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Production Soudano-Sahélienne (PSS)
Exploitation optimale des éléments nutritifs en élevage

Projet de coopération scientifique

A model of a perennial grass (*Andropogon gayanus*) for West Africa (PGWA): description and user's guide

Santiago Bonachela Castaño, AB-DLO [1)]

[1)] AB-DLO, B.P. 14, 6700 AA Wageningen, les Pays-Bas

IER, Bamako
AB-DLO, Wageningen, Haren
DAN-UAW, Wageningen

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Abstract

PGWA is a model for water and nitrogen limited growth conditions. It simulates phenological development and growth, storage and recirculation of non-structural carbohydrates, water use and forage exploitation of a perennial grass crop in tropical areas with a well-pronounced dry season, such as the Sahel and Sudan zones of West Africa. Development and parametrization of the model is based on Andropogon gayanus, a tall, tufted grass that forms part of the vegetation of many savannah areas throughout Africa south of the Sahara. Nutrient and organic matter balances were not considered in this version. A discussion on the main crop processes simulated is included.

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1. Introduction

1.1. Description of perennial grasses in the Sahel and Sudan zones

1.1.1. Tropical perennial grasses

Most cultivated grasses and a large number of valuable wild grasses belong to three subfamilies of the *Gramineae* (Bogdan, 1977): the festucoid (temperate grasses); the panicoid (tropical and subtropical grasses); and the chloridoid (a few cultivated tropical grasses and a number of valuable wild grasses of the tropics and of warmer areas of North America) subfamilies. The *Andropogoneae* is the largest tropical tribe in the panicoid subfamily.

The majority of tropical grasses belong to the C_4 species. They have a higher optimum temperature (30-40 deg.C) and a higher optimum light intensity (50 000-60 000 lux) for photosynthesis than temperate grasses (C_4 species), and they also have a lower minimum plant nitrogen concentration (Penning de Vries & Van Keulen, 1991). Moreover, most of the tropical grasses are either short-day plants (flowering occurs earlier under short than under long photoperiods) or are photoperiod neutral.

Annual tropical grasses die at the onset of the dry season or even earlier, but in areas with less pronounced dry seasons they can survive longer than one season. All the tillers can potentially bear seeds and are uniform in structure. They constitute the main grazing in arid and semi-arid areas with insufficient moisture in the soil in the dry season to support perennial grasses. Annuals grasses can also be abundant in bush, light forest in less dry areas, overgrazed pastures and as fodder crops.

Perennial tropical grasses have normally a more complex structure than annual grasses. The morphology of grass plants varies especially in the geotropism of the shoots and the length of the internodes, which determine the spatial and hierarchical position of the perennating buds. The extremes are represented by (Humphreys, 1981):

- Tufted or tussock-forming grasses with erect culms having long internodes, that originate from basal shoots with short internodes (such as *Andropogon gayanus*). They usually form tufts that spread on the out side by repeated tillering or through rhizomes with very short internodes from which new groups of tillers originate. Tufted perennials usually develop two types of tillers: fertile or seed-producing tillers with elongated internodes and distant leaves; and sterile tillers with very short, practically invisible internodes and long crowded leaves often forming the bulk of the grazeable herbage. Sterile tillers can remain as such for years or elongate and flower in the next season. Tufted grasses usually form the main bulk in permanent, savannah-type grasslands and some are grown in leys and in sown permanent grasslands (*Panicum maximum, Pennisetum purpureum, Andropogon gayanus, Paspalum dilatatum, Hyparrhenia rufa, Melinis minutiflora and Cenchrus ciliaris*);

- Creeping or sod-forming grasses with horizontal stems, either belowground (rhizomes) or close to the soil surface (stolons), from which erect or decumbent shoots originate with short internodes and form more even stands than tufted grasses. Rhizomatous grasses with creeping underground shoots usually occur in more moist areas or on sands, avoiding dry areas with hard and dry soil that is difficult to penetrate, common in swampy areas but not in seasonally waterlogged soil (*e.g. Oryza longistaminata*).

A number of rhizomatous grasses can form both rhizomes and stolons (*e.g. Cynodon dactylon, Pennisetum clandestinum*). Purely stoloniferous grasses occur predominantly in the tropics and warm regions. The stolons creep horizontally on the soil surface rooting at the internodes (*e.g. Chloris gayana, Paspalum notatum*). Stoloniferous, and sometimes rhizomatous grasses as well, are often pioneer species able to occupy quickly the bare ground of denuded pastoral land or arable land when it is left fallow. They can represent a certain phase in plant succession, often as a second stage after the dominance of annual weeds in fallows, and are in turn eventually replaced by tufted grasses or bush.

Perennial grasses have a fasciculate root system. Roots originating from the seed are known as primary roots, whereas secondary or adventitious roots develop from the nodes of tillers or creeping stems. Each tiller or group of tillers develops its own roots which makes it independent to a certain degree from other tillers or parts of the tuft with respect to obtaining water and mineral nutrients, although some connection between living tissues of different parts of the tuft can remain for a considerable time. Water and nutrients can be absorbed only by young root tips, densely covered with root hairs, old roots loose this ability. The majority of grass roots are found in the upper soil layers, but a number of roots can penetrate deep into the soil, down to 2 metres or deeper (Taerum, 1970).

1.1.2. Distribution of perennial grasses in the Sahel and Sudan zones

Based on species composition and vegetation distribution, wildlife and livestock distribution and land use patterns, the Sahel and the Sudan zones were classified into (Le Houérou & Popov, 1981):
Sahel zone
- Saharo-Sahelian transition subzone (100-200 mm long-term rainfall);
- Sahel zone proper subzone (200-400 mm);
- Sudano-Sahelian transition subzone (400-600 mm);

Sudan zone
- North Sudanian subzone (600-800 mm);
- South Sudanian subzone (800-1000 mm);
- Sudano-Guinean subzone.

Guinean zone

Perennial grasses are an important part of the herbaceous vegetation in the Sudan zone (*Andropogon gayanus, Hyparrhenia dissoluta, Cymbopogon giganteus, Hyparrhenia rufa, Hyparrhenia smithiana, Andropogon tectorum, Andropogon ascinodis*, etc.). They also used to play a significant role in the Saharo-Sahelian subzone and the Sudano-Sahelian subzone, but not in the Sahel proper subzone (Le Houérou, 1989). Saharan and Sahelo-Saharian species (*Aristida pallida, Aristida pappossa, Cymbopogon schoenanthus, Panicum turgidum*) are extremely drought-tolerant but sensitive to fire. Biomass of these species during the dry season is not enough fuel load and their tussocks are too sparsely distributed to carry fire over large distances. Perennial species of the Sudano-Sahelian subzone (*Andropogon gayanus, Aristida longiflora, Hyparrhenia dissoluta and Cymbopogon giganteus*), mostly belonging to the *Andropogoneae* tribe, are extremely tolerant to fire, but they are at the dry limit of their geographical distribution area. The paucity of perennial grasses in the Sahel zone proper has been explained by the combined effect of the fire, that limits the development of Saharian species, and water availability and crop exploitation, that limit the settlement of Sudanian *Andropogoneae* species.

At present, perennial grasses have almost disappeared in the Sahel zone, even in areas where there has been little or no grazing by livestock (Le Houérou, 1993). In the Sudan zone, *Andropogon gayanus* grows in areas with more than 700 mm of mean annual precipitation (Breman & De Ridder, 1991).

1.2. A growth simulation model of a perennial grass crop (PGWA)

During the last decades, the combination of an exponentially growing anthropozoic pressure (human and livestock populations) on the land, with prolonged drought periods has resulted in crop expansion over rangelands, a reduction of length of the fallow periods and severe degradation of savannahs in the Sahel zone (Le Houérou, 1989). This has lead to a sharp imbalance between natural resources and their exploitation, resulting in exhaustion and degradation of the soils. Degradation of soils has led to bare sand enclosed in a ring of species with a very short growth cycle on sandy soils and to bare plains with a hard crust, carrying only few microdunes with vegetation on loamy soils (Breman *et al.*, 1991). Degradation of savannahs has led to elimination of perennial grasses (*Andropogon gayanus, Aristida longiflora*, etc.) and replacement of annual grasses of good fodder quality by less productive, palatable and nutritious annual species (Le Houérou, 1989). These processes of degradation, to a less extent, have also taken place in the north Sudan zone (Breman, per. comm.). Natural re-establishment of perennial grasses has not occurred after the drought, not even in areas without rangeland exploitation (Breman & De Ridder, 1991).

Establishment of perennial grass crops, such as *Andropogon gayanus*, in integrated farming systems can be a feasible way of improving degraded rangelands or cropping areas (Dieng, 1991) and it could provide a fodder resource to reduce weight losses of livestock in the long dry season (Breman & De Ridder, 1991). *Andropogon gayanus*, a large tufted perennial grass, appears to be the best adapted to monsoonal climates with long dry seasons (Jones, 1979): it was common in protected Sudano-Sahelian areas prior to the drought of 1969-73 and it still occurs in the Louga and Dahra areas of Senegal (Le Houérou, 1993).

At present, more than 300 000 ha of poor acid soils in the tropical America have been planted with *Andropogon gayanus* cv. *bisquamulatus*. Seeds were introduced from northern Nigeria by CIAT in 1973. It has also been introduced as a temporary forage crop within a groundnut-cotton rotation in the groundnut basin of Senegal (Dieng *et al.*, 1991). Technology for crop establishment and management was also developed.

This study was aimed to construct a model for a perennial grass crop in the Sahel and Sudan zones with the following future objectives:
- to provide an interactive tool for modellers and field scientists to identify those crop or soil processes for which more insight is required;
- to understand the added value of perennial grasses in the production systems of the region compared to annual species;

- to identify agro-ecosystems in which the introduction or stimulation of perennial grasses are technically and economically feasible.

The model parametrization has been based on *Andropogon gayanus* data. Some parts of the model, such as storage and recirculation of reserve carbohydrates or crop survival, serve as research tools due to the early stage of understanding.

1.3. Description of Andropogon gayanus

Andropogon gayanus Kunth belongs to the grass tribe *Andropogoneae*, subfamily *Panicoideae*. It is a tall, coarse, erect, perennial grass with culm height of 1-3 m and forms tussocks up to 1 m in diameter as results of short rhizome internodes and intravaginal branching.

The species occurs in Africa almost exclusively between the 400 mm and 1500 mm (Bowden, 1964) under a wide range of edaphic conditions: well adapted to low fertility conditions and acid soils (Amezquita *et al.*, 1990). *Andropogon gayanus* is highly productive and moderately nutritious in pure stands without nitrogen fertilization (Jones, 1979) and a constituent of most of the savannahs of tropical Africa south of the Sahara (Bowden, 1964).

Four botanical varieties are distinguished (Keller-Grein & Schultze-Kraft, 1990).
- The variety *polycladus* Hack. [syn. var. *squamulatus* (Hochst.) Stapf] is the most widely distributed of the four varieties: it occurs north and south of the equator in Africa.
- The variety *bisquamulatus* (Hochst.) Hack. has a geographical distribution almost identical to that of var. *polycladus* north of the equator, but it does not occur south of the equator. Bowden (1963a) and Mejía-M. (1984) suggested that *bisquamulatus* is more vigorous and aggressive than the other varieties.
- The variety *gayanus* (syn. var. *genuinus* Hack) has a distribution similar to that of var. *bisquamulatus*. It occurs, often as a dominating species, in seasonal swamps and flood plains (Clayton, 1972; Bogdan, 1977).
- The variety *tridentatus* Hack. mostly occurs in semi-desert grassland vegetation in West Africa (Bogdan, 1977).

The native habitat of the *bisquamulatus* and *polycladus* varieties is characterized by a long dry season of 2-9 month (Bowden, 1964). These varieties retain green leaves for much of this period, and rapidly start a regrowth at the onset of the rains (Bowden, 1963a; Bogdan, 1977). They are dominating species over large areas of the Guinean and Sudanian (*Isoberlia-Hyparrhenia-Andropogon*) savannahs and are also frequent in the drier Sahelian zone (*Acacia-Terminalia-Andropogon, Acacia-Combretum-sorghum* and *Combretum-Cenchrus* savannahs) as well as in the West African derived and coastal shrub-savannahs (Keller-Grein & Schultze-Kraft, 1990).

The root system of *Andropogon gayanus* var. *bisquamulatus* consists of (Bowden, 1963b):
- short-branched rhizomes forming a compact mass near the soil surface (90% of root dry matter);
- fibrous roots, fine, profusely branched, distributed just beneath the surface and growing horizontally;
- vertical roots, fine, less branched and growing vertically;

- cord roots, short and thick that anchor the plant and store starch.

Virtually all savannahs in which *Andropogon gayanus* occurs naturally are exposed to periodic burning, which removes almost all aerial parts. *Andropogon gayanus* is able to regrow after a fire because its rhizomes and roots are below the soil surface (Bowden, 1964).

2. Model development

The present version of the model, called PGWA, is based on the model PGWL-FSE, described in a provisional version of this report. It is written in FORTRAN-77 using the Fortran Simulation Environment FSE, version 2 (van Kraalingen, unpublished).

PGWA simulates regrowth and emergence, growth and development, senescence, water use, forage exploitation, storage and recirculation of reserve carbohydrates and survival of a perennial grass crop in tropical areas with a pronounced dry season, such as the Sahel and Sudan regions. Nutrient and organic matter balances are not considered in this version.

A listing of model variables is in the Appendix A.

2.1. Germination and regrowth

Regrowth of perennial grasses starts at the beginning of the rainy season, which occurs some time after the first rains (Breman, 1991; de Bie, 1991; Cesar, 1992). In field experiments carried out in Senegal (Dieng, 1991) and in Mali (R. Groot, personal communication) the onset of growth of perennial grasses was observed after approximately 25 mm of rainfall in one or few subsequent days. Water availability is regarded the major factor determining crop regrowth and seed germination. Temperature is not considered a limiting factor under Sahel-Sudan conditions. Simulation of germination and regrowth is based on the emergence part of the spring wheat model of van Keulen & Seligman (1987)

Andropogon gayanus can be planted by using vegetative material in regions where labour availability and cost permit, but this system is not likely to be adopted because of the ease of seed production and harvesting (Spain & Couto, 1990). Crop establishment by sowing is assumed. Seeds of *Andropogon gayanus* have a very small caryopsis (900-1700 units per gram) and, hence, very limited nutrient reserves as a basis for initial development, which could explain the slow emergence observed under field conditions. Sowing depth of 1.5-2.5 cm (Bowden, 1963a) or 2-4 cm (Zimmer *et al.*, 1983) is considered optimum. Germination is assumed to start and proceed through its various phases if soil moisture in the upper 10 cm of the soil exceeds a threshold value. This value is calculated as 1.3 (CRWCCG, file CROP. DAT) times the water content at wilting point. Emergence occurs after eight days of unhampered germination processes (Dieng, 1991). If the soil dries out below the critical soil water content within four days after the onset of germination, the process is halted but will resume after rewetting from the point where it stopped. However, if drying out occurs five or more days after the onset of germination and dry soil conditions persist for more than six days, seeds are assumed to die (sowing failure). Thus, drying out of the soil after the onset of germination will delay emergence and could also reduce the final number of seedlings and, therefore, initial crop biomass. To account for a poor emergence a reduction factor (RFIBWS, -) has been introduced, equal to the ratio between actual and maximum possible days with dry soil conditions after the onset of germination, to modify the initial crop biomass.

Crop regrowth is simulated similarly to crop emergence, but because of the higher availability of reserves in adult plants, sprouting occurs faster than seedling emergence. As in seedling emergence a reduction factor (RFIBWS, -), accounting for dry soil conditions during the regrowth process is used to modify initial shoot biomass.

Dates of regrowth and germination after sowing are calculated with a subroutine called PGCR (Appendix B).

2.2. Phenological development

Major processes like dry matter partitioning, storage and recirculation of assimilates and nutrients, senescence as well as nitrogen concentration and forage quality of perennial grasses depend directly or indirectly on the physiological age of the plant. Thus, a description of phenology in quantitative terms is required for crop modelling.

Most of the tropical perennial grasses are either short-day plants (flowering earlier under short than under long photoperiods) or are day-neutral. In the Sahel and Sudan regions, the main growth cycle of perennial grasses starts at the beginning of the regular rains (May to July) and ends in the cool dry season (November to February). Subsequently, if water is available in the soil, a new growth cycle can start after cutting or burning. During this new growing period, stem elongation and flowering can occur again when the cycle starts in the cool dry season (short day lengths), but not when the cycle starts later in the hot dry season due to the increasing day length (Dieng *et al.*, 1991).

Andropogon gayanus is a short-day plant with a critical day length for flowering of 12-14 h (above which plants do not flower). Similar values of critical day length have been reported for other *Andropogoneae* grasses (Tompsett, 1976). Flowering and stem elongation of *Andropogon gayanus* occurred earlier when day length was shortened from 12 to 8 h. Moreover, there may be a juvenile phase of development of around 6 weeks when flowering and stem elongation cannot be induced, even under inductive photoperiods (Tompsett, 1976). Tompsett also observed a close association between stem elongation and flowering events in all his experiments, and suggested a close relation between the internal mechanisms controlling these events.

As the processes governing phenological development of *Andropogon gayanus* are not well understood, a descriptive model is used. The life cycle is divided into two phases using the main development stages (DVS):
- pre-anthesis, from emergence or regrowth (DVS equal to 0) to flowering (DVS equal to 1);

- post-anthesis, from flowering to grain maturity (DVS equal to 2);

Following grain maturity, all living aboveground biomass produced during the growing season will die. This phase is called shoot senescence (SSS, -): from grain maturity (SSS equal to 0) to complete death of the aboveground biomass (SSS equal to 1). During this phase DVS is equal to 2.

Crop phenology is simulated in a subroutine called PGPHE (Appendix B).

2.2.1. Pre-anthesis phase

A significant correlation between latitude of the collection site (origin of the accession) and flowering date of *Andropogon gayanus* was found by Foster (1962) in Nigeria: accessions from northern Nigeria started to flower earlier than those from the southern part. Annual grass species from Mali behaved in the same way (de Ridder, 1979).

Foster (1962) throughout Nigeria and Dieng (1991) at Thies (Senegal) observed that flowering of *Andropogon gayanus* coincided with the end of the wet season. In Senegal, Monniaux (1978) found that time to flowering was closely correlated to the number of rainy days per year and that neither mean annual precipitation nor mean annual temperature improved the prediction. Flowering response of *Andropogon gayanus* accessions collected in Africa from sites between 8 and 12 deg.N was well synchronized with the end of the rainy season at similar or higher latitudes in tropical America, but at lower latitudes flowering started long before the end of the rainy season because of the shorter day lengths (Miles & Grof, 1990).

This flowering behaviour, that is a result of different photoperiod responses among genotypes, could be an adaptation of *Andropogon gayanus* to the length of the rainy season (Grof & Thomas, 1990).

Field data on the stage of stem elongation are very rough (Haggar, 1970; Dieng *et al.*, 1991; Cesar, 1992). The close association between stem elongation and flowering of *Andropogon gayanus* observed by Tompsett (1976) appears not to be confirmed by these field data.

To simulate the rate of development during the pre-anthesis phase (DVR1, d^{-1}) three options are offered by the current version of the model.

2.2.1.1. Geographical approach

The last day of the rainy season (ER, in Day Of the Year, doy) was considered a good indicator of flowering date in the rainy season across the Sahel and Sudan regions (Foster, 1962; Monniaux, 1978; Dieng *et al.*, 1991). In Mali (13deg.-17 deg.N), Hiernaux (1984) found a close relation between average date of the last rains and latitude (r = -0.90). The end of the rainy season is defined as the last day with rainfall of 15 mm or more, or the first day of the last five consecutive days with accumulated rainfall of 20 mm or more. For West Africa, the end of the rainy season could be estimated for any specific site from latitude (LATS, degrees) and longitude (LONS, degrees) as follows (Kowal & Kassam, 1978):

ER = 352 - 5.7*LATS - 0.7*LONS (1)

Table 1 presents experimental values of flowering date in the rainy season for *Andropogon gayanus* and estimation of end of the rains for several sites in West Africa.

Estimations of ER were close to the experimental flowering dates (Table 1), with the exception of Thies. Dieng *et al.* (1991) pointed out that flowering coincided with ER, but they did not define this environmental characteristic. Using the definition of Hiernaux (1984), ER occurred the julian calendar day 275 (average value for 1987-1990 years). The influence of the Atlantic Ocean at Thies (located near the coast) could explain the later ending of the rains.

Table 1. Experimental flowering date (FDRS, doy) and estimated values of end of the rains (ER, doy) calculated with the equation 1 for several sites in West Africa.

Site	Latitude	Longitude	FDRS	Source	ER
Niono (Mali)	14deg. 16' N	5deg. 58'	264[1]	de Ridder, 1979	267
N'Tarla (Mali)	12deg. 35' N	5deg. 42' W	285	Traoré, 1995	277
Shika (Nigeria)	11deg. 12' N	7deg. 33 E	289	Haggar, 1970	283
Thies (Senegal)	14deg. 48' N	16deg. 57' W	300	Dieng *et al.*, 1991	258
Ivory Coast	5deg. N	1deg. W	324	Cesar, 1992	323
	|	|	|		|
	10deg. N	1deg. W	300		294

1) FDRS was estimated as the date of beginning of flowering plus 10 days

2.2.1.2. Photothermic approach

The onset of the rainy season is extremely variable in West Africa: for several sites in Mali, where rainfall records for 30 years were available, the extreme values for the beginning of the rainy season varied more than 100 days among years. However, flowering of *Andropogon gayanus* occurred at similar dates regardless the onset of the growth period (de Ridder, 1979; Dieng *et al*., 1991). Photoperiod has a regulatory effect on flowering date of *Andropogon gayanus* under different starting dates of the growing season (de Ridder, 1979). However, this photoperiodic regulation is limited: for a very early or very late start of the growing season the flowering date of *Andropogon gayanus* differed markedly (de Ridder, 1979). For those situations the geographical approach for determining flowering date is not suitable.

