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Heft 5

Nitrogen Carbon Interaction Model

NCIM

Documentation: Model Version 3.00

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Dedicated to

The International Earth System Modelling Community

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Chapter 1

Introduction

This Version 3.00 of the Nitrogen Carbon Interaction Model (NCIM) is the first NCIM Version which has been released.

NCIM is a global generic model of the terrestrial carbon and nitrogen cycles. It was designed to investigate the coupling in nature of the carbon and nitrogen cycles of terrestrial ecosystems and the influences both cycles have on each other. This is important because carbon and nitrogen compounds are major atmospheric greenhouse gases and the cycles of these two elements, besides others, are strongly affected by human activities. Carbon and nitrogen pools interact considerably with the processes of carbon and nitrogen turnover in the ecosystems und with the climate system. NCIM allows the investigation of these interactions, their importance on the global or regional scale, and the role of natural and anthropogenic influences, on time scales from month to centuries.

NCIM is regionalized on a 0.5 degrees grid of geographical latitude and longitude (62 483 grid elements). The carbon and nitrogen cycles in the model are independent and closed. Mass–balance is maintained. During a regular model run, no amounts of carbon and/or nitrogen or C/N ratios are prescribed. Rather, the C/N ratios of all biospheric and soil compartments are calculated from the respective pools in each model time step.

The coupling of the carbon and nitrogen cycles has been performed in the way we prefer: Information on the system state (pools, state variables) is used for steering or regulating the processes (fluxes). For this purpose the coefficients of the process equations are calculated from the respective state variables by use of empirical functions (for the model structure see Figures 2.1 and 2.2 on pages 12 and 13).

These empirical functions, as well as the flux equations, were calibrated using data sets from our own experiments which were carried out in natural ecosystems of many climate zones of the world, in open top chambers, the phytotron of the Justus–Liebig–University and the Giessen

Table 1.1: Some terms which are frequently used in this document together with the explanation of their meaning in this documentation. The variables which represent the terms in the model code may be (rarely) scalars or one– to multi–dimensional arrays.

term	synonym	meaning
pool	state variable	the compartments of the system containing matter (carbon, nitrogen, etc.) or energy
flux	process	transport of matter or energy from one pool to another. Fluxes are used to balance the pools
coefficient		variable in an equation which is updated once at the beginning or several times during a model time step. The current values of coefficients depend on the state of the system (pools) and/or on the current boundary conditions and driving forces (which are state variables in other systems).
parameter		variable in an equation which is set at the very beginning of the model run. Parameters depend on either initial conditions or boundary conditions which are assumed to be constant during the model run (i.e., vegetation type, soil type and texture, etc.).
driving force	control variable	(independent) variable in an equation which changes during time but is not changed by the model itself. Driving forces may either be read from files or provided by other coupled model(s). They are pools (state variables) in other than the currently modelled systems.
initial condition		Value assigned to a pool before the time evolution of the model starts.

FACE Experiment (Jäger et al., 2003).

The model makes use of a global digital vegetation data set on the 0.5 degrees grid, derived from the Atlas for Biogeography (Atlas zur Biogeographie, Schmithüsen 1976). This vegetation data set includes 176 vegetation units throughout the world. The soil information on soil types and textures was digitizes from the Soil Map of the World (FAO–Unesco 1974 ff.).

NCIM's structure is modular. Each module is independent of the other modules and consists of a number of "tasks" which again are independent. The tasks work on the entire model grid, so that the state variables, coefficients, parameters, and driving forces are arrays of the respective grid. The dimensions of the commonly used arrays of variables in the model code are:

$$igrid \;=\; 1, \ldots, 62\,483 \qquad \text{(model grid)}$$

$$
\begin{aligned}
icount &= 1, \ldots, 149 && \text{(country structure)} \\
ibiome &= 1, \ldots, 176 && \text{(biomes, vegetation types)} \\
ip &= 1, \ldots, 56 && \text{(pools = state variables)}
\end{aligned}
$$

The documentation follows the **Module** and **Task** structure of the model code.

In this documentation, we use several terms which are explained in Table 1.1. The following conventions are used unless differently indicated:

- Variables in mathematical terms are written in $italics$.
- Variables related to the program code are written in `typewriter`.
- m^2 means square meter of ground surface area.
- g means gram of carbon or nitrogen.

The program code of NCIM has been written in standard FORTRAN 77. Only two exceptions were made: (1) we use the command `include` to include common block structures in the modules, and (2) we use the non standard character _ (underline) in names of variables. Either have become standard with FORTRAN 90.

Chapter 2

Model structure

2.1 Structure of the carbon and nitrogen cycles

The carbon cycle in NCIM consists of carbon pools and carbon fluxes. Its nitrogen cycle includes nitrogen pools and nitrogen fluxes. Each pool is balaced by the fluxes which are connected to this pool.

The carbon and nitrogen cycles are calculated for a standard m^2 of each grid element, with a monthly time–step. The dimension of the pools is [g·m^{-2}], and the dimension of the fluxes is [g·m^{-2}·$month^{-1}$], therefore.

In addition, NCIM uses a number of pools which we call “dummy”–pools. They are used to collect fluxes for output purposes.

In NCIM the pools are two–dimensional arrays, of the notation `p(igrid,ip)`, with `igrid` being the respective grid element, and `ip` the type of the carbon or nitrogen pool (see Tables 2.1 and 2.2 respective 2.3 and 2.4).

For the fluxes (processes) we use one dimensional arrays of the form `flux(igrid)` with `i` being a grid element, to balance the pools by differential equations. The flux terms are assigned to these arrays. The carbon and nitrogen fluxes are found in the Tables 2.5 and 2.6.

The differential equations are integrated in time using a forth–order Runge–Kutta method. The time–step of integration is two days.

The Figures 2.1 and 2.2 on pages 12 and 13 show the structure of the carbon and nitrogen cycles of NCIM. Some ecosystem compartments are represented in either the carbon and nitrogen cycles. These include the atmosphere (`atmc` and `atmn`), the phytomass (`pc` and `pn`), the litter (`lc` and `ln`), the soil organisms (`micc` and `micn`), and soil humus (`humc` and `humn`). Slowly decomposed organic residues (`ligc`) are assumed to originate from plant lignin compounds and be free of nitrogen. Nitrogen pools without analogous carbon pools include the

Table 2.1: Carbon pools

meaning	ipool
phytomass carbon herbaceous above–ground	pcha
phytomass carbon herbaceous below–ground	pchb
phytomass carbon woody above–ground	pcwa
phytomass carbon woody below–ground	pcwb
litter carbon herbaceous above–ground	lcha
litter carbon herbaceous below–ground	lchb
litter carbon woody above–ground	lcwa
litter carbon woody below–ground	lcwb
carbon in lignin compounds	ligc
carbon in humic substances	humc
carbon in the biomass of litter and soil organisms	micc

Table 2.2: Carbon dummy pools (pools which are used to collect fluxes during a time period for output).

meaning	ipool
net primary productivity carbon, herbaceous material	nppch
net primary productivity carbon, woody material	nppcw
litter production carbon from herbaceous material	lpch
litter production carbon from woody material	lpcw
litter depletion carbon, herbaceous litter	ldch
litter depletion carbon, woody litter	ldcw
lignin production carbon	ligpc
lignin depletion carbon	ligdc
humic substances production carbon	humpc
humic substances depletion carbon	humdc
carbon (CO_2) segregated as excess carbon from soil organisms	misc
carbon respiration by soil organisms	mirc
carbon by mortality of soil organisms	mimc
carbon removed by deforestation	dforc

Table 2.3: Nitrogen pools

meaning	ipool
phytomass nitrogen herbaceous above–ground	pnha
phytomass nitrogen herbaceous below–ground	pnhb
phytomass nitrogen woody above–ground	pnwa
phytomass nitrogen woody below–ground	pnwb
litter nitrogen herbaceous above–ground	lnha
litter nitrogen herbaceous below–ground	lnhb
litter nitrogen woody above–ground	lnwa
litter nitrogen woody below–ground	lnwb
reserve nitrogen stored in plants, which is available for allocation to phytomass compartments	resn
nitrogen available (soluble) in litter and soil	avn
nitrogen in the biomass of litter and soil organisms	micn
nitrogen in humic substances	humn
nitrogen in soil buffer pool (immobilized ammonium)	puffn

mobile nitrogen reserves in plants (resn), the mineral "available" nitrogen in the soil (avn), and the nitrogen adsorbed on clay and humic substances in the soil (puffn).

In the carbon cycle, the main ecosystem turnover includes the atmospheric carbon pool as major object, and the fluxes connected with the atmosphere are the most important processes (net primary productivity nppc and depletion processes miscf, mimcf and mircf). In contrast, in the nitrogen cycle, the main turnover includes soil, plants, and soil organisms. The exchange with the atmospheric nitrogen pool is maintained by relatively minor fluxes like N_2 fixation by symbionts or free living microorganisms (legnf, azonf, actnf) and denitrification processes producing N_2 and N_2O from organic compounds (n2onf).

Although the carbon and nitrogen cycles are independant of each other and are mass–balanced each, they interact strongly. The state of nitrogen pools is used for steering some fluxes in the carbon cycle: net primary productivity nppc, litter depletion ldc, depletion of slowly decomposible organic compounds ligdc, production of excess CO_2 by soil organisms miscf, and the production and depletion of humic substances humpcf and humdcf. On the other side, the state of carbon pools is similarly used for steering nitrogen fluxes: segregation of excess nitrogen by soil organisms misnf, uptake of available nitrogen by plants avunf, and the three

Table 2.4: Nitrogen dummy pools (pools which are used to collect fluxes during a time period for output).

meaning	`ipool`
nitrogen allocated by the net primary productivity	`nppn`
nitrogen transported with litter production	`lpn`
nitrogen transported to soil organisms by litter depletion	`ldn`
nitrogen excreted by soil organisms (humic substances nitrogen)	`humpn`
nitrogen transported to soil organisms by humus depletion	`humdn`
nitrogen transported to organisms from available N in litter and soil	`mign`
nitrogen mineralized by mortality of soil organisms	`mimn`
nitrogen segregated by soil organisms as excess N	`misn`
nitrogen uptake by plants from available nitrogen	`avun`
re-allocation of nitrogen from senescent leaves	`raln`
nitrogen fixed by symbionts in legume root nodules	`legn`
nitrogen fixed by *Azospirillum* symbionts in C4 grasses and cereals	`azon`
nitrogen fixed by actinomycetes	`actn`
N_2O and N_2 gas eliminated from litter nitrogen pools by denitrification processes correlated with gross mineralization	`n2on`
nitrogen leached from soil to ground water and surface waters	`lean`
nitrogen deposition as NO_x and HNO_3 from anthropogenic sources	`depn`

fluxes of N_2 fixation `legnf`, `azonf`, and `actnf`.

In the Figures 2.1 on page 12 and 2.2 on page 13 the steering influences on fluxes are indicated by black arrows marked with “N” and “C”, respectively.

