Grassland data from PASK study
&
Testing of LINGRA

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ABSTRACT

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The PASK study appears to be the best source of information on grassland resources over Europe. The information has been evaluated for its use to calibrate the grassland model LINGRA. The main conclusions are that the yield data for grassland are scarce and also in the PASK study and that observed yield data for grasslands are often representative for suboptimal growing conditions and poor management and cannot be compared well with the modelled yield data.

The LINGRA model has been tested for three locations over Europe. The main conclusions are that the modelling results for both potential and water-limited growing conditions at the three locations are plausible and that also the sensitivity analyses for two input variables (i.e. initial number of tillers and initial amount of reserves available for grass re-growth) give plausible results

Keywords: Growth monitoring, LINGRA, Lolium perenne L., MARS, PASK, Simulation model, ryegrass

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Preface

The calculations of grassland production over Europe with the LINGRA model require field data for its calibration (i.e. to derive site-specific sets of crop parameters). The original LINGRA model was calibrated for rye grass under optimal growing conditions. To compute grassland yields for a large range of environmental and management conditions over Europe, a large amount of field observations on grassland production systems over Europe are needed for the calibration of LINGRA over Europe. The PASK study delivered information on grassland production systems over Europe. This information and its possible use for the LINGRA calibration are to be evaluated in this study. Next, the LINGRA model is tested for a range of conditions. It is assumed that new observed grassland data will regularly come available in the future and these will be used for updating the datasets of crop parameters in CGMS.

Summary

CGMS is used for regional monitoring of the growing conditions for the main crops over Europe, for issuing alarm warnings in the case of abnormal conditions, and for simulating growth and yields for arable crops with the WOFOST model and for grasslands with the LINGRA model. The calibration of these models for their use in CGMS is to be performed on the basis of different crop data sets.

The PASK study appears to be the best source of information on grassland resources over Europe. The use of this information for the calibration of the CGMS-LINGRA model has been evaluated. The main conclusions are:

- Yield data for grassland are scarce as shown by the information from the PASK study
- Grass yield data for small countries or for regions per country may be used for calibrations of LINGRA, if the spatial variation in environmental conditions is limited
- LINGRA model simulates the growth and yield of Lolium perenne L. (rye grass) grasslands under good growing conditions and optimal management
- Observed yield data for grasslands are often representative for suboptimal growing conditions and poor management and cannot be compared well with the yield data from LINGRA (see previous point)

An additional point is if the inter-annual yield variation as simulated by LINGRA for an optimally managed rye grass field on the basis of the variation in weather conditions between years, may represent the actual yield sensitivity to weather variation for the large range of grassland types and management practices over Europe.

The LINGRA model has been tested for three locations, i.e. Wageningen, Bologna and Sevilla, which strongly differ with respect to the length of the growing season and the incoming radiation level and hence, represent well the range of climate conditions over Europe. The model's behaviour has been analyzed for both potential and water limited conditions and besides, its sensitivity to changes in input variables has been analyzed. The main conclusions are:

- The modelling results for both potential and water-limited growing conditions at the three locations are plausible
- Sensitivity analyses have been performed for two input variables (i.e. initial number of tillers and initial amount of reserves available for grass re-growth) and gave plausible results

1 Introduction

The Crop Growth Monitoring System (CGMS), a module of the MARS Crop Yield Forecasting System of the European Commission, is applied for analysing the influence of weather conditions during the current year on crop growth and yields. CGMS is used for regional monitoring of the growing conditions for the main crops over Europe, for issuing alarm warnings in the case of abnormal conditions, and for simulating growth and yields with the simulation model CGMS-WOFOST for arable crops and CGMS-LINGRA for grassland crops.

For Lot I, Task 1 (Calibration of CGMS-WOFOST and CGMS-LINGRA) within the ASEMARS project, crop parameter sets are to be compiled for the main crop types in Europe. For each of the main crop types, the distribution of their main varieties over Europe should be established and crop parameter sets for CGMS-WOFOST and CGMS-LINGRA should be compiled for the whole range of agro-climatic conditions over Europe. CGMS includes the WOFOST model for annual crops and the LINGRA model for grasslands. The calibration of CGMS-WOFOST and CGMS-LINGRA is to be performed on the basis of the different crop data sets available from JRC (e.g. Boons-Prins (Boons-Prins et al., 1993), KUL (Willekens et al., 1998) and MOCA (GISAT, 2003) data bases for arable crops; PASK data bases for grasslands, see Section 2), CGMS datasets that already exist in the system, and the datasets to be collected in the ASEMARS project (see Lot II, task 3).

The existing CGMS parameter sets have been compiled largely during the years 1992-2000 and require an update on existing crops in order to increase their consistency and accuracy. For this update, the different crop data sets, as mentioned in the previous paragraph, are to be used. In addition, new crop types will be added and new varieties for existing crop types will be entered for new agro-climatic conditions in the new EU countries (i.e. EU25) due to the EU expansion. This requires definition of new crop types and varieties.

Table 1-1 gives an overview of the calibration update during the period 2005 to 2008 within the ASEMARS project with first, the current crop types and their parameter sets in CGMS-WOFOST and CGMS-LINGRA that have to be re-calibrated and second, the new crop types and their parameter sets that are to be newly inserted.

Table 1-1 Overview of the calibration update for CGMS in Lot I, Task 1. This update consists of: a) EU25 revision: crop data sets partly recalibrated; b) EU25 upgrade: new data sets derived for new crop varieties in the new EU countries due to the EU expansion, c) New crop: new data sets for new crop types and their varieties for whole EU25

Lot I Task 1.1	2005	2006	2007	2008
Type of data change in CGMS	**EU25 revision**	**EU25 upgrade (inc. 1 new crop)**	**New crop (inc. 1 upgrade)**	**New crop (inc. 1 upgrade)**
Calibrated model	**7 crops**	**5 crops**	**4 crops**	**3 crops**
WOFOST	Winter wheat	Durum wheat	Rye	Field peas
WOFOST	Spring Barley	Winter barley	Oats	Soybean (upgrade)
WOFOST	Winter rapeseed	Rice	Spring rapeseed	Tomato (other model?)
WOFOST	Grain maize		Field beans (upgrade)	
WOFOST	Sugar beet			
WOFOST	Potato			
WOFOST	Sunflower			
LINGRA		Rye grass		
LINGRA		Alfalfa (new crop)		

The update of the crop data sets in CGMS as listed in Table 1-1, consists for grassland and forage crops in year 2006 of:

- Update of current parameter set for rye grass
- New parameter set for alfalfa
- Expansion of parameter sets for grassland crops to new agro-climatic zones of EU25

The information on forage crops and grasslands that can be derived from the PASK study for LINGRA calibration is evaluated in Section 2. The Crop Growth Monitoring System (CGMS) is shortly described in Section 3. The LINGRA model is tested in Section 4, both analyzing its behaviour under strongly different climate conditions and its sensitivity to changes in input variables. Finally, Section 5 gives some general conclusions from this study. The LINGRA model as applied in this study, is incorporated in C code within CGMS, but is translated here into FST (FORTRAN Simulation Translator, see download information on this simulation language) to allow easy model testing. The listing of the LINGRA model (in FST) is given in Annex A.

2 Evaluation of the PASK study

2.1 Introduction

The PASK (Pasture Knowledge base) data base consists of the most recent pasture data for the EU and was released in 2003. The data are spatialised at grid cell level (50x50 km). The data base for pastures and the final report of the PASK study was prepared under the Contract No. 20101-2002-11 F1ED ISP IT and carried out by Progress Consulting S.r.l. (It). A CD-ROM is available at JRC with this final report.

The main information in the PASK study is given in the following, and also the main grassland classes as defined by Eurostat. Next, the possible use of the information from the PASK study for the calibration of CGMS-LINGRA is evaluated. Finally, grassland data that are needed for the calibration of CGMS-LINGRA are described.