Using date of flowering in *Andropogon gayanus* in relation to date of emergence in Niono, Mali (de Ridder, 1979), the rate of development from emergence to beginning of flowering could be estimated. For that purpose, it was considered that the rate of development in the pre-anthesis period depends linearly on the mean air temperature (TMPA, deg.C) and on the photoperiodically active daylength (DAYLP, h), without interactions between both factors (Robert & Summerfield, 1987). A critical daylength (CRDAYL, h) was also assumed at or below which flowering of *Andropogon gayanus* accessions depends on temperature, regardless of photoperiod, but beyond this critical daylength development rates increase when photoperiod shortens. This assumption is based on the flowering behaviour of several short day crops in tropical and sub-tropical areas (Hadley *et al*., 1983) including *Andropogon gayanus* (de Ridder, 1979).

If the photoperiod exceeds CRDAYL:

DVR1 = A2 + B2 * DAYLP (3)

A2 and B2 are parameters (CROP.DAT file)

If the photoperiod is shorter than CRDAYL:

DVR1 = C2 + D2 * TMPA (2)

C2 = BTD / TUEA

D2 = 1 / TUEA

where, BTD is the base temperature for plant development, a value of 10 deg.C being used in other C_4 species (Heemst, 1986) was assumed. TUEA is the thermal sum (deg.C d) from emergence to anthesis (CROP.DAT file). TUEA can be calculated from the de Ridder data.

Using the de Ridder (1979) data set A2 and B2 were optimized (Table 2) with the FSEOPT program (Stol *et al*., 1992).

Table 2. Optimum parameter values.

A2	=	0.49458
B2	=	-0.03659
C2	=	-0.01179
D2	=	0.00114

CRDAYL	=	12.84

Simulated data are similar to experimental values, except for the first emergence date (Table 3). Flowering of this emergence date was considerably later than of the following emergences. Other factors in addition to photoperiod and temperature must have caused this response.

Table 3. Experimental and simulated flowering dates (doy) under different emergence dates (doy).

Emergence date	**Date of beginning of flowering**	
	Field	**Simulated**
115	275	232
141	251	248
171	250	256
198	261	261
232	283	282
252	302	303

In this study, flowering date data refer to newly emerged crops. In Senegal, no dif ferences were found in the date of flowering of *Andropogon gayanus* in the first and second year after sowing (Dieng *et al.*, 1991).

The variety of *Andropogon gayanus* used in this study (de Ridder, 1979) was *tridentatus*, that appears to have an earlier flowering date than *bisquamulatus* (Table 1).

2.2.1.3. Direct approach

If the date of beginning of stem elongation [SEDRS (doy) in the rainy season and SEDDS (doy) in the dry season] and the date when 50 % of the plants have flowered [FDRS (doy) in the rainy season and FDDS (doy) in the dry season] are known for a specific site and variety, the development rate is calculated as follows:

in the rainy season:

before the onset of stem elongation in the sowing year:

DVR1 = SEDVS / (SEDRS - EMERGD) (4a) before the onset of stem elongation in subsequent years:

DVR1 = SEDVS / (SEDRS - BGRS) (4b)

after the onset of stem elongation in the sowing and subsequent years:

DVR1 = (1 - SEDVS) / (FDRS - SEDRS) (4c)

where, BGRS (doy) is the date of beginning of crop growth in the rainy season and EMERGD (doy) emergence date after sowing (both calculated in the PGCR subroutine, Appendix B)

in the dry season:

before the onset of stem elongation:

VR1 = SEDVS / (SEDDS - BGDS) (5a)

after the onset of stem elongation:

VR1 = (1 -SEDVS)/ (FDDS - SEDDS) (5b)

where, BGDS (d) is the date of starting a new crop cycle in the dry season. SEDVS is a numerical value between 0 and 1, arbitrarily set to 0.35, for the stage of beginning of stem elongation.

2.2.2. Post-anthesis and shoot senescence phases

The development rate during the post-anthesis phase (DVR2, d^{-1}) is temperature-dependent only. This assumption is used on cereals (van Keulen & Seligman, 1987) and other annual crop (Penning de Vries *et al.*, 1989) models. Time from flowering to harvest of *Andropogon gayanus* was relatively constant among years in the Brazilian Cerrados (de Andrade *et al.*, 1983), lasting on average 40 days, In a Sudan area of Mali the time from flowering to crop maturity was longer, lasting around two months (Traoré, 1995).

DVR2 = BTD / TUAM + 1 / TUAM * TMPA (6)

TUAM is the thermal sum (deg.C d) from anthesis to crop maturity, a value of 1000 being used (Traoré, 1995). Parameter values are in file CROP.DAT (Appendix C).

In the geographical and direct approaches, while the actual to potential transpiration ratio (TRANSR, -) reduces the rate of development during the pre-anthesis phase, it accelerates it during the post-anthesis phase.

The development rate during the phase of shoot death (SSR, d^{-1}) is also temperature-dependent only.

SSR = BTD / TUMD + 1 / TUMD * TMPA (7)

TUMD is the thermal sum (deg.C d) from crop maturity to complete death of shoot (file CROP.DAT, Appendix C).

2.3. Dry matter production

2.3.1. Cycle of biomass production and nitrogen store of perennial grasses in West African savannahs

In the Sudanian and Guinean savannahs of Ivory Coast (Cesar, 1992) and the Sudanian savannahs of Burkina Faso (Fournier, 1987), mostly comprising of perennial grasses, the main growth cycle starts at the beginning of the regular rains (May to July), maximum aboveground biomass (2500-7000 kg ha^{-1}) is reached at the end of the rainy season (September to November) and seed formation usually occurs at the beginning of the dry season. Burning is a common practice, carried out from the beginning of the dry season onwards (December to April). Between the end of the rainy season and burning a new growing period could start (new tillers appear from the base of the tussocks), if water is available in the rooted soil (Piot, 1968; Monnier, 1968; Cesar, 1992). Growth is assumed to start when light reaches the dormant buds at the base of tussocks, but it could be masked by old dead parts of the plant. After burning (almost the entire aboveground biomass disappears), a new growing period starts. In the Guinean zone, perennial grasses grows continuously until the next rainy season, but in the Sudan zones regrowth is usually small (leaves do not reach more than 5 cm) and growth stops soon because of soil water depletion. Subsequently, green leaves wilt and die and no new regrowth takes place until the next rainy season (Fournier, 1987; Cesar, 1992).

The nitrogen store in the aerial biomass is minimal during the dry season (after burning) and the beginning of the rainy season. Subsequently, the nitrogen store increases, reaches a maximum (15-35 kg ha^{-1}) before or around flowering and later decreases due to seed fall, leaching, volatilization or recirculation (Haggar, 1970; Egunjobi, 1974; Breman, 1991; Abbadie, 1984; Traoré, 1995).

Root biomass of perennial grasses varies seasonally. In most of the studies, root biomass continuously increased during the rainy season, achieving a maximum at the beginning of the dry season (post-flowering phase) and later decreased during the dry season (San Jose *et al.*, 1982; Fournier, 1987; Dieng *et al.*, 1991; Cesar, 1992; Traoré, 1995). Data on root biomass were much more variable than on shoots. Root biomass also responded to variable weather conditions among years. Root biomass in the Guinean and Sudanian savannahs decreased to one fourth of their previous values after the drought period of 1971-1973 (Cesar, 1992).

Perenniality is associated with a high rate of root growth relative to that of shoots. Belowground biomass was greater than aboveground biomass in savannahs from Ivory Coast (10 000-20 000 kg ha^{-1}) and Burkina Faso (3000-10 000 kg ha^{-1}). However, in sown grasslands of *Andropogon gayanus* located in the Sudan-Sahel transition zone (Dieng *et al*., 1991) and in the Sudan zone (Traoré, 1995), root biomass (3000-5000 kg ha^{-1}) was considerably lower than that of the shoots (10 000-17 000 kg ha^{-1}). It is difficult to explain such considerable differences. In some savannahs, they could be partly caused by the presence of geophyte species with large root systems.

The store of nitrogen in the roots in a Sudanian savannah vegetation varied rapidly throughout the year (Abbadie, 1984) with no clearly defined trend. In *Andropogon gayanus* grasslands in Mali the maximal nitrogen store occurred during the post-flowering phase (Breman, 1991; Traoré, 1995).

2.3.2. Dry matter production

The rate of dry matter production of a perennial grass is determined, on a daily basis, with the equation developed by ten Berge *et al.* (1994), but the nitrogen content of shoots (ANSH, g shoot nitrogen per m^2 ground surface) is used instead of nitrogen content of leaves. Thus, the maximum rate of dry matter production (MXDMP, kg ha^{-1} d^{-1}) is calculated from daily incident global radiation (RDD, MJ m^{-2} d^{-1}) and the amount of nitrogen contained in the shoots with the equation:

$$\mathbf{MXDMP = 10\ p\ ANSH\ [1 - e^{-epsil\ RDD/(p\ ANSH)}]} \quad (8)$$

where p is the initial shoot nitrogen use coefficient (grams of dry matter produced per day and per gram shoot nitrogen), epsil is the initial global radiation use coefficient (grams of dry matter produced per MJ incident global radiation). The parameter p represents the overall efficiency with which shoot nitrogen is used in producing dry matter. Both parameters can be estimated directly from experimental data.

Dry matter production is calculated in the subroutine PGDM (Appendix B).

Limitations to dry matter production:

1) Below a threshold value of the shoot nitrogen concentration (AVNCSH, kg kg^{-1}), dry matter production (DMP, kg ha^{-1} d^{-1}) is progressively reduced when the shoot nitrogen concentration approaches the minimum shoot nitrogen concentration (MNNCSH, kg nitrogen per kg dry matter) and is null below MNNCSH. This is a physiological limitation: when the level of nitrogen in the shoots falls below a minimum net assimilation becomes negative (van Keulen & Seligman, 1987). Above AVNCSH, the rate of dry matter production is equal to MXDMP.

The minimum and maximum nitrogen concentration in the shoots decrease with plant development because of synthesis of nitrogen-poor components later in the crop's life. If the nitrogen source becomes exhausted, the decrease is even stronger because of intensive nitrogen redistribution. Fig. 1 shows the maximum and minimum concentrations of nitrogen in the aboveground biomass of *Andropogon gayanus* during the main growth cycle. This figure summarizes data from different areas of West Africa (Oyenuga, 1957; Haggar, 1970; Egunjobi, 1974; Cissé & Breman, 1980; Dieng *et al* ., 1991; Traoré, 1995). Minimum shoot nitrogen concentration is around 5 g per kg DM until flowering and later decreases to 2-3 g per kg DM. These values of minimum shoot nitrogen concentration are similar to *Andropogon gayanus* data collected by Breman & De Ridder (1991). Maximum and minimum nitrogen concentrations of *Andropogon gayanus*, a perennial C_4 grass, are also similar to values of annual C_4 grasses summarized by Penning de Vries & Van Keulen (1991).

Figure 1. Maximum and minimum shoot nitrogen in Andropogon gayanus.

2) Limited water supply results in a reduction in water use and crop growth (van Keulen & Seligman, 1987). To account for water-limited conditions, the ratio actual to potential transpiration (TRANSR, -) is used as a reduction factor that multiply DMP. Below a threshold value of TRANSR (CRTRCA, -, file CROP.DAT) the rate of dry matter production is set to 0.

3) The growth rate of *Andropogon gayanus* during the dry season was lower than in the rainy season even under optimum water supply. This behaviour has been attributed to low air humidities at Sotuba, Mali (Krul & Breman, 1991) but also to low minimum temperatures at Thies (Dieng *et al.* , 1991).

Under laboratory conditions, stomata of *Andropogon gayanus* showed no response to external air humidity [leaf-air vapour pressure deficit (VPD) from 1 to 4 kPa], but the rate of leaf photosynthesis steadily decreased beyond a value around 2.5-3.0 kPa leaf-air VPD. The leaf water potential also decreased substantially with increasing leaf-air VPD (El-Sharkawy *et al.* , 1984).

Andropogon gayanus species do not occur in areas where the mean minimum temperature of the coldest month is less than 4.4 deg.C (Bowden, 1964), although it is tolerant to light frost (Singh & Chatterjee, 1968), but no data are available about crop dormancy caused by low temperature.

Table 4 shows monthly values of minimum temperature and VPD of the air during the above mentioned dry seasons of Thies and Sotuba (Kita, a nearby weather station is used instead of Sotuba).

Table 4. Monthly average of daily values of minimum temperature (TMMN, deg.C) and air vapour pressure deficit (VPD, kPa) during the dry season of 1988/89 at Thies and 1978/79 at Kita.

Site	**Thies (Senegal)**		**Kita (Mali)**	
Month	**TMMN**	**VPD**	**TMMN**	**VPD**
November	18.8	2.26	18.3	2.49
December	16.3	2.66	17.3	2.90

January	16.5	2.80	19.6	3.31
February	18.0	2.60	22.1	3.73
March	17.8	2.66	24.3	4.60
April	17.4	2.38	26.0	4.78
May	19.9	2.26	27.9	4.35
June	22.5	2.02	23.4	2.00

At Sotuba, after burning (January 1979), the aerial living biomass of *Andropogon gayanus* was slightly higher under optimum water supply (150 kg ha^{-1} in March and 320 kg ha^{-1} in June) than without irrigation (60 and 100 kg ha^{-1}, respectively). Crop photosynthesis might be reduced by low values of VPD during the dry season, but not by temperature. From March onwards, minimum temperature was equal to or higher than the optimum flowering temperature (Tompsett, 1976).

At Thies, low night temperatures during the cold dry season could lead to accumulation of starch in leaf chloroplasts and reduced dry matter production. This response to low night temperatures has been described for other C4 species (West, 1973). VPD values are not likely limiting crop growth.

Further insight of growth of perennial grasses during the dry season is needed. It seems difficult to explain the low observed values of aerial biomass through air humidity or temperature limitations only.

The model assumes that low air humidity can reduce dry matter production. A reduction factor (RFCAAH, -), function of air vapour pressure deficit, is introduced to account for this effect. This factor is equal to 1 below a VPD threshold value (CRVPD1, file CROP.DAT) of 3.0 kPa (El-Sharkawy *et al*., 1984) and from there on decreased linearly till 0 at CRVPD2 (arbitrarily set to 5 kPa, file CROP.DAT). Temperature is not considered to limit growth for West African conditions.

Thus, the actual rate of dry matter production (ADMP, kg ha^{-1} d^{-1}) is calculated as follows:

ADMP = DMP * MIN(TRANSR, RFCAAH) (9)

2.3.3. Growth rate of the crop

The growth rate of the crop consists of two terms: actual dry matter production (ADMP) and non-structural carbohydrates translocated from senescent shoots and roots (Subsection 2.5).

The maximum growth rate calculated for C_4 species (most of the perennial grasses of West Africa) is approximately 400 kg ha^{-1} d^{-1} (Lövenstein *et al*., 1992), but the maximum growth rate reported (MXGRCR, file CROP.DAT) of *Andropogon gayanus* grass was 305 kg ha^{-1} d^{-1} (Traoré, 1995). This value is used as maximum growth rate in the current version of the model.

Thus, the actual growth rate of the crop (GRCR, kg ha^{-1} d^{-1}) is calculated as:

GRCR = MAX[MXGRCR, ADMP + (WCTSH+WCTRT)/ASRQCR)] (10)

where WCTSH (kg ha^{-1} d^{-1}) and WCTRT (kg ha $^{-1}$ d^{-1}) are carbohydrates translocated from senescent shoots and roots, respectively, and ASRQCR is the assimilate requirement for dry matter production of the crop.

2.3.4. Dry matter partitioning

Under potential growth conditions, partitioning of dry matter between shoot and roots is a function of the stage of plant development. However, biomass allocation may be modified, either by environmental constraints (water shortage and nutrient deficiencies) or by crop management (forage exploitation).

The fraction of dry matter allocated to the shoots (FBSH, -) and roots (FBRT, -) under potential growth conditions has been estimated from experimental data in Mali (Traoré, 1995).

Dry matter partitioning is calculated in the subroutine PGDM (Appendix C).

2.3.4.1. Growth rate of shoots

Under potential growth conditions, the growth rate of shoots (GRSH, kg ha^{-1} d^{-1}) is calculated as the fraction of dry matter allocated to shoots times actual rate of dry matter production. However, water stress or nitrogen deficiency can modify dry matter partitioning in favour of the roots (Brouwer, 1963; Hamblin, 1987). RFSGWS (-) is a reduction factor introduced to account for water stress effects on shoot growth rate: its value is equal to 1 when the plant water uptake meet the transpirational demand and equal to 0.9 (rather arbitrarly assumed) times TRANSR under water-limited conditions. RFSGND, (-) is a reduction factor accounting for nitrogen deficiency effects on shoot growth rate: if the shoot nitrogen concentration approaches to its minimum value, the value of RFSGND decreases with decreasing nitrogen concentration.

Growth rate of shoots is constrained to the maximum reported value: 260 kg ha^{-1} d^{-1} (Egunjobi, 1974) in the pre-anthesis phase and 20 kg ha^{-1} d^{-1} (Traoré, 1995) in the post-anthesis phase. The recorded increase in shoot biomass after flowering has been small, zero or negative (Haggar, 1970; Egunjobi, 1974; Breman, 1991; Dieng *et al.*, 1991; Traoré, 1995). Seed production is low and extremely variable: the maximum yield of pure seed recorded was about 350 kg ha^{-1} but under commercial conditions, seed production is in the range of 65-120 kg ha^{-1} (Ferguson, 1990).

2.3.4.2. Growth rate of roots

Under potential growth conditions, the root growth rate (GRRT, kg ha^{-1} d^{-1}) is calculated as the fraction of dry matter allocated to the roots times actual rate of dry matter production. However, as mentioned before, water stress or nitrogen deficiency can reduce shoot growth and therefore more dry matter can be allocated to the roots.

Root growth temporarily ceases after cutting or grazing and all assimilates are allocated to the shoots (Sibma & Ennik, 1988). This limitation continues as long as the shoot to root ratio is less than a critical value. In the model this critical ratio (SHRTR, -, file CROP.DAT) was set, rather arbitrarily, to 0.5.

Root growth also ceases when the nitrogen concentration in the roots is equal to or below a minimum value. Fig. 2 shows the root nitrogen concentration of *Andropogon gayanus* at N'Tarla and Cinzana (Traoré, 1995) during the rainy season. No systematic decrease in root nitrogen concentration with plant age was observed as in the shoots. The same behaviour has been reported for annual grasses (Penning de Vries & Van Keulen, 1991). The store of root nitrogen is calculated as a fraction of the total crop nitrogen store. This fraction has been estimated from experimental data in Mali (Traoré, 1995).

Figure 2. Maximum and minimum root nitrogen in Andropogon gayanus.

2.4. Senescence

In the Sudanian savannahs (Fournier, 1987; Cesar, 1992), significant increases in dead shoot biomass start in August-September, the senescence process accelerate strongly after ripening (November) and most of the shoot biomass are dead in December. In Guinean savannahs, shoot senescence is delayed, particularly in wetter areas or years, compared to Sudanian savannahs (Cesar, 1992).

Dynamics of senescence and disappearance of perennial grass roots were described in the *Trachypogon* savannahs of the High Central Plains of Venezuela (San Jose *et al.*, 1982), an area characterised by a pronounced seasonal rainfall of 1300 mm and a four months dry season. While most of the root biomass was functioning during the first half of the wet season (vegetative growing period), most of it was non-functional during the dry season (functional roots remained constant circa 240 kg ha^{-1}). Non-functional root biomass increased during the second half of the rainy season and decreased during the dry season and more rapidly during the beginning of the next wet season.

Measurements of turnover rates of the perennial grass roots (ratio between annual belowground growth and maximum belowground dry matter) suggest that roots may survive on the average for one year: values of 1.08 for an *Andropogoneae* Guinean savannah (Menaut & Cesar, 1979); 0.85 for Sudanian savannahs (Fournier, 1987), around 1 for a *Trachypogon* savannah (San Jose *et al.*, 1982) and 0.72 for an *Andropogon* grassland (Dieng *et al.*, 1991) have been recorded. A root turnover rate of 1 has been assumed in the present model.

PGWA assumes that senescence of perennial grasses starts at the stage of stem elongation (Fournier, 1987; Cesar, 1992). Death rate of shoots and roots is calculated as the relative death rate times the living biomass of shoots and roots, respectively. The relative death rate increases with crop age: for shoots it is calculated in such a way that approximately half of the shoot biomass is dead at crop maturity (Fournier, 1987); for roots it is arbitrarly assumed to be half that of the shoots. Shoot senescence data of Traoré (1995), who reported only 10 % of the aboveground biomass dead in December, are quite different from savannah data (Fournier, 1987; Cesar, 1992).

Water stress accelerates crop death rates (Fournier, 1983). In the current model it is assumed that the relative senescence rate of shoot and roots increases by a factor (WSESSH and WSESRT, -, respectively), defined as a function of the intensity and duration of water stress (Tables WSESST and WSESRT, file CROP.DAT).

Following crop maturity, the remaining living shoots senescence. During that period, the rate of shoot senescence is a function of air temperature and living biomass (Subsection 2.2.2).

Root death continues after crop maturity, but this process is limited by the minimum structural roots needed for reserve storage. As reserves are used, structural roots progressively die.