Table 2.5: Carbon fluxes of NCIM.

meaning	`flux` array name
net primary productivity carbon into herbaceous above–ground parts	`npppha`
net primary productivity carbon into herbaceous below–ground parts	`nppphb`
net primary productivity carbon into woody above–ground parts	`nppwa`
net primary productivity carbon into woody below–ground parts	`nppwb`
litter production carbon of above–ground herbaceous material	`lpcha`
litter procuction carbon of below–ground herbaceous material	`lpchb`
litter production carbon of above–ground woody material	`lpcwa`
litter production carbon of below–ground woody material	`lpcwb`
carbon losses of above–ground woody material by deforestation	`dforca`
carbon losses of below–ground woody material by deforestation	`dforcb`
litter depletion carbon of above–ground herbaceous material	`ldcha`
litter depletion carbon of below–ground herbaceous material	`ldchb`
litter depletion carbon of above–ground woody material	`ldcwa`
litter depletion carbon of below–ground woody material	`ldcwb`
lignin production carbon	`ligpc`
lignin depletion carbon	`ligdcf`
humus production carbon	`humpcf`
humus depletion carbon	`humdcf`
carbon loss by respiration of soil organisms	`mircf`
carbon release by mortality of soil organisms	`mimcf`
carbon (CO_2) segregated as excess carbon from soil organisms	`miscf`

Table 2.6: Nitrogen fluxes of NCIM.

meaning	`flux` array name
allocation of nitrogen due to net primary productivity into herbaceous above–ground parts	`nppnha`
allocation of nitrogen due to net primary productivity into herbaceous below–ground parts	`nppnhb`
allocation of nitrogen due to net primary productivity into woody above–ground parts	`nppnwa`
allocation of nitrogen due to net primary productivity into woody below–ground parts	`nppnwb`
re–allocation of nitrogen from senescent leaves	`realnf`
litter production nitrogen of herbaceous above–ground material	`lpnha`
litter production nitrogen of herbaceous below–ground material	`lpnhb`
litter production nitrogen of woody above–ground material	`lpnwa`
litter production nitrogen of woody below–ground material	`lpnwb`
nitrogen losses of above–ground woody material by deforestation	`dforna`
nitrogen losses of below–ground woody material by deforestation	`dfornb`
litter depletion nitrogen of above–ground herbaceous material	`ldnha`
litter depletion nitrogen of below–ground herbaceous material	`ldnhb`
litter depletion nitrogen of above–ground woody material	`ldnwa`
litter depletion nitrogen of below–ground woody material	`ldnwb`
humus depletion nitrogen	`humdnf`
excretion of nitrogen with humic substances by soil organisms	`humpnf`
uptake of available nitrogen by soil organisms	`mignf`
release of nitrogen by mortality of soil organisms	`mimnf`
segregation of excess nitrogen by soil organisms	`misnf`
uptake of available nitrogen by plant roots	`avunf`
fixation of available nitrogen on buffer in soil	`avnpuf`
return flux of nitrogen from buffer to available nitrogen	`puavnf`
N_2 fixation by symbionts in legume roots	`legnf`
N_2 fixation by *Azospirrillum* symbionts of C_4 grasses and cereals	`azonf`
N_2 fixation by actinomycetes in tree roots and sandy soils	`actnf`
nitrogen deposition due to NO_x and HNO_3 immissions	`depnf`
nitrogen flux to the atmosphere by denitrification in soil	`n2onf`
leaching of soluble N compounds from soil to groundwater	`leanf`

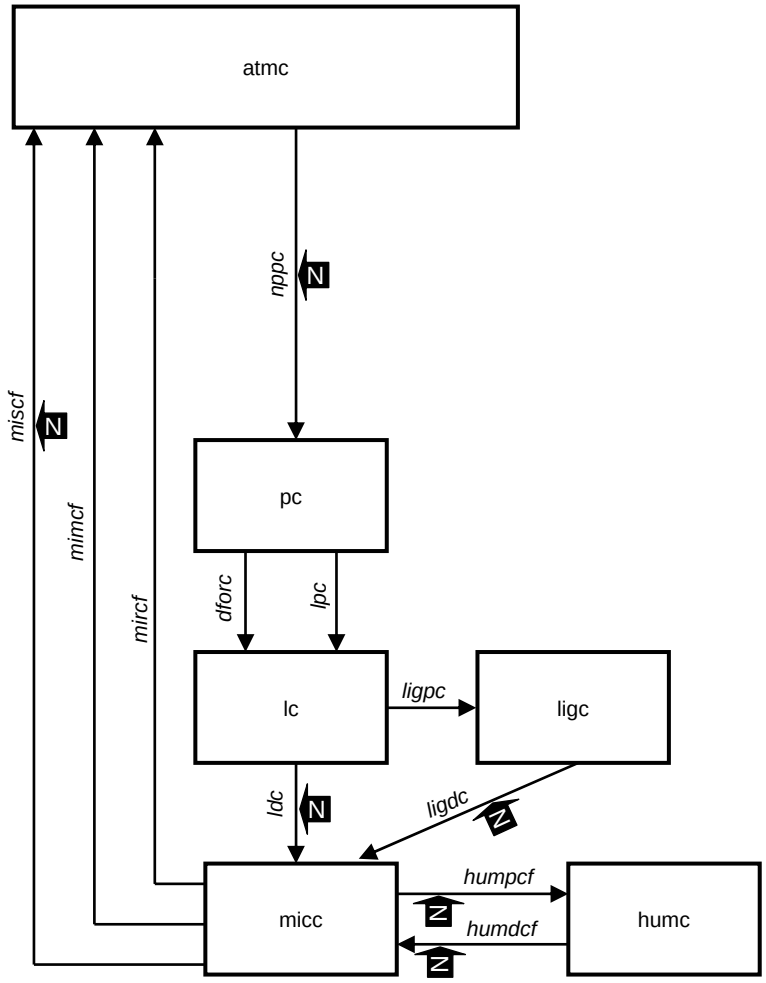

Figure 2.1: Structure of the carbon cycle of NCIM. Pools (state variables) are represented by squares, fluxes by arrows. The notation corresponds with Table 2.1 and Table 2.5. The pools `pc`, `lc` and the fluxes `nppc, lpc, ldc` exist four times each for herbaceous, woody, above ground and below ground materials. The black arrows indicated with “N” mark fluxes (processes) which depend on state variables of the nitrogen cycle.

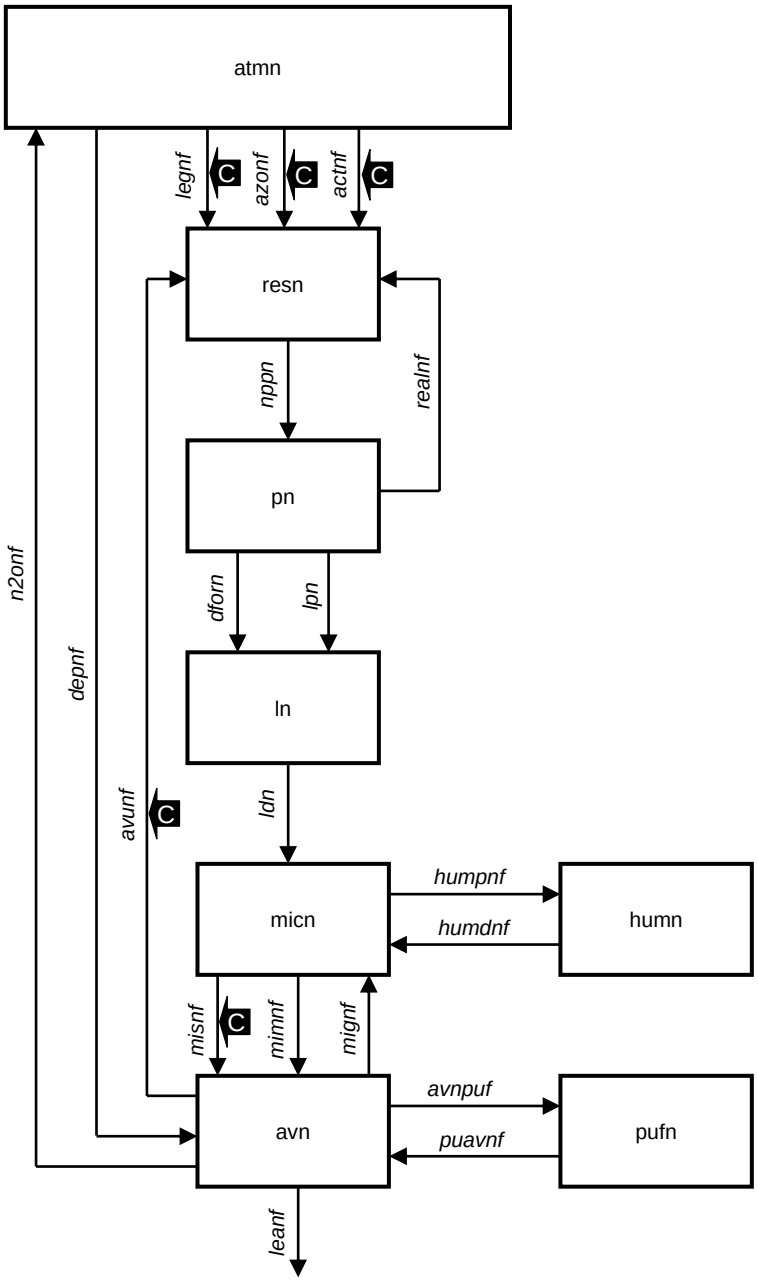

Figure 2.2: Structure of the nitrogen cycle of NCIM. Pools (state variables) are represented by squares, fluxes by arrows. The notation corresponds with Table 2.3 and Table 2.6. The pools `pn, ln` and the fluxes `nppn, lpn, ldn` exist four times each for herbaceous, woody, above ground and below ground materials. The black arrows indicated with “C” mark fluxes (processes) which depend on state variables of the carbon cycle.

2.2 Structure and function of the model code

The model code consists of modules, which are independent of each other (Figure 2.3 on page 15) and which interact with other modules using well–defined data interfaces. Each module includes one or several to many tasks, pieces of work of some independence, which contribute to the function of the module.

Data exchange between the modules is organized by common blocks. The only exception is the exchange of state variables and their estimates between `timint` and `dgl` respective `ndgl`. These three modules exchange data using a calling list.

The `main` module `ncim 3.00` represents the main program. It organizes the time management of the model, i.e. the calling sequence of the other modules. The module `timint` includes the time–integration by a 4th–order Runge–Kutta method. The innermost time loop `iday` of `main` is subdivided in `timint` into a number of integration steps `istep`. Each integration step executes four calls to the two modules which include the mass–balance equations, `dgl` and `ndgl`.

The grid element loops (62 483 grid elements of a 0.5 degrees latitude and longitude grid) are placed in the tasks of the modules.

After declaration of the variables, `main` calls five modules to read driving forces and boundary conditions of the model as input data from files. Next some initial calculations are carried out to get data derived from the input data.

The model pools are filled with initial conditions in the initializing modules. Initial conditions are selected to be able to start a stable model run, i.e. a run without numerical problems. These values are not a steady–state solution of the model for any environmental conditions. The steady state–pool values for a given set of conditions, that means the initial values for a productive model run, are calculated by the model itself during a spin–up process, which we call “prerun”. Two different preruns are carried out for about 5 000 model years each. In a first prerun, carbon/nitrogen (C/N) ratios of the relevant model fluxes, mainly the fluxes `nppc` and `nppn`, are kept constant. In prerun two, all C/N ratios are released and calculated by the model from the pools, until the model reaches steady–state. It is assumed that steady–state was achieved as soon as long–term trends of pool values are no longer observed (but seasonal changes are always present).

Productive model runs start with a steady–state set of pool values as initial conditions, which were derived by a prerun using the same boundary conditions and driving forces as in the first year of the produktive model run period. Driving forces and boundary conditions change during the model run. Gridded or scalar data sets must be available for the modelling period (we use

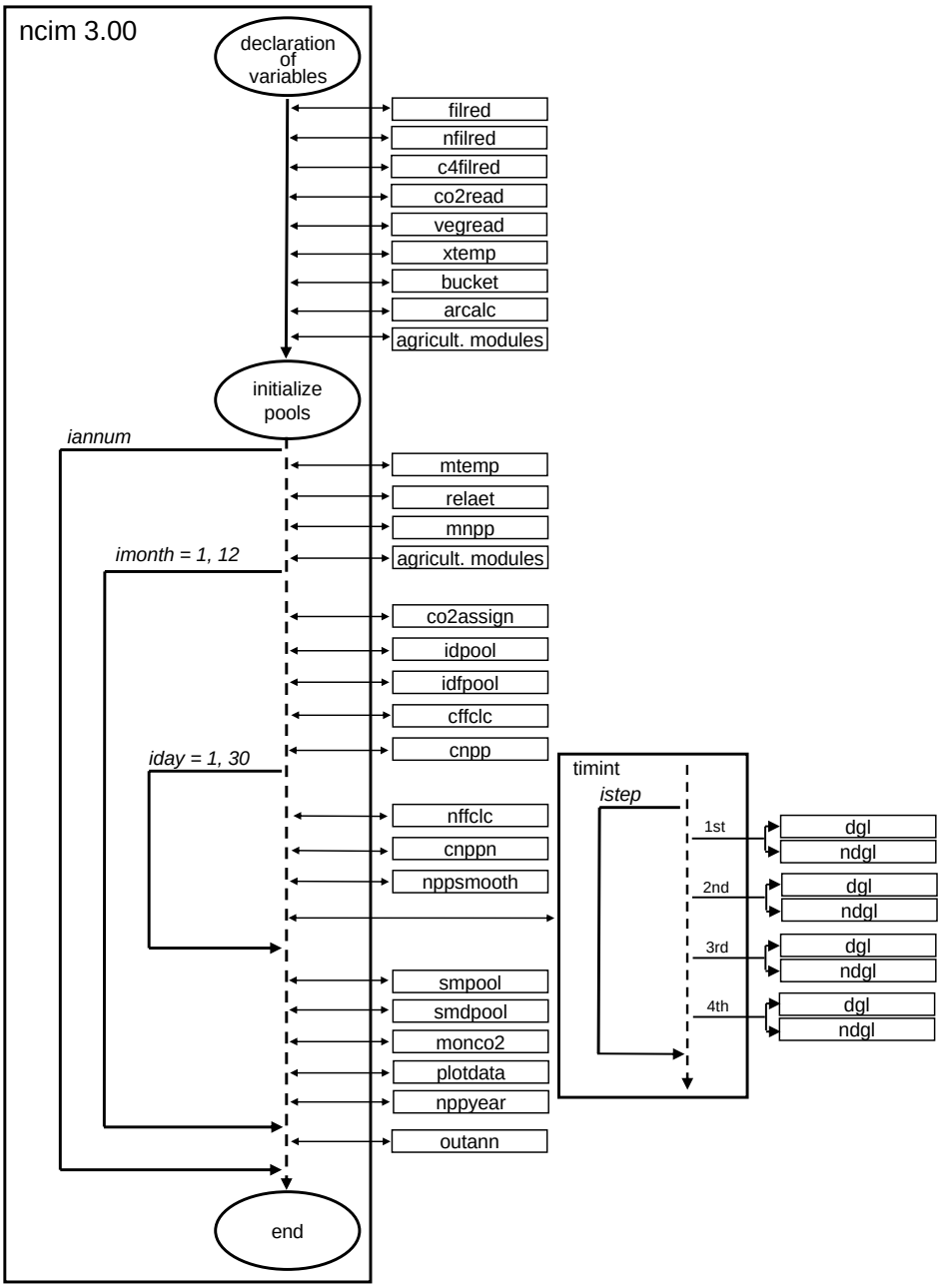

Figure 2.3: Structure of the NCIM program code. The code consists of 42 modules, including main (ncim 3.00), 6 modules in the initialize pools routine, and 7 agricultural modules. A detailed description of the modules in alphabetical order is given in chapter 3 beginning on page 17.

atmospheric CO_2 concentrations from 1400 AD and climate anomalies and land–use changes from 1860 AD on).