2.2 Overview of grassland resources and forage production systems at European level

Eurostat defines four main classes:
(1) perennial green fodder (defined by predominance (>80%) of legumes and are seldom grazed; lucerne or clovers & mixtures); (2) temporary grasses and grazings (occupy soils from one to five years and are made up of graminaceous plants or of grasses mixed with legumes and other species but graminaceous are the majority; grasses are mainly harvested by mowing and grazings mainly by grazing); (3) permanent meadows (at least 5 years in grass; little grazing value and primarily used for conservation as hay); (4) permanent grazings (at least 5 years in grass; primarily used for grazing).

2.3 Information from PASK study

The PASK study gives for grass (forage) land in the 15 member states and 13 candidate/new member states the following information:

- Harmonization of national grassland definitions with Eurostat definitions (see Section 2.2) of grassland categories
- Description of main grassland types by country and their relationship with environmental conditions (landscape, altitude, flooding, etc.)
- Statistical analysis of grassland area, yield and production (note that information on production and yield levels is very limited and uncertain, being strongly dependent on management and environmental conditions)
- Agronomic practices on the main grassland types by country

The study gives also:

- Inventory, storage in GIS and mapping of different agronomic practices, crops and farming calendar (e.g. pastoral type, grazing regime, number of cuts, fertilizer application, grassland type)
- Description sheet per grass (forage) type (spatial distribution, description, ecology and physiology, phenology, pest and diseases)
- Inventory of existing agro-meteorological models for calculating biomass production from grasslands (consists of short model description and evaluation, required model inputs and produced model outputs)

The points listed above give only a short overview of the information in the PASK study that might be of use for the calibration and application of the LINGRA model. For more detailed information, see the executive summary and the main objectives of the PASK study.

2.4 PASK information for CGMS-LINGRA calibration

Calibration of the grass growth and yield calculations within CGMS requires observed grass growth and yield data for well-defined sites, environmental conditions and agronomic practices.

Available grass yield data and related data in the PASK study that might be of use for the CGMS-LINGRA calibration and application are:

- Area distribution over the different grassland types per country (from Eurostat); types are: temporary grasses, temporary grazings, permanent grassland, permanent meadow, and permanent grazings
- Arable land areas used for fodder crops per country (from Eurostat)
- Yield data for grassland type-altitude combinations: one site in Austria
- mean yield data for clover, lucerne and grass species for optimal and poor conditions in Estonia
- mean yield data for temporary grasses & grazing and permanent grassland for regions in France
- mean yield data for grassland in regions of Hungary
- mean yield data for pasture and rangeland types in Greece
- National yield data over a number of years for clovers and mixtures for Austria (from Eurostat)
- national yield data over a number of years for permanent meadows for Bulgaria, Czech republic, France, Germany, Italy, Luxemburg, Rumania, Slovakia and Slovenia (from Eurostat)
- National yield data over a number of years for permanent grazings for Czech Republic, France, Germany, Italy, Luxemburg and Rumania (from Eurostat)
- National yield data over a number of years for temporary grasses and grazings for Germany (from Eurostat)
- national yield data over a number of years for lucerne for Bulgaria, Czech republic, Denmark, France, Greece, Hungary, Italy, Poland, Rumania, Slovakia and Spain (from Eurostat)
- National yield data over a number of years for perennial green fodder for Latvia, Lithuania and Slovenia (from Eurostat)

2.5 Main problems in PASK information for CGMS-LINGRA calibration

- Observed yield data for grasslands are often representative for strongly suboptimal growing conditions (poor soils, limited fertilizer application, poor management, insufficient rainfall, sloping areas, etc.)
- Observed grass yield data are often given as fresh material with unknown moisture content
- LINGRA model simulates the growth and yield of Lolium perenne L. (rye grass) grasslands under optimal growing conditions. The simulation of grass morphological development accounts for regular defoliation due to cutting. This means that the LINGRA simulation describes the most optimal management and most productive grassland systems
- An important question is if the inter-annual yield variation as simulated by LINGRA for an optimally managed perennial rye grass field on the basis of the variation in weather conditions between years may represent the actual yield sensitivity to weather variation for the large range of grassland types and agronomic practices over Europe

2.6 Required yield data for calibration of LINGRA

A number of remarks can be made about the required yield data for calibration of the LINGRA model and the PASK data:

1) Grass yield data over at least 10 year are needed for the LINGRA calibration, to indicate both the mean yield level and the yield variation
2) Grass yield data for small countries (e.g. Netherlands, Luxemburg, Denmark etc.) or for regions per country (e.g. for France) may be used for calibrations of LINGRA, assuming that the spatial variation in environmental conditions is limited
3) No clear indication could be derived from the Eurostat yield data in the PASK study which type of grassland is more intensively managed and has a higher yield level and hence, corresponds best with the grassland yields as calculated with LINGRA
4) Amount of yield data for grassland is very limited (see yield data in PASK study as listed in Section 2.4), and hence, we propose to use the yield data for one of the three grassland classes with the longest data series over the years from (a) temporary grasses and grazings, (b) permanent meadows, or (c) permanent grazings
5) The inter-annual yield variation in observed yield data can be used for comparison with that for simulated yields, but first, the mean observed yield level may often be strongly different from the mean simulated yield level due to strong differences in management practices (e.g. fertilizer application, grassland management, grazing regime, number of cuts per year, etc.) and second, see the last point (i.e. question) of Section 2.5.

2.7 Grassland data from Eurostat

Some data on grassland production can be derived from Eurostat.
See Eurostat data for agriculture in AgrIS table:
http://epp.eurostat.cec.eu.int/portal/page?_pageid=0,1136206,0_45570467&_dad=portal&_schema=PORTAL
It is not yet clear if these Eurostat data on grassland yields are also available at the regional scale. The grassland yield data from Eurostat at the national scale can generally not be used for the LINGRA calibrations, as the spatial variation in environmental conditions over most countries is too large.

3 Crop Growth Monitoring System (CGMS)

The MARS Crop Yield Forecasting System (MCYFS) of the European Commission (EC) was developed as part of the MARS activities to supply DG-AGRI (Directorate General Agriculture) of the EC and EUROSTAT with early information on crop development, growing conditions and expected yields of the main crops in Europe. MARS stands for Monitoring Agriculture with Remote Sensing. The MCYFS consists of several independent modules:

a) maintenance of meteorological data bases and weather monitoring;
b) application of a regional crop growth model and crop growth monitoring system (**CGMS**);
c) processing of low-resolution satellite data;
d) analyses of yield statistics;
e) quantitative yield forecasts for the main crops over the European Union.

For more detailed information on MCYFS, see Boogaard et al., 2002.

The Crop Growth Monitoring System (CGMS) of MCYFS analyses the influence of weather conditions during the current year on crop growth and yields. This approach assumes implicitly that the influence of all factors other than weather (e.g. farm management, socio-economic conditions) are constant, which is of course not true. Hence, the final synthesis of MCYFS includes also other sources such as information derived from remote sensing images. These images show the integrated effect of e.g. weather, soil moisture, and management on crop growth and yields, however, the individual factors cannot be separated (Boogaard et al., 2002).