2.5. Storage and recirculation of non-structural carbohydrates and nutrients

It is accepted that a minimum level of energy is necessary to ensure plant survival and to start regrowth after complete defoliation or burning of perennial tropical grasses (Humphreys, 1981). Circulation of assimilates and nutrients between above and belowground parts of perennial tropical grasses has been hypothesized (de Rham, 1971; Villecourt *et al*., 1979; Abbadie, 1984; Cesar, 1992; Breman, 1991) to explain regrowth, either after burning in the dry season (most of the aboveground plant material has disappeared) or at the beginning of the rainy season (most of the aboveground plant material is dead). That could also explain the higher biomass production and nutrient store of perennial grasses in comparison to annual grasses observed in the Sahel zone (Cissé & Breman, 1980). During the last part of the growing cycle, leaves and stems wilt and die. In these processes they loose about half their dry matter (Fournier, 1987; Cesar, 1992); part of this biomass is translocated to the seeds (low demand), but the remainder could be transported to roots and basal parts of stems, where it is stored. At the beginning of regrowth, these reserves are remobilized and used to develop new rooted shoots until the plant is photosynthetically independent. In other natural ecosystems such as tundras, storage and internal recirculation of nutrients are important attributes of perennial plants, enabling them to survive where the availability of nutrients is extremely low (Berendse & Jonasson, 1992).

Some experimental evidence is available to support this hypothesis, e. g. nitrogen translocation from shoots to roots at the end of the growth cycle in the rainy season has been measured in *Andropogon gayanus* plants (Breman, 1991). However, most of the data used to support the hypothesis on storage and recirculation of carbohydrates and nutrients are indirect indications, such as the dynamics of shoot and root biomass (Fournier, 1987; Cesar, 1992) where seasonal variations in root biomass are often masked by the high variability in observed data (Fournier, 1987; Abbadie, 1984; Cesar, 1992), by the distinction between living and dead roots and by interseasonal variations, *e.g*. major drought periods, (Cesar, 1992). Further research is needed to determine whether or not the internal recirculation of nutrients and energy exists and to assess the importance of these processes.

PGWA assumes the existence of storage and internal recirculation of energy between above and belowground parts of tropical perennial grasses. Accumulation of carbohydrates takes place in the roots and stem bases of perennial herbaceous grasses (Stoddart *et al*., 1975). For *Andropogon gayanus* is assumed to occur in the upper part of the root system, which includes rhizomes and cord roots (94 % of the total dry matter of the roots, Bowden, 1963b), because of the common practice of shoot burning.

Translocation of root reserves for regrowth could start either after an effective rainfall event at the onset of the rainy season or after burning or cutting of dead aboveground biomass in the dry season, if enough water is available in the soil [higher than a threshold value set to 25 mm (CRWARC, mm, CROP. DAT)]. The length of time during which store reserves are being depleted with the onset of growth used to be a few days for grasses (White, 1973). It has been arbitrarily set to 3 and 10 days. for the dry and rainy season, respectively (TCRTDS and TCRTRS, file CROP.DAT). The rate of translocation of reserves is defined as the difference between potential and actual rate of growth and the potential growth rate is calculated with a relative growth rate (RGR, file CROP.DAT). Below a minimum concentration of the reserves, set to 0.05 kg kg^{-1} (MNCRS, file CROP.DAT), translocation stop.

As vegetative growth proceeds, there is a gradual replenishment of stored carbohydrates (Stoddart *et al*., 1975). Storage of carbohydrates is assumed to start once translocation of reserves for regrowth has ceased: a fraction of the assimilates allocated to the roots (FRBARS, -, file CROP.DAT) is stored as reserves. Moreover, if production exceeds the demand of carbohydrates, the surplus is also stored as reserves. The concentration of non-structural carbohydrates is limited to a maximum value of 0.3 kg kg^{-1} (MXCRS, file CROP.DAT) derived from data for lucerne (Versteeg, 1985).

A fraction of non-structural carbohydrates (WCWSH from shoots and WCWRT from roots, kg ha^{-1} d^{-1}) and nutrients from senescent material may be translocated to other plant parts, where it can be used either for dry matter production or stored as reserves. During the shoot senescence phase (SSS 0 to 1), non-structural carbohydrates are assumed to be used for maintenance respiration of the crop.

Once active growth ceases, stored reserves gradually decline though the dormant period, being used in respiration. That which remains at the end of the dormant season provides the material with which growth begins (Stoddart *et al*., 1975).

2.6. Survival of perennial grasses

In the Sahel and Sudan zones, the rate of crop growth during the long dry season is usually to be low (limited either by water, nutrients or climatic conditions). This could be a mechanism for avoiding or delaying extreme water stress. Normally, most of available water is depleted soon in the dry season and the aerial parts of the plant wilt and die (Cesar, 1992). Subsequently, plants remain in dormancy until the

first effective rainfall event triggers regrowth in the next rainy season. During this dormancy period plants maintain perennating buds, that become rooted shoots when conditions are favourable for plant growth. The survival mechanisms of tropical perennial grasses are not well understood, but it is accepted that perennating bud survival requires (Humphreys, 1981): - maintenance of a root system able to extract soil moisture to maintain plant turgor and promote the nutrient uptake needed for bud elongation;
- accumulation of energy to cover respiratory losses during the dormant periods and to translocate reserve carbohydrates to activate buds until they become photosynthetically independent.

These requirements are indirectly supported by experimental data.
- Perennial grasses at the dry limit of their geographical distribution area, such as *Andropogon gayanus* in the Sudan-Sahel transition subzone and the North Sudan zones disappeared from these regions after the severe drought periods of 1969-1973 and 1982-83 (Diarra, 1976; Le Houérou, 1989). If the rate of plant water uptake cannot meet the transpiration requirement to maintain plant turgor, plant water status declines and the plant dies when a critical relative water content (RWC, -) is reached. Sinclair & Ludlow (1985) reported that leaves of 27 C_4 grasses died at a average value of RWC of 25% (s.e. of 1%).

- *Andropogon gayanus* (var. *tridentatus*) plants died under forage exploitation, but not without exploitation (Cissé & Breman, 1980). Defoliation, by reducing the level of energy interception and hence carbohydrate production reduces the store of non-structural carbohydrates in the plant (Richards & Caldwell, 1985). Subsequently, plant death can occur when the energy required for maintenance of the existing biomass during the dormant period or for root activity and bud elongation at the onset of the growth period is not met.

In PGWA, plant death can be caused either by depletion of available soil water or by exhaustion of non-structural carbohydrate reserves.

Water

Transpirational demand is defined as a function of dry matter production and vapour pressure deficit (Section 8.1.3) in growing periods, and is equal to the cuticular transpiration rate in periods of aboveground biomass senescence (SSS 0 to 1) and plant dormancy. During summer dormancy, the water use of some perennial plants (*Agropyrum elongatum*, *Oryzopsis holciformis, Medicago sativa and Hordeum bulbosum*) in the Central Negev Highlands (Israel) was measurable, fluctuating from 0.1 to 0.3 mm d^{-1} (Tadmor *et al.*, 1966). PGWA assumes that cuticular transpiration rate fluctuates within this range depending on aboveground biomass.

Once available water for transpiration is used, dehydration of plants starts and they die after a few days (TCCDWE equals to 8 d, file CROP.DAT).

Non-structural carbohydrates

During crop dormancy, carbohydrates from reserves are respired to provide energy for maintenance of existing biomass. Maintenance requirements of roots and shoots are calculated using fixed coefficients and taking into account temperature effects (Penning de Vries & Van Laar, 1982). The reference temperature is assumed to be 25 deg.C. Because of the low plant activity during crop dormancy, compared with growth periods, a reduction factor, set to 0.05 (RFMR, file CROP.DAT) is used to estimate actual respiration losses.

Build-up of carbohydrate reserves in roots occurs during the growing periods (Subsection 2.5).

When non-structural carbohydrate reserves are exhausted, some structural plant parts are respired and plants die after a few days (TCCDRE equals to 8 d, file CROP.DAT).

2.7. Forage exploitation

Data on adaptation of *Andropogon gayanus* to forage exploitation seem conflicting. High forage yields of *Andropogon gayanus* were observed in a Sudano-sahelian area of Senegal with Atlantic influence (Dieng *et al.*, 1991) and in wetter areas of West Africa (Audrau *et al.*, 1966; Haggar, 1970; Barrault, 1973) and India (Singh & Chatterjee, 1968), with 3-4 cuttings per year and with fertilizer application. No plant mortality was reported. However, a very high plant mortality under light exploitation regimes in the wet season of 1974 was observed in the Sudano-Sahelian zone of Mali (Cissé & Breman, 1980), and the disappearance of *Andropogon gayanus* and other perennial grasses in the Sudano-Sahelian transition zone has also been attributed to overgrazing (Le Houérou & Guillet, 1985). In these two cases death of *Andropogon gayanus* plants occurred immediately after the prolonged drought period of 1969-73 in a zone where *Andropogoneae* perennial grass species are at the drier limit of their geographical distribution. Thus, the observed mortality of already extremely weak plants may be explained by the reduction in the carbohydrate pool caused by the forage exploitation (Caldwell *et al.*, 1981).

PGWA simulates forage exploitation in a simple way, based on the assumption that shoot biomass density is independent of height. The fraction of biomass (living and dead) removed by exploitation is calculated as the difference between height of the crop and height of exploitation (file CROP.DAT). Height of the crop is defined as a function of crop development stage, calculated as the fraction of the maximum height of the canopy (Dieng *et al.*, 1991) times the maximum canopy height. This parameter is equal to 2.5 m in the rainy season (MXHCRS, file CROP.DAT) and 1 m in the dry season (MXHCDS, file CROP.DAT) according to Dieng *et al.* (1991). The maximum height of the canopy may be lower because of previous exploitation, but water or nutrient effects on height of the canopy are not considered.

As tufted perennial grass species exhibit rapid internode elongation from the onset of stem elongation (around September for *Andropogon gayanus*), active apical and intercalary meristems are elevated and could therefore be removed by cutting or grazing. When this happens regrowth, that can only proceed after activation of new basal axillary meristems is delayed and reduced (Richards & Caldwell, 1985). In the model, removal of the active meristems by cutting or grazing from the beginning of stem elongation results in the onset of a new vegetative cycle (Audrau *et al.*, 1966) with translocation of carbohydrate reserves from roots to shoots and the death in a few days of most of the living biomass left below the exploitation height.

2.8. Soil water balance

The Sahel water balance developed by van Keulen (1975) and adapted to the Fortran Simulation Environment, version 2.0, by van Kraalingen (unpublished) is used in the model (Appendix B: DRSAHE.FOR). The soil profile is divided into a maximum number of 10 layers or compartments. Thickness of soil compartments and plant characteristics are inputs to the model (file SOIL.DAT, Appendix C).

Four specific volumetric water contents (cm^3 H_2O cm^{-3} soil) are directly or indirectly (by definition of the texture classification of each layer) required: saturation (WCST), field capacity (WCFC), wilting point (WCWP) and air dry (WCAD)

Run-off occurs when the water supplied (rainfall plus run-on) exceeds the infiltration capacity of the soil and the water accumulated at the soil surface exceeds surface storage capacity. Run-off from a field can be 0-20 % of precipitation and even higher on unfavourable soils or with large and high intensity showers (Stroosnijder & Koné, 1991). Because of lack of detailed information, infiltrated rainfall (INRAIN, mm d^{-1}), actual rainfall minus run-off (or plus run-on), is calculated with an empirical relation as a function of daily rainfall (RAIN, mm d^{-1}):

INRAIN = MAX [0, RAIN1*(RAIN - RAIN2)] (11)

RAIN1 (-) and RAIN2 (mm d^{-1}) are input parameters (file CROP.DAT)

Redistribution of the infiltrated water is assumed to occur within one day. This is reasonable except in heavy clay soils. Thus, if infiltrated water exceeds the water holding capacity of a layer, the excess drains into the next layer. If more water enters the profile than can be retained at field capacity, the excess drains below the root zone (DRAIN, mm d^{-1}). Waterlogging conditions are not simulated.

2.8.1. Evapotranspiration

Potential evapotranspiration in the Sahel, calculated with Penman's formula, varies from less than 1800 mm yr^{-1} in the south to over 2200 to the north (Cochemé & Franquin, 1967; Davy *et al.*, 1976). The difference between experimentally measured and calculated values was less than 4% (Riou, 1975). Daily potential evapotranspiration is around 4 mm d^{-1} in the cool dry season and 6.5 mm d^{-1} in the hot dry season, with lower values along the ocean shore and higher values in continental areas with strong winds (Le Houérou, 1989)

The Penman-Monteith combination equation (van Laar *et al.*, 1992) is used to calculate potential evapotranspiration (PET, mm d^{-1}) in the subroutine PETP (Appendix B).

2.8.1.1. Soil evaporation

Water losses through soil evaporation are especially important at the beginning of the rainy season when soil cover is low or absent and soil temperatures are very high. Temperature values between 50-60 deg.C were measured in June in a Sudano-Sahelian area of Mali, Stroosnijder & Koné (1991). Soil evaporation continues, albeit at a decreasing rate, until the soil is air dry. Potential soil evaporation rate (EVSC, mm d^{-1}) is calculated, taking into account shading of the soil surface by living and dead plant material, with an adaptation of Ritchie's equation (1972). An extinction coefficient for the crop canopy of 0.5 (van Laar *et al*., 1992) and SCC (m^2 m^{-2}), the shading cover of living and dead aboveground biomass, instead of leaf area index are used. SCC is tabulated as a function of total living and dead shoot biomass (Traoré, 1995):

EVSC = PET * EXP(-.5*SCC) (12)

Actual soil evaporation rate (EVSW, mm d^{-1}) is calculated using the formulation of Stroosnijder (1982) in the subroutine DRSAHE (Appendix B). A distinction is made between days with rain and days without rain. In the former case, actual evaporation rate is set equal to the potential, taking into account that the top layer cannot be depleted beyond air-dry water content. For days without rain actual evaporation rate is below the potential and the reduction is approximated using the experimental field observation that cumulative evaporation is proportional to the square root of time after the last rain (Stroosnijder, 1982, 1987). The proportionality factor (mm $d^{-1/2}$) is assumed to be equal to the product of 0.6 ($d^{-1/2}$) the potential evaporation rate times the time of integration (van Laar *et al*., 1992).

2.8.1.2. Depth and distribution of roots

The rooted depth (ZRT, m) is defined as the deepest point from which the crop effectively extracts water. The potential elongation rate of roots (PRER, m d^{-1}) is set equal to 0.08, but physical, chemical and biological factors both in the soil and in the crop can lead to lower extension rates (Hamblin, 1987). For annual cereals in temperate and Mediterranean conditions the value of PRER was around 0.02 m d^{-1} (Gregory *et al*., 1978; Barraclough & Leigh, 1984). In West African conditions a higher value of 0.03 m d^{-1} has been assumed (Jansen & Gosseye, 1986) as temperatures are more favourable. A reduction factor (WRFRE, -) is introduced to account for low soil moisture conditions where root tips are located (Salim *et al*., 1965). WRFRE is assumed to be equal to the water uptake reduction factor for that soil compartment.

The maximum rooting depth (MXRDCC, m) depends on species and cultivar characteristics: on friable soils, rooting depths of *Andropogon gayanus* of 3 m have been found (Schultze-Kraft, unpublished); this value has been set for MXRDCC. Maximum rooting depth also depends on soil characteristics (MXRDSC, m), as root penetration ceases when an impermeable layer in the profile is reached.

Moreover, generally root extension ceases around flowering (Penning de Vries *et al.*, 1989), but if water is present in the layer where root tips are located root extension may continue after flowering (Gregory *et al.*, 1978; McGowan *et al.*, 1984; Bonachela, 1991).

Most of the roots of perennial grasses in West Africa savannahs are concentrated in the upper soil layers (Menaut & Cesar, 1979; Cesar, 1992). In Ivory Coast, cumulative biomass distribution of perennial grass roots (CWRT, kg ha^{-1}) from different savannah types could accurately be described by a negative exponential function (Cesar, 1992). Similar root distribution patterns were observed in *Andropogon gayanus* in Mali (Breman, 1991; Traoré, 1995). However, the root distribution varied between the rainy and dry season: relatively more roots were found in deeper layers in the dry than in the rainy season (Traoré, 1995).

The model simulates biomass distribution of the roots on the basis of a negative exponential function:

$$\mathbf{CWRT = WSRT * (1 - e^{RTDE*DEPTH/ZRT})} \quad (13)$$

where WSRT (kg ha^{-1}) is the structural root biomass, DEPTH (m) is the depth of upper or lower boundary of a layer and RTDE is a parameter describing the extinction coefficient for the exponential function.

A value of RTDE of 5 (-), mean value from different Guinean savannahs (Cesar, 1992), is used during the rainy season. This value gives fair estimates for the root biomass distribution of *Andropogon gayanus* (Traoré, 1995) at the end of the rainy growing season, but not at the end of the dry growing season (Table 5). For that season, a value of RTDE equal to 3 gives better root distribution estimates.

Table 5. Comparison of cumulative root distribution (%) of Andropogon gayanus within the profile at the end of the rainy growing season (21.1.94) and at the end of the dry season (27.4.94) with simulated values obtained with a negative exponential function using different values of the exponent RTDE. N'Tarla (Mali).

	Measured		**Simulated**		
Season	rainy	dry			
RTDE (-)			3	5	6
Depth					
0.0 - 0.2	77	52	45	63	70
0.2 - 0.4	85	68	70	86	91
0.4 - 0.6	92	84	83	94	97
0.6 - 0.8	97	93	91	98	97

0.8 - 1.0	100	100	100	100	100

An average value of 100 m g^{-1} (Siddique *et al.*, 1990) for the specific root dry matter is used to determine root length in each rooted layer (RL, m m^{-2}).

2.8.1.3. Crop transpiration

Potential transpiration rate (MTRANS, mm d^{-1}) is determined directly from daily dry matter production, taking into account nitrogen-limited conditions (DMP, g m^{-2} d^{-1}), but not air humidity conditions (RFCAAH, Subsection 2.3.2).

Tanner & Sinclair (1983) showed that transpirational efficiency of a crop species is conservative over a wide range of conditions. Thus, on a daily basis, the transpiration rate could be estimated as (Amir & Sinclair, 1991):

MTRANS = DMP*VPD/(WUEC*10 (14)

where WUEC is the water-use efficiency coefficient, assumed to be equal to 12 Pa for *Andropogon gayanus* based on Tanner & Sinclair (1983). Mean daily vapour pressure deficit (VPD, kPa) is estimated from the air water vapour content [vapour pressure early in the morning VP (kPa)] and minimum temperature (TMMN deg.C)] and mean day temperature (MDT, deg.C), defined as (Peake *et al.*, 1978):

MDT = TMMX - 0.25*(TMMX-TMMN) (15)

where TMMX is the maximum daily temperature (deg.C)

Water uptake by the roots depends on maximum transpiration rate (MTRANS) and availability of water in the soil. For a gramineous annual crop rooting density is not, normally, considered a limiting factor for water uptake (van Keulen, 1975). Most available field data, for example for cereal crops, show no relationship between water uptake and root length density (Gregory *et al.*, 1978; Hamblin *et al.*, 1990; Siddique *et al.* , 1990). In these cases, water uptake is limited by water potential in the rooted soil volume rather than by root density (van Keulen & Seligman, 1987).

However, in some situations this assumption may be not valid. Roots of various species extracted water from the upper half of the soil profile, where most of roots are concentrated, until soil moisture potential fell below -1.5 MPa, but in deeper layers some residual water was left (Jordan & Miller, 1980; Bonachela, 1991). Jordan *et al.* (1983) suggested that the low root density in the deeper layers could limit water uptake. Moreover, below a root length density of 1 cm cm^{-3} the residual water in the profile at the end of the growth cycle increased as root length density decreased (Cooper *et al.*, 1987; Bonachela, 1991).

Perennial grass crops usually continue growth during rainless periods even when most of the available water is in the deeper soil layers, where root density is usually very low (Breman, 1991; Dieng *et al.*, 1991; Cesar, 1992). Thus, under those conditions, root density could limit the rate of water uptake and affect the rate of growth and survival of the crop. A maximum transpiration rate per unit of root length (MXTRRL) of 1.25 kg m^{-1} d^{-1} (Azam-Ali *et al.*, 1984) is used in the model to account for root density limitations.

The model treats each soil compartment individualy but compensatory water use can occur, i.e. when part of the root system is in dry soil compartments, those parts that are in wetter compartments, will take up more water (cf. Lawlor, 1973).

Water uptake by roots is equal to water demand (MTRANS) under optimum water supply, but decrease below a critical water content (water-limited conditions). The calculation of water uptake capacity under water-limited conditions is based on Doorenbos & Kassam (1979) and Driessen (1986). A critical moisture content (WCCR, cm^3 H_2O cm^{-3} soil) per soil compartment is defined that denotes the transition from potential to water-limited conditions, through the soil water depletion fraction (SWDF, -). The value of SWDF depends on species or variety and evaporative demand (Driessen, 1986).

For each soil layer, the following variables are calculated:

critical water content:

WCCR(I) = (1.-SDWF)*(WCFC(I)-WCWP(I))+WCWP(I) (16)

water availability (WACWC, mm d^{-1}) before water stress can occur:

WACWC(I) = MAX(0., (WCLQT(I)-WCCR(I))*TKL(I)*1000) (17)

maximum water extractable by roots (WARL, mm d^{-1}), obtained by multiplying the maximum transpiration rate per unit root length (kg H_2O m^{-1} root d^{-1}) by the root length (RL, m m^{-2}):

WARL(I) = MXTRRL*RL(I) (18)

maximum water availability (mm d^{-1}) taking into account water availability and root length:

MXWA(I) = MIN (WACWC(I), WARL(I)) (19)

a reduction factor for water uptake due to low water availability (-):

RFWU(I) = MIN(1., MAX(0.,(WCLQT-WCWP(I))/(WCCR(I)-WCWP(I)))) (20)

Thus, the rate of water wptake for transpiration for each soil layer is calculated as:

TRWL(I) =MTRANS* ERL(I)/ERLB * RFWU(I) (21)

where ERL is effective root length (m m^{-2}) per layer, that it is equal to the root length (RL, m m^{-2}), and ERLB is the cumulative effective root length (m m^{-2}).