In the annual loop `iannum` some long–term trends are updated first (land–use on per country level, soil, vegetation). The output of annual model results (summary non–gridded results) occurs at the end of the annual loop.

In the monthly loop `imonth` monthly changing driving forces are assigned, the dummy pools are set to zero (emptied to be filled again in the following month), and the coefficients of the flux–equations of the carbon cycle are calculated (`cffclc`, `cnpp`), thus creating the seasonality of the model. At the end of the monthly loop, upscaling of pools from square–meter to full grid element takes place and the output of gridded results takes place (`plotdata`).

The inner daily loop `iday` calls modules for the calculation of the coefficients of the nitrogen cycle. It also calls the integration module `timint` which evolves the model time by one day (Hoffstadt, Esser, 1997). One day is subdivided into several integration steps `istep`. The number of `istep` is selected so that numerical stability of the integration is maintained and integration biasses are minimized. The two modules `dgl` and `ndgl` include the mass balance equations for the carbon and nitrogen cycles and the related processes as shown in Figures 2.1 and 2.2 on pages 12 and 13.

Chapter 3

The NCIM modules

In this chapter, the modules of NCIM 3.00 are explained in alphabetical order. The role of each module in the model, its interface, and, if applicable, important algorithms and equations are explained. In the FORTRAN 77 source code of the model, the modules are subroutines (exept ncim, which is main) and are stored in seperate files each. The filenames are similar to the module names but with the extension `*.f`. Detailed comments of the model code may be found in the source code files of the modules.

3.1 Agricultural modules

A number of modules are called if land–use is to be considered in a model run. These modules provide information on the areas used for agricultural purposes on country basis in the modelling period, on the grid elements which are used in the different years, and on the probability of the cultivation of C3 or C4 crops.

3.1.1 Module agc4su

This module ranks all grid elements according to their probability to be useful for cultivation of C4 crops. A probability is calulated for each of the following C4 crops: maize, sugar cane, millet, and sorghum.

agc4su interface		
In:	monthly temperature	`it(igrid,12)`
	monthly precipitation	`ipp(igrid,12)`
	annual mean temperature	`itann(igrid)`
	annual precipitation	`ippann(igrid)`
	soil fertility	`fsoil(igrid)`
Out:	probability for cultivation of four C4 crops	`prpc4(nc4,igrid)`

Call frequency is once at the begin of a model run and once per year from AD 1860 on.

3.1.2 Module agrc4pat

This subroutine determines the pattern of grid elements used for cultivation of C4 crops in a given model year.

agrc4pat interface		
In:	required area for four C4 crops (AD 1860-1991)	`agc4re(nc4,icount,1860:1991)`
	standard map of the distribution of four C4 crops	`usec4std(igrid)`
	probability for cultivation of four C4 crops	`prpc4(nc4,igrid)`
	duration of land–use for each grid element (years)	`useyr(igrid)`
Out:	use–matrix of grid elements for the four C4 crops	`useann(igrid)`

The integer numbers assigned to the matrix `useann` mean:

0 natural vegetation, no use
1 C3 field crops
2 sugar cane
3 maize
4 millet
5 sorghum

Call frequency is once at the begin of a model run and once per year from AD 1860 on.

3.1.3 Module agrfut

Module to provide data on the possible change of the use–matrix `useann` in the period 1991 to 2050 (land–use scenario). Based on a given ratio of agricultural net primary production to the population number of each country, it changes the use–matrix once a year so that the ratio is as close as possible to the given value.

Entire grid elements are transformed from useann = 0 to useann = 1, or vice versa. This is done if the required change of the country's agricultural production exceeds 60% of the productivity of the next grid element to be taken into or out of use.

The population data per country are calculated by use of polynomials. Those were calculated from the FAO population estimates for the period 1980 to 2050.

agrfut interface		
In:	model year (period AD 1991–2050)	`iannum`
	area of each grid element	`area(igrid)`
	10 years running mean of potential agricultural npp of a grid element	`nppyrm(igid)`
	four parameters for population polynomial per country	`apop(icount,iparam)`
	relative agricultural productivity per country	`rap(icount)`
	annual modification factor for `rap` in the period 1991 to 2050	`fymult(icount)`
	relative agricultural productivity per grid element	`rapg(igrid)`
	probability of land–use of a given grid element in the given year	`agrprp(igrid)`
Out:	land–use–matrix of grid elements	`useann(igrid)`
	duration of land–use for each grid element (years)	`useyr(igrid)`

The call frequency is once per year for the period 1991 to 2050.

3.1.4 Module agrpat

This module provides the actual pattern of grid elements used for agricultural purposes in a given model year in the matrix `useann(igrid)`. The matrix `useann` includes values of zero for grid elements presently not in use, and 1 for those in use. If the module `agrc4pat` is called in advance of `agrpat`, the matrix `useann` may also include the values 2 through 5 which correspond with a variety of C4 field crops.

This module applies to model years up to 1990. Compare also module `agrfut` which provides land–use scenarios from 1991 on.

agrpat interface		
In:	correction matrix to calculate the agriculturally used areas in each country in the current model year	`korri(icount,1860:1990)`
	standard map of the distribution of agricultural crops in AD 1980	`usestd(igrid)`
	probability of each grid element to be agriculturally used in the current year	`agrprp(igrid)`
	actual model year	`iannum`
	year of start of model run AD	`ianns`
	area of each grid element	`area(igrid)`
Out:	use–matrix of grid elements	`useann(igrid)`
	duration of land–use for each grid element (years)	`useyr(igrid)`

The module `agrpat` is called in the first model year and once every year in the period 1860 through 1990.

3.1.5 Module agryie

This module provides the relative agricultural net primary productivity for each country and assignes the value `rap(icount)` to each grid element of the country `rapg(igrid)`. The computation of `rap` depends on the current model year `iannum`.

- If *iannum* is equal to or lower than 1980, `rap` is set to the value of AD 1980.
- If `iannum` is greater than 1980 but equal to or lower than 1990, `rap` is determined by linear interpolation between the values of 1980 and 1990.
- For further scenarios, `rap` in 2050 of each country can be modified by a special factor considering individual developments `fymult`. Alternatively, `rap` in 2050 of all countries can be set to a fixed value `scfut`. The value `rap` for the current year is computed by linear interpolation between the value of AD 1990 and of AD 2050.

agryie interface		
In:	global value for relative agricultural productivity in AD 2050	`scfut`
	current model year	`iannum`
	relative agricultural productivity in AD 1980	`rap80(icount)`
	relative agricultural productivity in AD 1990	`rap90(icount)`
	factor to modify relative agricultural productivity in each country	`fymult(icount)`
Out:	relative agricultural productivity in the current model year for each country	`rap(icount)`
	relative agricultural productivity assigned to grid elements in current model year	`rapg(igrid)`

Module `agryie` ist called once per year in the period 1980 through 2050.

3.1.6 Module agrsuit

In this module, the grid elements are ranked according to a “clearing probability” `agrprp`, which is defined as a product of several individual probabilities. At the present state, these individual probabilities include:

- probability based on the production potential: the higher the natural productivity, the higher the probability to be taken into use, the productivity is estimated by the Miami model (Lieth 1975).

- probability from soil quality: the higher the soil fertility, given by the array soil factor `fsoil`, the higher the probability to be used for agriculture,

- agricultural status of surrounding grid elements.

agrsuit interface		
In:	standard map of the distribution of agricultural crops in AD 1980	`usestd(igrid)`
	use–matrix of grid elements	`useann(igrid)`
	latitude of grid element (lower left corner)	`lat(igrid)`
	longitude of grid element (lower left corner)	`lon(igrid)`
	annual mean temperature of grid element	`itann(igrid)`
	annual precipitation of grid element	`ippann(igrid)`
	soil fertility factor	`fsoil(igrid)`
	actual model year	`iannum`
Out:	probability of each grid element to be agriculturally used in the current year	`agrprp(igrid)`

The call frequency is once in the first model year and once a year from AD 1860 on.

3.1.7 Module c4filrd

Module to read from files the information on the areas per country which are cultivated with C4 crops in the period 1961–1991, and a standard map of the distribution of grid elements dominated by C4 crops.

c4filrd interface		
In:	file dc4map	`usec4std(igrid)`
	file dsugar	`agc4re(sug,icount,iannum)`
	file dmaize	`agc4re(mai,icount,iannum)`
	file dmillet	`agc4re(mil,icount,iannum)`
	file dsorghum	`agc4re(sor,icount,iannum)`
Out:	standard map of grid elements cultivated with C4 crops	`usec4std(igrid)`
	required agricultural area for sugar cane	`agc4re(sug,icount,iannum)`
	required agricultural area for maize	`agc4re(mai,icount,iannum)`
	required agricultural area for millet	`agc4re(mil,icount,iannum)`
	required agricultural area for sorghum	`agc4re(sor,icount,iannum)`

Call frequency is once in the first model year and once per year in the period 1961 through 1991.

3.2 Module arcalc

This module computes the area of each grid element from the latitude of its lower left (south–western) corner and the grid width. In addition it provides some information on the extremes of grid element sizes per country and global.

arcalc interface		
In:	latitude of lower left corner of grid element	`lat(igrid)`
	number of the first grid element of each country	`lcgrid(icount)`
	number of the last grid element of each country	`mcgrid(icount)`
Out:	area [m^2] of each grid element	`area(igrid)`
	area of the smallest grid element	`aremin`
	area of the smallest grid element of each country	`aremi(icount)`
	area of the largest grid element of each country	`arema(icount)`
	mean area of the grid elements of each country	`aremea(icount)`

`arcalc` is called once at the beginning of the model run.

3.3 Module bucket

`bucket` estimates monthly potential and actual evapotranspiration from a simple "bucket" soil moisture accounting scheme, using the Priestley/Taylor evapotranspiration formula. This module was adopted from the IIASA biome model (Prentice et al. 1992). In NCIM 3.00 actual evapotranspiration is used to influence seasonality, especially in the tropics and subtropics.

bucket interface		
In:	latitude of grid element (lower left corner)	`lat(igrid)`
	longitude of grid element (lower left corner)	`lon(igrid)`
	annual mean temperature of grid element	`itann(igrid)`
	annual precipitation of grid element	`ippann(igrid)`
	monthly temperatures of grid element	`it(igrid,imonth)`
	monthly precipitation of grid element	`ipp(igrid,imonth)`
	monthly mean cloudfreeness of grid element	`icloud(igrid,imonth)`
Out:	monthly actual evapotranspiration of each grid element	`aetm(igrid, imonth)`

`bucket` is called once per model year.

3.4 Module cffclc

Module to provide the coefficients for the fluxes litter production and litter depletion, soil organic carbon production and soil organic carbon depletion and for the additional deforestation flux. `cffclc` determines the coefficients for each grid element in a given month.