The CGMS module consists of 1) collection and processing of input data; 2) spatial schematisation; 3) regional crop simulation; 4) spatial aggregation; 5) production of weather and crop indicator maps. CGMS is applied for regional monitoring of the growing conditions for the main crops over Europe, for issuing alarm warnings in the case of abnormal conditions, and for simulating growth and yields with the crop growth simulation model WOFOST for arable crops and with the LINGRA model for grassland crops. These simulated values for growth and yields are used as inputs for the Quantitative Yield Forecasting module. The different parts of the CGMS module are described shortly in the following. For more detailed information, see Boogaard et al. (2002)

Collection and processing of input data

Interpolated daily weather data for each grid unit over Europe are combined with crop and soil data, to do grid-specific crop growth simulations with the WOFOST and the LINGRA models within CGMS. In the present study, the main focus is on the crop data. For the main crop species in Europe, the characteristics are specified in crop-specific data sets of crop variables. For example, the sensitivity of photosynthesis to temperature or the temperature sum required for phenological development from emergence to flowering are specified for each crop species. Part of the crop characteristics may differ, when going from northern Europe to southern

Europe. Hence, for each crop species, different crop varieties are specified in CGMS for the different climate zones over Europe.

Spatial schematisation
To do growth simulations and yield forecasting for large regions, spatial units that are homogeneous with respect to meteorological data and soil characteristics, should be identified. Growth simulations are done for the main crop varieties in each of these unique spatial units.

Regional crop simulation
The growth simulations are done with the WOFOST model for arable crops (Boogaard et al., 1998) and with the LINGRA model for grassland crops (Schapendonk et al., 1998; Rodriguez et al., 1999). Growth simulations are done for two production situations, i.e. the potential and the water-limited production situation. The water-limited production situation applies to rainfed growing conditions with optimal nutrient supply, crop protection and management. The water-limited yield level is assumed to be limited only by the crop's growing potential under the site-specific light and temperature conditions and by the degree of drought stress during the growth period. The potential yield is often even higher than the water-limited yield, assuming the same optimal growing conditions but in addition, no risk for moisture stress due to sufficient irrigation. The LINGRA and WOFOST models use the same routines for calculating water use, soil water flow and changes, and growth reduction by drought.

Spatial aggregation
For each 10-day period, crop indicators (e.g. crop variable, yield level) simulated for each of the unique spatial units, are spatially aggregated to the climatic grid cells for the production of crop indicator maps and to the administrative (i.e. NUTS) units for the regional yield forecasting.

Production of crop indicator maps
Crop indicator maps as produced by CGMS, may, for example, give the difference between the yield of the current year and the long-term average yield, or the possibly unfavourable growing conditions during sensitive growth phases for a crop type in the current season.

In the present study, the LINGRA model as incorporated in CGMS has been tested (see Section 4) for potential and water limited growth conditions at three locations over Europe. These locations have strongly different climate conditions. Hence, the modelling results show if the application of CGMS-LINGRA over the whole of Europe may be expected to be successful.

4 Results of testing the LINGRA model as implemented in CGMS

4.1 Introduction

The CGMS-LINGRA model simulates the growth and yields of Lolium perenne L. (rye grass) grasslands. Described processes are light utilization, leaf formation, leaf elongation, tillering and carbon partitioning to leaves and roots (Schapendonk et al., 1998). CGMS-LINGRA has been tested in this study for both potential and water-limited growing conditions at three locations over Europe. These locations have strongly different climate conditions. The applied model is listed completely in Annex A. For more background information about the CGMS-LINGRA model, see the journal articles by Schapendonk et al. (1998) and Rodriguez et al. (1999).

A number of important input data and parameters used for the following runs are: initial tiller density (TILLERI) = 7000 per m^2, initial reserves (WRESI) = 200 kg dry matter ha^{-1}, radiation use efficiency = 3.0 g dry biomass (MJ PAR)$^{-1}$, extinction coefficient for diffuse light (KDIF)= 0.60. Leaves die at a rate in dependence of the degree of self-shading and drought stress above the base death rate of 1% of leaf total per day. These data are identical to those used by the LINGRA version in the CGMS system. Note that the source-limited growth rate (which is determined by the rate of CO_2 assimilation) is not negatively affected by high temperatures at present and that the relative death rate of leaves is also not affected by high temperatures.

Harvest of grass was done at Julian days 135, 165, 200, 240, 280 and 330 and only in case the dry weight of green leaves was at least 1800 kg ha^{-1} at these days. This was different from the harvest days in the CGMS data base which were 13 in total, appearing rather unrealistic.

4.2 Results for potential growing conditions at three locations

The simulation runs of rye grass growth with LINGRA were done for optimal water supply, optimal nutrient supply, and the actual atmospheric CO_2 concentration, and with the model parameterisation described in Section 4.1. The simulations cover a whole year (from day 1 to day 365) and have been done for five years at three locations over Europe (Wageningen, Netherlands; Bologna, Italy; and Sevilla, Spain). The results are given in Table 4-1.

Table 4-1 Results from the CGMS-LINGRA modelling of rye grass growth over a whole year at three locations in Europe with ***optimal supply of nutrients and water*** (with LINGRA version as implemented in CGMS and with input data and parameters from the CGMS data file, see text)

Location, Year	**YIELD**[1] (kg DM ha^{-1})	**GRASS**[1] (kg DM ha^{-1})	**WLVD**[1] (kg DM ha^{-1})	**WRES**[1] (kg DM ha^{-1})	**WRT**[1] (kg DM ha^{-1})	**TOTAL**[1] (kg DM ha^{-1})	**TILLER**[1] (m^{-2})
Wageningen, 1986	14881	14845	8893	0	4757	28531	14005

Idem, 1987	14570	14570	8300	0	4572	27442	14207
Idem, 1988	15239	15224	10093	0	5065	30397	14023
Idem, 1989	16446	16438	13348	11	5947	35752	14178
Idem, 1990	16605	16605	14240	0	6144	36989	13991
Sevilla, 1986	18902	17199	23735	10493	8485	61615	6752
Idem, 1987	18830	16750	24134	9312	8549	60825	5993
Idem, 1988	19202	17252	23898	9717	8576	61393	7153
Idem, 1989	18438	16767	23859	12491	8417	63205	6686
Idem, 1990	18881	17033	23893	11677	8512	62963	7361
Bologna, 1982	18594	18158	15068	27	6711	40400	14053
Idem, 1983	18476	17934	18664	0	7398	44538	6554
Idem, 1984	18008	17884	14586	42	6500	39136	13956
Idem, 1985	18241	18049	17673	0	7156	43070	7588
Idem, 1986	17697	17432	14598	0	6441	38736	13914

[1)] YIELD= total harvested grass and total harvestable grass on field at day 365; GRASS= = total harvested grass at day 365; WLVD= dead leaf mass at day 365; WRES= reserves available for grass growth at day 365; WRT= root mass at day 365; TOTAL= sum of YIELD, WLVD, WRES and WRT at day 365; Tiller= tiller density at day 365

The grass yields and in particular the total biomass production (YIELD and TOTAL in Table 4-1) appear to increase from Wageningen to Bologna to Sevilla. This is caused by the length of the growing season and the amount of intercepted radiation over the year which increases for the three locations from 1200-1600 MJ PAR m^{-2} to 1700-2000 MJ PAR m^{-2} to 2700-2800 MJ PAR m^{-2}, respectively.

The increase in intercepted radiation (RADI) from Wageningen to Bologna gives a higher total biomass production (TOTAL) which does not result in more reserves (WRES), indicating that sink-limitation is not yet limiting growth. However, the increase in RADI results in a higher grass yield (YIELD) and in a much higher dead leaf mass (WLVD). WLVD is much higher because the higher biomass production results on average in a higher LAI and thus in more leaf senescence due to self-shading.

The increase in RADI from Bologna to Sevilla gives again a much higher total biomass production (TOTAL) which results in much more reserves (WRES), indicating a clear sink limitation for growth. The sink limitation is caused by first, the lower tiller density (Table 4-1) than at the other locations which is due to the relatively high temperatures over the year and second, the high source-limited growth rates due to the high radiation levels at Sevilla. WLVD is even higher than at Bologna, because the higher biomass production results on average in an even higher LAI and thus in more leaf senescence due to self-shading.