If total available water within the rooted profile is higher than the water demand (MTRANS) water supply is optimal (rate of water uptake from layers where RFWU is equal to 1 is increased to compensate for those layers with RFWU below 1); alternatively the crop is under water stress and the transpiration rate is below the potential.

The sum of TRWL over the profile is actual transpiration (TWE, mm d^{-1}). The ratio between actual and potential transpiration rate is the transpiration ratio (TRANSR, -).

3. User's manual

3.1. Introduction

This chapter guides users in running the model and also offers field researchers the possibility to contribute to further development of the model. Many of the model assumptions have been introduced in the form of input parameters in the file CROP.DAT and, therefore, can be easily modified.

A separate description of the Fortran Simulation Environtment (version 2) and the SAHEL water balance is in preparation (contact to D.W.G. van Kraalingen). The description of the WEATHER system (van Kraalingen *et al.* , 1991), RADIAT and PENMAN (van Kraalingen & Van Keulen, 1987) and the TTUTIL system (Rappoldt & Van Kraalingen, 1990) can be obtained from the AB-TPE group. These modules will therefore not be further treated in this manual.

3.2. Model framework

The PGWA model consists of the following parts:

- framework module, FSE 2.0
- modules manager, MODELS
- modules
    - emergence and regrowth (PGCR)
    - beginning of the rains (PGRAIN)
    - water uptake (PGWU)

    - water balance (DRSAHE)
    - potential evaporation (PETP, PENMAN and ASTRO)
    - crop growth (PGDM)
        - phenology (PGPHE)
        - forage exploitation (PGEXP)
- Weather and TTUTIL
- Input files:
    - TIMER.DAT (FSE, MODELS)
    - CONTROL.DAT (FSE)
    - WEATHER.DAT (FSE)
    - RERUNS.DAT (FSE)
    - CROP.DAT (PGDM, MODELS)
    - SOIL.DAT (DRSAHE)

3.3. Additional information

3.3.1. PGRAIN module

PGRAIN determines the beginning of the rainy season (DBRR, doy) each year. DBRR tries to simulate the start of regular rains. It is calculated using the Hiernaux (1984) definition: DBRR is defined as the first day with rain equal to or higher than 25 mm (RAIN1, file CROP.DAT) or the first of five consecutive days with accumulated rain equal to or higher than 25 mm (RAIN3, file CROP.DAT). To reduce the effect of very early rains in the year, outside the main rainy season, an additional condition, i. e. that accumulated rain during 20 days (TCRD1, file CROP.DAT) following the possible date of start of the rainy season must be higher than 20 mm (RAIN3, file CROP.DAT), has been included.

3.3.2. Crop data file (CROP.DAT)

Depending on data availability, different approaches can be used to simulate crop development (Appendix B: PGPHE.FOR). Before running the model, definition of the integer variables IVPDRS and IVPDDS permit select one of them:
- IVPDRS or IVPDDS is equal to 0 when the flowering date is known; in that case values have to be assigned to the integer variable FDRS and also to FDDS (Appendix A) if occurs flowering in the dry season.
- IVPDRS is equal to 1 when flowering date is estimated from the geographical data of the site (LATS and LONGS). This approach can only be used in the rainy season.
- IVPDRS or IVPDDS is equal to 2 when flowering date is estimated from daylength and temperature data. In that case site-specific or accession-specific values have to be assigned to the variables C2, D2 and TUEA.

IVPDRS or IVPDDS = 0
FDRS : flowering date in rainy season

FDDS : flowering date in the dry season
IVPDRS = 1
LATS : latitude of the simulation site
FDDS : flowering date in the dry season, if present
IVPDRS or IVPDDS = 2
BTD : base temperature for development
TUEA : thermal sum from emergence to anthesis
CRDAYL : critical daylength

For the post-anthesis and crop senescence phases accession-specific values have to be assigned to TUAM and TUMD variables.

Shoot nitrogen data can be introduced as follows:
- as a function of development stage (IVSCNS equals 0);
- as a function of day of the year (IVSCNS equals 1).

Forage exploitation always occurs, by burning (TYPEXP equals 0) or cutting (TYPEXP equals to 1, cutting height can be selected with the variable HEC, m), at the end of the shoot senescence phase in the dry season.

Exploitation of forage may be simulated using either of three approaches:
- by introducing the date of the first exploitation, the time interval between exploitations and their total number;
- by introducing the critical value of aboveground biomass that triggers exploitation;
- by introducing the development stages at which exploitation is triggered.
The selection among these aproaches is governed by the integer variables EDRS in the rainy season and EDDS in the dry season:
- EDRS = 0 or EDDS = 0, for the time interval approach;
- EDRS = 1 or EDDS = 1, for the critical biomass approach;
- EDRS = 2 or EDRS = 2, for the critical phenological stage approach.

The soil water depletion fraction (SWDF) for *Andropogon gayanus* can be determined from crop groups 4 and 5 (Doorenbos *et al*., 1978).

3.3.3. Soil data file (SOIL.DAT)

Basic input requirements:
TKL : thickness of soil compartments
WCLQT : initial water content

Soil moisture characteristics can be defined by the user:
WCAD : water content at air dry;

WCWP : water content at wilting point;
WCFC : water content at field capacity;
WCST : water content at saturation.

For more information about the DRSAHE water balance contact to D.W.G. van Kraalingen (AB-DLO).

3.3.4. Timer file (TIMER.DAT)

In the TIMER.DAT file (Appendix C) an integer variable (IVSSC) has been introduced to select the starting point of the model (there are two possible ways of running PGWA):
- if IVSSC is equal to 0 the model simulates several subsequent growing years from sowing; sowing date (SD) must be defined in file CROP.DAT.
- if IVSSC is equal to 1 the model simulates several subsequent years from an established crop; initial values of aboveground (IWSH) and belowground biomass (IWRT) and rooting depth (IZRT) must be defined in the CROP.DAT file.
The model must always start before the beginning of the rainy season (parameter DAYB).

Basic input requirements
DAYB : start day of simulation
FINTIM : last day of simulation
IYEAR : start year of simulation
WTRDIR : directory of weather data
CNTR : country code of weather data
ISTN : station number of weather data
IVSSC : Selection of the starting point of the model
IVSSC = 0
SD : sowing date
IVSSC = 1
IWSH : initial shoot weight
IWRT : initial root weight
IZRT : initial rooting depth

3.3.5. Control file (CONTROL.DAT)

This file is used to name the timer, crop, and soil files.

Appendix A: List of variable acronyms PGWA model

Appendix B: PGWA Fortran modules

Appendix C: PGWA data files

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Appendix A: List of variable acronyms PGWA model

A auxiliar variable to calculate flowering date d PENMAN
A1 parameter used in the flowering date equation d PGPHE
A1GRRS auxiliar variable used to calculate rate of reserves growth

kg ha-1 PGDM =
A1GRSH auxiliar variable used in the calculation of shoot growth
rate kg ha-1 PGDM =
A1MRRC auxiliar variable used to calculate rate of maintenance
crop respiration kg ha-1 d-1 PGDM =
A1SDND auxiliar variable used to calculate the date when shoots
die (nitrogen deficiency) - PGDM =
A2 parameter used in the development rate equation d-1 PGPHE
A2GRRS variable used to calculate storage of non-structural
carbohydrates kg ha-1 PGDM =
ACR variable used to calculate cumulative rainfall (onset of
regular rains) mm PGRAIN =
ACR1 variable used to calculate cumulative rainfall (onset of
regular rains) mm PGRAIN =
ADMP actual dry matter production kg ha-1 d-1 PGDM =
ADR cumulative daylength reduction from maximum daylength date to
flowering date h PGDR =
PGPHE
ADWSRT auxiliar variable used to calculate water stress effects on

root senescence - PGDM =
ADWSSH auxiliar variable used to calculate water stress effects on

shoot senescence - PGDM =
AIRDR parameter for airdry m3 m-3 DRSAHE =
ALB albedo of a vegetation/soil system for a herbaceous vegetation

- PETP =
ANCR amount of nitrogen in the crop kg ha-1 PGDM =
ANGA parameter of the Ängstrom equation - MODELS
PETP
ANGB parameter of the Ängstrom equation - MODELS
PETP
ANRT amount of nitrogen in roots kg ha-1 PGDM =

ANSH amount of nitrogen in shoots kg ha-1 PGDM =
ANSHDS amount of shoot nitrogen in the dry season kg ha-1 PGDM =
ANSHRS amount of shoot nitrogen in the rainy season kg ha-1 PGDM =
AOB auxillary variable - ASTRO =
ASRQCR assimilate requirement for crop dry matter kg CH2O kg-1 DM crop PGDM =
ASRQRT assimilate requirement for root dry matter kg CH2O kg-1 DM root PGDM
ASRQSH assimilate requirement for shoot dry matter kg CH2O kg-1 DM

shoot PGDM
ASRQSO assimilate requirement for storage organ dry matter kg CH2O

kg-1 DM storage organ PGDM
ATMTR atmospheric transmission - PETP =
PENMAN
AV1GRR auxiliar variable used to estimate the rate of reserve growth kg ha-1 d-1 PGDM =
AV1WU auxiliar variable used for water compensation between soil layers - PGWU =
AVAIL amount of water in the soil stored above airdry per layer mm

d-1 DRSAHE =
AVANSH auxiliar variable used to calculate rate of shoot growth kg

ha-1 PGDM =
AVCDRE auxiliar variable used to trigger crop death (reserves exhaustion) d PGDM =
AVCDWE auxilar variable used to trigger crop death (soil water depletion) d PGDM =
AVCL1 do loop counter d PGEXP =
AVCL2 do loop counter d PGEXP =
AVCRS auxiliar variable used to re-allocate non-structural carbohydrates
(limited by a maximum reserve concentration) kg kg-1 PGDM =
AVCWRT cumulative weigth of roots in the soil profile kg ha-1 PGWU

=
AVDE auxiliar variable used to count the number of days d PGEXP =
AVDMP cumulative shoot growth in the five last days of simulation kg ha-1 PGDM =
AVDNCC real value of the integer variable DNCC d PGDM =
AVGRRS auxiliar variable used to estimate growth rate of root

reserves kg ha-1 d-1 PGDM =
AVGRRT auxiliar variable used to estimate growth rate of
structural roots kg ha-1 d-1 PGDM =
AVGRSH auxiliar variable used to estimate growth rate of shoots kg

ha-1 d-1 PGDM =
AVHCDS auxiliar variable used to estimate height of crop canopy in

the dry season kg ha-1 d-1 PGDM =
AVHCRS auxiliar variable used to estimate height of crop canopy in

the dry season kg ha-1 d-1 PGDM =
AVMHDB auxiliar variable to estimate maximum height of dead shoots

m PGDM =
AVMRRC auxiliar variable used in the calculation of the rate of
crop maintenance respiration kg ha-1 PGDM =
AVNCSH threshold value of shoot nitrogen concentration, below
which the shoot growth rate
is progressively reduced kg kg-1 PGDM =
AVRAD local equivalent of daily total solar radiation J m-2 d-1
PENMAN
AVRFWU auxiliar variable used to calculate a reduction factor
affecting water uptake - PGWU =
AVRTRT auxiliar variable used to calculate reserve translocation
to roots kg ha-1 PGDM =
AVRTSH auxiliar variable used to calculate reserve translocation
to shoots kg ha-1 PGDM =
AVSDND auxiliar variable used to calculate the date of shoot death

(nitrogen limitation) - PGDM =
AVSE1 auxiliar variable used to separate dead and living shoots
removed by exploitation - PGDM =
AVSE2 auxiliar variable used to separate dead and living shoots
removed by exploitation m2 PGDM =
AVSE3 auxiliar variable used to separate dead and living shoots
removed by exploitation m2 PGDM =
AVSGND threshold value of shoot nitrogen concentration used in the

calculation of
the shoot growth rate under limited-nitrogen conditions kg kg-1
PGDM =
AVSS auxiliar variable used to simulate water stress effects on

crop phenology d PGDM =
PGPHE =
AVSS1 auxiliar variable to simulate water stress effects on
phenology - PGPHE =
AVTWD auxiliar variable used in the calculation of cumulative
water drainage mm PGWU =
AVVP array variable used to store vapour pressure values in the
ten last days of simulation kPa PGDM =
AVWDRT auxiliar variable used to estimate weight of dead roots kg
ha-1 PGDM =
AVWU array variable used for water compensation between soil
layers - PGWU =
B local equivalent of coefficient of the Ångström equation -
PENMAN
B1 parameter of the flowering date equation d degrees-1 PGPHE
B2 parameter of the development rate equation d-1 h-1 PGPHE
BALANS intermediate variable used to check the biomass balance kg
ha-1 PGDM =
BG date of beginning of crop regrowth d PGDM =
PGPHE =
BGDS date of beginning of crop regrowth in the dry season d PGDM =
PGPHE =
BTD base temperature for crop development °C PGPHE
BU coefficient in wind function for calculating evaporative demand

s m-1 PENMAN =
C1 parameter of the flowering date equation d degrees-1 PGPHE
CAP maximum water flow which can be stored in a soil layer mm d-1
DRSAHE =
CDMP average dry matter production in the last five days of
simulation kg ha-1 d-1 PGDM =
CHECK water balance check variable mm DRSAHE =
CHKPBB variable used in the biomass balance kg ha-1 PGDM =
CIR cumulative infiltrated rainfall mm PGWU =
CIRDS cumulative infiltrated rainfall in the dry season mm PGWU =
CIRRS cumulative infiltrated rainfall in the rainy season mm PGWU
=
CORF auxiliar variable used to do the biomass balance kg ha-1 d-1
PGDM =
COSLD amplitude of sine of solar height - ASTRO =
MODELS
PGDR
CR cumulative rain per year mm PGWU =

CRDAYL critical photoperiodically active daylength h PGPHE
CRDD cumulative radiation MJ m-2 PGDM =
CRDP cumulative rainfall in the dormant phase mm PGWU =
CRDS cumulative rainfall in the dry season mm PGWU =
CRRS cumulative rainfall in the rainy season mm PGWU =
CRSRT concentration of reserves in roots kg kg-1 PGDM =
CRTRCT critical transpiration ratio below which crop assimilation
stops - PGDM
PGPHE
CRVPD critical vapour pressure deficit (crop assimilation
limitation) kPa PGDM
CRVPER critical vapour pressure to indicate the end of the rainy
season kPa PGDM
CRWARC critical amount of water extractable by the roots that
trigger a new regrowth mm PGDM
CRWCCG multiplication factor used to calculate critical water
content in crop germination - PGCR
CRWCCS critical water content value for crop regrowth m3 m-3 PGCR

CSHRTR maximum value of the root:shoot ratio for new root growth -

PGDM
CVP cumulative vapour pressure in the ten last days of simulation
kPa PGDM =
CWDRT cumulative weight of dead roots kg ha-1 PGDM =
CWDSH cumulative weight of dead shoots kg ha-1 PGDM =
CWRT auxiliar variable used to calculate cumulative weight of
roots kg ha-1 PGWU =
CWSEDS threshold value of aboveground biomass from which
exploitation occur
in the dry season kg ha-1 PGEXP
CWSERS threshold value of aboveground biomass from which
exploitation occur
in the rainy season kg ha-1 PGEXP
CWV concentration of water vapour kg m-3 PGDM =
DAYL astronomic daylength h ASTRO =
MODELS
PGDR
DAYLF daylength at flowering date h PGDR =
DAYLP photoperiodically active daylength h ASTRO =
MODELS
PGDR

PGDM
PGPHE
DBRR date of beginning of the regular rains d PGRAIN =
PGDM
DCGS days after the onset of crop growth simulation d PGPHE =
DEC declination of the sun radians ASTRO =
DELT time step of integration d DRSAHE
MODELS
PETP
PGDM
PGPHE
DELTA derivative of satured vapour pressure with respect to
temperature mbar K-1 PENMAN =
PETP
DEPTH depth of the centre of each soil compartment m DRSAHE =
PGWU =
DFAR day of the year when the first active rainfall event occur d
PGRAIN =
PGDM
DGSE day of the year when growth start after crop exploitation d
PGDM =
DLAI leaf area index of living and dead leaves m2 m-2 PETP =
PGDM =
MODELS
DLSE auxillary variable for number of soil layer - DRSAHE =
DMND day of the year when minimum daylength occur d PGDR =
PGPHE
DMP dry matter production kg ha-1 d-1 PGDM =
DMXD day of the year when maximum daylength occur d PGDR =
PGPHE
DNCC number of days after a regrowth cycle start d PGPHE =
PGDM
DOY day number within the year of simulation d MODELS
DR difference in day length between a given day value and the
maximum value of the year h PGDR =
DRAICU cumulative value of water percolation beyond total soil
profile mm DRSAHE =
MODELS
PGWU
DRAIQT percolation of water beyond total soil profile mm DRSAHE =
DRRT death rate of roots kg ha-1 d-1 PGDM =
DRRT1 death rate of roots in the growth phase kg ha-1 d-1 PGDM =
DRRT2 death rate of roots in the shoots death phase kg ha-1 d-1

PGDM =
DRRT3 death rate of structural roots after reserves have been used

kg ha-1 d-1 PGDM =
DRSH actual death rate of shoots kg ha-1 d-1 PGDM =
DRSH1 death rate of shoots during growth phases kg ha-1 d-1 PGDM =
DRSH2 death rate of shoots during shoot death phases kg ha-1 d-1
PGDM =
DRSHEX death rate of shoots remaining after exploitation kg ha-1
d-1 PGDM =
DS0 daily extraterrestrial radiation J m-2 d-1 ASTRO =
MODELS
PETP
PGDR
DSINB daily total of sine of solar height s ASTRO =
MODELS
PGDR
DSINBE daily total of effective solar height s ASTRO =
MODELS
PGDR
DSLR number of days without significant infiltration counted from
the last day
with significant infiltration d DRSAHE =
DVR development rate d-1 PGDM =
PGPHE =
DVR1 development rate from emergence to crop flowering d-1 PGPHE =
DVR2 development rate from flowering to crop maturity d-1 PGPHE =
DVRC constant value of development rate d-1 PGPHE
DVS development stage - PGDM =
PGPHE =
PGEXP
DVSEDS array variable used to indicate development stage when
exploitation occur
in the dry season - PGEXP
DVSERS array variable used to define development stage when
exploitation occur
in the rainy season - PGEXP
DVSEX variable used to estimate development stage after
exploitation - PGPHE =
DWD auxiliar variable equal to daily water drainage rate mm d-1
PGWU =
E0 potential evaporation of open water mm d-1 PENMAN =
PETP =

E4 conversion constant m2 ha-1 PETP =
EA isothermal evaporation mm d-1 PENMAN =
EAC evaporative demand of the atmosphere mm d-1 PENMAN =
PETP
ECTTB table of epidermical transpiration as a function of living
biomass mm d-1 PGWU
EDAYDS variable used to count number of days and used to simulate
crop exploitation
in the dry season d PGEXP =
EDAYRS variable used to count number of days and used to simulate
crop exploitation
in the reany season d PGEXP =
EDDS option to select a simulation approach for forage
exploitation in the dry season - PGEXP
EDRS option to select a simulation approach for forage
exploitation in the rainy season - PGEXP
EDS variable used to define whether or not exploitation occur in
the dry growth season - PGEXP
EES soil evaporation proportionality factor m-1 DRSAHE
ELEV elevation of the site m MODELS
PENMAN
PETP
EMERG flag to indicate emergence date - PGCR =
PGDM =
MODELS
EMERGD emergence date d PGDM =
EPSIL initial global radiation use coefficient g MJ-1 PGDM
ERL effective root length per soil layer m m-2 PGWU =
ERLB cumulative effective root length m m-2 PGWU =
ERS variable used to know whether or not exploitation occur in the

rainy growth phase - PGEXP
ES0 potential evaporation of soil mm d-1 PENMAN =
PETP =
ET0 potential evapotranspiration mm d-1 PENMAN =
PETP =
ETRANS epidermical transpiration mm d-1 PGWU =
EVAPD drying power term of ET0 mm d-1 PETP =
EVAPR radiation term of ET0 mm d-1 PETP =
EVSC potential soil evaporation rate mm d-1 DRSAHE =
PETP =
MODELS
EVSD soil evaporation rate as function of DSLR mm d-1 DRSAHE =

EVSH soil evaporation rate as function of available soil water mm
DRSAHE =
EVSW actual soil evaporation rate mm d-1 DRSAHE =
MODELS
PGWU
EVSW2 intermediate value of EVSW mm d-1 DRSAHE =
EVSWCU cumulative evaporation mm DRSAHE =
MODELS
EXPDVS flag to indicate whether or not exploitation will affect
crop development stage - PGPHE =
PGDM
EXPTYP type of exploitation when the whole aboveground biomass
produced in the rainy
season dies - PGEXP
FBRT fraction of biomass allocated to roots - PGDM =
FBSH fraction of biomass allocated to shoots - PGDM =
FBSHTB table of biomass allocation to the shoots - PGDM
FCNART fraction of crop nitrogen allocated to roots - PGDM =
FCWRT fraction carbohydrates withdrawn from dead roots - PGDM
FCWSH fraction of carbohydrates withdrawn from the dead shoots -
PGDM
FD date of flowering d PGPHE =
FDBRE fraction of dead aboveground biomass removed by exploitation