These coefficients are required to calculate carbon and nitrogen fluxes in the modules `dgl` and `ndgl`. In `cffclc` the coefficients of the slower processes are updated monthly. The faster processes are updated daily in the module `nffclc`.

`cffclc` translates the driving forces on a grid element level into coefficients which occur in flux equations. This module together with `nffclc` is an important interface between environmental conditions an the biosphere, therefore.

Due to the relative importance of this module a more detailed description is given here.

While this module ist called the first time, the C/N ratio of litter production material is set to the standard value 32. Thus, it remained fixed during the first prerun (spin–up) procedure.

Next, `cdfor` is set to 0.06 for all grid elements under land–use. This results in a half–life time of the clearing progress of one year.

Next, the litter production coefficients for harbaceous material are set. It is assumed, that litter production only occurs in month with decreasing evapotranspiration. The coefficient's share in a given month is proportional to the amount of decrease of `aetm` in comparison to the total decrease in sequence `aetdsu`:

$$clpha(igrid) = \frac{aetdm(igrid, imonth)}{aetdsu(igrid)} \cdot \frac{herb(ibiome(igrid))}{0.59181 \cdot ageh(ibiome(igrid))^{0.79216}} \tag{3.1}$$

If no month with decreasing evapotranspiration occurs, litter production coefficients are evenly distributed over the months of a year:

$$clpha(igrid) = \frac{1}{12} \cdot \frac{herb(ibiome(igrid))}{0.59181 \cdot ageh(ibiome(igrid))^{0.79216}} \tag{3.2}$$

Litter production coefficients for woody material are evenly distributed throughout a year and are calculated analogously:

$$clpwa(igrid) = \frac{1}{12} \cdot \frac{1 - herb(ibiome(igrid))}{0.59181 \cdot agew(ibiome(igrid))^{0.79216}} \tag{3.3}$$

The coefficients for below–ground material are set equal to the analogous above–ground materials.

cffclc interface

In:	monthly decrease of `aetm`	`aetdm(igrid,imonth)`
	`aetm` in december of the last year	`aetmdc(igrid)`
	annual sum of negative monthly values of `aetdm`	`aetdsu(igrid)`
	use–matrix of grid elements for agriculture	`useann(igrid)`
	soil fertility factor	`fsoil(igrid)`
	share factor of herbaceous productivity of each biome	`herb(ibiome(igrid))`
	share factor of above–ground productivity of each biome	`abvgrd(ibiome(igrid))`
	mean age of herbaceous parts of each biome	`ageh(ibiome(igrid))`
	mean age of woody parts of each biome	`agew(ibiome(igrid))`
	long–term mean temperature of warmest months	`mtwa(igrid)`
	long–termmean temperature of coldest month	`mtco(igrid)`
	vegetation type of each grid element	`ibiome(igrid)`
	monthly temperatures of grid element	`it(igrid,imonth)`
	monthly precipitation of grid element	`ipp(igrid,imonth)`
	most important soil unit of the grid element	`soilat(igrid)`
	current month	`imonth`
Out:	coefficient litter production herbaceous above ground	`clpha(igrid)`
	coefficient litter production herbaceous below ground	`clphb(igrid)`
	coefficient litter production woody above ground	`clpwa(igrid)`
	coefficient litter production woody below ground	`clpwb(igrid)`
	coefficient litter depletion herbaceous above ground	`cldha(igrid)`
	coefficient litter depletion herbaceous below ground	`cldhb(igrid)`
	coefficient litter depletion woody above ground	`cldwa(igrid)`
	coefficient litter depletion woody below ground	`cldwb(igrid)`
	coefficient soil organic carbon production from herbaceous material	`csocph(igrid)`
	coefficient soil organic carbon production from woody material	`csocpw(igrid)`
	coefficient soil organic carbon depletion	`socd(igrid)`
	coefficient of deforestation	`cdfor(igrid)`
	counter for the number of month with litter production in sequence	`ifall(igrid)`
	flag indicating month with litter production	`lfall(igrid)`

For the biomes of the temperate and boreal zones, i.e. cold–deciduous biomes, the monthly coefficient of litter production will be set to $(2 \cdot \ln 2)$ in the first three month in which the monthly temperature drops (NOT rises) to or below the half of the mean temperature of the warmest month.

Next, C/N ratios for litter material are calculated from the respective carbon and nitrogen pools. This is done after the two preruns (spin–up) have been completed (the ratios for the preruns are set in module `initn` to standard values). The C/N ratios are only calculated if the amount of carbon in a litter pool is not less than 10^{-5} g. If it is less, C/N ratios are set to standard values.

The depletion coefficients for litter and soil organic materials are calculated from climate variables and depend on the nitrogen content of the material. They depend on climate in a complex way:

$$\begin{aligned} cldh &= \exp\left(p_1 + p_2 \cdot \ln(ipp) - p_3 \cdot ipp^{p_4}\right) \\ &\quad + \exp(p_5) \cdot \tanh(p_6 \cdot ipp) \end{aligned} \tag{3.4}$$

with the parameters

$$\begin{aligned} p_1 &= -1.96628 \cdot (it - 5) - 12.39641 \\ p_2 &= 0.002236189 \cdot (it + 55)^2 \\ p_3 &= 4.568434 \cdot \exp(-0.1041649 \cdot (it - 5)) \\ p_4 &= 0.0001132567 \cdot (it + 55)^2 \\ p_5 &= 0.07315304 \cdot (it - 5) - 3.51145 \\ p_6 &= \exp\left(\frac{15000}{(it + 55)^2} - 6.5\right) \end{aligned}$$

and the restrictions

$$\begin{aligned} &\text{If} \quad ipp = 0.0 \quad \text{then} \quad cld = 0.0 \\ &\text{If} \quad it < -30.0 \quad \text{then} \quad cld = \exp(p_5) \cdot \tanh(p_6 \cdot ipp) \end{aligned}$$

Function (3.4) was developed using data for above ground herbaceous material (see Esser, 1986, for a list of the data used). It is modified for each compartment of litter according to

$$\begin{aligned} cldha &= cldhb = cldh \\ cldwa &= cldwb = 0.3 \cdot cldh \end{aligned}$$

The plot of function (3.4) is given in Figure 3.1.

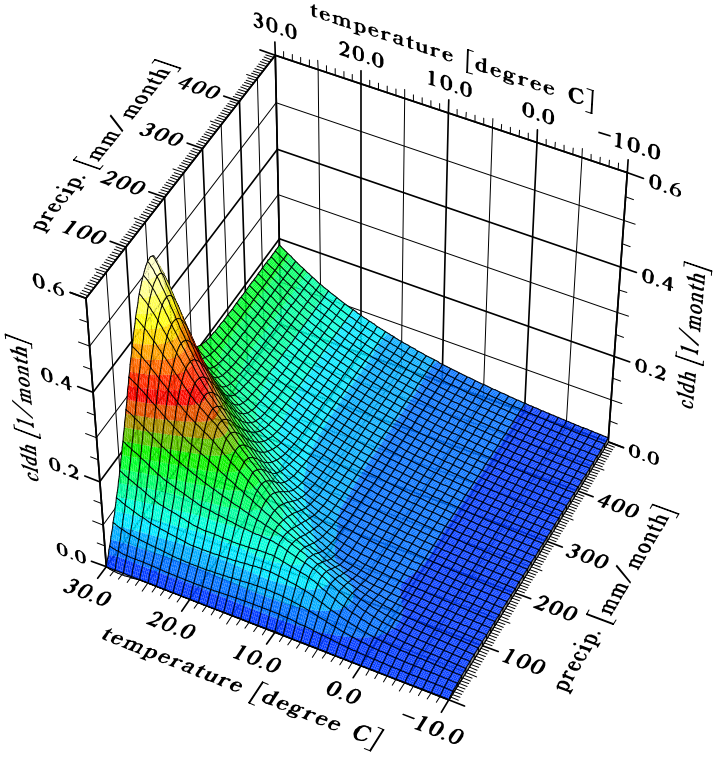

Figure 3.1: Plot of the litter depletion coefficient as a function of monthly precipitation and temperature (eq. 3.4).

Since function (3.4) requires a considerable amount of computing time, we have pre–calculated the depletion coefficients for a 100×100 matrix of monthly temperature and precipitation intervals, in the range of temp -10 to 30 °C, precip 0 to 500 mm·month^{-1}. Access to this matrix is then possible randomly by temp and precip classes.

Litter depletion coefficients as calculated from climate variables are then corrected according to the deviation of the actual nitrogen content of the material from a mean content:

$$cldha(igrid) = cldh \cdot \left(\frac{1.7}{1 + 1.4 \cdot \exp(0.1 \cdot (cnlha(igrid) - cnmean))} + 0.3 \right) \qquad (3.5)$$

The depletion coefficients for the materials woody above–ground, herbaceous below–ground, and woody below–ground are corrected analogously.

The depletion coefficients for humic substances and for lignin compounds are derived from the depletion coefficient for herbaceous material as calculated by equation (3.4). Since lignin compounds are nitrogen free, the nitrogen status of the soil organisms is considered for the depletion coefficient of lignin:

$$chumd(igrid) = cldh \cdot 0.0008 \qquad (3.6)$$

$$cligd(igrid) = \frac{6}{cnmic(igrid)} \cdot cldh \cdot 0.05 \qquad (3.7)$$

For certain soil types, $chumd$ and $cligd$ are modified:

$$chumd \begin{cases} \cdot 0.2 & \text{for Histosols} \\ \cdot 0.5 & \text{for gelic Gleysols} \end{cases}$$

$$cligd \begin{cases} \cdot 0.038 & \text{for Histosols} \\ \cdot 0.5 & \text{for gelic Gleysols} \end{cases}$$

Finally, the lignin production coefficients are set. It was assumed therefore, that the lignin content of plant material will contribute to the formation of slowly decomposed humic acids in the soil. Thus, the lignin production coefficients are set to the mean share of lignin in herbaceous and woody plant material:

$$cligph(igrid) = 0.176 \tag{3.8}$$

$$cligpw(igrid) = 0.48 \tag{3.9}$$

The module `cffclc` is called once every month.

3.5 Module cnpp

This subroutine provides monthly net primary productivity for the array of grid elements. It considers climate on an annual basis, according to the Miami model (Lieth 1975). From the annual NPP value a part is allocated to the actual month according to the share of actual evapotranspiration of the current month, weighted by an exponent.

NPP from climate is then modified by correction factors for soil influence (`fsoil`), and the CO_2 fertilization effect (`co2fak`). If the grid element is considered to be agriculturally used, the `npp` is further corrected by a factor (`rapg`) which represents the "Relative Agricultural Productivity" of the respective country. For further explanation see Esser (1995) or Esser (1994).

cnpp interface

In:	annual mean temperature of grid element	`itann(igrid)`
	annual precipitation of grid element	`ippann(igrid)`
	monthly temperatures of grid element	`it(igrid,imonth)`
	monthly actual evapotranspiration of each grid element	`aetm(igrid,imonth)`
	soil fertility factor of grid element	`fsoil(igrid)`
	relative agricultural productivity of grid element	`rapg(igrid)`
	share factor of herbaceous productivity of each biome	`herb(ibiome(igrid))`
	share factor for above–ground productivity of each biome	`abvgrd(ibiome(igrid))`
	potential natural vegetation of grid element	`ibiome(igrid)`
	CO_2 concentration in the atmosphere of a given month $[\mu l \cdot l^{-1}]$	`co2`
Out:	monthly net primary productivity of herbaceous above–ground material	`nppha(igrid)`
	monthly net primary productivity of herbaceous below–ground material	`npphb(igrid)`
	monthly net primary productivity of woody above–ground material	`nppwa(igrid)`
	monthly net primary productivity of woody below–ground material	`nppwb(igrid)`

Net primary productivity is calculated as the minimum of two potential productivities which were derived from temperature and precipitation. The fraction of NPP in a given month is calculated using information on actual evapotranspiration. The factor 0.45 transforms dry matter into carbon.

$$nppt = \frac{3000}{1 + \exp\left(1.315 - 0.119 \cdot itann(igrid)\right)} \tag{3.10}$$

$$npppp = 3000 \cdot \left(1 - \exp\left(-0.000664 \cdot ippann(igrid)\right)\right) \tag{3.11}$$

$$nppann = \min(nppt, npppp) \tag{3.12}$$

$$npp(igrid) = nppann \cdot \frac{aetml(igrid, imonth)^3}{aetsu2(igrid)} \cdot fsoil(igrid) \cdot rapg(igrid) \cdot fco2 \cdot 0.45 \tag{3.13}$$

In equation (3.13) `aetml` is equal to `aetm`, except in the case that `aetm` is less than 45 mm month^{-1} in the given month and at least three month exist having `aetm` greater than 45 mm month^{-1}. `aetsu2` is the annual sum of `aetml`^{3}.