For Wageningen, an increase in radiation use efficiency (from 3 to 4 and 5 g dry biomass (MJ PAR)$^{-1}$) appears to have practically the same effects on YIELD, WLVD, WRES and TOTAL, as described above for a shift to locations (Bologna and Sevilla) with a higher level of incoming radiation. This is a logical outcome as the source-limited growth of grass is calculated as intercepted radiation times radiation use efficiency. These results are not given here.

4.3 Results for water-limited growing conditions at three locations

The same calculations for rye grass growth with CGMS-LINGRA as given in Table 4-1, have been repeated for a situation with water stress. The reduction factor for both the growth rate and the transpiration rate (TRANRF) which is equal to the ratio between the actual and the maximal transpiration rate and depends mainly on the soil moisture content, is set to 0.5 for the whole year and is made independent of the actual water availability. The simulations cover a whole year and have been done again for five years at three locations over Europe (Wageningen, Netherlands; Bologna, Italy; and Sevilla, Spain). The results are given in Table 4-2.

Table 4-2 Results from the CGMS-LINGRA modelling of rye grass growth over a whole year at three locations in Europe with ***optimal supply of nutrients and continuous drought stress*** (with LINGRA version as implemented in CGMS and with input data and parameters from the CGMS data file; drought stress by setting TRANRF continuously at 0.5, see text)

Location, Year	**YIELD**[1] (kg DM ha^{-1})	**GRASS**[1] (kg DM ha^{-1})	**WLVD**[1] (kg DM ha^{-1})	**WRES**[1] (kg DM ha^{-1})	**WRT**[1] (kg DM ha^{-1})	**TOTAL**[1] (kg DM ha^{-1})	**TILLER**[1] (m^{-2})
Wageningen, 1986	2515	2515	3915	0	1767	8197	13997
Idem, 1987	2341	2341	3760	0	1673	7774	14106
Idem, 1988	2529	2529	4246	0	1861	8636	14446
Idem, 1989	3500	3500	4913	2	2310	10725	14049
Idem, 1990	3781	3781	5465	0	2533	11779	14010
Sevilla, 1986	7711	7408	10492	0	5036	23239	14148
Idem, 1987	7551	7380	10432	0	4976	22959	14219
Idem, 1988	7689	7518	10536	0	5042	23267	14063
Idem, 1989	7787	7484	11424	0	5311	24522	14058
Idem, 1990	7802	7568	11244	0	5266	24312	14262
Bologna, 1982	4291	4291	5452	5	2699	12447	14038
Idem, 1983	5128	5128	6126	0	3094	14348	14106
Idem, 1984	4259	4259	5526	9	2695	12489	13977
Idem, 1985	5391	5391	6334	0	3220	14945	13979
Idem, 1986	4179	4179	5514	0	2677	12370	13921

[1)] YIELD= total harvested grass and total harvestable grass on field at day 365; GRASS= = total harvested grass at day 365; WLVD= dead leaf mass at day 365; WRES= reserves available for grass growth at day 365; WRT= root mass at day 365; TOTAL= sum of YIELD, WLVD, WRES and WRT at day 365; Tiller= tiller density at day 365

The grass yields and in particular the total biomass production (YIELD and TOTAL in Table 4-2) also increase under continuous drought stress from Wageningen to Bologna to Sevilla. This is caused by the length of the growing season and the amount of intercepted radiation over the year which increase in the same order. However, the total biomass production (TOTAL in Table 4-2) under drought stress is roughly 30 to 35% of that under optimal water supply at the three locations (Table 4-1). This is caused by the 50% lower growth rate (i.e. TRANRF= 0.50) at similar conditions and the reduced light interception due to the slower leaf re-growth after cutting. The grass yields under continuous drought stress are roughly 20%, 26% and

40% (Table 4-2) of those under optimal water supply at respectively Wageningen, Bologna and Sevilla. At Wageningen the drought stress in combination with the relatively low light conditions results in the slowest re-growth after cutting and hence, the strongest yield reduction by the continuous drought stress. The reserves (WRES) remain nil at the three locations, as the source-limited growth rate under continuous drought stress is low and is clearly lower than the sink-limited growth rate. The dead leaf mass (WLVD) is relatively high as the modelled senescence of leaves increases with increasing drought stress.

4.4 Sensitivity analyses

Sensitivity analyses for the rye grass growth modelling with LINGRA have been performed for input variables, for which the values could not easily be derived. These analyses show to what extent the modelling results (Table 4-3) vary, if different values for the input variables are entered. Analyses have been done for both Wageningen, the Netherlands and Bologna, Italy and for different initial values for number of tillers (TILLERI) and for reserves available for grass re-growth (WRESI). The initial values as used in CGMS and used for the modelling results in Tables 4-1 and 4-2 were 7000 per m^2 for TILLERI and 200 kg DM per ha for WRESI.

Table 4-3 Results from the LINGRA modelling of rye grass growth over a whole year at two locations in Europe with optimal supply of nutrients and water and with ***different initial values*** for number of tillers (TILLERI, m^{-2}) and for reserves available for grass growth (WRESI, kg DM ha^{-1}) (with LINGRA version as implemented in CGMS)

Location, Year, TILLERI, WRESI	**YIELD**[1] (kg DM ha^{-1})	**GRASS**[1] (kg DM ha^{-1})	**WLVD**[1] (kg DM ha^{-1}	**WRES**[1] (kg DM ha	**WRT**[1] (kg DM ha^{-1})	**TOTAL**[1] (kg DM ha^{-1})	**TILLER**[1] (m^{-2})
Wageningen,1986, 3000, 100	13794	13758	10013	0	4764	28571	13983
Wageningen,1986, 3000, 600	14157	14121	11236	0	5077	30470	13997
Wageningen,1986, 12000, 100	14639	14603	8600	0	4652	27891	13976
Wageningen,1986, 12000, 600	15292	15256	9409	0	4940	29641	13984
Bologna, 1982, 3000, 100	17837	16561	14586	1356	6466	40245	9166
Bologna, 1982, 3000, 600	17457	16181	14398	3421	6354	41630	9163
Bologna, 1982, 12000, 100	18565	18129	14176	27	6529	39297	13957
Bologna, 1982, 12000, 600	18701	18266	15457	27	6809	40994	14062

[1)] YIELD= total harvested grass and total harvestable grass on field at day 365; GRASS= = total harvested grass at day 365; WLVD= dead leaf mass at day 365; WRES= reserves available for grass growth at day 365; WRT= root mass at day 365; TOTAL= sum of YIELD, WLVD, WRES and WRT at day 365; Tiller= tiller density at day 365

For Wageningen, a higher initial value for the number of tillers (TILLERI) results in a higher grass yield (Table 4-3). This can be explained from the larger sink-limited growth in spring due to the larger number of tillers in spring which results in larger grass cuts and a higher grass yield. An increase in the initial amount of reserves (WRESI) results also in a larger (source-limited) growth in spring which again results in larger grass cuts and a higher grass yield. Growth in spring appears to be alternatively source- and sink-limited.

For Bologna, a higher initial value for the number of tillers (TILLERI) results in a higher grass yield (Table 4-3). This can be explained in the same way as for Wageningen. At a low value for TILLERI a clear sink-limitation does occur, as shown by the high reserves (WRES) at day 365. An increase in the initial amount of reserves (WRESI) does not result in a larger growth in spring and a higher grass yield, even with a high value for TILLERI. The reason is that the initial growth in spring is strongly sink-limited and cannot be increased by additional reserves in spring.