- PGDM =
FDDS date of flowering in the dry season d PGPHE
FDRS date of flowering in the rainy season d PGPHE =
PGDM
PGDR
FIELD parameter for field capacity m3 m-3 DRSAHE =
FILEI1 name of input file no. 1 - MODELS
PGCR
PGDM
PGEXP
PGPHE
PGRAIN
PGWU
FILEI2 name of input file no. 2 - MODELS
FILEI3 name of input file no. 3 - MODELS
FILEI4 name of input file no. 4 - MODELS
FILEI5 name of input file no. 5 - MODELS
FILEIT name of timer input file - MODELS
FILIN name of file with soil data - DRSAHE

FINTIM finish time of simulation d MODELS
FLBRE fraction of living aboveground biomass removed by
exploitation- - PGDM =
FLOW infiltration into the upper layer mm d-1 DRSAHE =
FLXCU cumulative flux for each layer boundary mm DRSAHE =
MODELS
FLXQT layer boundary fluxes (rates) mm d-1 DRSAHE =
MODELS
FMHCTB table of fraction of maximum height of crop canopy - PGDM
FRABS fraction absorbed PAR or RDD per species - PETP =
FRBARS fraction of root growth allocated to reserves - PGDM
FSBRE fraction of standing biomass removed by exploitation - PGDM
=
GAMMA psychometric constant mbar K-1 PENMAN =
PETP
GRCR actual growth rate of the crop kg ha-1 d-1 PGDM =
GRNSH maximum daily amount of nitrogen allocated to shoots kg ha-1

d-1 PGDM =
GRRS actual growth rate of reserves kg ha-1 d-1 PGDM =
GRRT actual growth rate of structural roots kg ha-1 d-1 PGDM =
GRSH actual growth rate of shoots kg ha-1 d-1 PGDM =
GRSHTB table of maximum growth rate of shoots kg ha-1 d-1 PGDM
HCC crop canopy height m PGDM =
PGEXP =
HCCDS height of crop canopy in the dry season m PGDM =
HCCRS height of crop canopy in the rainy season m PGDM =
HE height above soil surface of forage exploitation m PGEXP =
PGDM
HEC height above soil surface of forage exploitation after the
whole aboveground biomass
produced in the rainy season die m PGEXP
HEDS height above soil of forage exploitation in the dry season m
PGEXP
HERS height above soil of forage exploitation in the rainy season
m PGEXP
HLP1 local auxiliar variable used used to calculate water balance
in DRSAHE module - DRSAHE =
I do loop counter - PGCR
PGDM
PGEXP
PGRAIN
PGWU

I1 do loop counter - PGDM =
PGRAIN
I2 do loop counter - PGRAIN
I3 do loop counter - PGRAIN
IBR variable used to indicate the onset regrowth d PGDM =
ICE1 auxiliar variable used to calculate soil compartment number
used in crop emergence
simulation m PGCR =
ICE2 auxiliar variable used to calculate the number of soil
compartments used in
crop regrowth simulation m PGCR =
IDMP initial value of DMP kg ha-1 PGDM =
IDOY julian day number d ASTRO
MODELS
PGDM
PGDR
PGPHE
PGRAIN
PGWU
PGEXP
IDOY1 auxiliar variable equal to julian day number d PGPHE =
IECTTN epidermical transpiration as a function of living biomass
mm d-1 PGWU
IEDS time interval between two exploitations in the dry season d
PGEXP
IEDS1 date when the first forage exploitation occur after BGDS d
PGEXP
IERS time interval between two exploitations in the rainy season d

PGEXP
IERS1 date when the first forage exploitation occur after BGRS d
PGEXP
IFBSHN number of elements in FBSHTB - PGDM
IFMHCN number of elements in the FMHCTB table - PGDM
IGRSHN number of elements in GRSHTB - PGDM
IL soil layer indication number - DRSAHE
IMHDBN number of elements in MHDBTB - PGDM
IMNL local equivalent of INLAYX (number of soil compartiments) -
DRSAHE =
IMNNCR number of elements in MNNCRT - PGDM
IMNNCS number of elements in MNNCST - PGDM
IMXNCS number of elements in MXNCST - PGDM
IN deepest soil compartment at which root growth occurs - PGWU =

MODELS
INARTN number of elements in NARTTB - PGDM
INF water infiltration rate into the soil mm d-1 DRSAHE =
INFCU cumulative infiltration mm DRSAHE =
MODELS
INLAY number of soil compartments - DRSAHE =
PGWU =
MODELS
INLAYX number of soil compartiments - MODELS =
DRSAHE
PGCR
PGDM
PGWU
INRAIN infiltrated rainfall mm MODELS =
PGRAIN =
PGWU
INTBMX integer variable to set size of local arrays - PGDM =
PGEXP =
PGWU =
IRDRTN number of elements in RDRTTB - PGDM
IRDSHN number of elements in RDSHTB - PGDM
ISDSAN number of elements in SSATB - PGDM
ISHNDS number of elements in SHNDST - PGDM
ISHNRS number of elements in SHNRST - PGDM
ISSAN number of elements in SSATB - PGDM
ISTAT2 variable used in the WEATHR routine - PGRAIN
ISWDFN number of elements in SWDFTB - PGWU
ITASK task that subroutine should perform - DRSAHE
MODELS
PETP
PGCR
PGDM
PGEXP
PGPHE
PGRAIN
PGWU
ITMP intermediate variable in calculation of the soil moisture characteristic - DRSAHE =
ITYL integer version of TYL (type of soil per compartment) - DRSAHE =
IUNIT unit number to be used, see file usage below - DRSAHE
IUNITD unit that can be used for input files - MODELS
PGCR

PGDM
PGEXP
PGPHE
PGRAIN
PGWU
IUNITL unit used for log file - MODELS
IUNITO unit of output file - MODELS
PGEXP
PGCR
PGDM
PGPHE
PGRAIN
PGWU
IUNLOG local equivalent of IUNITL - DRSAHE
IVCG auxiliar variable used to calculate crop emergence date d
PGCR =
IVCG1 auxiliar variable used to calculate crop emergence date d
PGCR =
IVCS auxiliar variable used to calculate crop sprouting date d
PGCR =
IVCS1 auxiliar variable used to calculate crop sprouting date d
PGCR =
IVEF auxiliar variable used to estimate sowing failure d PGCR =
IVEF1 auxiliar variable used to estimate sowing failure d PGCR =
IVPDS option to select the simulation approach for crop
development in the dry season - PGPHE
IVPRS option to select the simulation approach for crop
development in the rainy season - PGPHE
IVRT variable used to indicate when reserves mobilisation occur -
PGDM =
IVSCNS option to select how crop nitrogen data are supplied - PGDM

IVSF auxiliar variable used to estimate sprouting failure d PGCR =
IVSF1 auxiliar variable used to estimate sprouting failure d PGCR
=
IVSSC option to select the crop status at the onset of crop
simulation - PGDM =
MODELS
PGCR
IWDRT initial weight of dead roots of an stablished crop kg ha-1
PGDM
IWDSH initial weight of dead shoot of an stablished crop kg ha-1

PGDM
IWRS initial weight of reserves of and stablished crop kg ha-1
PGDM
IWRT initial weight of roots of an stablished crop kg ha-1 PGDM
IWRTS Initial weight of roots at emergence kg ha-1 PGDM
IWSERS number of elements in WSERST - PGDM
IWSESS number of elements in WSESST - PGDM
IWSH initial weight of stems of an stablished crop kg ha-1 PGDM
IWSHS initial weight of shoots at emergence kg ha-1 PGDM
IYEAR year of simulation - MODELS
IZRT initial root depth after crop emergence or sprouting m PGCR =
MODELS
PGDM
IZRT1 initial root depth at onset of crop regrowth m PGDM
IZRTR initial root depth at crop sprouting m PGCR
PGDM
IZRTS initial root depth at crop regrowth m PGCR
KL PAR extinction coefficient - MODELS
PETP
LAI leaf area index m2 m-2 PETP =
PGDM =
MODELS
LAT latitude of weather station degrees MODELS
LATS latitude of simulation site degrees ASTRO
MODELS
PGDM
PGDR
PGPHE
LDRT last day of reserves translocation d PGDM =
LHVAP latent heat of evaporation of water J kg-1 PENMAN =
LHVP latent heat of evaporation of water J kg-1 PENMAN =
PETP
LONGS longitude of the site degrees PGPHE
LVCC flag to trigger a new regrowth after exploitation - PGPHE =
LVCDDS flag to identify a crop senescence phase after a dry growth

season - PGDM =
PGPHE =
PGEXP
LVCDP flag to identify crop dormant phase - PGDM =
PGPHE =
PGEXP
LVCDRS flag to indentify a crop senescence period after the rainy

growing season - PGDM =
PGPHE =
PGEXP
LVCGDS flag to identify a crop growth phase in the dry season -
PGDM =
PGPHE =
PGWU =
PGEXP
MODELS
LVCGRS flag to indentify a crop growth period in the rainy season
- PGDM =
PGPHE =
PGWU =
PGEXP
MODELS
LVCS flag to indicate that crop growth simulation start -, MODELS
=
PGDM =
PGWU =
PGEXP
PGPHE
LVDMA logical variable to indicate that exploitation has occurred
- PGDM =
LVEX flag to indicate whether or not exploitation has occurred -
PGEXP =
PGPHE =
PGDM
LVRSVP logical variable to indicate the occurrence of the rainy
season - PGDM =
LVSS logical variable that indicates whether or not shoot death is

going to occur (water stress) - PGPHE =
PGDM
LWRT rate of losses of roots kg ha-1 d-1 PGDM =
LWSH rate of losses of shoots kg ha-1 d-1 PGDM =
MAINRT maintenance respiration coefficient of roots kg CH2O PGDM
MAINSH maintenance respiration coefficient of shoots kg CH2O PGDM

MAINSO maintenance respiration coefficient of storage organs kg
CH2O PGDM
MDSE maximum depth affected by soil evaporation (mod.) m DRSAHE
MDT mean day temperature °C PGDM =

MHDB maximum height of dead shoots m PGDM =
MHDBTB table of maximum height of dead shoot as a function of DVS
- PGDM
MNCRS minimum concentration of reserves kg kg-1 PGDM
MNDAYL minimum value of photoperiodically active daylength h PGDR
=
MNNCRT minimum nitrogen concentration in roots kg kg-1 PGDM =
MNNCSH minimum nitrogen concentration in shoots kg kg-1 PGDM =
MNNCST table of minimum nitrogen concentration in shoots kg kg-1
PGDM
MRRCR maintenance respiration rate of crop kg ha-1 d-1 PGDM =
MRRRS maintenance respiration rate of storage organs kg ha-1 d-1
PGDM =
MRRRT maintenance respiration rate of roots kg ha-1 d-1 PGDM =
MRRSH maintenance respiration rate of shoots kg ha-1 d-1 PGDM =
MSVPDT mean day saturated vapour pressure kPa PGDM =
MSWCA gamma in Driessen equation (user-defined) - DRSAHE
MSWCAT gamma in Driessen equation (standard set) - DRSAHE =
MTRANS maximum crop transpiration (no water limitations) mm d-1
PGDM =
PGWU =
MODELS
MVP mean daily value over 10-days intervals of vapour pressure
early in the morning kPa PGDM =
MVPDT mean day vapour pressure kPa PGDM =
MXAR maximum amount of assimilates remobilisated kg ha-1 d-1 PGDM

MXCRS maximum concentration of reserves in the roots kg kg-1 PGDM

MXDAYL maximum value of photoperiodically active daylength h PGDR
=
PGPHE
MXDMP maximum dry matter production kg ha-1 d-1 PGDM =
MXGRCR maximum growth rate of the crop kg ha-1 d-1 PGDM
MXGRRS maximum growth rate of reserves kg ha-1 d-1 PGDM
MXGRSH maximum growth rate of shoots kg ha-1 d-1 PGDM =
MXHCDS maximum crop canopy height in the dry season m PGDM
MXHCRS maximum crop canopy height in the rainy season m PGDM
MXNCSH maximum nitrogen concentration in shoots kg kg-1 PGDM =
MXNCST table of maximum nitrogen concentration in shoots kg kg-1
PGDM

MXTDM total dry matter per crop cycle kg ha-1 PGDM =
MXTRRL maximum transpiration rate per unit of root length kg m-1
d-1 PGWU
MXTWD maximum total water drainage per crop cycle mm PGWU =
MXTWE maximum total water evaporated per crop cycle mm PGWU =
MXTWT maximum total water transpired per crop cycle mm PGWU =
MXTWU cumulative evapotranspiration per year mm PGWU =
MXVPD maximum vapour pressure deficit for crop assimilation kPa
PGDM
MXWA available water above the critical water content and taking
into account the
maximum transpiration rate of roots (layer) mm d-1 PGWU =
MXWAWS available water above the critical water content and taking

into account
the maximum transpiration rate of roots (rooted profile) mm d-1
PGWU =
MXWCR maximum weigth of the crop in the rainy season kg ha-1 PGDM
=
MXWCRD maximum weigth of the crop in the dry season kg ha-1 PGDM =
MXWRT maximum weigth of roots in the rainy season kg ha-1 PGDM =
MXWRTD maximum weigth of roots in the dry season kg ha-1 PGDM =
MXWSH maximum weigth of shoots in the rainy season kg ha-1 PGDM =
MXWSHD maximum weigth of shoots in the dry season kg ha-1 PGDM =
NARTTB table of nitrogen allocated to the roots - PGDM
NCRT nitrogen concentration in roots kg kg-1 PGDM =
NCSH nitrogen concentration in shoots kg kg-1 PGDM =
NEDS number of cuttings in the dry season - PGEXP
NERS number of cuttings in the rainy season - PGEXP
NL local equivalent of INLAY - DRSAHE
NRDTYP number of soil types defined (Rijtema/Driessen system) -
DRSAHE =
NSCCG number of soil compartments used in crop germination
simulation - PGCR =
NSCCS number of soil compartments used in crop regrowth simulation

- PGCR =
NSH shoot nitrogen g m-2 PGDM =
NUE overall shoot nitrogen use efficiency g g-1 d-1 PGDM =
NVGTYP number of soil types defined (Van Genuchten system) -
DRSAHE =
OUTPUT flag to indicate if output should be done - DRSAHE
PETP

PGDM
PGPHE
PGWU
MODELS
P initial shoot nitrogen use coefficient g g-1 d-1 PGDM
PBAR barometric pressure mbar PENMAN =
PBRS possible date of onset of regular rains d PGRAIN =
PCE potential crop evapotranspiration mm d-1 PETP =
PCRS auxiliar variable used to calculate concentration of reserves

kg kg-1 PGDM =
PF relative moisture content as function of pF (array) - DRSAHE =
PFWC00 pF values at a relative water content of 0.0 (array) -
DRSAHE
PFWC01 pF values at a relative water content of 0.1 (array) -
DRSAHE
PFWC02 pF values at a relative water content of 0.2 (array) -
DRSAHE
PFWC03 pF values at a relative water content of 0.3 (array) -
DRSAHE
PFWC04 pF values at a relative water content of 0.4 (array) -
DRSAHE
PFWC05 pF values at a relative water content of 0.5 (array) -
DRSAHE
PFWC06 pF values at a relative water content of 0.6 (array) -
DRSAHE
PFWC07 pF values at a relative water content of 0.7 (array) -
DRSAHE
PFWC08 pF values at a relative water content of 0.8 (array) -
DRSAHE
PFWC09 pF values at a relative water content of 0.9 (array) -
DRSAHE
PFWC10 pF values at a relative water content of 1.0 (array) -
DRSAHE
PGRCR potential growth rate of crop kg ha-1 d-1 PGDM =
PGRRT potential growth rate of roots kg ha-1 d-1 PGDM =
PGRSH potential growth rate of shoots kg ha-1 d-1 PGDM =
PI ratio of circumference to diameter of a circle (3.141592654) -
ASTRO =
PRRE potential rate of root extension m d-1 PGDM
PSE potential evaporation mm d-1 PETP =
PSYCON psychrometric instrument constant mbar K-1 PENMAN =
PTRANS potential transpiration mm d-1 PETP =

MODELS
Q10 factor accounting for increase of maintenance respiration with

a 10 °C rise temperature - PGDM
R1 flag to indicate that the ACR is higher than a certain
threshold - PGRAIN =
R2 flag to indicate that the ACR1 is higher than a certain
threshold - PGRAIN =
RAD conversion constant (PI/180) rad degr-1 ASTRO =
RAIN daily amount of rainfall mm d-1 DRSAHE =
MODELS =
PGRAIN
PGWU
RAIN1 constant value of amount of rainfall mm PGRAIN
RAIN2 constant amount of rainfall used in DBRR estimation mm
PGRAIN
RAIN3 constant of amount of rainfall used in DBRR estimation mm
PGRAIN
RAINCU cumulative value of amount of rainfall / irrigation mm
DRSAHE =
RAINF value of runoff or runon mm d-1 MODELS =
PGRAIN =
RAINF1 parameter of the equation for runoff/runon simulation -
MODELS
PGRAIN
RAINF2 parameter of the equation for runoff/runon simulation mm
d-1 MODELS
PGRAIN
RB net outgoing longwave radiation J m-2 d-1 PENMAN =
PETP
RDD daily total solar radiation J m-2 d-1 PGDM =
MODELS
PETP
PGRAIN
RDMSOL maximum root depth by soil limitation m PGDM
RDNIL root penetration in the deepest soil compartment m PGWU =
RDRRT relative death rate of roots d-1 PGDM =
RDRRTC relative death rate of structural roots after reserves are
used d-1 PGDM
RDRSH relative death rate of shoots d-1 PGDM =
RDRTTB table of relative death rates of roots tabulated as
function of DVS - PGDM
RDSHTB table of relative death rates of shoots tabulated as

function of DVS - PGDM
RDSLR rate of change in number of days since last rain (DSLR) -
DRSAHE =
REFCFC reflection coefficient for RDD of a closed vegetation -
PENMAN =
REFCFS reflection coefficient for RDD of a soil surface - PENMAN =
REFCFW reflection coefficient for RDD of a water surface - PENMAN
=
RELSSD intermediate variable in the PENMAN calculation - PENMAN =
RER actual root extension rate m d-1 PGDM =
RESOIL soil evaporation rate per layer mm d-1 DRSAHE =
RFCAAH reduction factor affecting crop assimilation acounting by
low air humidity - PGDM =
RFCFC reflection coefficient for RDD of a closed vegetation -
PENMAN =
PETP
RFCFS reflection coefficient for RDD of a soil surface - PENMAN =
PETP
RFIBWS reduction factor that modify the initial biomass (water
limitation) - PGCR =
PGDM =
MODELS
RFLWU reduction factor that limit maximum water use of the crop -
PGDM =
RFMR reduction factor that modify the maintenance respiration in
the dormant crop phase - PGDM
RFSGND reduction factor that modify shoot growth (nitrogen
deficiency) - PGDM =
RFSGWS reduction factor that modify shoot growth (water
availability) - PGDM =
RFWU reduction factor that modify water uptake per layer - PGWU =
RGRRT relative growth rate of roots kg kg-1 d-1 PGDM
RGRSH relative growth rate of shoots kg kg-1 d-1 PGDM
RL root length of each soil layer m m-2 PGWU =
RNC net absorbed radiation of a closed vegetation mm d-1 PENMAN =
RNEFF growth per unit of radiation and unit of shoot nitrogen g
g-1 MJ-1 m-2 PGDM =
RNS net absorbed radiation of a soil surface mm d-1 PENMAN =
RNSC net absorbed radiation by vegetation and soil J m-2 d-1 PETP
=
RNW net absorbed radiation of a water surface mm d-1 PENMAN =
RRD relative root depth - PGWU =
RTDE parameter discribing the extinction coefficient of the

exponential function used to
simulated root distribution in the soil - PGWU =
RTDEDS parameter discribing the extinction coefficient of the exponential function used to
simulated root distribution during the dry season in the soil - PGWU
RTDERS parameter describing the extinction coefficient of the exponential function used to
simulated root distribution during the rainy in the soil - PGWU
RTRT reserve translocation to roots kg ha-1 d-1 PGDM =
RTSH reserve translocation to shoots kg ha-1 d-1 PGDM =
RUE overall radiation use efficiency g MJ-1 PGDM =
SC solar constant J m-2 s-1 ASTRO =
MODELS
PGDR
SD sowing date d DRSAHE =
MODELS
PGDM
SDCG soil depth used to simulate crop germination m PGCR
SDCS soil depth used to simulate crop regrowth m PGCR
SDEX logical variable that trigger shoots death after exploitation

- PGDM =
SDSATB table of specific dead shoot area as a function of DVS ha kg-1 PGDM
SDSHA specific dead shoot area ha kg-1 PGDM =
SED date of beginning of stem elongation d PGPHE =
SEDDS date of beginning of stem elongation stage in the dry season

d PGPHE
SEDRS date of beginning of stem elongation stage in the rainy season d PGPHE
SEDVS numerical value of the development stage at the beginning of

stem elongation - PGDM
PGPHE
SHBDP biomass remaining in the dormant phase kg ha-1 PGDM
SHNDST table of actual nitrogen accumulated in the shoots in the dry season kg ha-1 PGDM
SHNRST table of actual nitrogen accumulated in the shoots in the rainy season kg ha-1 PGDM
SHRTR shoot to root biomass ratio - PGDM =
SINLD seasonal offset of sine of solar height - ASTRO =

