter MJ^{-1}
$f_{d,E}$	effect of day of the year on light use efficiency	-
$f_{H,l}$	harvesting loss fraction, relative to the gross amount of harvested material	-
f_l	shape parameter of the response of daily herbage dry matter intake per animal to the amount of available herbage dry matter per animal	-
$f_{L,c}$	ratio of nitrogen concentrations of leaf material below cutting height and that of all leaf material	-
$f_{L,E}$	effect of leaf area index on light use efficiency	-
$f_{N,D,mx}$	maximum effect on leaf death rate due to nitrogen stress conditions	-
f_{pg}	preference factor for leaf intake relative to total grass dry matter intake during grazing	-
f_{rs}	factor for partitioning dry matter to the reserves in sheaths and true stems	-
$f_{rs,x}$	maximum fraction of reserve dry matter in sheaths and true stems	g reserve dry matter g^{-1} stem dry matter
f_{rt}	factor for partitioning dry matter to the roots	-
$f_{s,N}$	sink strength factor of shoot biomass for nitrogen	-
$f_{st,f}$	factor for partitioning dry matter to the true stems	-
$f_{T,E}$	effect of daily average air temperature on light use efficiency	-
$f_{T,R}$	effect of daily average soil temperature (0-5 cm) on relocation rate of reserve dry matter	-
$f_{w,D,mx}$	maximum effect on leaf death rate due to water stress conditions	-
f_{λ}	ratio of specific leaf areas of leaf material below cutting height and that of all leaf material	-
I_m	maximum herbage dry matter intake	kg dry matter $(animal)^{-1}$ d^{-1}
k_p	extinction coefficient for photosynthetically active radiation (PAR)	m^2 ground m^{-2} leaf
p_{lv}	part of the leaf laminae in total leaf dry matter	-
p_{st}	part of the leaf sheaths, excluding the reserves in the sheaths, in total leaf dry matter	-
q_{N1}	threshold for nitrogen deficiency at which the minimum nitrogen concentration is calculated for dead plant material	-
q_{N2}	threshold for nitrogen deficiency at which the maximum nitrogen concentration is calculated for dead plant material	-
$r_{rs,mx}$	maximum relative relocation rate of reserve dry matter located in the sheaths and true stems	d^{-1}

Table IV.1. (Continued)

Parameter	Description	Unit
$S_{c,L}$	threshold for net carbohydrate supply from current production at which the maximum relocation rate of reserve dry matter due to carbohydrate availability is calculated	g CH_2O m^{-2} d^{-1}
$S_{c,U}$	threshold for net carbohydrate supply from current production at which the relocation rate of reserve dry matter equals zero	g CH_2O m^{-2} d^{-1}
tc_{rt}	time coefficient in calculating maximum nitrogen uptake as function of root nitrogen demand	d
tc_{sh}	time coefficient in calculating maximum nitrogen uptake as function of shoot nitrogen demand	d
$Td_{C,t}$	threshold for cumulative transpiration deficit at which the minimum value for shoot biomass beneath cutting height due to drought conditions is calculated	d
$Tr_{r,d}$	threshold for transpiration ratio at which the rate of change in cumulative transpiration deficit equals zero	-
$Tr_{r,t}$	threshold for transpiration ratio at which leaf death rate is not increased by water conditions	-
$Tr_{\lambda 1}$	threshold for transpiration ratio at which the specific leaf area of currently growing leaves equals zero	-
$Tr_{\lambda 2}$	threshold for transpiration ratio at which the specific leaf area of currently growing leaves is halved due to water stress conditions	-
$Tr_{\lambda 3}$	threshold for transpiration ratio at which the specific leaf area of currently growing leaves is not decreased by water conditions	-
$W_{lv,b}$	leaf laminae dry matter below cutting height	g dry matter m^{-2}
$W_{sr,b}$	sheath dry matter below cutting height, including reserve dry matter in sheaths	g dry matter m^{-2}
$W_{ts,b}$	true stem dry matter below cutting height, including reserve dry matter in true stems	g dry matter m^{-2}
$\eta_{N,o}$	fraction of the attainable leaf nitrogen concentration at which leaf death rate is not increased by nitrogen conditions and at which specific leaf area of currently growing leaves is not decreased by nitrogen conditions	-
λ_p	potential specific leaf area of currently growing leaves	m^2 leaf g^{-1} leaf dry matter
σ	scattering coefficient of individual leaves for PAR	-