5 Conclusions

The main conclusions from the required yield data for CGMS-LINGRA calibration and the PASK information are:

- Yield data for grassland are scarce as shown by the information from the PASK study
- Grass yield data for small countries (e.g. Netherlands, Luxemburg, Denmark etc.) or for regions per country (e.g. for France) may be used for calibrations of CGMS-LINGRA, if the spatial variation in environmental conditions is limited
- Observed grass yields over at least 10 year are needed to derive (for the CGMS-LINGRA calibration) both the mean yield level and the yield variation for a location
- CGMS-LINGRA model simulates the growth and yield of Lolium perenne L. (rye grass) grasslands under good growing conditions and optimal management
- Observed yield data for grasslands are often representative for suboptimal growing conditions (e.g. poor soils) and poor management (e.g. low fertilizer application, irregular cutting) and cannot be compared well with the yield data from CGMS-LINGRA (see previous point)

An additional point is if the inter-annual yield variation as simulated by CGMS-LINGRA for an optimally managed rye grass field on the basis of the variation in weather conditions between years, may represent the actual yield sensitivity to weather variation for the large range of grassland types and management practices over Europe.

The main conclusions from the testing of the CGMS-LINGRA model are:

- The three locations for which the testing of CGMS-LINGRA has been done, i.e. Wageningen, Bologna and Sevilla, strongly differ with respect to the length of the growing season and the incoming radiation level and hence, represent well the range of climate conditions over Europe
- The modelling results for both the potential and the water-limited growing conditions at the three locations are plausible
- The modelling results could not be compared with observed grassland data and hence, do not allow conclusions on model calibration and validation
- Sensitivity analyses with CGMS-LINGRA have been performed for two input variables (i.e. initial number of tillers and initial amount of reserves available for grass re-growth)and gave plausible results (i.e. location-specific pattern in source- and sink-limitation for grass growth in spring)

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Annex A - Listing of the LINGRA model in CGMS as written in FST for testing