MODELS
PGDR
SPROUT flag to indicate a new regrowth caused by new rains - PGCR
=
PGDM =
MODELS
SRTW specific root weight m g-1 PGWU
SSATB table of specific shoot area as a function of DVS ha kg-1
PGDM
SSHA specific shoot area ha kg-1 PGDM =
SSR shoot senescence rate d-1 PGPHE =
PGDM
SSS shoot senescence stage - PGDM =
PGPHE =
PGEXP
STBC Stefan Boltzmann constant J m-2 d-1 K-1 PENMAN =
STTIME start time of simulation d MODELS
SUM summation auxillary variable - DRSAHE =
PETP =
SVAP local equivalent of SVP mbar PENMAN =
SWD seasonal water drainage mm PGWU =
SWDF soil water depletion fraction - PGWU =
SWDFTB table of soil water depletion fraction - PGWU
SWE seasonal water evaporated mm PGWU =
SWIT6 switch variable used to initialize soil moisture content -
DRSAHE
SWIT8 switch variable used to initialize soil moisture
characteristic - DRSAHE
SWIT9 switch variable used to initialize soil moisture
characteristic - DRSAHE
SWITC1 auxiliar variable used to switch - PGDM =
PGEXP =
PGPHE =
SWITC2 auxiliar variable used to switch - PGDM =
PGEXP =
SWITC3 auxiliar variable used in the calculation of reserve
translocation - PGDM =
SWITCH auxiliar variable used in different routines as a swicth -
PGDM =
PGPHE =
PGRAIN =
PGWU =
SWT seasonal water transpired mm PGWU =

SWU seasonal water evapotranspired mm PGWU =
TCCDRE time constant used to calculate crop death (reserves
exhaustion) d PGDM
TCCDWE time constant used to calculate crop death (water
depletion) d PGDM
TCCE time constant used to calculate crop emergence d PGCR
TCCS time constant used to calculate crop regrowth d PGCR
PGDM
TCEF time constant used to simulate sowing failure d PGCR
TCRD1 time constant used to estimate DBRR d PGRAIN
TCRD2 time constant used to estimate DBRR d PGRAIN
TCRTDS time constant used to simulate reserve translocation in the

dry season d PGDM
TCRTRS time constant used to simulate reserve translocation in the

rainy season d PGDM
TCSDND time coefficient used to simulate shoot death (nitrogen
deficiency) d PGDM
TCSF time constant used to simulate regrowth failure d PGCR
TCSS time constant used to simulate aboveground biomass death
after forage exploitation d PGDM
TCWSCD time constant used to simulate aboveground biomass death
(water stress) d PGPHE
TDIF difference between maximum and minimum temperature °C PENMAN
=
TDM total dry matter kg ha-1 PGDM =
TDMP total dry matter of the previous day kg ha-1 PGDM =
TERMNL flag to indicate if simulation is to stop - PGCR =
PGDM =
PETP
PGPHE
PGWU
MODELS
TIME time of simulation d DRSAHE
MODELS
TINY auxiliar variable used to avoid calculation errors - PGDM =
PGPHE =
TKL thickness of soil compartments m DRSAHE
TKLX thickness of soil compartments m DRSAHE =
MODELS
PGCR
PGDM

PGWU
TMAX local equivalent of TMMX °C PENMAN
TMIN local equivalent of TMMN °C PENMAN
TMMN daily minimum temperature °C MODELS
PETP
PGDM
PGRAIN
TMMX daily maximum temperature °C MODELS
PETP
PGDM
PGRAIN
TMNNCR table of minimum nitrogen concentration in roots - PGDM
TMPA daily mean temperature °C PENMAN =
PGDM =
PGPHE
TRADEF auxiliar variable used for water compensation between soil
layers mm PGWU =
TRANSR transpiration ratio - PGDM =
PGWU =
MODELS
PGPHE
TREF reference temperature for maintenance respiration °C PGDM
TRW total water uptake rate from the soil by the canopy mm d-1
DRSAHE =
TRWCU cumulative transpiration mm DRSAHE =
MODELS
TRWL actual rate of water extraction per soil compartment mm d-1
DRSAHE =
PGWU =
MODELS
TSNCDM multiplicative factor used to define a threshold value of
shoot nitrogen concentration
below which dry matter production is reduced - PGDM
TSNCSG multiplicative factor used to define a threshold value of
shoot nitrogen concentration
below which shoot growth rate is reduced - PGDM
TSWE total water evaporated per year mm PGWU =
TUAM thermal units from anthesis to maturity °C d PGPHE
TUEA thermal units from emergence to anthesis °C d PGPHE
TUMDDS thermal units from maturity to death of the total seasonal
aboveground biomass
in the dry season °C d PGPHE
TUMDRS thermal units from maturity to death of the total seasonal

aboveground biomass
in the rainy season °C d PGPHE
TWA total water availability above wilting point in the rooted
soil mm PGWU =
MODELS
PGDM
TWD total water drainage per year mm PGWU =
TWE total water evaporated per year mm PGWU =
TWS total water stored in the soil profile mm PGWU =
TWT total water transpired by roots mm d-1 PGWU =
TWU total water extracted by roots mm d-1 PGWU =
TYL type of soil per compartment - DRSAHE
VAP vapour pressure mbar PENMAN =
VAR amount of water available for evaporation of layer (array) mm
DRSAHE =
VGA parameter of the van Genuchten equation - DRSAHE
VGAT parameter of the van Genuchten equation cm-1 DRSAHE =
VGM parameter of the van Genuchten equation - DRSAHE =
VGN parameter of the van Genuchten equation - DRSAHE
VGNT parameter of the van Genuchten equation - DRSAHE =
VGR parameter of the van Genuchten equation - DRSAHE
VGWRT parameter of the van Genuchten equation - DRSAHE =
VGWST parameter of the van Genuchten equation - DRSAHE =
VP early morning vapour pressure kPa PETP =
MODELS
PGDM
PGRAIN
VPD vapour pressure deficit kPa PGDM =
WA available water above wilting point per soil compartment mm d-1

PGWU =
WACWC available water above critical water content per soil
compartment mm d-1 PGWU =
WARL available water taking into account the maximum root capacity

for transpiration mm d-1 PGWU =
WATCH auxiliar variable used to trigger crop regrowth - PGDM =
WCAD water content at airdry m3 m-3 DRSAHE =
WCADX volumetric water content airdry m3 m-3 DRSAHE =
MODELS
WCCG total water content in the upper soil layers used to simulate

crop emergence mm PGCR =

WCCR soil water content in the upper layer used used in crop
sprouting estimation mm PGWU =
WCCS total water content in the upper soil layers used to simulate

crop regrowth mm PGCR =
WCFC water content at field capacity m3 m-3 DRSAHE =
WCFCX volumetric water content at field capacity m3 m-3 DRSAHE =
MODELS
PGWU
WCL intermediate value of volumetric water content per soil
compartment m3 m-3 DRSAHE =
WCLCH rate of change of water content per soil compartment (array)

mm d-1 DRSAHE =
WCLQT initial volumetric water content per soil compartment m3 m-3

DRSAHE =
MODELS
PGCR
PGDM
PGWU
WCLQTM intermediate value of WCLQT (volumetric water content per
soil compartiment) m3 m-3 DRSAHE =
WCR weight of living crop kg ha-1 PGDM =
WCST volumetric water content at saturation m3 m-3 DRSAHE =
WCSTT volumetric soil moisture content at saturation in Driessen
eq. (standard set) m3 m-3 DRSAHE =
WCSTX global equivalent of volumetric water content at saturation
m3 m-3 DRSAHE =
MODELS
WCTRT weight of carbohydrate reserves translocated to roots kg
ha-1 PGDM =
WCTSH weight of carbohydrate reserves translocated to shoots kg
ha-1 PGDM =
WCUM total amount of soil water mm DRSAHE =
WCUMCH rate of change in amount of stored soil water, averaged
over DELT mm d-1 DRSAHE =
WCUMO total amount of soil water of previous time step mm DRSAHE =
WCWP water content at wilting point m3 m-3 DRSAHE =
WCWPCG total water content at wilting point in the upper soil
layers used to simulate
crop emergence mm PGCR =
WCWPCS soil water stored at wilting point mm PGCR =

WCWPX volumetric water content at wilting point per compartment -
DRSAHE =
MODELS
PGCR
PGDM
PGWU
WCWRT weight of carbohydrates withdrawn from roots kg ha-1 d-1
PGDM =
WCWSH weight of carbohydrates withdrawn from shoots kg ha-1 d-1
PGDM =
WDCR weight of dead crop kg ha-1 PGDM =
WDRT weight of dead roots kg ha-1 PGDM =
WDSH weight of dead shoots kg ha-1 PGDM =
WDSHE weight of dead shoot exploitated kg ha-1 PGDM =
WDSHRE weight of dead shoot removed by exploitation kg ha-1 d-1
PGDM =
WILTP parameter for wilting point m3 m-3 DRSAHE =
WIND local equivalent of WN m s-1 PENMAN
WN average wind speed m s-1 MODELS
PETP
PGRAIN
WORT2 auxiliar variable used to calculate death rate of roots in
the shoot death phase kg ha-1 PGDM =
WOSH2 auxiliar variable used to calculate death rate of shoots in
the shoot death phase kg ha-1 PGDM =
WOSHDE auxiliar variable used to calculate death rate of shoots
after exploitation kg ha-1 PGDM =
WOSRT weigth of old structural roots that are going to die after
crop regrowth kg ha-1 PGDM =
WREL intermediate variable in calculation of soil characteristic
according to Van Genuchten - DRSAHE =
WRFRE reduction factor that affect the rate of root extension
(soil moisture in the deepest compartment) - PGDM =
PGWU =
MODELS
WRMFD weight of reserves translocated the first day of
mobilisation kg ha-1 PGDM
WRS weight of reserves kg ha-1 PGDM =
WRT weight of living roots kg ha-1 PGDM =
WRT2 weight of roots when DVS = 2 kg ha-1 PGDM =
WS water stored per soil compartment mm PGWU =
WSB weight of standing biomass kg ha-1 PGDM =
WSERST table of water stress effects on the relative death rate of

roots as a function of
accumulated days of water stress - PGDM
WSESRT variable that quantify water stress effects on the relative

death rate of roots - PGDM =
WSESSH variable that quantify water stress effects on the relative

death rate of shoots - PGDM =
WSESST table of water stress effects on the relative death rate of

shoots as a function of
accumulated days of water stress - PGDM
WSH weight of living shoots kg ha-1 PGDM =
PGWU =
MODELS
PGEXP
WSH2 weight of leaves when DVS = 2 kg ha-1 PGDM =
WSHE weight of total living shoot exploitated kg ha-1 d-1 PGDM =
WSHRE weight of living shoot removed by exploitation kg ha-1 d-1
PGDM =
WSRT weight of structural roots kg ha-1 PGDM =
PGWU =
MODELS
WSTAT status code from weather system - MODELS
WTRTER flag whether weather can be used by model - MODELS
WUEC water use efficiency coefficient Pa PGDM
YEAR year of simulation - MODELS
ZRT root depth m MODELS =
PGDM =
PGWU =
ZRTMS maximum rooting depth as soil characteristic m DRSAHE =
MODELS

variable description unit module(s)

variable description unit module(s)

Rapports PSS No 2

Appendix B: PGWA Fortran modules

Table des matières

PGWA.FOR
MODELS.FOR
PGCR.FOR
PGRAIN.FOR
PGWU.FOR
DRSAHE.FOR
PETP.FOR
PENMAN.FOR
ASTRO.FOR
PGDM.FOR
PGPHE.FOR
PGEXP.FOR

PGWA.FOR

```
      PROGRAM MAIN
      CALL FSE
      END
*-----------------------------------------------------------------------*
*
    *
*
    *
*             FORTRAN Simulation Environment (FSE 2.0a)
    *
*                          September, 1993
    *
*
    *
*
    *
*     FSE 2.0 is a simulation environment suited for simulation of
    *
*     biological processes in time, such as crop and vegetation
growth,*
*     insect population development etc.
```

*
*
*
*   The MAIN program, subroutine FSE and subroutine MODELS are
*
*   programmed by D.W.G. van Kraalingen, DLO Centre for
*
*   Agrobiological Research, PO Box 14, 6700 AA, Wageningen, The
*
*   Netherlands (e-mail: d.w.g.van.kraalingen@cabo.agro.nl).
*
*
*
*   A manual of FSE 2.0 is in preparation.
*
*
*
*   Version 1.0 of FSE is described in:
*
*   Kraalingen, D.W.G. van 1991. The FSE system for crop simulation, *
*   Simulation Report CABO-TT No.23, Centre for Agrobiological
*
*   Research, Dept. of Theoretical Production Ecology, 77 pp.
*
*
*
*   Data files needed for FSE 2.0:
*
*   (excluding data files used by models called from MODELS):   *
*   - CONTROL.DAT (contains file names to be used),
*
*   - timer file whose name is specified in CONTROL.DAT,
*
*   - optionally, a rerun file whose name is specified in
*
*   CONTROL.DAT,
*
*   - weather data files as specified in timer file
*
*   Object libraries needed for FSE 2.0:
*

```
*       - TTUTIL (at least version 3.2)
   *
*       - WEATHER (at least version from 17-Jan-1990)
   *
*-------------------------------------------------------------------*

      SUBROUTINE FSE

      IMPLICIT REAL (A-Z)

*-----Standard declarations for simulation and output control

      INTEGER   ITASK   , INSETS, ISET  , IPFORM, IL, ILEN
      LOGICAL   OUTPUT  , TERMNL, RDINQR
      CHARACTER COPINF*1, DELTMP*1
      INTEGER   INPRS

      INTEGER   IMNPRS
      PARAMETER (IMNPRS=100)
      CHARACTER PRSEL(IMNPRS)*11

*-----Declarations for time control
      INTEGER   IDOY, IYEAR
      REAL      DELT, DOY, FINTIM, PRDEL, STTIME, TIME, YEAR

*-----Declarations for weather system
      INTEGER   IFLAG    , ISTAT1, ISTAT2 , ISTN
      REAL      ANGA     , ANGB  , ELEV   , LAT , LONG, RDD
      REAL      TMMN     , TMMX  , VP     , WN  , RAIN
      LOGICAL   WTRMES   , WTRTER
      CHARACTER WTRDIR*80, CNTR*7, WSTAT*6, DUMMY*1

*-----Declarations for file names and units
      INTEGER   IUNITR   , IUNITD   , IUNITO   , IUNITL   , IUNITC
      CHARACTER FILEON*80, FILEOL*80
      CHARACTER FILEIC*80, FILEIR*80, FILEIT*80
      CHARACTER FILEI1*80, FILEI2*80, FILEI3*80, FILEI4*80,
FILEI5*80

*-----Declarations for observation data facility
      INTEGER   INOD , IOD

      INTEGER   IMNOD
```

```
      PARAMETER (IMNOD=100)
      INTEGER   IOBSD(IMNOD)

*-----Unit numbers for control file (C), data files (D),
*     output file (O), log file (L) and rerun file (R). File name
for
*     control file and empty strings for input files 1-5.
*     WTRMES flags any messages from the weather system

      DATA IUNITC /10/, IUNITD /20/, IUNITO /30/
      DATA IUNITL /40/, IUNITR /50/
      DATA FILEIC /'CONTROL.DAT'/
      DATA FILEI1 /' '/, FILEI2 /' '/, FILEI3 /' '/
      DATA FILEI4 /' '/, FILEI5 /' '/
      DATA WTRMES /.FALSE./

*-----Open control file and read names of normal output file, log
file
*     and rerun file (these files cannot be used in reruns)
      CALL RDINIT (IUNITC,0, FILEIC)
      CALL RDSCHA ('FILEON', FILEON)
      CALL RDSCHA ('FILEOL', FILEOL)
      CALL RDSCHA ('FILEIR', FILEIR)
      CLOSE (IUNITC)

*-----Open output file and possibly a log file
      CALL FOPENS  (IUNITO, FILEON, 'NEW', 'DEL')
      IF (FILEOL.NE.FILEON) THEN
        CALL FOPENS  (IUNITL, FILEOL, 'NEW', 'DEL')
      ELSE
        IUNITL = IUNITO
      END IF

*-----See if rerun file is present, and if so read the number of
rerun
*     sets from rerun file

      CALL RDSETS (IUNITR, IUNITL, FILEIR, INSETS)

*======================================================================*
*======================================================================*
*
    *
```

```
*                Main loop and reruns begin here
   *
*
   *
*==========================================================================*
*==========================================================================*



      DO 10 ISET=0,INSETS

      WRITE (*,'(A)') '   FSE 2.0a: Initialize model'

*-----Select data set
      CALL RDFROM (ISET, .TRUE.)


*==========================================================================*
*
   *
*                    Initialization section
   *
*
   *
*==========================================================================*

      ITASK  = 1
      TERMNL = .FALSE.
      WTRTER = .FALSE.

*-----Read names of timer file and input files 1-5 from control
*     file (these files can be used in reruns)
      CALL RDINIT (IUNITC,IUNITL,FILEIC)
      CALL RDSCHA ('FILEIT', FILEIT)
      IF (RDINQR ('FILEI1')) CALL RDSCHA ('FILEI1', FILEI1)
      IF (RDINQR ('FILEI2')) CALL RDSCHA ('FILEI2', FILEI2)
      IF (RDINQR ('FILEI3')) CALL RDSCHA ('FILEI3', FILEI3)
      IF (RDINQR ('FILEI4')) CALL RDSCHA ('FILEI4', FILEI4)
      IF (RDINQR ('FILEI5')) CALL RDSCHA ('FILEI5', FILEI5)
      CLOSE (IUNITC)

*-----Read time, control and weather variables from timer file
      CALL RDINIT (IUNITD  , IUNITL, FILEIT)
```

```
      CALL RDSREA ('STTIME', STTIME)
      CALL RDSREA ('FINTIM', FINTIM)
      CALL RDSREA ('PRDEL' , PRDEL )
      CALL RDSREA ('DELT'  , DELT  )
      CALL RDSINT ('IYEAR' , IYEAR )
      CALL RDSINT ('ISTN'  , ISTN  )
      CALL RDSINT ('IPFORM', IPFORM)
      CALL RDSCHA ('COPINF', COPINF)
      CALL RDSCHA ('DELTMP', DELTMP )
      CALL RDSCHA ('WTRDIR', WTRDIR)
      CALL RDSCHA ('CNTR'  , CNTR)
      CALL RDSINT ('IFLAG' , IFLAG)

*-----See if observation data variable exists, if so read it
      IF (RDINQR('IOBSD')) THEN
        CALL RDAINT ('IOBSD' , IOBSD, IMNOD, INOD)
        IF (IOBSD(1).EQ.0) INOD = 0
      ELSE
        INOD = 0
      END IF

*-----See if variable with print selection exists, if so read it
      IF (RDINQR('PRSEL')) THEN
        CALL RDACHA ('PRSEL',PRSEL,IMNPRS,INPRS)
      ELSE
        INPRS = 0
      END IF
      CLOSE (IUNITD)

*-----Initialize TIMER and OUTDAT routines
      CALL TIMER2 (ITASK, STTIME, DELT, PRDEL, FINTIM,
     &            IYEAR, TIME  , DOY , IDOY , TERMNL, OUTPUT)
      YEAR = REAL (IYEAR)
      CALL OUTDAT (ITASK, IUNITO, 'TIME', TIME)

*-----Open weather file and read station information and return
*     weather data for start day of simulation.
*     Check status of weather system, WTRMES flags if warnings or
errors
*     have occurred during the whole simulation. WTRTER flags if
the run
*     should be terminated because of missing weather
```

```
      CALL STINFO (IFLAG , WTRDIR, ' ', CNTR, ISTN, IYEAR,
     &             ISTAT1, LONG  , LAT, ELEV, ANGA, ANGB)
      CALL WEATHR (IDOY  , ISTAT2, RDD, TMMN, TMMX, VP, WN, RAIN)
      IF (ISTAT1.NE.0.OR.ISTAT2.NE.0) WTRMES = .TRUE.
      IF (ISTAT1.GE.0) THEN
         WRITE (WSTAT,'(I6)') ABS (ISTAT2)
      ELSE
         WSTAT  = '444444'
      END IF

*-----Conversion of total daily radiation from kJ/m2/d to J/m2/d
      RDD = RDD*1000.

*-----Call routine that handles the different models
      CALL MODELS (ITASK , IUNITD, IUNITO, IUNITL,
     &             FILEI1, FILEI2, FILEI3, FILEI4, FILEI5,
     &             FILEIT, OUTPUT, TERMNL,
     &             DOY   , IDOY  , YEAR  , IYEAR ,
     &             TIME  , STTIME, FINTIM, DELT  ,
     &             LAT   , WSTAT , WTRTER,
     &             RDD   , TMMN  , TMMX  , VP    , WN, RAIN)


*=====================================================================*
*
   *
*                    Dynamic simulation section
   *
*
   *
*=====================================================================*

      WRITE (*,'(A)') '   FSE 2.0a: DYNAMIC loop'

20    IF (.NOT.TERMNL) THEN

*----------------------------------------------------------------*
*                   Integration of rates section
   *
*----------------------------------------------------------------*

      IF (ITASK.EQ.2) THEN
```

```
*--------Carry out integration only when previous task was rate
*        calculation

         ITASK = 3

*--------Call routine that handles the different models
         CALL MODELS (ITASK , IUNITD, IUNITO, IUNITL,
     &                FILEI1, FILEI2, FILEI3, FILEI4, FILEI5,
     &                FILEIT, OUTPUT, TERMNL,
     &                DOY   , IDOY  , YEAR  , IYEAR ,
     &                TIME  , STTIME, FINTIM, DELT  ,
     &                LAT   , WSTAT , WTRTER,
     &                RDD   , TMMN  , TMMX  , VP    , WN, RAIN)

*--------Turn on output when TERMNL logical is set to .TRUE.
         IF (TERMNL) OUTPUT = .TRUE.

      END IF

*----------------------------------------------------------------------*
*                Calculation of driving variables section
    *
*----------------------------------------------------------------------*

      ITASK = 2

*-----Write time of output to screen and file
      IF (OUTPUT) THEN
         IF (ISET.EQ.0) THEN
            WRITE (*,'(13X,A,I5,A,F7.2)')
     &        'Default set, Year:', IYEAR, ', Day:', DOY
         ELSE
            WRITE (*,'(13X,A,I3,A,I5,A,F7.2)')
     &        'Rerun set:', ISET, ', Year:', IYEAR, ', Day:', DOY
         END IF
         IF (OUTPUT) CALL OUTDAT (2, 0, 'TIME', TIME)
      END IF

*-----Get weather data for new day and flag messages
      CALL STINFO (IFLAG , WTRDIR, ' ', CNTR, ISTN, IYEAR,
     &             ISTAT1, LONG  , LAT, ELEV, ANGA, ANGB)
      CALL WEATHR (IDOY, ISTAT2, RDD, TMMN, TMMX, VP, WN, RAIN)
      IF (ISTAT1.NE.0.OR.ISTAT2.NE.0) WTRMES = .TRUE.
```

```
      IF (ISTAT1.GE.0) THEN
         WRITE (WSTAT,'(I6)') ABS (ISTAT2)
      ELSE
         WSTAT  = '444444'
      END IF

*-----Conversion of total daily radiation from kJ/m2/d to J/m2/d
      RDD = RDD*1000.

*----------------------------------------------------------------------*
*              Calculation of rates and output section
   *
*----------------------------------------------------------------------*

*-----Call routine that handles the different models
      CALL MODELS (ITASK , IUNITD, IUNITO, IUNITL,
     &             FILEI1, FILEI2, FILEI3, FILEI4, FILEI5,
     &             FILEIT, OUTPUT, TERMNL,
     &             DOY   , IDOY  , YEAR  , IYEAR ,
     &             TIME  , STTIME, FINTIM, DELT  ,
     &             LAT   , WSTAT , WTRTER,
     &             RDD   , TMMN  , TMMX  , VP    , WN, RAIN)

      IF (TERMNL.AND..NOT.OUTPUT.AND.PRDEL.GT.0.) THEN
*--------Call model routine again if TERMNL is switched on while
*        OUTPUT was off (this call is necessary to get output to
file
*        when a finish condition was reached and output generation
*        was off)
         OUTPUT = .TRUE.
         CALL OUTDAT (2, 0, 'TIME', TIME)
         CALL MODELS (ITASK , IUNITD, IUNITO, IUNITL,
     &                FILEI1, FILEI2, FILEI3, FILEI4, FILEI5,
     &                FILEIT, OUTPUT, TERMNL,
     &                DOY   , IDOY  , YEAR  , IYEAR ,
     &                TIME  , STTIME, FINTIM, DELT  ,
     &                LAT   , WSTAT , WTRTER,
     &                RDD   , TMMN  , TMMX  , VP    , WN, RAIN)
      END IF

*----------------------------------------------------------------------*
*                          Time update
   *
```

```
*-----------------------------------------------------------------------*

*-----Check for FINTIM, OUTPUT and observation days
      CALL TIMER2 (ITASK, STTIME, DELT, PRDEL, FINTIM,
     &            IYEAR, TIME  , DOY , IDOY , TERMNL, OUTPUT)
      YEAR = REAL (IYEAR)
      DO 30 IOD=1,INOD,2
        IF (IYEAR.EQ.IOBSD(IOD).AND.IDOY.EQ.IOBSD(IOD+1))
     &      OUTPUT = .TRUE.
30    CONTINUE

      GOTO 20
      END IF



*=======================================================================*
*
   *
*                          Terminal section
   *
*
   *
*=======================================================================*

      ITASK = 4

      WRITE (*,'(A)') '   FSE 2.0a: Terminate model'

      CALL OUTDAT (2, 0, 'TIME', TIME)

*-----Call routine that handles the different models
      CALL MODELS (ITASK , IUNITD, IUNITO, IUNITL,
     &            FILEI1, FILEI2, FILEI3, FILEI4, FILEI5,
     &            FILEIT, OUTPUT, TERMNL,
     &            DOY   , IDOY  , YEAR  , IYEAR ,
     &            TIME  , STTIME, FINTIM, DELT  ,
     &            LAT   , WSTAT , WTRTER,
     &            RDD   , TMMN  , TMMX  , VP    , WN, RAIN)

*-----Generate output file dependent on option from timer file
      IF (IPFORM.GE.4) THEN
        IF (INPRS.EQ.0) THEN
          CALL OUTDAT (IPFORM, 0, 'Simulation results',0.)
```

```
       ELSE
*          Selection of output variables was in timer file
*          write tables according to output selection array PRSEL
           CALL OUTSEL (PRSEL,IMNPRS,INPRS,IPFORM,'Simulation
results')
       END IF
     END IF

     IF (WTRTER) THEN
       WRITE (*,'(/,A,/,/,/)')
    &     ' The run was terminated due to missing weather'
       WRITE (IUNITO,'(/,A,/,/,/)')
    &     ' The run was terminated due to missing weather'
       IF (IUNITO.NE.IUNITL) WRITE (IUNITL,'(/,A,/,/,/)')
    &     ' The run was terminated due to missing weather'
     END IF

*-----Delete temporary output file dependent on switch from timer
file
     IF (DELTMP.EQ.'Y'.OR.DELTMP.EQ.'y') CALL OUTDAT (99, 0, ' ',
0.)

10   CONTINUE

     IF (INSETS.GT.0) CLOSE (IUNITR)

*-----If input files should be copied to the output file,
*     copy rerun file (if present) and timer file and if there,
input
*     files 1-5

     IF (COPINF.EQ.'Y'.OR.COPINF.EQ.'y') THEN
       IF (INSETS.GT.0) CALL COPFL2 (IUNITR, FILEIR, IUNITO,
.TRUE.)
       CALL COPFL2 (IUNITD, FILEIT, IUNITO, .TRUE.)
       IF (FILEI1.NE.' ') CALL COPFL2 (IUNITD, FILEI1, IUNITO,
.TRUE.)
       IF (FILEI2.NE.' ') CALL COPFL2 (IUNITD, FILEI2, IUNITO,
.TRUE.)
       IF (FILEI3.NE.' ') CALL COPFL2 (IUNITD, FILEI3, IUNITO,
.TRUE.)
       IF (FILEI4.NE.' ') CALL COPFL2 (IUNITD, FILEI4, IUNITO,
.TRUE.)
```

```
        IF (FILEI5.NE.' ') CALL COPFL2 (IUNITD, FILEI5, IUNITO,
.TRUE.)
      END IF

*-----Delete all .TMP files that were created by the RD* routines
*     during simulation
      CALL RDDTMP (IUNITD)

*-----Write to screen which files contain what
      IL = ILEN (FILEON)
      WRITE (*,'(/,3A)') ' File: ',FILEON(1:IL),
     &  ' contains simulation results'
      WRITE (*,'(2A)') ' File: WEATHER.LOG',
     &  ' contains messages from the weather system'
      IL = ILEN (FILEOL)
      WRITE (*,'(3A,/)') ' File: ',FILEOL(1:IL),
     &  ' contains messages from the rest of the model'

*-----Write message to screen and output file if warnings and/or
errors
*     have occurred from the weather system, pause and wait for
return
*     from user to make sure he has seen this message

      IF (WTRMES) THEN

        WRITE (*,'(/,A,/,A,/,A)') ' WARNING from FSE:',
     &     ' There have been errors and/or warnings from',
     &     ' the weather system, check file WEATHER.LOG'
        WRITE (IUNITO,'(A,/,A,/,A)') ' WARNING from FSE:',
     &     ' There have been errors and/or warnings from',
     &     ' the weather system, check file WEATHER.LOG'

        WRITE (*,'(A)') ' Press <Enter>'
        READ  (*,'(A)') DUMMY

      END IF

*-----Close output file and temporary file of OUTDAT
      CLOSE (IUNITO)
      CLOSE (IUNITO+1)

*-----Close log file (if used)
```

```
      IF (FILEOL.NE.FILEON) CLOSE (IUNITL)

*-----Close log file of weather system
      CLOSE (91)

      RETURN
      END
```