The factor `fco2` in equation (3.13) represents the CO_2 fertilization effect. In NCIM 3.00 it is calculated from the actual atmospheric CO_2 concentration $[\mu l \cdot l^{-1}]$and the soil fertility according to equation (3.14).

$$co2fak \quad = \quad a \cdot [1 - \exp\{-r \cdot (co2 - 80)\}] \tag{3.14}$$

where $a = 1 + fsoil(igrid)/4$ and $r = -\ln(1 - 1/a)/240$.

The CO_2 fertilization effect is only applied to natural vegetation. If the grid element is agriculturally used, the factor will be set to 1 assuming supply limited by minerals rather than by the CO_2 concentration.

Finally, monthly net primary productivity is distributed to the four compartments herbaceous and woody and above–ground and below–ground:

$$\begin{aligned}
nppha(igrid) &= npp(igrid) \cdot herb(ibiome(igrid)) \cdot abvgrd(ibiome(igrid)) && (3.15)\\
npphb(igrid) &= npp(igrid) \cdot herb(ibiome(igrid)) \\
&\quad \cdot (1 - abvgrd(ibiome(igrid))) && (3.16)\\
nppwa(igrid) &= npp(igrid) \cdot (1 - herb(ibiome(igrid))) \\
&\quad \cdot abvgrd(ibiome(igrid)) && (3.17)\\
nppwb(igrid) &= npp(igrid) \cdot (1 - herb(ibiome(igrid))) \\
&\quad \cdot (1 - abvgrd(ibiome(igrid))) && (3.18)
\end{aligned}$$

Module `cnpp` is called once a month.

3.6 Module cnppn

This module saves the monthly NPP as provided by cnpp after the soil correction has been eliminated. As often as called, cnppn corrects the monthly saved NPP according to the actual C/N ratio in the plant material. If cnpp was called, cnppn updates the saved NPP values.
In this module, the actual C/N ratios in the plant material are updated first.

$$\begin{aligned}
cnacha(igrid) &= \frac{pool(igrid, pcha)}{pool(igrid, pnha)} && (3.19)\\
cnachb(igrid) &= \frac{pool(igrid, pchb)}{pool(igrid, pnhb)} && (3.20)\\
cnacwa(igrid) &= \frac{pool(igrid, pcwa)}{pool(igrid, pnwa)} && (3.21)\\
cnacwb(igrid) &= \frac{pool(igrid, pcwb)}{pool(igrid, pnwb)} && (3.22)
\end{aligned}$$

In the next step, NPP is corrected according to the deviation of the actual C/N ratio in leaves from a biome–typical standard C/N ratio `cnh(ibiome)`. The variable names ending with "o" refer to the old values of these variables.

$$
\begin{aligned}
x &= \frac{cnh(ibiome(igrid))}{cnacha(igrid)} \\
fn &= 1.7465 \cdot (1 - \mathrm{e}^{-1.7 \cdot (x - 0.5)}) \\
fnmean(igrid) &= \frac{fnmeano(igrid) \cdot (2 \cdot 15 - 1) + fn}{2 \cdot 15} && (3.23) \\
nppha(igrid) &= fnmean(igrid) \cdot npphao(igrid) && (3.24) \\
npphb(igrid) &= fnmean(igrid) \cdot npphbo(igrid) && (3.25) \\
nppwa(igrid) &= fnmean(igrid) \cdot nppwao(igrid) && (3.26) \\
nppwb(igrid) &= fnmean(igrid) \cdot nppwbo(igrid) && (3.27)
\end{aligned}
$$

3.7 Module co2assign

The model uses values for the CO_2 concentration of the atmosphere from AD 1400 on. These values are global means of each year. The module `co2assign` uses a simple interpolation procedure to calculate monthly means of the atmospheric CO_2 concentration. The seasonal cycle is not considered. The monthly values help prevent high annual steps which would cause instabilities in the model. Prior to AD 1400 the monthly CO_2 concentration is set to the annual value for AD 1400.

co2assign interface		
In:	annual mean CO_2 concentration $[\mu l \cdot l^{-1}]$	`co2ann(iannum)`
Out:	mean CO_2 concentration of current month $[\mu l \cdot l^{-1}]$	`co2`

This module is called monthly.

3.8 Module co2read

Read annual data of the atmospheric CO_2 concentration `co2ann(iannum)` $[\mu l \cdot l^{-1}]$ for the period AD 1400 including AD 2002 from file.

co2read interface		
In:	file CO2.data	`co2ann(iannum)`
Out:	annual mean CO_2 concentration $[\mu l \cdot l^{-1}]$	`co2ann(iannum)`

Called once at the beginning of a model run.

3.9 Module dgl

Module `dgl` contains, together with its "sister"module `ndgl` (see page 38), the calculation of the fluxes (processes) and the mass–balance equations for carbon and nitrogen. Module `dgl` includes the "slow" fluxes of carbon, while `ndgl` includes the "fast" carbon fluxes and the nitrogen fluxes.

dgl interface		
In:	monthly net primary productivity of herbaceous above–ground material	`nppha(igrid)`
	monthly net primary productivity of herbaceous below–ground material	`npphb(igrid)`
	monthly net primary productivity of woody above–ground material	`nppwa(igrid)`
	monthly net primary productivity of woody below–ground material	`nppwb(igrid)`
	coefficient litter production herbaceous above ground	`clpha(igrid)`
	coefficient litter production herbaceous below ground	`clphb(igrid)`
	coefficient litter production woody above ground	`clpwa(igrid)`
	coefficient litter production woody below ground	`clpwb(igrid)`
	coefficient litter depletion herbaceous above ground	`cldha(igrid)`
	coefficient litter depletion herbaceous below ground	`cldhb(igrid)`
	coefficient litter depletion woody above ground	`cldwa(igrid)`
	coefficient litter depletion woody below ground	`cldwb(igrid)`
	coefficient lignin production from herbaceous material	`cligph(igrid)`
	coefficient lignin production from woody material	`cligpw(igrid)`
	coefficient of deforestation	`cdfor(igrid)`
In by list:	array of C and N pools	`p(igrid,ip)`
Out by list:	array of time–derivatives of pools	`dp(igrid,ip)`

3.9.1 Calculation of fluxes (processes)

To prevent redundancy, fluxes are calculated first and assigned to arrays of local variables.

Litter production carbon fluxes:

$$lpcha(igrid) = clpha(igrid) \cdot p(igrid, pcha) \quad (3.28)$$

$$lpchb(igrid) = clphb(igrid) \cdot p(igrid, pchb) \quad (3.29)$$

$$lpcwa(igrid) = clpwa(igrid) \cdot p(igrid, pcwa) \quad (3.30)$$

$$lpcwb(igrid) = clpwb(igrid) \cdot p(igrid, pcwb) \quad (3.31)$$

Deforestation carbon fluxes:

$$dforca(igrid) = cdfor(igrid) \cdot p(igrid, pcwa) \quad (3.32)$$

$$dforcb(igrid) = cdfor(igrid) \cdot p(igrid, pcwb) \quad (3.33)$$

Litter depletion carbon fluxes:

$$ldcha(igrid) = cldha(igrid) \cdot p(igrid, lcha) \quad (3.34)$$

$$ldchb(igrid) = cldhb(igrid) \cdot p(igrid, lchb) \quad (3.35)$$

$$ldcwa(igrid) = cldwa(igrid) \cdot p(igrid, lcwa) \quad (3.36)$$

$$ldcwb(igrid) = cldwb(igrid) \cdot p(igrid, lcwb) \quad (3.37)$$

Lignin depletion carbon flux:

$$ligdcf(igrid) = cligd(igrid) \cdot p(igrid, ligc) \quad (3.38)$$

3.9.2 Time–derivatives of the pools (mass–balance equations)

After calculating the carbon fluxes, the mass–balance equations follow. Mass–balance of carbon pools is maintained by balancing the input aud output fluxes:
Phytomass carbon:

$$dp(igrid, pcha) = nppha(igrid) - lpcha(igrid) \quad (3.39)$$

$$dp(igrid, pchb) = npphb(igrid) - lpchb(igrid) \quad (3.40)$$

$$dp(igrid, pcwa) = nppwa(igrid) - lpcwa(igrid) - dforca(igrid) \quad (3.41)$$

$$dp(igrid, pcwb) = nppwb(igrid) - lpcwb(igrid) - dforcb(igrid) \quad (3.42)$$

Litter carbon:

$$dp(igrid, lcha) = lpcha(igrid) - ldcha(igrid)$$
(loss to soil lignin pool:)
$$- cligph(igrid) \cdot lpcha(igrid) \quad (3.43)$$

$$dp(igrid, lchb) = lpchb(igrid) - ldchb(igrid) - cligph(igrid) \cdot lpchb(igrid) \quad (3.44)$$

$$dp(igrid, lcwa) = lpcwa(igrid) + dforca(igrid) - ldcwa(igrid) - cligpw(igrid) \cdot lpcwa(igrid)$$
(due to clearing:)
$$- cligpw(igrid) \cdot dforca(igrid) \quad (3.45)$$

$$dp(igrid, lcwb) = lpcwb(igrid) + dforcb(igrid) - ldcwb(igrid) - cligpw(igrid) \cdot lpcwb(igrid)$$
(due to clearing:)
$$- cligpw(igrid) \cdot dforcb(igrid) \quad (3.46)$$

Soil lignin pool (residuals of litter pools):

$$\begin{aligned} dp(igrid, ligc) = {} & cligph(igrid) \cdot lpcha(igrid) \\ & + cligph(igrid) \cdot lpchb(igrid) \\ & + cligpw(igrid) \cdot lpcwa(igrid) \\ & + cligpw(igrid) \cdot lpcwb(igrid) \\ & + cligpw(igrid) \cdot dforca(igrid) \\ & + cligpw(igrid) \cdot dforcb(igrid) \end{aligned}$$
(lignin depletion, the carbon uptake by organisms while feeding on lignin:)
$$- ligdcf(igrid) \quad (3.47)$$

In the following, the equations for the collection of fluxes in "dummy" pools are found (for the list of dummy pools and their notation see Tables 2.2 and 2.4 on pages 7 and 9).

$$dp(igrid, nppch) = nppha(igrid) + npphb(igrid) \quad (3.48)$$

$$dp(igrid, nppcw) = nppwa(igrid) + nppwb(igrid) \quad (3.49)$$

$$dp(igrid, lpch) = lpcha(igrid) + lpchb(igrid) \quad (3.50)$$

$$dp(igrid, lpcw) = lpcwa(igrid) + lpcwb(igrid) \quad (3.51)$$

$$dp(igrid, ldch) = ldcha(igrid) + ldchb(igrid) \quad (3.52)$$

$$dp(igrid, ldcw) = ldcwa(igrid) + ldcwb(igrid) \quad (3.53)$$

$$\begin{aligned} dp(igrid, ligpc) = {} & cligph(igrid) \cdot lpcha(igrid) \\ & + cligph(igrid) \cdot lpchb(igrid) \end{aligned}$$

$$+ cligpw(igrid) \cdot lpcwa(igrid)$$
$$+ cligpw(igrid) \cdot lpcwb(igrid) \quad (3.54)$$

$$dp(igrid, ligdc) = ligdcf(igrid) \quad (3.55)$$
$$dp(igrid, humdc) = humdcf(igrid) \quad (3.56)$$

$$dp(igrid, dforc) = dforca(igrid) + dforcb(igrid) \quad (3.57)$$

The module `dgl` is called `istep` times every model day (`iday`), see module `timint` and Figure 2.3 on page 15.

3.10 Module filred

This module is one of several which organize the input of data into the model. Those data include driving forces and boundary conditions. Files having names that end with the extension $*$.05 contain gridded (0.5 degrees) data which are organized countrywise. For each country, a header record with the continent code, the country code, and the number of grid elements that belong to the country, starts the country data, followed by the data records for this country (each record includes data for one grid element).

Module `filred` is called once at the beginning of a model run.

3.11 Modules idpool and idfpool

In the model, we use so called "dummy" pools to add up fluxes of the model during a month for output (see Table 2.2 on page 7 and Table 2.4 on page 9). At the end of the month, those "dummy" pools contain the monthly accumulated sum of the material transported by the flux. The "dummy" pools are handeled like ordinary pools, i.e. they are balanced by the flux(es) they should collect, and integrated in the modules `dgl` or `ndgl`.