There are two differences in this version compared to the CGMS version in LINGRA, as described below.

```
DEFINE_CALL MOWING(INPUT,INPUT,INPUT_ARRAY, ...
      INTEGER_INPUT,INPUT,INPUT,INPUT, ...
       INPUT,INPUT,OUTPUT,OUTPUT)
DEFINE_CALL TILSUB(INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT, ...
        OUTPUT)
DEFINE_CALL SOSUB(INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT, ...
        OUTPUT,OUTPUT)
DEFINE_CALL PENMAN(INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,   OUTPUT,OUTPUT)
DEFINE_CALL EVAPTR(INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT, ...
                   INPUT,INPUT,                          OUTPUT,OUTPUT)
DEFINE_CALL DRUNIR(INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT, ...
                   INPUT,INPUT,INPUT,              OUTPUT,OUTPUT,OUTPUT)

ARRAY MNDAT (1:NH)
ARRAY_SIZE NH=10

TITLE LINGRA-new-JRC

* Version adapted for rye grass April 4, 2006, Joost Wolf for
* FST modelling;
* Model is based on LINGRA model in CGMS
* for grassland growth and yield simulation which was written in FORTRAN
* (GRSIM.pfo) and later in C; Application of the model is the
* simulation of perennial ryegrass (Lolium perenne L.) growth under both
* potential and water-limited growing conditions.
*
* Model is different from LINGRA model in CGMS with respect to:
*  1) evaporation, transpiration, water balance, root depth growth
*  and growth reduction by drought stress (TRANRF) are derived from LINGRA
*  model for thimothee (e.g. subroutine PENMAN, EVAPTR and DRUNIR)
*  2) running average to calculate soil temperature (SOITMP) is derived from
*  approach in LINGRA model for thimothee (i.e. each day one tenth of the difference
* between soil temperature and daily mean temperature is added to soil temperature)
*
* Variables:
*     Biomass in leaves, reserves, etc. in kg DM / ha
*     Terms of water balance in mm/day
*
************************************************************************
***   1. Initial conditions and run control
************************************************************************

INITIAL

INCON ZERO   = 0.
INCON ROOTDI = 0.4
INCON LAII   = 0.1; SOITMI = 5.; TILLI = 7000.; ...
      WREI  = 200. ; WRTI   =  4.
      WAI    = 1000. * ROOTDI * WCI
*     Initial leaf weight is initialized as initial
*     leaf area divided by initial specific leaf area, kg ha-1
       WLVGI   = LAII / SLA
*
```

```
*     Remaining leaf weight after cutting is initialized at remaining
*     leaf area after cutting divided by initial specific leaf area, kg ha-1
      CWLVG = CLAI/SLA
*      Maximum site filling new buds (FSMAX) decreases due
*      to low nitrogen contents, Van Loo and Schapendonk (1992)
*      Theoretical maximum tillering size = 0.693
       FSMAX = NITR/NITMAX*0.693


TIMER STTIME = 1.; FINTIM = 365.; DELT = 1.; PRDEL = 1.; IPFORM = 5
TRANSLATION_GENERAL DRIVER='EUDRIV'
PRINT YEAR, DAVTMP, DTR, DAYL, LAI, TILLER, YIELD, ...
      WLVG, WLVD1, WRE, WRT, WRTMIN, ...
      RRATIO, SLA, PARCU, LUEYCU, RUNNR,GRASS, TADRW, YIELD,NEWBIO,...
      TRANRF, TRAN, PTRAN, EVAP, PEVAP, WC, WA, RAIN, RAINCU, VP, WN,...
      TRAMCU, TRACU, EVAMCU, EVACU, IRRCU

DYNAMIC

************************************************************************
***   2. Environmental data
************************************************************************

WEATHER CNTR='NL'; ISTN=1; WTRDIR='D:\Wolf\Asemars\LINGRA\...
          test-LINGRA-versions\'; IYEAR=1986
        DAVTMP = 0.5 * (TMMN + TMMX)
        PHOTMP= (TMMN + 3. * TMMX)/4.
        PI     = 3.1416
        RAD    = PI / 180.
        DEC    = -ASIN (SIN (23.45*RAD)*COS (2.*PI*(DOY+10.)/365.))
        DECC   = LIMIT( ATAN(-1./TAN(RAD*LAT)), ...
                        ATAN( 1./TAN(RAD*LAT)), DEC)
        DAYL   = 0.5 * ( 1. + 2. * ASIN(TAN(RAD*LAT)*TAN(DECC)) / PI )
*     From J/ha/d to MJ/ha/d
        DTR    = RDD / 1.E+6
        PARAV  = 0.5 * DTR / DAYL
*       soil temperature changes
        RSOITM = (DAVTMP-SOITMP) / 10.
        SOITMP = INTGRL( SOITMI, RSOITM )

        EFFTMP = MAX ( DAVTMP, TBASE )

************************************************************************
***   3. State variables
************************************************************************
*      Cumulative intercepted PAR, MJ PAR intercepted m-2
         PARCU = INTGRL (ZERO, PARINT)

*        Cumulative transpiration, mm
         TRACU = INTGRL (ZERO, TRAN)
*
*        Cumulative maximal transpiration, mm
         TRAMCU = INTGRL (ZERO, PTRAN)

*       Cumulative evaporation, mm
         EVACU = INTGRL (ZERO, EVAP)
*
*        Cumulative maximal evaporation, mm
         EVAMCU = INTGRL (ZERO, PEVAP)
*
*       Cumulative irrigation, mm
         IRRCU = INTGRL (ZERO, IRRIG)

*        Sum of temperatures above base temperature, gr. C.d
         TSUM = INTGRL (ZERO, TMEFF)
```

```
*
*        Hypothetical development stage, 600 gr. C.d taken from
*        subroutine TILSUB
         DVS = TSUM / 600.
*
*        Leaf area index, ha ha-1
         LAI = INTGRL (LAII, RLAI)
*
*        Days after HARV, d
         DAHA = INTGRL (ZERO, RDAHA)
*
*        Number of tillers, tillers m-2
         TILLER = INTGRL (TILLI, DTIL)
*
*        Dry weight of green leaves, kg ha-1
         WLVG = INTGRL (WLVGI, RLV)
*
*        Dry weight of dead leaves, kg ha-1 incl. harvests
         WLVD = INTGRL (ZERO, DLV)
*        Dry weight of dead leaves, kg ha-1
         WLVD1= WLVD - GRASS

*        Harvestable leaf weight
         HRVBL=WLVG-CWLVG

*        Dry weight of cutted green leaves, kg ha-1
         GRASS = INTGRL (ZERO, HARV)
*
*        Dry weight of storage carbohydrates, kg ha-1
         WRE = INTGRL (WREI, RRE)
*
*        Dry weight of roots, kg ha-1
         WRT = INTGRL (WRTI, GRT)
*
*        Total above ground dry weight including harvests, kg ha-1
         TADRW = GRASS + WLVG
*
*        Harvestable part of total above ground dry weight
*        and previous harvests, kg ha-1
         YIELD = GRASS + MAX (0., HRVBL)
*
*        Length of leaves, cm
         LENGTH = INTGRL (ZERO, LERA2)
*
*        Running specific leaf area in model, ha kg-1
         SLAINT = LAI / NOTNUL(WLVG)

*        Rooting depth (from LINGRA for timothee)
         ROOTD= INTGRL(ROOTDI, RROOTD)

*        Soil water in rooted zone  (from LINGRA for timothee)
         WA     = INTGRL( WAI,RWA )

*        Cumulative rainfall
         RAINCU = INTGRL( ZERO, RAIN )
*************************************************************************
***   4. Rate variables
*************************************************************************
         REDTMP = AFGEN(LUERD1,SOITMP)

         REDRDD = AFGEN (LUERD2,RDD/1.E6)
*
         TMEFF =  MAX (DAVTMP-TMBAS1, 0.)
*
```

```
*        Daily photosynthetically active radiation, MJ m-2 d-1
         PAR = RDD/1.0E6 * 0.50
*
*        Fraction of light interception
         FINT = (1.-EXP (-KDIF*LAI))
*
*        Light use efficiency, g MJ PAR-1
         LUE1 = LUEMAX * REDTMP * REDRDD
*
*        Total intercepted photosynthetically active
*        radiation, MJ m-2 d-1
         PARINT = FINT * PAR
*
*        Fraction of dry matter allocated to roots, kg kg-1
         FRT = AFGEN (FRRTTB, TRANRF)
         FLV = 1.-FRT

*        Call to subroutine for grassland management options
         CALL MOWING (IMOPT,INCUT,MNDAT,NH,TIME,WLVG, ...
         CWGHT,CWLVG,DAHA,RDAHA,HARV)
*
*        Temperature dependent leaf appearance rate, according to
*        (Davies and Thomas, 1983), soil temperature (SOITMP)is used as
*        driving force which is estimated from a 10 day running
*        average
         LEAFN=   FCNSW(REDTMP, 0., 0.,SOITMP * 0.01 )
*
*        Leaf elongation rate affected by temperature
*        cm day-1 tiller-1
         LERA= FCNSW(DAVTMP-TMBAS1, 0., 0.,...
          0.83*LOG(MAX(DAVTMP, 2.))-0.8924 )
*
         LERA2 = INSW (HARV-0.1, LERA, -LENGTH)

         CALL TILSUB (TILLER,FSMAX,LAI,LAICR,DAHA,LEAFN,TSUM,REDTMP, ...
                      DTIL)

*        Rate of sink limited leaf growth, unit of TILLER is tillers m-2 (!),
*        1.0E-8 is conversion from cm-2 to ha-1, ha leaf ha ground-1 d-1
         DLAIS = (TILLER * 1.0E4 * (LERA * 0.3)) * 1.0E-8

*        Source limited growth rate of crop, kg ha-1 d-1
         CALL SOSUB (PARINT,LUE1,CO2A,NITR,NITMAX,TRANRF, ...
                    HARV,LUE2,GTWSO1)
*
         GTWSO2 = GTWSO1+WRE/DELT
         DRE   = WRE/DELT
*
*        Conversion to total sink limited carbon demand,