MODELS.FOR

```
*  - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - *
*
   *
*                          MODELS
   *
*
   *
* Purpose: this subroutine is the interface routine between the
   *
*          FSE-driver and the simulation submodels. This
subroutine    *
*          is called by the FSE-driver at each new task at each
   *
*          time step
   *
*
   *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)
   *
* name   type meaning                              units
class *
* ----   ---- -------                              -----
----- *
* ITASK   I4  task that subroutine should perform           -
 I  *
* IUNITD  I4  unit that can be used for input files         -
 I  *
* IUNITO  I4  unit used for output file                     -
 I  *
* IUNITL  I4  unit used for log  file                       -
 I  *
* FILEI1  C*  name of input file no. 1                      -
 I  *
```

```
* FILEI2  C*  name of input file no. 2                -
 I  *
* FILEI3  C*  name of input file no. 3                -
 I  *
* FILEI4  C*  name of input file no. 4                -
 I  *
* FILEI5  C*  name of input file no. 5                -
 I  *
* OUTPUT  L4  flag to indicate if output should be done      -
 I  *
* TERMNL  L4  flag to indicate if simulation is to stop      -
I/O *
* DOY     R4  day number within year of simulation (REAL)    d
 I  *
* IDOY    I4  day number within year of simulation (INTEGER) d
 I  *
* YEAR    R4  year of simulation (REAL)                   y
 I  *
* IYEAR   I4  year of simulation (INTEGER)                y
 I  *
* TIME    R4  time of simulation                        d
 I  *
* STTIME  R4  start time of simulation                  d
 I  *
* FINTIM  R4  finish time of simulation                 d
 I  *
* DELT    R4  time step of integration                  d
 I  *
* LAT     R4  latitude of weather station               degrees
 I  *
* WSTAT   C7  status code from weather system               -
 I  *
* WTRTER  L4  flag whether weather can be used by model      -
 O  *
* RDD     R4  daily shortwave radiation                 J/m2/d
 I  *
* TMMN    R4  daily minimum temperature                 degrees C
 I  *
* TMMX    R4  daily maximum temperature                 degrees C
 I  *
* VP      R4  early morning vapour pressure             kPa
 I  *
* WN      R4  average wind speed                        m/s
```

```
 I  *
* RAIN    R4  daily amount of rainfall                  mm/d
 I  *
*
   *
* fatal error checks: none
   *
* warnings         : none
   *
* subprograms called: RDINIT, RDSREA, RDSINT, OUTDAT, TIMER2,
   *
*                  PGCR, PGRAIN, ASTRO, PETP, PEWU, DRSAHE and
PGDM *
* file usage       : FILEI1 and FILE2 (see CONTROL.DAT)
   *
*  - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - *

     SUBROUTINE MODELS (ITASK , IUNITD, IUNITO, IUNITL,
    &                 FILEI1, FILEI2, FILEI3, FILEI4, FILEI5,
    &                 FILEIT, OUTPUT, TERMNL,
    &                 DOY   , IDOY  , YEAR  , IYEAR,
    &                 TIME  , STTIME, FINTIM, DELT ,
    &                 LAT   , WSTAT , WTRTER,
    &                 RDD   , TMMN  , TMMX  , VP   , WN, RAIN)


     IMPLICIT REAL(A-Z)

* --- formal parameters
   *
     INTEGER   ITASK, IUNITD, IUNITO, IUNITL, IDOY, IYEAR
     LOGICAL   OUTPUT, TERMNL, WTRTER
     CHARACTER FILEI1*(*), FILEI2*(*) , FILEI3*(*)
     CHARACTER FILEI4*(*), FILEI5*(*), FILEIT*(*)
     REAL DOY, YEAR, TIME, STTIME, FINTIM, DELT, LAT
     REAL RDD, TMMN, TMMX, VP, WN, RAIN
     CHARACTER WSTAT*6

* --- local declarations
   *
     INTEGER IVSSC
     REAL ANGA,ANGB,ELEV
```

```
      REAL KL,LAI,DLAI

* --- PGCR module
*
      INTEGER SD
      LOGICAL EMERG,SPROUT
      REAL IZRT

* --- DRSAHE module
*
      INTEGER INLAYX,INLAY
      REAL EVSW
      REAL DRAICU,EVSWCU,INFCU,TRWCU,ZRTMS

      PARAMETER (INLAYX = 10)

      REAL TRWL(INLAYX),TKLX(INLAYX)
      REAL WCADX(INLAYX),WCWPX(INLAYX),WCFCX(INLAYX),WCSTX(INLAYX)
      REAL WCLQT(INLAYX),FLXQT(INLAYX+1),FLXCU(INLAYX+1)

* --- PGWU module
*
      INTEGER IN
      REAL TWA,WRFRE,TRANSR

* --- PETP module
*
      REAL PTRANS,EVSC

* --- PGDM module
*
      LOGICAL LVCGRS,LVCGDS,LVCS

* --- ASTRO module
*
      REAL LATS,SC,DS0,SINLD,COSLD,
     &     DAYL, DAYLP, DSINB, DSINBE

      REAL INRAIN

      SAVE
*
----------------------------------------------------------------- *
```

```
    IF (ITASK .EQ. 1) THEN

      CALL RDINIT (IUNITD,IUNITO,FILEIT)

* ----- variable to select how crop simulation starts and the
water    *
*      balance model
   *
      CALL RDSINT ('IVSSC', IVSSC)

      CLOSE (IUNITD,STATUS='DELETE')

      CALL RDINIT (IUNITD,IUNITO,FILEI1)

* ----- sowing date
   *
      IF (IVSSC.EQ.0) THEN
        CALL RDSINT ('SD'    , SD    )
      END IF

* ----- parameters of the Angstrom equation and latitude and
   *
*      elevation of the site
   *
      CALL RDSREA ('ANGA', ANGA)
      CALL RDSREA ('ANGB', ANGB)
      CALL RDSREA ('ELEV', ELEV)
      CALL RDSREA ('LATS', LATS)

* ----- extinction coefficient;
   *
      CALL RDSREA ('KL'    , KL    )

* ----- parameters of the calculatio of infiltrated rainfall
   *
      CALL RDSREA ('RAINF1', RAINF1)
      CALL RDSREA ('RAINF2', RAINF2)

      CLOSE (IUNITD,STATUS='DELETE')

* ----- initial value of the logical variable used to trigger crop
   *
```

```
*       growth simulation
    *
       LVCS   = .FALSE.
     END IF



* --- photosyntetic active daylength (DAYLP, h)
    *
     IF (ITASK.EQ.2) THEN
       CALL ASTRO (IDOY, LATS, SC, DS0, SINLD, COSLD,
    &              DAYL, DAYLP, DSINB, DSINBE)
     END IF

* --- infiltrated rainfall (INRAIN, mm/d)
    *
     RAIN = MAX(0., RAIN)
     IF (ITASK .EQ. 2) THEN
       IF (RAIN.GE.RAINF2) THEN
         RAINF  = RAINF1 * MAX(0., RAIN-RAINF2)
         INRAIN = MAX(0., RAIN - RAINF)
       ELSE
         INRAIN = RAIN
       END IF
     END IF

* --- potential evaporation and transpiration
   *
     CALL PETP (ITASK,OUTPUT,TERMNL,DELT,
    &          ELEV,ANGA,ANGB,DS0,RDD,TMMN,TMMX,VP,WN,
    &          KL,LAI,DLAI,PTRANS,EVSC)

     IF (ITASK.EQ.2) THEN
* ----- water uptake
   *
       CALL PGWU (ITASK,IUNITD,IUNITO,FILEI1,OUTPUT,TERMNL,
    &            INLAYX,TKLX,WCFCX,WCWPX,WCLQT,ZRT,IDOY,
    &            LVCGRS,LVCGDS,LVCS,EVSW,DRAICU,RAIN,MTRANS,
    &            INRAIN,WSH,WSRT,
    &            TWA,WRFRE,TRANSR,TRWL)
     END IF

* --- water balance
 *
```

```
      CALL DRSAHE (ITASK,IUNITD,IUNITL,FILEI5,INLAYX,
     &            TIME,DELT,OUTPUT,EVSC,INRAIN,TRWL,
     &            INLAY,TKLX,ZRTMS,
     &            WCADX,WCWPX,WCFCX,WCSTX,
     &            EVSW,FLXQT,WCLQT,
     &            DRAICU,EVSWCU,INFCU,TRWCU,FLXCU)

* --- emergence date
 *
      IF (ITASK.EQ.1 .OR. (IVSSC.EQ.0 .AND. ITASK.EQ.3
     &    .AND. .NOT.LVCS .AND. IDOY.GE.SD)) THEN
        CALL PGCR (ITASK,IUNITD,IUNITO,FILEI1,TERMNL,INLAYX,TKLX,
     &            WCLQT,WCWPX,IVSSC,EMERG,SPROUT,IZRT,RFIBWS)
        IF (EMERG) ZRT=IZRT
      END IF

* --- water uptake
 *
      IF (ITASK.EQ.3 .OR. ITASK.EQ.1) THEN
        CALL PGWU (ITASK,IUNITD,IUNITO,FILEI1,OUTPUT,TERMNL,
     &            INLAYX,TKLX,WCFCX,WCWPX,WCLQT,ZRT,IDOY,
     &            LVCGRS,LVCGDS,LVCS,EVSW,DRAICU,RAIN,MTRANS,
     &            INRAIN,WSH,WSRT,
     &            TWA,WRFRE,TRANSR,TRWL)
      END IF
* --- crop growth module
   *
      CALL PGDM (ITASK,IUNITD,IUNITO,OUTPUT,TERMNL,FILEI1,
     &          IDOY,DELT,RDD,TMMX,TMMN,VP,DAYLP,
     &          IVSSC,EMERG,RFIBWS,LATS,
     &          WRFRE,TRANSR,TWA,MTRANS,
     &          INLAYX,WCLQT,WCWPX,TKLX,
     &          LAI,DLAI,ZRT,LVCS,LVCGRS,LVCGDS,
     &          WSH,WSRT)


      RETURN

      END


PGCR.FOR
*
```

```
----------------------------------------------------------------- *
*
   *
*   R e g r o w t h (s p r o u t i n g) a n d e m e r g e n c
e   *
*           o f p e r e n n i a l g r a s s e s
   *
*                          PGCR
   *
*
   *
*  author : Santiago Bonachela-Castano
   *
*
   *
*  date   : December 1993
   *
*
   *
*  purpose: the programme calculates:
   *
*          - emergence date of a perennial grass crop, taken into
   *
*            account the soil water content in the upper 10 mm of
   *
*            soil;
   *
*          - sprouting or regrowth date, taken into account the
   *
*            soil water content in the upper 20 mm of soil.
   *
*          It is based on the spring wheat model from Van Keulen
and  *
*          Seligman (1987).
   *
*
   *
*
   *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)
   *
*  name  type   meaning                          units
class    *
```

```
* ---- ---- -------                    -----
----- *
* WCLQT  R()  vol. water content per soil compartment  -    I
  *
* WCWPX  R()  vol. water content at wilting point      -    I
  *
* INLAYX  I4  number of soil compartiments             -    I
  *
* TKLX   R()  thickness of soil compartiments          m    I
  *
* IVSSC   I   to indicate if the simulation starts
  *
*             from sowing or from an stablished crop   -    I
  *
* EMERG   L   variable to identify the date of
  *
*             emergency                                -    O
  *
* SPROUT  L   variable used to identify the date of
  *
*             sprouting                                -    O
  *
* IZRT   R4   initial root depth after emergence or
  *
*             sprouting                                m    O
  *
* RFIBWS  R4  reduction factor due to water stress
  *
*             that multiply the initial biomass        -    O
  *
*
  *
*
  *
* Subroutines and functions called : RDSREA,RDSINT
  *
* File usage : FILEI1
  *
*
---------------------------------------------------------------- *

     SUBROUTINE PGCR
(ITASK,IUNITD,IUNITO,FILEI1,TERMNL,INLAYX,TKLX,
```

```
     &                WCLQT,WCWPX,IVSSC,EMERG,SPROUT,IZRT,RFIBWS)

      IMPLICIT REAL (A-Z)

* --- formal arguments
   *
      INTEGER IUNITD,IUNITO,ITASK,IVSSC,INLAYX
      REAL TKLX(INLAYX),WCLQT(INLAYX),WCWPX(INLAYX)
      REAL RFIBWS,IZRT
      CHARACTER FILEI1*(*)
      LOGICAL TERMNL,EMERG,SPROUT

* --- local declarations
   *
      INTEGER IVCG,IVCG1,IVEF,IVEF1,NSCCG,TCCE,TCEF,I,
     &        IVCS,IVCS1,IVSF,IVSF1,NSCCS,TCCS,TCSF
      REAL WCCG,WCCS,WCWPCG,WCWPCS

      SAVE


*
---------------------------------------------------------------------*
*                I n i t i a l i z a t i o n
   *
*
---------------------------------------------------------------------*

      IF (ITASK.EQ.1) THEN

        CALL RDINIT (IUNITD,IUNITO,FILEI1)

*  - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - *
*
   *
* ----- E m e r g e n c e...
   *

        IF (IVSSC.EQ.0) THEN
* ------- initial root depth at crop emergence (m)
   *
          CALL RDSREA ('IZRTS' , IZRTS )
```

```
* ------- soil depth for crop germination (m)
  *
      CALL RDSREA ('SDCG'  , SDCG  )

* ------- critical water content for crop germination (CRWCCG, -)
  *
      CALL RDSREA ('CRWCCG', CRWCCG )

* ------- time constant for crop emergence (TCCE, d) and sowing
  *
*        failure (TCEF, d)
  *
      CALL RDSINT ('TCCE'  , TCCE   )
      CALL RDSINT ('TCEF'  , TCEF   )
     END IF

*  - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - *
*
  *
* ---   S p r o u t i n g...
  *

* ----- initial root depth at crop sprouting (m)
  *
     CALL RDSREA ('IZRTR' , IZRTR )

* ----- soil depth for crop sprouting (m)
  *
     CALL RDSREA ('SDCS'  , SDCS  )

* ----- critical water content for crop sprouting (CRWCCS, -)
  *
     CALL RDSREA ('CRWCCS', CRWCCS )

* ----- time constant for crop crop sprouting (TCCS, d) and
   *
*      sprouting failure (TCSF, d)
   *
     CALL RDSINT ('TCCS'  , TCCS   )
     CALL RDSINT ('TCSF'  , TCSF   )
```

```
      CLOSE (IUNITD,STATUS='DELETE')


* ---   initial values:
   *
      IZRT   = 0.
      IVCG   = 0
      IVEF   = 0
      IVCS   = 0
      IVSF   = 0
      WCCG   = 0.
      WCWPCG = 0.
      IVCG1  = 0
      IVEF1  = 0
      EMERG  = .FALSE.
      WCCS   = 0.
      WCWPCS = 0.
      IVCS1  = 0
      IVSF1  = 0
      RFIBWS = 1.
      SPROUT = .FALSE.

* ---   number of soil compartments considered for crop
germination    *
*      (NSCCG,- ) and crop sprouting (NSCCS, -)
   *
      ICE1 = 0.
      IF (IVSSC.EQ.0) THEN
        DO 10 I=1, INLAYX
          ICE1 = ICE1 + TKLX(I)
          WCWPCG = WCWPCG + WCWPX(I)*TKLX(I)*1000.
          IF (ICE1.GE.SDCG) THEN
            NSCCG = I
            GO TO 20
          END IF
10        CONTINUE
      END IF
20      CONTINUE
      ICE2 = 0.
      DO 30 I=1, INLAYX
        ICE2 = ICE2 + TKLX(I)
        WCWPCS = WCWPCS + WCWPX(I)*TKLX(I)*1000.
        IF (ICE2.GE.SDCS) THEN
```

```
          NSCCS = I
          GO TO 40
        END IF
30      CONTINUE
40      CONTINUE


*
-------------------------------------------------------------------*
*                   I n t e g r a t i o n
   *
*
-------------------------------------------------------------------*

     ELSE IF (ITASK.EQ.3) THEN

* ---   emergence date (EMERG)
   *
       IF (IVSSC .EQ. 0) THEN
        WCCG = 0.
        DO 100 I=1,NSCCG
          WCCG = WCCG + WCLQT(I)*TKLX(I)*1000.
100       CONTINUE
        IF (WCCG .GE. CRWCCG*WCWPCG) THEN
          IVCG = 1
        ELSE
          IVCG = 0
        END IF
        IF (IVCG.LT.1 .AND. IVCG1.GT.(1/2*TCCE)) THEN
         IVEF = 1
        ELSE
         IVEF = 0
        END IF
        IVCG1 = IVCG1 + IVCG
        IVEF1 = IVEF1 + IVEF
        IF (IVEF1.GT.TCEF) THEN
          WRITE(*,*) ' Sowing failure:'
          TERMNL = .TRUE.
          IVCG1  = 0
          IVEF1  = 0
        ELSE IF (IVCG1.GT.TCCE) THEN
          IF (IVEF1.GT.0) RFIBWS=MAX(0.2,(1.-IVEF1/TCEF))
          EMERG  = .TRUE.
```

```
        END IF
        IF (EMERG) THEN
          IZRT  = IZRTS
        END IF
      END IF

* ---   sprouting date (SPROUT)
*
      IF (IVSSC .GE. 1) THEN
        WCCS = 0.
        DO 110 I=1,NSCCS
          WCCS = WCCS + WCLQT(I)*TKLX(I)*1000.
110       CONTINUE
        IF (WCCS .GT. CRWCCS*WCWPCS) THEN
          IVCS = 1
        ELSE
          IVCS = 0
        END IF
        IF (IVCS.EQ.0 .AND. IVCS1.GE.1) THEN
          IVSF = 1
        ELSE
          IVSF = 0
        END IF
        IVCS1 = IVCS1 + IVCS
        IVSF1 = IVSF1 + IVSF
        IF (IVSF1.GT.TCSF) THEN
          IVCS1 = 0
          IVSF1 = 0
        ELSE IF (IVCS1.GT.TCCS) THEN
          SPROUT = .TRUE.
          IF (IVSF1.GT.0) RFIBWS=MAX(0.2,(1.-IVSF1/TCSF))
          IVCS1  = 0