At the beginning of each month, "dummy" pools are set to zero, which means they are made empty. This is done in the two modules `idpool` and `idfpool`. These modules are called every month at the beginning of the monthly loop.

filred interface

In:	file korrmatrix_1990	`korri(icount,year)`
	file fyield8090.country	`rap80(icount)`
		`rap90(icount)`
	file popparam	`apop(icount,iparam)`
	file fymult.2050	`fymult(icount)`
	file coord.05	`lat(igrid)`, `lon(igrid)`
	file temp_cramer.05	`it(igrid,imonth)`
		`itann(igrid)`
	file prec_cramer.05	`ipp(igrid,imonth)`
		`ippann(igrid)`
	file clou_cramer.05	`icloud(igrid,imonth)`
	file soilfactors.05.mod1805	`soilasc`, `fsoil(igrid)`
	file usestd_1980_circl0.05	`usestd(igrid)`
	file fossil.year	`fossc(iannum)`
	file cldmatrix	`cld(nx,ny)`
Out:	correction matrix to calculate the agriculturally used areas in each country in the current model year	`korri(icount,iannum)`
	relative agricultural productivity in AD 1980	`rap80(icount)`
	relative agricultural productivity in AD 1990	`rap90(icount)`
	four parameters for population polynomial per country	`apop(icount,iparam)`
	annual modification factor for `rap`, 1991 to 2050	`fymult(icount)`
	latitude of the lower left corner of a grid element	`lat(igrid)`
	longitude of the lower left corner of a grid element	`lon(igrid)`
	monthly temperature	`it(igrid,imonth)`
	mean annual temperature	`itann(igrid)`
	monthly precipitation	`ipp(igrid,imonth)`
	annual precipitation	`ippann(igrid)`
	“cloudfreeness” of the month	`icloud(igrid,imonth)`
	soil type (coded)	`soilat(igrid)`
	soil fertility factor	`fsoil(igrid)`
	standard map of agricultural crops in 1980	`usestd(igrid)`
	emissions of carbon (CO_2) from fossil sources	`fossc(iannum)`
	depletion coefficients for a 100×100 matrix of monthly temperature and precipitation values	`cld(nx,ny)`

3.12 Module mnpp

Module calculates 10–years running mean of the annual sum of net primary productivity of agriculturally used grid elements (NPP_{agri}). If a grid element is coverd with natural vegetation, the NPP_{agri} is calculated as if it were used.

mnpp interface		
In:	annual sum of net primary productivity	`nppyr(igrid)`
	relative agricultural productivity	`rapg(igrid)`
	vegetation type	`ibiome(igrid)`
Out:	10–year running mean of annual NPP	`nppyrm(igrid)`

Module called once a year.

3.13 Module monco2

Assign the monthly CO_2 concentration to an annual array at the end of the month.

monco2 interface		
In:	CO_2 concentration of the month $[\mu l \cdot l^{-1}]$	`co2`
Out:	array of monthly CO_2 concentrations	`co2mon(imonth)`

To be called monthly at the end of the month.

3.14 Module mtemp

This module assigns the the mean temperature of the warmest month of a given model year and grid element to the array `mtwa(igrid)`, and the temperature of the coldest month to the array `mtco(igrid)`.

Besides that, it calculates a 50–years running mean of `mtwa` and assigns it to the array `mtwam(igrid)`.

mtemp interface		
In:	monthly temperature	`it(igrid,imonth)`
Out:	mean temperature of warmest month	`mtwa(igrid)`
	mean temperature of coldest month	`mtco(igrid)`
	50–years running mean of `mtwa`	`mtwam(igrid)`

Module is called once a year.

3.15 Module ncim 3.00

This module represents the main program in FORTRAN code. Its main responsibility is to organize the call sequence and call frequencies of the modules of the model. For details and the model structure see Figure 2.3 on page 15.

Besides that `ncim` reads some data which are required for the configuration of an individual model run, from a configuration file `ncimdata`. This file is expected to be accessible at the beginning of a model run in the directory in which the model is started. The variables read and their possible values are as follows:

variable	meaning	values
`ipresw`	prerun switch	0 (no prerun performed)
		1 (prerun, pools will be initialized)
		2 (prerun, initial pools read from file)
`iprern`	prerun duration (years)	$0, \ldots, 10\,000$
`iannb`	starting year AD	$1860 \rightarrow$
`iannend`	ending year AD	$\rightarrow 2050$
`fire`	fire switch	0 (no vegetation fires considered)
		1 (vegetation fires considered)
`co2`	initial CO_2 concentration $[\mu l \cdot l^{-1}]$	$200, \ldots, 600$
		preindustrial value 280.86
`nannpr`	nitrogen prerun 1 (years)	$0, \ldots, 10\,000$
`nannzu`	nitrogen prerun 2 (years)	$0, \ldots, 10\,000$
`agri`	agriculture switch	`.true.` or `.false.`

There are no other input data of this module. Output data include the model year `iannum`, the current month `imonth`, and the current day `iday`.

3.16 Module ndgl

Module `ndgl` contains, together with its "sister"module `dgl` (see page 32), the calculation of the fluxes (processes) and the mass–balance equations for nitrogen and carbon. Module `ndgl` includes the "fast" fluxes of carbon and the nitrogen fluxes, while `dgl` includes the "slow" carbon fluxes.

ndgl interface

In:	monthly net primary productivity of herbaceous above–ground material	`nppha(igrid)`
	monthly net primary productivity of herbaceous below–ground material	`npphb(igrid)`
	monthly net primary productivity of woody above–ground material	`nppwa(igrid)`
	monthly net primary productivity of woody below–ground material	`nppwb(igrid)`
	coefficient litter production herbaceous above ground	`clpha(igrid)`
	coefficient litter production herbaceous below ground	`clphb(igrid)`
	coefficient litter production woody above ground	`clpwa(igrid)`
	coefficient litter production woody below ground	`clpwb(igrid)`
	coefficient litter depletion herbaceous above ground	`cldha(igrid)`
	coefficient litter depletion herbaceous below ground	`cldhb(igrid)`
	coefficient litter depletion woody above ground	`cldwa(igrid)`
	coefficient litter depletion woody below ground	`cldwb(igrid)`
	coefficient lignin production from herbaceous material	`cligph(igrid)`
	coefficient lignin production from woody material	`cligpw(igrid)`
	coefficient of deforestation	`cdfor(igrid)`
	depletion coefficient humic substances	`chumd(igrid)`
	allocation coefficient for N to herbaceous above–ground material	`calha(igrid)`
	allocation coefficient for N to herbaceous below–ground material	`calhb(igrid)`
	allocation coefficient for N to woody above–ground material	`calwa(igrid)`
	allocation coefficient for N to woody below–ground material	`calwb(igrid)`
	coefficient of N (avn)uptake by soil organisms	`cgmic(igrid)`
	coefficient of mortality of soil organisms	`cmmic(igrid)`
	coefficient of N (avn) uptake by plants	`cassn(igrid)`
	coefficient of fixation of NH_4^+ in soil	`cavnpu(igrid)`
	coefficient of desorption of N from soil	`cpuavn(igrid)`
	leaching coefficient of available N to groundwater	`cleach(igrid)`
	respiration coefficient of soil organisms	`crmic(igrid)`
	share of NPP by legumes	`legnpp(ibiome(igrid))`
	share of NPP by C4 plants	`c4npp(ibiome(igrid))`
	N deposition standard year	`atmdep(igrid,imonth)`
	change of N deposition period 1860–1990	`kordep(land,iannum)`
	standard C/N ratio of herbaceous material	`cnh(ibiome(igrid))`
	standard C/N ratio of woody material	`cnw(ibiome(igrid)`
	portion of recycled N before leaves are shed	`rcych(ibiome(igrid))`
	current model year	`iannum`
by list:		
In:	array of C and N pools	`p(igrid,ip)`
Out:	array of time–derivatives of pools	`dp(igrid,ip)`

In a first step, the C/N ratios for the different materials are calculated. Before the model run starts, i.e. during the two prerun procedures (spin–up), C/N ratios are set to standard values. After the start of the model run, C/N ratios for the 4 phytomass compartments, for the 4 litter compartment, for humic substances, and for the soil organisms are calculated by division of the respective carbon and nitrogen pools.

3.16.1 Calculation of fluxes (processes)

The next task in this module `ndgl` is to calculate the fluxes (processes):

Depletion of humic substances:

$$humdcf(igrid) = chumd(igrid) \cdot p(igrid, humc) \tag{3.58}$$

Allocation of nitrogen from the N–reserve pool in plants to structural N compounds in the herbaceous above–ground phytomass:

$$\begin{aligned} nppnha(igrid) &= calha(igrid) \\ &\quad \cdot \left(\frac{p(igrid, resn)}{resn0(igrid)} \right)^{zalloc} \\ &\quad \cdot 10^{min\left(1, \frac{\ln \frac{cnacha(igrid)}{cnh(ibiome(igrid))}}{(\ln 2.)^3}\right)} \end{aligned} \tag{3.59}$$

The coefficient $calha$ is provided by the module `nffclc`. The second term in equation (3.59) is the correction of allocation due to the availability of mobile nitrogen in the N–reserve pool of the plants. In the third term, the actual C/N ratio of the plant material ($cnacha$) is compared with the "normal" C/N ratio (cnh) of the material under consideration, thus detecting N deficiency or N abundance. This term provides an non–linear correction of allocation depending on the actual N–state of the tissues.

Similar equations are used for the allocation to the other three phytomass compartments $nppnhb$, $nppnwa$, and $nppnwb$.

During the preruns (spin–up procedure) the allocation of nitrogen is calculated differently, providing an input of carbon and nitrogen into the plant material with fixed C/N ratios:

$$nppnha(igrid) = \frac{nppha(igrid)}{cnh(ibiome(igrid))} \tag{3.60}$$

$$nppnhb(igrid) = \frac{npphb(igrid)}{cnh(ibiome(igrid))} \tag{3.61}$$

$$nppnwa(igrid) = \frac{nppwa(igrid)}{cnw(ibiome(igrid))} \tag{3.62}$$

$$nppnwb(igrid) = \frac{nppwb(igrid)}{cnw(ibiome(igrid))} \tag{3.63}$$

Nitrogen in the produced litter is assumed to be proportional to the respective pool in plant material, so that the litter production has variable C/N ratios:

$$lpnha(igrid) = clpha(igrid) \cdot p(igrid, pnha) \quad (3.64)$$

$$lpnhb(igrid) = clphb(igrid) \cdot p(igrid, pnhb) \quad (3.65)$$

$$lpnwa(igrid) = clpwa(igrid) \cdot p(igrid, pnwa) \quad (3.66)$$

$$lpnwb(igrid) = clpwb(igrid) \cdot p(igrid, pnwb) \quad (3.67)$$

Deforestation Nitrogen:

$$dforna(igrid) = cdfor(igrid) \cdot p(igrid, pnwa) \quad (3.68)$$

$$dfornb(igrid) = cdfor(igrid) \cdot p(igrid, pnwb) \quad (3.69)$$

Litter Depletion Nitrogen:

$$ldnha(igrid) = cldha(igrid) \cdot p(igrid, lnha) \quad (3.70)$$

$$ldnhb(igrid) = cldhb(igrid) \cdot p(igrid, lnhb) \quad (3.71)$$

$$ldnwa(igrid) = cldwa(igrid) \cdot p(igrid, lnwa) \quad (3.72)$$

$$ldnwb(igrid) = cldwb(igrid) \cdot p(igrid, lnwb) \quad (3.73)$$

Humus Depletion Nitrogen:

$$humdnf(igrid) = chumd(igrid) \cdot p(igrid, humn) \quad (3.74)$$

Excretion of humic substances by microorganisms, assumed to be 5% of total mineralized litter N:

$$humpnf(igrid) = (ldnha(igrid) + ldnhb(igrid) + ldnwa(igrid) + ldnwb(igrid)) \cdot 0.05 \quad (3.75)$$

Uptake of available nitrogen (avn) by organisms:

$$mignf(igrid) = cgmic(igrid) \cdot max(0, p(igrid, avn))^{zmign} \quad (3.76)$$

Mortality of microorganisms:

$$mimnf(igrid) = cmmic(igrid) \cdot p(igrid, micn) \quad (3.77)$$

Segregation of excess nitrogen, if the C/N ratio is < 6. At the moment, the maximum coefficient (at $cnmic = 0$) is $3/4$ per month, or 0.025 per day:

$$misnf(igrid) = \frac{3}{4} \cdot \frac{6 - min(6, cnmic(igrid))}{6} \cdot p(igrid, micn) \quad (3.78)$$

Uptake of available nitrogen avn by plants:

$$\begin{aligned} avunf(igrid) &= cassn(igrid) \cdot p(igrid, pcha) \\ &\cdot \frac{2}{1. + exp(1 \cdot (p(igrid, resn) - resn0(igrid)))} \\ &\cdot p(igrid, avn)^{zavn} \end{aligned} \tag{3.79}$$