*        kg leaf ha ground-1 d-1
         GTWSI= FCNSW(HARV,DLAIS * (1./SLA) * (1./FLV),...
            DLAIS * (1./SLA) * (1./FLV), 0.)
*
*        Actual growth switches between sink- and source limitation
*        (more or less dry matter formed than can be stored)
         GRE= FCNSW(GTWSO2-GTWSI,0.,0., GTWSO2-GTWSI)
         GTW= FCNSW(GTWSO2-GTWSI,GTWSO2,GTWSO2, GTWSI)

*        Change in reserves
         RRE = GRE-DRE

*        Relative death rate of leaves due to self-shading, d-1
         RDRSH = LIMIT (0., 0.03, 0.03 * (LAI-LAICR) /LAICR)
*
*        Relative death rate of leaves due to drought stress, d-1
```

```
         RDRSM = LIMIT(0., 0.05, 0.05 * (1.-TRANRF))
*
*        Maximum of relative death rate of leaves due to self-shading
*        and drought stress, d-1
         RDRS = MAX (RDRSH, RDRSM)
*
*        Actual relative death rate of leaves is sum of base death
*        rate plus maximum of death rates RDRSM and RDRSH, d-1
         RDR = RDRD + RDRS
*
*        Actual growth rate of roots, kg ha-1 d-1
         GRT = GTW * FRT

*        Actual growth rate of leaf area, ha ha-1 d-1
         GLAI = GTW * FLV * SLA
*
*        Actual death rate of leaf area, due to relative death
*        rate of leaf area or rate of change due to cutting, ha ha-1 d-1
         DLAI= FCNSW(HARV, LAI * (1. - EXP(-RDR * DELT)), ...
          LAI * (1. - EXP(-RDR * DELT)),HARV*SLAINT )

*        Change in LAI
         RLAI= GLAI-DLAI

*        Actual death rate of leaves, kg ha-1 d-1 incl. harvested leaves
         DLV = DLAI / NOTNUL (SLAINT)
*
*        rate of change of dry weight of green leaves due to
*        growth and senescence of leaves or periodical harvest, kg ha-1 d-1
         GLV= FCNSW(HARV,GTW*FLV,GTW*FLV, 0.)

*        Change in green leaf weight
         RLV = GLV-DLV
************************************************************************
***   5. Water balance and root depth growth (from LINGRA for thymothee)
************************************************************************

      CALL PENMAN( DAVTMP,VP,DTR,LAI,WN,RNINTC, ...
                   PEVAP,PTRAN )
      CALL EVAPTR( PEVAP,PTRAN,ROOTD,WA,WCAD,WCWP,WCFC,WCWET,WCST,...
                   DELT,EVAP,TRAN )
      CALL DRUNIR( RAIN,RNINTC,EVAP,TRAN,IRRIGF,...
                   DRATE,DELT,WA,ROOTD,WCFC,WCST,...
                   DRAIN,RUNOFF,IRRIG )

      RROOTD = RRDMAX * REAAND( ROOTDM-ROOTD, WC-WCWP )
      EXPLOR = 1000. * RROOTD * WCFC
      RNINTC = MIN( RAIN, 0.25*LAI )
      TRANRF = INSW( -PTRAN, TRAN / NOTNUL(PTRAN), 1. )
      RWA    = (RAIN+EXPLOR+IRRIG) - (RNINTC+RUNOFF+TRAN+EVAP+DRAIN)
      WC     = 0.001 * WA / ROOTD

************************************************************************
***   9. Additional variables and parameters for output
************************************************************************

      NEWBIO = WLVG+WRT+WRE - (WLVGI+WRTI+WREI)  + GRASS
      RRATIO = LIMIT  ( 0., 1., (WRT-WRTI) / NOTNUL(NEWBIO) )

      LUEYCU = YIELD  / NOTNUL(PARCU)

      WRTMIN = -WRT


PARAM RUN    = 0.
```

```
      RUNNR  = RUN

************************************************************************
***   10. Functions and parameters for grass
************************************************************************

* Parameters
PARAM CO2A   = 360. ; KDIF  = 0.60 ; LAICR  = 4. ; TBASE  = 0.
PARAM LUEMAX= 3.0      ; IMOPT= 2. ; INCUT= 0.
PARAM SLA= 0.0025 ; CLAI= 0.8 ; NITMAX= 3.34 ; NITR= 3.34 ; RDRD= 0.01
PARAM TMBAS1= 3. ; CWGHT= 1800.

* Parameters for water relations from LINGRA for thimothee
PARAM DRATE  = 50.   ; IRRIGF = 1.   ; ROOTDM = 0.4   ; RRDMAX = 0.012
PARAM WCAD   = 0.005; WCWP   = 0.12  ; WCFC   = 0.29
PARAM WCI    =  0.29 ; WCWET  = 0.37 ; WCST   = 0.41



* Harvest dates
PARAM MNDAT(1)= 135.; MNDAT(2)=165. ; MNDAT(3)= 200.;  ...
      MNDAT(4)= 240.; MNDAT(5)= 280.; MNDAT(6)= 330.; MNDAT(7:NH)=999.

************************************************************************
***   11. Data
************************************************************************


FUNCTION LUERD1 = -20.,    0.,  3.,  0.,  8.,  1., 40.,   1.
FUNCTION LUERD2 = 0.,  1.,  10.,  1.,  40.,  0.33
FUNCTION FRRTTB = -10., 0.263, 0., 0.263, 1., 0.165

**************************** RERUNS ************************************

* reruns for other years (5 year in total) for Wageningen, Netherlands
* and next for Sevilla, Spain (5 year in total) and next for
* Bologna, Italy (5 year in total)
END
PARAM RUN = 1.
WEATHER  IYEAR= 1987
END
PARAM RUN = 2.
WEATHER  IYEAR= 1988
END
PARAM RUN = 3.
WEATHER  IYEAR= 1989
END
PARAM RUN = 4.
WEATHER  IYEAR= 1990
END
PARAM RUN = 5.
WEATHER CNTR = 'SEVI';  IYEAR= 1986
END
PARAM RUN = 6.
WEATHER  IYEAR= 1987
END
PARAM RUN = 7.
WEATHER  IYEAR= 1988
END
PARAM RUN = 8.
WEATHER  IYEAR= 1989
END
PARAM RUN = 9.
WEATHER  IYEAR= 1990
END
```

```
PARAM RUN = 10.
WEATHER CNTR = 'BOLO';  IYEAR= 1982
END
PARAM RUN = 11.
WEATHER  IYEAR= 1983
END
PARAM RUN = 12.
WEATHER  IYEAR= 1984
END
PARAM RUN = 13.
WEATHER  IYEAR= 1985
END
PARAM RUN = 14.
WEATHER  IYEAR= 1986
END
STOP

************************* SUBROUTINES ********************************

* --------------------------------------------------------------------*
*     SUBROUTINE PENMAN                                               *
*     Purpose: Computation of the PENMAN EQUATION                     *
* --------------------------------------------------------------------*
      SUBROUTINE PENMAN(DAVTMP,VP,DTR,LAI,WN,RNINTC,
     $                  PEVAP,PTRAN)
      IMPLICIT REAL (A-Z)

      DTRJM2 = DTR * 1.E6
      BOLTZM = 5.668E-8
      LHVAP  = 2.4E6
      PSYCH  = 0.067

      BBRAD  = BOLTZM * (DAVTMP+273.)**4 * 86400.
      SVP    = 0.611 * EXP(17.4 * DAVTMP / (DAVTMP + 239.))
      VP     = MIN(VP, SVP)
      SLOPE  = 4158.6 * SVP / (DAVTMP + 239.)**2
      RLWN   = BBRAD * MAX(0.,0.55*(1.-VP/SVP))
      NRADS  = DTRJM2 * (1.-0.15) - RLWN
      NRADC  = DTRJM2 * (1.-0.25) - RLWN
      PENMRS = NRADS * SLOPE/(SLOPE+PSYCH)
      PENMRC = NRADC * SLOPE/(SLOPE+PSYCH)

      WDF    = 2.63 * (1.0 + 0.54 * WN)
      PENMD  = LHVAP * WDF * (SVP-VP) * PSYCH/(SLOPE+PSYCH)

      PEVAP  =  EXP(-0.5*LAI)  * (PENMRS + PENMD) / LHVAP
      PTRAN  = (1.-EXP(-0.5*LAI)) * (PENMRC + PENMD) / LHVAP
      PTRAN  = MAX( 0.0, PTRAN-0.5*RNINTC )

      RETURN
      END

* --------------------------------------------------------------------*
*     SUBROUTINE EVAPTR                                               *
*     Purpose: To compute actual rates of evaporation and transpiration*
* --------------------------------------------------------------------*
      SUBROUTINE EVAPTR(PEVAP,PTRAN,ROOTD,WA,WCAD,WCWP,WCFC,WCWET,WCST,
     $                  DELT,EVAP2,TRAN)
      IMPLICIT REAL (A-Z)

      WC   = 0.001 * WA   / ROOTD
      WAAD = 1000. * WCAD * ROOTD
      WAFC = 1000. * WCFC * ROOTD

      EVAP1  = PEVAP * LIMIT( 0., 1.,(WC-WCAD)/(WCFC-WCAD) )
```

```
         WCCR = WCWP + 0.5 * (WCFC-WCWP)
         IF (WC.GT.WCCR) THEN
             FR = LIMIT( 0., 1., (WCST-WC)/(WCST-WCWET) )
         ELSE
             FR = LIMIT( 0., 1., (WC-WCWP)/(WCCR-WCWP)  )
         ENDIF
      TRAN = PTRAN * FR

         AVAILF = MIN( 1., ((WA-WAAD)/DELT)/NOTNUL(EVAP+TRAN) )
      EVAP2 = EVAP1 * AVAILF
      TRAN = TRAN * AVAILF

      RETURN
      END

* -----------------------------------------------------------------------*
*     SUBROUTINE DRUNIR                                                  *
*     Purpose: To compute rates of drainage, runoff and irrigation       *
* -----------------------------------------------------------------------*
      SUBROUTINE DRUNIR(RAIN,RNINTC,EVAP,TRAN,IRRIGF,
     $                  DRATE,DELT,WA,ROOTD,WCFC,WCST,
     $                  DRAIN,RUNOFF,IRRIG)
      IMPLICIT REAL (A-Z)

      WC   = 0.001 * WA   / ROOTD
      WAFC = 1000. * WCFC * ROOTD
      WAST = 1000. * WCST * ROOTD

      DRAIN  = LIMIT( 0., DRATE, (WA-WAFC)/DELT +
     $               (RAIN - RNINTC - EVAP - TRAN)                 )

      RUNOFF =          MAX( 0., (WA-WAST)/DELT +
     $               (RAIN - RNINTC - EVAP - TRAN - DRAIN)         )

      IRRIG  = IRRIGF *    (     (WAFC-WA)/DELT -
     $               (RAIN - RNINTC - EVAP - TRAN - DRAIN - RUNOFF) )

      RETURN
      END

C ------------------------------------------------------------------------
C     Author       : A.H.C.M Schapendonk, B.A.M. Bouman, D.W.G. van Kraalingen
C                    and W. Stol              Company : AB-DLO
C     Date  V1.0   : 4 april 1996
C
C     Subroutine    : SOSUB
C
C     Purpose  : Calculation of source-limited growth of total
C              : weight of perennial ryegrass.
C ------------------------------------------------------------------------
:
C                    name   type    description                                     unit
C
C     Parameters in: PARINT REAL    Intercepted photosynthetic active radiation
C                                                                        MJ PAR.m-2.d-1
C                    LUE     REAL   Light use efficiency                  g dm MJ PAR-1
C                    CO2A    REAL   Atmospheric CO2 concentration                   ppm
C                    NITR    REAL   Actual nitrogen content                     kg.kg-1
C                    NITMAX  REAL   Maximum nitrogen content                    kg.kg-1
C                    TRANRF  REAL   Transpiration reduction factor                    -
C                    HARV    REAL   Daily harvest rate of dry matter        kg.ha-1.d-1
C
C    Parameters out: GTWSO   REAL   Source-limited growth of total weight   kg.ha-1.d-1
C                    LUED    REAL   Actual light use efficiency           g dm.MJ PAR-1
```

```
C
C -----------------------------------------------------------------------
C
      SUBROUTINE SOSUB (PARINT, LUE, CO2A, NITR, NITMAX,
     &                  TRANRF, HARV, LUED, GTWSO)
C ----------------------------------------------------------------------
C      Formal parameters: declaration
C ----------------------------------------------------------------------
      IMPLICIT REAL (A-Z)
C
      LUED = MIN (LUE * (0.336+0.224*NITR)/(0.336+0.224*NITMAX),
     $       LUE*TRANRF)
C
C     start of growing season
      GTWSO = 0.
C
      IF (HARV.EQ.0.) THEN
C        normal growth
C        (10: conversion from g m-2 d-1 to kg ha-1 d-1)
         GTWSO = LUED * PARINT * (1.+0.8*LOG (CO2A/360.)) * 10.
      END IF
C
      RETURN
      END

C ----------------------------------------------------------------------
C      End of SOSUB
C ----------------------------------------------------------------------

C ----------------------------------------------------------------------
C     Authors       : A.H.C.M Schapendonk, B.A.M. Bouman, D.W.G. van Kraalingen
C                      and W. Stol              Company : AB-DLO
C     Date  V1.0   : 4 april 1996
C
C     Subroutine    : TILSUB
C
C     Purpose  : Calculation of tiller growth rate of perennial ryegrass.
C ----------------------------------------------------------------------
C
C                    name   type    description                                  unit
C     Parameters in: TILLER  REAL   Tiller number                             tiller.m-2
C                    FSMAX   REAL   Maximum site filling new buds    tiller.tiller-1.d-1
C                    LAI     REAL   Green leaf area index            ha leaf.ha-1 ground
C                    LAICR   REAL   Critical leaf area index beyond which death to
C                                   self-shading occurs              ha leaf.ha-1 ground
C                    DAHA    REAL   Days after harvest                                 d
C                    LEAFN   REAL   Leaf appearance rate                 leaf.leaf-1.d-1
C                    TSUM    REAL   Temperature sum above base temperature       gr.d-1
C                    RED     REAL   Temperature reduction factor on light use efficiency
C                                                                                      -
C     Parameters out:DTIL    REAL   Rate of tiller emergence             tiller.m-2.d-1
C
C ----------------------------------------------------------------------
      SUBROUTINE TILSUB (TILLER,FSMAX,LAI,LAICR,DAHA,
     &                   LEAFN,TSUM,RED,DTIL)
C ----------------------------------------------------------------------
C      Formal parameters: declaration
C ----------------------------------------------------------------------
      IMPLICIT REAL (A-Z)
C ----------------------------------------------------------------------
C     Local variables, necessary since IMPLICIT NONE
C ----------------------------------------------------------------------
C
      DTIL = 0.
```

```
      IF (DAHA.LT.8.) THEN
C        Relative rate of tiller formation when defoliation less
C        than 8 days ago, tiller tiller-1 d-1
         REFTIL = MAX (0., 0.335-0.067*LAI) * RED
      ELSE
C        Relative rate of tiller formation when defoliation is more
C        than 8 days ago, tiller tiller-1 d-1
         REFTIL = LIMIT (0., FSMAX, 0.867-0.183*LAI) * RED
      END IF

C     Relative death rate of tillers due to self-shading (DTILD),
C     tiller tiller-1 d-1
      DTILD = MAX (0.01*(1.+TSUM/600.), 0.05 * (LAI-LAICR)/LAICR)
C
      IF (TILLER.LE.14000.) THEN
         DTIL = (REFTIL-DTILD) * LEAFN * TILLER
      ELSE
         DTIL = -DTILD * LEAFN * TILLER
      END IF

      RETURN
      END
C -------------------------------------------------------------------------
C      End of TILSUB
C -------------------------------------------------------------------------

C ------------------------------------------------------------------------
C     Subroutine MOWING
C     Author       : A.H.C.M Schapendonk, B.A.M. Bouman, D.W.G. van Kraalingen
C                    and W. Stol              Company : AB-DLO
C     Date  V1.0   : 4 april 1996
C
C     Purpose  : Calculation of dry weight of harvested leaves
C                of perennial ryegrass and number of days since harvest.
C ------------------------------------------------------------------------
:
C
C                    name   type    description                               unit
C     Parameters in: IMOPT  REAL    Switch variable that defines crop management      -
C                    INCUT  REAL    Number of swards harvested (cuttings)             -
C                    MNDAT  REAL    Data of periodical harvests                       d
C                    NH     INTEGER Maximum number of periodical harvests             -
C                    TIME   REAL    Day number within year of simulation              d
C                    WLVG   REAL    Dry weight of green leaves                 kg.ha-1
C                    CWGHT  REAL    Dry weight of green leaves after which
C                                   cutting of sward is initiated              kg.ha-1
C                    CWLVG  REAL    Remaining dry weight of green leaves after
C                                   cutting of sward                           kg.ha-1
C                    DAHA   REAL    Number of days after harvest                      -
C     Parameters out:RDAHA  REAL    Rate of number of days after harvest              -
C                    HARV   REAL    Dry weight of harvested green leaves       kg.ha-1
C --------------------------------------------------------------------------

      SUBROUTINE MOWING (IMOPT,INCUT,MNDAT,NH,TIME,WLVG,
     &                   CWGHT,CWLVG,DAHA,RDAHA,HARV)
      IMPLICIT NONE
C -------------------------------------------------------------------------
C      Formal parameters: declaration
C -------------------------------------------------------------------------
      INTEGER NH, I1
      REAL MNDAT(NH)
      REAL   TIME,  WLVG, CWGHT, CWLVG, DAHA, RDAHA, HARV, IMOPT, INCUT
      LOGICAL MOWDAY
C
      MOWDAY = .FALSE.
```

```
      DO 10 I1 = 1,NH
         IF (TIME .EQ. MNDAT(I1)) MOWDAY = .TRUE.
 10   CONTINUE

C     mowing at criterium of WLVG: CWGHT
C     reset days after HARV
      IF (IMOPT.EQ.1. .AND.WLVG.GE.CWGHT) THEN

         HARV  = WLVG-CWLVG
         RDAHA = -DAHA
         INCUT = INCUT + 1.

C     mowing at observation dates, periodical harvests
C     reset days after HARV
      ELSE IF (IMOPT.EQ.2. .AND.MOWDAY.AND.WLVG.GT.CWLVG) THEN

         HARV  = WLVG-CWLVG
         RDAHA = -DAHA
         INCUT = INCUT + 1.

C     no mowing in current season, do not increase rate
C     of days after HARV
      ELSE IF (INCUT.EQ. 0.) THEN

         HARV  = 0.
         RDAHA = 0.

C     mowing in current season, increase rate of days
C     after harvests
      ELSE IF (INCUT.NE. 0.) THEN

         HARV  = 0.
         RDAHA = 1.

      END IF

      RETURN
      END

C -----------------------------------------------------------------------
C      End of MOWING
C -----------------------------------------------------------------------
```