Ammonium fixation on buffer in soil:

$$avnpuf(igrid) = cavnpu(igrid) \cdot p(igrid, avn) \tag{3.80}$$

And return flux from buffer to avn:

Calculate actual adsorption–capacity in grid element:

$$\begin{aligned} cap(igrid) &= (1 - sand(igrid)) \cdot fsoil(igrid) \cdot 105 \qquad \text{(from clay minerals)} \\ &+ p(igrid, humc) \cdot 3.5 \cdot 10^{-2} \qquad \text{(from humic compounds)} \end{aligned} \tag{3.81}$$

Correct the desorption coefficient by the calculated free capacity:

$$\begin{aligned} puavnf(igrid) &= cpuavn(igrid) \\ &\cdot \frac{cap(igrid)}{cap(igrid) - p(igrid, puffn)} \\ &\cdot p(igrid, puffn) \end{aligned} \tag{3.82}$$

Respiration of microorganisms:

$$mircf(igrid) = crmic(igrid) \cdot p(igrid, micc) \tag{3.83}$$

Mortality of microorganisms:

$$mimcf(igrid) = cmmic(igrid) \cdot p(igrid, micc) \tag{3.84}$$

Output of excess CO_2 by microorganisms if they feed on carbon–rich compounds: Use a saturation function. The saturation function has half–saturation at $cnmic = 9$. The coefficient is scaled to $3/4$ per month or 0.025 per day.

$$\begin{aligned} miscf(igrid) &= \frac{max(6, cnmic(igrid)) - 6}{max(6, cnmic(igrid)) - 3} \\ &\cdot \frac{3}{4} \cdot p(igrid, micc) \end{aligned} \tag{3.85}$$

There are “open” fluxes, which connect the atmospheric N_2 pool to the biospheric nitrogen pools. These “open” fluxes are the only way to add to the biosphere additional nitrogen in order to compensate for the additional carbon (CO_2 from fossil sources) which is incorporated into the

biosphere. This makes these fluxes most important. Equations (3.86) through (3.88) provide *preliminary* descriptions of these fluxes.

Nitrogen fixation by symbionts in legume roots:

$$\begin{aligned} legnf(igrid) &= legnpp(ibiome(igrid)) \cdot 0.3 \\ &\cdot \left(\frac{nppha(igrid) + npphb(igrid)}{cnh(ibiome(igrid))} + \frac{nppwa(igrid) + nppwb(igrid)}{cnw(ibiome(igrid))} \right) \\ &\cdot \frac{resn0(igrid)}{p(igrid, resn)} \qquad \text{(correct for N–requirements)} \end{aligned} \tag{3.86}$$

N fixation by *Azospirillum* symbionts in C4 grasses and cereals:

$$\begin{aligned} azonf(igrid) &= c4npp(ibiome(igrid)) \cdot 0.03 \\ &\cdot \frac{nppha(igrid) + npphb(igrid)}{cnh(ibiome(igrid))} \\ &\cdot \frac{resn0(igrid)}{p(igrid, resn)} \end{aligned} \tag{3.87}$$

N fixation by Actinomycetes in tree roots on sandy soils. (Assumed to be proportional to the respiration flux of soil organisms and to the sand fraction in the soil):

$$actnf(igrid) = 0.01 \cdot mircf(igrid) \cdot sand(igrid) \tag{3.88}$$

Anthropogenic nitrogen immissions (deposition of gaseous and particulate compounds) from emissions by traffic, heating devices, power plants, and others. For years prior to 1860 the deposition values of AD 1860 are assumed. Monthly values on per country level are calculated:

$$depnf(igrid) = atmdep(igrid, imonth) \cdot kordep(land(igrid), max(1860, iannum)) \tag{3.89}$$

Leaching of available nitrogen (`avn`) into groundwater. The leaching coefficient $cleach$ is provided by the module `nffclc`.

$$leanf(igrid) = cleach(igrid) \cdot p(igrid, avn) \tag{3.90}$$

Calculate the denitrification flux (N2ONF) of a grid element from the net mineralization. This flux includes the N_2O and N_2 production from soil. We use an algorithm proposed by Nevison et al. (1996) which assumes that denitrification depends on net mineralization. It may be replaced in the near future.

$$n2onf(igrid) = \begin{cases} 9.5 \cdot 10^{-4} \cdot mimnf(igrid) & \text{for} \quad mimnf \leq 2.3 \\ \left.\begin{array}{l} 7.2 \cdot 10^{-5} \cdot mimnf(igrid)^2 \\ \quad + 3.3 \cdot 10^{-4} \cdot mimnf(igrid) \\ \quad + 1.0 \cdot 10^{-3} \end{array}\right\} & \text{for} \quad mimnf > 2.3 \end{cases} \tag{3.91}$$

3.16.2 Time–derivatives of the pools (Mass–balance equations)

In the module `ndgl` the time–derivatives of the nitrogen pools and the "fast" carbon pools are calculated by balancing of the fluxes.

Humus Carbon:

$$\begin{aligned} dp(igrid, humc) = \; & humpnf(igrid) \cdot cnhum(igrid) && \text{(C flux from N flux)} \\ & \cdot cnmic(igrid)/6 && \text{(regulating production)} \\ & - humdcf(igrid) \end{aligned} \tag{3.92}$$

Carbon content of organisms in litter and soil:

$$\begin{aligned} & dp(igrid, micc) = \\ & \left.\begin{aligned} & ldcha(igrid) + ldchb(igrid) + ldcwa(igrid) + ldcwb(igrid) \\ & + ligdcf(igrid) \\ & + humdcf(igrid) \end{aligned}\right\} \text{(feed on C sources)} \\ & - humpnf(igrid) \cdot cnhum(igrid) && \text{(excretion of humic substances)} \\ & - mircf(igrid) && \text{(respiration of organisms)} \\ & - mimcf(igrid) && \text{(output as } CO_2 \text{ due to mortality)} \\ & - miscf(igrid) && \text{(output of excess } CO_2\text{)} \end{aligned} \tag{3.93}$$

Phytomass Nitrogen:

$$dp(igrid, pnha) = nppnha(igrid) - lpnha(igrid) \tag{3.94}$$

$$dp(igrid, pnhb) = nppnhb(igrid) - lpnhb(igrid) \tag{3.95}$$

$$dp(igrid, pnwa) = nppnwa(igrid) - lpnwa(igrid) - dforna(igrid) \tag{3.96}$$

$$dp(igrid, pnwb) = nppnwb(igrid) - lpnwb(igrid) - dfornb(igrid) \tag{3.97}$$

Litter Nitrogen:

$$\begin{aligned} dp(igrid, lnha) = \; & lpnha(igrid) \\ & \cdot (1 - rcych(ibiome(igrid))) && \text{(recycle N before leaves shed)} \\ & - ldnha(igrid) \end{aligned} \tag{3.98}$$

$$\begin{aligned} dp(igrid, lnhb) = \; & lpnhb(igrid) \\ & - ldnhb(igrid) \end{aligned} \tag{3.99}$$

$$\begin{aligned} dp(igrid, lnwa) = \; & lpnwa(igrid) + dforna(igrid) \\ & - ldnwa(igrid) \end{aligned} \tag{3.100}$$

$$dp(igrid, lnwb) = lpnwb(igrid) + dfornb(igrid) - ldnwb(igrid) \quad (3.101)$$

Humus Nitrogen (excretion of humic substances minus uptake by organisms):

$$dp(igrid, humn) = humpnf(igrid) - humdnf(igrid) \quad (3.102)$$

Nitrogen in organisms in litter and soil. This pool is one of the most important "fast" nitrogen pools in litter and soil. It absorbs very fast (hours) available nitrogen (soluble nitrogen compounds) thus preventing or minimizing losses by leaching. Nitrogen in organisms is freely available for plants due to the short life–span of these organisms:

$$\begin{aligned} dp(igrid, micn) = & \\ & ldnha(igrid) + ldnhb(igrid) + ldnwa(igrid) + ldnwb(igrid) \\ & \qquad \text{(input from litter)} \\ & + mignf(igrid) \quad \text{(input from available N)} \\ & + humdnf(igrid) \quad \text{(input from depletion of humic substances)} \\ & - humpnf(igrid) \quad \text{(loss from production of humic substances)} \\ & - mimnf(igrid) \quad \text{(loss (mineralization) by mortality)} \\ & - misnf(igrid) \quad \text{(segregation of excess N if C/N}< 6\text{)} \end{aligned} \quad (3.103)$$

Available nitrogen in soil. This pool includes the soluble nitrogen compounds in soil (and litter) which are produced by mineralization or added by immissions or fertilizers, i.e. mainly the $NH_4^+ \leftrightarrow NO_2^- \leftrightarrow NO_3^-$ system.

$$\begin{aligned} dp(igrid, avn) = & \\ & mimnf(igrid) \quad \text{(mineralization by mortality of organisms)} \\ & + misnf(igrid) \quad \text{(segregation of excess N from organisms if C/N}< 6\text{)} \\ & + depnf(igrid) \quad \text{(immission of } NO_x\text{)} \\ & - mignf(igrid) \quad \text{(uptake by microorganisms)} \\ & - avunf(igrid) \quad \text{(uptake by plants)} \\ & - leanf(igrid) \quad \text{(leaching into groundwater)} \\ & - n2onf(igrid) \quad \text{(denitrification from net mineralization)} \\ & - avnpuf(igrid) \quad \text{(fixation by adsorption on buffer)} \\ & + puavnf(igrid) \quad \text{(desorption)} \end{aligned} \quad (3.104)$$

Balance of ammonium in the soil buffer system. This buffer system cuts peaks of available nitrogen, which would increase the leaching losses.

$$dp(igrid, puffn) = avnpuf(igrid) - puavnf(igrid) \tag{3.105}$$

Balance of reserve Nitrogen in plants. This pool serves as mobile nitrogen source for the allocation to the nitrogen in the phytomass compartments. Nitrogen uptake from soil, fixation of atmospheric N_2 by symbionts and re–allocation from senescent plant parts provide nitrogen for this pool.

$$\begin{aligned} dp(igrid, resn) = & \\ & avunf(igrid) && \text{(available N uptake from soil)} \\ & + lpnha(igrid) \cdot rcych(ibiome(igrid)) && \text{(re-allocation from senescent leaves)} \\ & + legnf(igrid) && \text{(fixation by symbionts in legume roots)} \\ & + azonf(igrid) && \text{(fixation by Azospirillum symbionts)} \\ & + actnf(igrid) && \text{(fixation by Actinomecetes)} \\ & \left.\begin{array}{l} - nppnha(igrid) - nppnhb(igrid) \\ - nppnwa(igrid) - nppnwb(igrid) \end{array}\right\} && \text{(allocation to phytomass compartments)} \end{aligned} \tag{3.106}$$

The module `ndgl` is called once per integration step `istep`.

3.17 Module nffclc

In this module the coefficients of the “fast” fluxes are calculated from their driving forces.

The allocation coefficients for nitrogen to the compartments of phytomass are assumed to be a standard fraction of the respective share of net primary productivity to this compartment:

$$calha(igrid) = \frac{nppha(igrid)}{cnh(ibiome(igrid))} \tag{3.107}$$

$$calhb(igrid) = \frac{npphb(igrid)}{cnh(ibiome(igrid))} \tag{3.108}$$

$$calwa(igrid) = \frac{nppwa(igrid)}{cnw(ibiome(igrid))} \tag{3.109}$$

$$calwb(igrid) = \frac{nppwb(igrid)}{cnw(ibiome(igrid))} \tag{3.110}$$

The coefficient of growth of soil organisms is assumed to be $15\times$ higher than the depletion coefficient of herbaceous litter:

$$cgmic(igrid) = 15 \cdot cldha(igrid) \tag{3.111}$$

nffclc interface

In:	standard C/N ratio of herbaceous plant material	`cnh(ibiome(igrid))`
	standard C/N ratio of woody plant material	`cnw(ibiome(igrid))`
	monthly net primary productivity of herbaceous above–ground material	`nppha(igrid)`
	monthly net primary productivity of herbaceous below–ground material	`npphb(igrid)`
	monthly net primary productivity of woody above–ground material	`nppwa(igrid)`
	monthly net primary productivity of woody below–ground material	`nppwb(igrid)`
	coefficient litter depletion herbaceous above–ground	`cldha(igrid)`
	monthly actual evapotranspiration of each grid element	`aetm(igrid,imonth)`
	monthly temperatures of grid element	`it(igrid,imonth)`
	monthly precipitation of grid element	`ipp(igrid,imonth)`
	mean temperature of the warmest month	`mtwam(igrid)`
	sand fraction of the soil $(0, \ldots, 1)$	`sand(igrid)`
Out:	allocation coefficient for N to herbaceous above–ground material	`calha(igrid)`
	allocation coefficient for N to herbaceous below–ground material	`calhb(igrid)`
	allocation coefficient for N to woody above–ground material	`calwa(igrid)`
	allocation coefficient for N to woody below–ground material	`calwb(igrid)`
	coefficient of growth of soil organisms	`cgmic(igrid)`
	coefficient of mortality of soil organisms	`cmmic(igrid)`
	coefficient of respiration of soil organisms	`crmic(igrid)`
	coefficient of N uptake by plant roots	`cassn(igrid)`
	coefficient of leaching of available N to ground water	`cleach(igrid)`
	coefficient of transport (adsorption) between available nitrogen and the soil buffer	`cavnpu(igrid)`
	coefficient of desorption from soil buffer	`cpuavn(igrid)`

It is assumed that the life span of soil–organisms depends on cldha.

$$cmmic(igrid) = 0.1 \cdot cldha(igrid) \tag{3.112}$$

The monthly respiration coefficient for soil organizms. This is the basic metabolic turnover of the soil organisms. It depends on temperature according to $Q_{10} = 2$ with a base–temperature of 20°C. It is assumed that it is not influenced by humidity!

$$\begin{aligned} q_{10} &= 2.0 \\ x &= \frac{\ln q_{10}}{10} \\ crmic(igrid) &= 0.05 \cdot \mathrm{e}^{x \cdot (it(igrid,imonth)-20)} \end{aligned} \tag{3.113}$$

Nitrogen uptake coefficient by plant roots (N assimilation rate) `cassn`. We assume a maximum rate of 0.013 [gN/gC/month]. It is assumed that soil moisture must not be considered since green leaves phytomass, which drives the flux, already depends on moisture. `cassn` is corrected for the temperature influence: The maximum rate is assumed to be valid for the "temperature of adaptation", i.e. the mean temperature of the warmest month (`mtwam`) and modified with $Q_{10} = 2$:

$$\begin{aligned} q_{10} &= 2.0 \\ x &= \frac{\ln q_{10}}{10} \\ cassn(igrid) &= 0.013 \cdot \mathrm{e}^{x \cdot (it(igrid,imonth)-mtwam(igrid))} \end{aligned} \tag{3.114}$$

Leaching rate of nitrogen into the ground water. The coefficient cleach depends on the water saturation of the soil and the composition (sand fraction) of the soil material. It is zero if the precipitation of the month is zero or less than the actual evapotranspiration or if the temperature is less than zero (frozen water):

$$cleach(igrid) = 0 \begin{cases} \text{for} & ipp(igrid, imonth) = 0 \\ \text{or} & ipp(igrid, imonth) < aetm(igrid, imonth) \\ \text{or} & it(igrid, imonth) < 0 \end{cases}$$

else:

$$cleach(igrid) = (0.1 + sand(igrid)) \cdot \left(1 - \frac{aetm(igrid, imonth)}{ipp(igrid, imonth)}\right) \tag{3.115}$$

Transport coefficients between available nitrogen in soil (`avn`) and soil buffer (mainly for ammonium). These are preliminary tentative values (Müller, Giessen, 2004, pers. comm.) and at present subject to further investigation.

$$cavnpu(igrid) = 10 \tag{3.116}$$

$$cpuavn(igrid) = \frac{cavnpu(igrid)}{60} \tag{3.117}$$

The module nffclc is called every day.

3.18 Module nfilrd

This module is one of several which organize the input of data into the model. This module reads data from files which are required to run the nitrogen cycle. Those data include driving forces and boundary conditions. Files having names that end with the extension $*.05$ contain gridded (0.5 degrees) data which are organized countrywise. For each country, a header record with the continent code, the country code, and the number of grid elements that belong to the country, starts the country data, followed by the data records for this country (each record includes data for one grid element).

nfilrd interface		
In:	file texture.05	`itext(igrid)`
	file atmdep.05	`depmax(igrid)`
		`scal(igrid,imonth)`
	file korratm.1860-1986.icount	`kordep(icount,iannum)`
Out:	sand–fraction in the soil of a grid element $(0, \ldots, 1)$	`sand(igrid)`
	nitrogen deposition for AD 1980 [g·m^{-2}·month^{-1}]	`atmdep(igrid,imonth)`
	correction matrix to calculate the deposited amounts of N in each country in the current model year	`kordep(icount,iannum)`

3.19 Module nppsmooth

Module nppsmooth takes the net primary productivity (NPP) arrays (nppha, npphb, nppwa, nppwb) as soon as they are provided by modules cnpp and cnppn. It stores these original values and then overwrites the arrays with the smoothed NPP values. Smoothing means calculating a 12–day running mean of the NPP arrays in order to prevent steps of NPP values as a new month begins (NPP is updated from driving forces every month.

The Module nppsmooth is called daily.

nppsmooth interface		
In:	monthly net primary productivity of herbaceous above–ground material	`nppha(igrid)`
	monthly net primary productivity of herbaceous below–ground material	`npphb(igrid)`
	monthly net primary productivity of woody above–ground material	`nppwa(igrid)`
	monthly net primary productivity of woody below–ground material	`nppwb(igrid)`
Out:	smoothed values of:	
	monthly net primary productivity of herbaceous above–ground material	`nppha(igrid)`
	monthly net primary productivity of herbaceous below–ground material	`npphb(igrid)`
	monthly net primary productivity of woody above–ground material	`nppwa(igrid)`
	monthly net primary productivity of woody below–ground material	`nppwb(igrid)`

3.20 Module nppyear

This module adds the dummy pools of net primary productivity for annual sums on a grid element basis (for output). This module is called every day.

nppyear interface		
In:	dummy pools of monthly net primary productivity	`p(igrid,nppch)`
		`p(igrid,nppcw)`
Out:	annual npp [$g \cdot m^{-2} \cdot yr^{-1}$]	`nppyr(igrid)`

3.21 Module outann

This subroutine produces model output of global sums of nitrogen and carbon pools. Dummy pools are also added to produce global annual sums of fluxes. Since the output requirements depend on the investigated problem, we assume that this subroutine is re–written for any new research activity. This module imports fields (arrays) of the form `poolsm(imonth)` from the

modules `smpool` and `smdpool`. These fields contain the global sums of nitrogen or carbon for the 12 month of a year.
This module is called at the end of a model year. It may be called at the end of any month of any model year for which model results are required.

3.22 Module plotdata

This module is used to write a complete model system state to an output file. The pools and dummy pools together with running means of certain pools are saved in this file. The values are on grid element level and have the dimension [g·m^{-2}·yr^{-1}]. The file may be used for several purposes, mainly (1) to restart the model if the computer run had to be stopped for any reason, (2) to produce thematic maps which show results on a 0.5 degrees resolution.
The module `plotdata` may be called in regular intervals to save the model state for security. It may be called on request to produce output results at a certain time.

3.23 Module relaet

The module `relaet` provides values that are necessary to distribute net primary productivity and the litter production over the months of a year.

relaet interface

In:	monthly actual evapotranspiration of each grid element	`aetm(igrid,imonth)`
Out:	monthly decrease of `aetm`	`aetdm(igrid,imonth)`
	`aetm` in december last year	`aetmdc(igrid)`
	annual sum of negative monthly values of `aetdm`	`aetdsu(igrid)`
	annual sum of actual evapotranspiration	`aetsum(igrid)`

Module `relaet` is called once a year at the beginning of the year.

3.24 Modules smpool and smdpool

In these modules, the fields (arrays) of the form `poolsm(imonth)` are produced, which are used by the output module `outann`. The pools respective dummy–pools on grid element level of the form `p(igrid,ip)` (see Tables 2.1 and 2.2 respective 2.3 and 2.4) are of the dimension [g·m^{-2}]. In these modules, the values for entire grid elements are calculated by multiplication

with the grid element area from the module `arcalc`. Then these values are globally added for global sums.
`smpool` and `smdpool` are called monthly.

3.25 module timint

This subroutine is a special module for time integration. It propagates the system state by SEC seconds. It uses the Runge–Kutta method (4th order). The time derivatives of the state variables (pools and dummy pools) are provided by the subroutines `dgl` and `ndgl`.

If we assume, that the basic time interval, one day, is subdivided into `nstep` integration steps, we can define several time steps for integration:

$$\begin{aligned} deltat &= \frac{1}{nstep} \\ dt2 &= \frac{deltat}{2} \\ dt3 &= \frac{deltat}{3} \\ dt6 &= \frac{deltat}{6} \end{aligned} \tag{3.118}$$

The integration of the mass balance system over one time step by `nstep` integration steps `istep` is then done as follows (`dp` being the time derivative of `pool`, `npool` the total number of state variables):

```
do 42  istep = 1, nstep

        call dgl  (pool,dp)
        call ndgl (pool,dp)
        do 421  ip = 1, npool
        do 421  igrid = lgrid, mgrid, jgrid
          ptmp(igrid,ip) = pool(igrid,ip) + dp(igrid,ip) * dt2
          psum(igrid,ip) = pool(igrid,ip) + dp(igrid,ip) * dt6
421     continue

        call dgl  (ptmp,dp)
        call ndgl (ptmp,dp)
        do 422  ip = 1, npool
        do 422  igrid = lgrid, mgrid, jgrid
```

```
          ptmp(igrid,ip) = pool(igrid,ip) + dp(igrid,ip) * dt2
          psum(igrid,ip) = psum(igrid,ip) + dp(igrid,ip) * dt3
422     continue

        call dgl  (ptmp,dp)
        call ndgl (ptmp,dp)
        do 423  ip = 1, npool
        do 423  igrid = lgrid, mgrid, jgrid
          ptmp(igrid,ip) = pool(igrid,ip) + dp(igrid,ip) * deltat
          psum(igrid,ip) = psum(igrid,ip) + dp(igrid,ip) * dt3
423     continue

        call dgl  (ptmp,dp)
        call ndgl (ptmp,dp)
        do 424  ip = 1, npool
        do 424  igrid = lgrid, mgrid, jgrid
          pool(igrid,ip) = psum(igrid,ip) + dp(igrid,ip) * dt6
424     continue

42     continue
```

In this algorithm, the two–dimensional array `pool(igrid,ip)` always contains the total system state.
Module `timint` is called every model day.

3.26 Module vegread

This module organizes the input into the model of the biomes and biome related parameters. Files having names that end with the extension $*$.05 contain gridded (0.5 degrees) data which are organized countrywise. For each country, a header record with the continent code, the country code, and the number of grid elements that belong to the country, starts the country data, followed by the data records for this country (each record includes data for one grid element). The information is based on tha “Atlas of Biogeography” by Schmithüsen (1976) which distinguishes 176 vegetation units of potential natural vegetation (biomes). We have aggregated these biomes into 31 biome–groups, for which vegetation parameters were established. These parameters are assigned to the 176 biomes.

vegread interface		
In:	file `schmithuesen.05`	`ibiome(igrid)`
	file `vegets`	`ibiome, igroup(ibiome)`
	file `groupparameters_c`	`grpno, gagew(grpno)`
		`gageh(grpno), gherb(grpno)`
		`gabvgr(grpno)`
	file `groupparameters_n`	`grpno, gcnh(grpno)`
		`grcych(grpno), gcnw(grpno)`
		`glegnp(grpno), gc4npp(grpno)`
Out:	potential natural vegetation of grid element	`ibiome(igrid)`
	standard C/N ratio of herbaceous plant material	`cnh(ibiome(igrid))`
	standard C/N ratio of woody plant material	`cnw(ibiome(igrid))`
	share factor of herbaceous productivity of each biome	`herb(ibiome(igrid))`
	share factor of above–ground productivity of each biome	`abvgrd(ibiome(igrid))`
	mean age of herbaceous parts of each biome	`ageh(ibiome(igrid))`
	mean age of woody parts of each biome	`agew(ibiome(igrid))`
	portion of recycled N before leaves are shed	`rcych(ibiome(igrid))`
	share of NPP by legumes	`legnpp(ibiome(igrid))`
	share of NPP by C4 plants	`c4npp(ibiome(igrid))`

The module `vegread` is called once at the beginning of a model run.

3.27 Module xtemp

Module to calculate growing degree days on a zero degree basis and growing degree days on a 5 degree basis.

xtemp interface		
In:	monthly temperature	`it(igrid,imonth)`
Out:	growing degree days on zero basis	`gdd0(igrid)`
	growing degree days on 5 degree basis	`gdd5(igrid)`

Called once at the beginning of a model run.

Chapter 4

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