          IVSF1  = 0
        END IF
        IF (SPROUT) THEN
          IVCS1 = 0
          IVSF1 = 0
        END IF
        IF (SPROUT) IZRT=IZRTR
      END IF
    END IF

    RETURN
```

```
    END

PGRAIN.FOR
*
--------------------------------------------------------------------- *
*
   *
*       B e g i n n i n g   o f  r e g u l a r   r a i n s
   *
*
   *
*                         PGRAIN
   *
*
   *
*  author : Santiago Bonachela-Castano
   *
*         AB-DLO, Wageningen
   *
*
   *
*  date   : December 1993
   *
*
   *
*  purpose: this programme calculates the date of the onset of the
   *
*         rainy season (DBRR, d) for perennial grasses in the
   *
*         Sahel and the Sudan zone of West Africa. The DBRR
   *
*         estimates the beginning of regular rainfall events.
Its    *
*         calculation is based on Hiernaux (1984) "Distribution
   *
*         des pluis et production herbace au Sahel". The DBRR is
   *
*         defined as the first day with rain equal or higher
than    *
*         RAIN1 (or the first of the first five consecutive days
   *
*         with accumulated rain equal or higher than RAIN2). To
```

```
   *
*          reduce the effect of very early rains in the year,
   *
*          outside the main rainy season, the additional
condition    *
*          that accumulated rain during 20 days (TCRD1) that
follow   *
*          the possible DBRR must be higher than 25 mm (RAIN3)
has    *
*          been added.
   *
*
   *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)
   *
*  name   type   meaning                              units
class   *
*  ----   ----   -------                              -----
-----   *
*  ACRAIN   I4   amount of rain which triggers new crop
   *
*              growth                                 mm     I
   *
*  TCRD1    I4   time constant for rain distribution      d      I
   *
*  TCRD2    I4   time constant for rain distribution      d      I
   *
*  RAIN1    R4   constant value of amount of rainfall    mm      I
   *
*  RAIN2    R4   constant value of amount of rainfall    mm      I
   *
*  RAIN3    R4   constant value of amount of rainfall    mm      I
   *
*  DBRR     I4   date of the beginning of regular rains   d      O
   *
*
   *
*  Fatal errors checks: none
   *
*
   *
*  Subroutines and functions called : WEATHR
   *
```

```
*  File usage : FILEI1
    *
*
--------------------------------------------------------------------- *

      SUBROUTINE PGRAIN
(ITASK,IUNITD,IUNITO,FILEI1,IDOY,DFAR,DBRR)

* --- formal arguments
    *
      IMPLICIT REAL (A-Z)
      INTEGER ITASK,IUNITD,IUNITO,IDOY,DFAR,DBRR
      CHARACTER FILEI1*(*)

* --- local variables
    *
      INTEGER TCRD1,TCRD2
      INTEGER PBRS,I,I1,I2,I3,ISTAT2
      LOGICAL R1,R2,SWITCH

      SAVE



* --- I n i t i a l i z a t i o n
    *

      IF (ITASK.EQ.1)  THEN

        CALL RDINIT (IUNITD,IUNITO,FILEI1)

* --- parameters of PGRAIN. Crop emergence is calculated as a
    *
*     function of rainfall events
    *
        CALL RDSINT ('TCRD1'  , TCRD1 )
        CALL RDSINT ('TCRD2'  , TCRD2 )
        CALL RDSREA ('RAIN1'  , RAIN1 )
        CALL RDSREA ('RAIN2'  , RAIN2 )
        CALL RDSREA ('RAIN3'  , RAIN3 )
        CALL RDSREA ('RAINF1' , RAINF1)
        CALL RDSREA ('RAINF2' , RAINF2)

        CLOSE (IUNITD,STATUS='DELETE')
```

```
* --- initial values
    *
        SWITCH = .TRUE.
        DBRR   = 0
        DFAR   = 0
        R1     = .FALSE.
        R2     = .FALSE.
        ACR    = 0.
        ACR1   = 0.

* --- c a l c u l a t i o n
    *

      ELSE IF (ITASK.EQ.3) THEN

* --- initial values
    *
        SWITCH = .TRUE.
        DBRR   = 0
        DFAR   = 0
        R1     = .FALSE.
        R2     = .FALSE.
        ACR    = 0.
        ACR1   = 0.

* --- request weather data
    *
        DO  10  I=IDOY, 365
        CALL WEATHR (I, ISTAT2, RDD, TMMN, TMMX,
     &               VP, WN, RAIN)

* --- infiltrated rainfall (INRAIN, mm/d)
    *
        IF (RAIN.GT.RAINF2) THEN
          RAINF  = RAINF1 * (RAIN - RAINF2)
          INRAIN = MAX(0., RAIN - RAINF)
        ELSE
          INRAIN = RAIN
        END IF
```

```
* --- calculation of the day of first active rainfall event
    *
      IF (SWITCH) THEN
        IF (INRAIN.GE.RAIN1) THEN
          DFAR   = I
          SWITCH = .FALSE.
        ELSE IF (INRAIN.GT.1. .AND. INRAIN.LT.RAIN1) THEN
          ACR = 0.
          DO 20  I1=I, I+TCRD2-1
            CALL WEATHR (I1, ISTAT2, RDD, TMMN, TMMX,
     &                   VP, WN, RAIN)
            IF (RAIN.GT.RAINF2) THEN
              RAINF  = RAINF1 * (RAIN - RAINF2)
              INRAIN = MAX(0., RAIN - RAINF)
            ELSE
              INRAIN = RAIN
            END IF
            ACR  = ACR+INRAIN
20          CONTINUE
          IF (ACR.GE.RAIN3) THEN
            DFAR   = I
            SWITCH = .FALSE.
          END IF
        END IF
      END IF

* --- calculation of the day of beginning of regular rains
    *
      IF (INRAIN.GE.RAIN1) THEN
        ACR  = 0.
        PBRS = I
        DO 30 I2=I+1, I+TCRD1
          CALL WEATHR (I2, ISTAT2, RDD, TMMN, TMMX,
     &                 VP, WN, RAIN)
          IF (RAIN.GT.RAINF2) THEN
            RAINF  = RAINF1 * (RAIN - RAINF2)
            INRAIN = MAX(0., RAIN - RAINF)
          ELSE
            INRAIN = RAIN
          END IF
          ACR = ACR+INRAIN
30        CONTINUE
        R1 = ACR.GE.RAIN2
```

```
        IF (R1) THEN
          DBRR = PBRS
          GOTO 50
        END IF
      ELSE IF (INRAIN.GT.1. .AND. INRAIN.LT.RAIN1) THEN
        ACR  = 0.
        ACR1 = 0.
        DO 40 I3=I, I+TCRD1+TCRD2-1
        CALL WEATHR (I3, ISTAT2, RDD, TMMN, TMMX,
     &               VP, WN, RAIN)
        IF (RAIN.GT.RAINF2) THEN
          RAINF  = RAINF1*(RAIN-RAINF2)
          INRAIN = MAX(0., RAIN - RAINF)
        ELSE
          INRAIN = RAIN
        END IF
        IF (I3 .LE. (I+TCRD2-1)) THEN
          ACR  = ACR+INRAIN
        ELSE
          ACR1 = ACR1+INRAIN
        END IF
40        CONTINUE
        R1 = ACR.GE.RAIN3
        R2 = ACR1.GE.RAIN2
        IF (R1 .AND. R2) THEN
          DBRR = I
          GO TO 50
        END IF
      END IF
10      CONTINUE

50      CONTINUE
    END IF
    RETURN

    END

PGWU.FOR
*
------------------------------------------------------------------ *
*
   *
*   W a t e r  u p t a k e  o f  p e r e n n i a l  g r a s s e s
```

```
    *
*
    *
*                              (PGWU)
    *
*
    *
*
    *
*   author: Santiago Bonachela Castano
    *
*
    *
*   date: March 1994
    *
*
    *
*
    *
*   purpose: to simulate water uptake of perennial grasses crops
    *
*   during several subsequent seasons (both rainy and dry)
    *
*
    *
*   main characteristics:
    *
*   - developed from the SAHEL water balance (van Keulen, 1975);
    *
*   - compensatory effects among soil compartments for water
uptake    *
*     takes place as result of the water availability and the root
    *
*     length density.
    *
*
    *
*
    *
*  Formal parameters:  (I=input,O=output,C=control,IN=init,T=time)
    *
*  name   type meaning                                units
class *
```

```
*  ----   ---- -------                          -----
----- *
*  ITASK   I4  task that subroutine should perform          -
 I  *
*  IUNITD  I4  unit of input file with plant data           -
 I  *
*  IUNITO  I4  unit of output file                          -
 I  *
*  FILEI1  C*  name of file with plant data                 -
 I  *
*  OUTPUT  L4  flag to indicate if output should be done    -
 I  *
*  TERMNL  L4  flag to indicate if simulation is to stop    -
I/O *
*  DELT    R4  time step of integration                     d
 I  *
*  INLAYX  I4  number of soil compartments                  -
 I  *
*  TKLX    R4  thickness of soil compartments               m
 I  *
*  WCWPX() R4  volumetric water content at wilting point    _
 I  *
*  WCFCX() R4  volumetric water content at field capacity   _
 I  *
*  WCLQT() R4  volumetric water content actual              _
 I  *
*  IDOY    I4  day of the year                              d
 I  *
*  ZRT     R4  root depth                                   m
 I  *
*  LVCGRS   L  logical variable to separate crop cycles     _
 I  *
*  LVCGDS   L  logical variable to separate crop            _
 I  *
*  LVCS     L  logical variable to indicate whether or not
   *
*              crop growth simulation has started           -
 I  *
*  EVSW    R4  actual evaporation rate                      mm/d
 I  *
*  DRAICU  R4  cumulative drainage by drains                mm
 I  *
*  RAIN    R4  amount of rainfall                           mm/d
```

```
 I  *
*  INRAIN  R4  infiltrated rainfall                       mm/d
 I  *
*  MTRANS  R4  maximum transpiration                      mm/d
 I  *
*  WSH     R4  weigth of shoots                           kg/ha
 I  *
*  WSRT    R4  weigth of structural roots                 kg/ha
 I  *
*  TWA     R4  total water availability                   mm
 O  *
*  WRFRE   R4  water reduction factor for root extension    mm
 O  *
*  TRANSR  R4  transpiration ratio                         -
 O  *
*  TRWL()  R4  actual rate of water extraction by roots
   *
*              per soil compartment                       mm/d
 O  *
*
   *
*
   *
*
   *
*  Routines called   : OUTDAT,RDINIT,RDSREA,RDAREA
   *
*  Functions called  : LINT
   *
*  File usage        : IUNITD, IUNITO
   *
*
----------------------------------------------------------------- *

      SUBROUTINE PGWU (ITASK,IUNITD,IUNITO,FILEI1,OUTPUT,TERMNL,
     &                 INLAYX,TKLX,WCFCX,WCWPX,WCLQT,ZRT,IDOY,
     &                 LVCGRS,LVCGDS,LVCS,EVSW,DRAICU,RAIN,MTRANS,
     &                 INRAIN,WSH,WSRT,
     &                 TWA,WRFRE,TRANSR,TRWL)


      IMPLICIT REAL (A-Z)
```

```
* --- formal parameters
     INTEGER ITASK,IUNITD,IUNITO,INLAYX,IDOY
     REAL TKLX(INLAYX),WCFCX(INLAYX),WCWPX(INLAYX),WCLQT(INLAYX),
    &     TRWL(INLAYX)
     LOGICAL OUTPUT,TERMNL,LVCGRS,LVCGDS,LVCS
     CHARACTER*(*) FILEI1
     REAL ZRT,WSRT,WSH,TRANSR,TWA,WRFRE,EVSW,MTRANS,INRAIN

* --- local declarations
     INTEGER I,IN,INLAY,INTBMX,ISWDFN,IECTTN,SWITCH
     PARAMETER (INLAY = 10)
     REAL DEPTH(INLAY),WCCR(INLAY),WA(INLAY),WACWC(INLAY),
    &     MXWA(INLAY),WARL(INLAY),RFWU(INLAY),
    &     CWRT(INLAY),RL(INLAY),ERL(INLAY),AVWU(INLAY)
     PARAMETER (INTBMX = 40)
     REAL SWDFTB(INTBMX),ECTTB(INTBMX)

     SAVE

*
---------------------------------------------------------------------- *
*                I n i t i a l i z a t i o n
   *
*
---------------------------------------------------------------------- *

     IF (ITASK.EQ.1) THEN

* ----- input section
   *
       CALL RDINIT (IUNITD, IUNITO, FILEI1)



*       P a r a m e t e r s
   *

* ----- specific root weight (SRTW, m/g)
   *
       CALL RDSREA ('SRTW'  , SRTW  )

* ----- parameter in the exponential function used to simulated
root   *
*       distribution in the rooted soil
```

```
 *
      CALL RDSREA ('RTDERS', RTDERS)
      CALL RDSREA ('RTDEDS', RTDEDS)

* ----- maximum transpiration rate per unit of root length
(MXTRRL,    *
*      kg/m/d)
 *
      CALL RDSREA ('MXTRRL', MXTRRL)

* ----- initial values of variables in the argument list
 *
*      availability;
 *
      TWA    = 0.
      TWS    = 0.
      ZRT    = 0.
      TRANSR = 1.
      MTRANS = 0.
      WSH    = 0.
      WSRT   = 0.
      WRFRE  = 0.
      LVCGRS = .FALSE.
      LVCGDS = .FALSE.
      LVCS   = .FALSE.

* ----- initial values:
 *
      MXTWT  = 0.
      MXTWE  = 0.
      MXTWD  = 0.
      MXTWU  = 0.
      SWT    = 0.
      SWE    = 0.
      SWD    = 0.
      SWU    = 0.
      CR     = 0.
      CIR    = 0.
      TWT    = 0.
      TSWE   = 0.
      TWU    = 0.
      TWD    = 0.
      DWD    = 0.
```

```
      AVTWD  = 0.
      CRRS   = 0.
      CRDS   = 0.
      CIRRS  = 0.
      CIRDS  = 0.
      CRDP   = 0.
      IN     = 0
      TWE    = 0.
      SWITCH = 0

*     F u n c t i o n s
*

* ----- epidermical transpiration as a function of living biomass
*
      CALL RDAREA ('ECTTB' , ECTTB,  INTBMX, IECTTN)

* ----- soil water depletion fraction as a function of MTRANS
*
      CALL RDAREA ('SWDFTB', SWDFTB, INTBMX, ISWDFN)


      CLOSE (IUNITD, STATUS='DELETE')

* ----- initial values
*
      DO 10 I=1,INLAYX
* ----- depth of the centre of each soil compartment
*
        IF (I.EQ.1) THEN
          DEPTH(1)=0.5*TKLX(1)
        ELSE
          DEPTH(I)=DEPTH(I-1)+0.5*TKLX(I-1)+0.5*TKLX(I)
        END IF
        TRWL(I)  = 0.
        CWRT(I) = 0.
        RL(I)    = 0.
        WA(I)    = 0.
        WACWC(I) = 0.
        MXWA(I)  = 0.
        ERL(I)   = 0.
        AVWU(I)  = 1.
10      CONTINUE
```

```
*
-------------------------------------------------------------------- *
*                r a t e   c a l c u l a t i o n
   *
*
-------------------------------------------------------------------- *



    ELSE IF (ITASK.EQ.2) THEN

* ----- initial values at the beginning of each running day
   *
      DO 20 I=1, INLAYX
       AVWU(I) = 1.
       TRWL(I) = 0.
20     CONTINUE
      TWE    = 0.
      ERLB   = 0.
      MXWAWS = 0.
      TRADEF = MTRANS
      AV1WU  = 0.

* ----- before crop emergence...
   *
      IF (ZRT.EQ.0. .OR. .NOT.LVCS) GO TO 30

* ----- maximum transpiration rate or water demand (mm/d)
   *
      ETRANS = LINT(ECTTB,IECTTN,WSH)
      IF (.NOT.LVCGRS .AND. .NOT.LVCGDS) THEN
       MTRANS = ETRANS
      ELSE IF (MTRANS.EQ.0.) THEN
       MTRANS = ETRANS
      ELSE
       MTRANS = MAX(0., ETRANS, MTRANS)
      END IF

* ----- root length distribution of each soil layer (RL,
   *
*      m root /m2 ground)
   *
      DO 40 I=1, IN
```

```
        IF (I.EQ.IN) THEN
          RRD = 1.
        ELSE
          RRD = MIN(1., (DEPTH(I)+0.5*TKLX(I))/ZRT)
        END IF
        IF (LVCGRS) THEN
          RTDE = RTDERS
        ELSE
          RTDE = RTDEDS
        END IF
        CWRT(I)  = 0.1 * WSRT * (1. - EXP(-RTDE*RRD))
        IF (I.EQ.1) THEN
          AVCWRT = 0.1 * WSRT * EXP(-RTDE)
          RL(I)  = (CWRT(I)+AVCWRT) * SRTW
        ELSE
          RL(I)  = (CWRT(I)-CWRT(I-1)) * SRTW
        END IF
40      CONTINUE

* ----- soil water depletion fraction (SWDF, -)
   *
       SWDF = LINT(SWDFTB,ISWDFN,MTRANS)

       DO 50 I=1,INLAYX
* ----- critical water content (WCCR, -) per soil layer
   *
        WCCR(I)  = (1.-SWDF) * (WCFCX(I)-WCWPX(I)) + WCWPX(I)
* ----- water availability above the critical water content (mm/d)
   *
        IF (I.EQ.IN) THEN
          WACWC(I) = MAX(0., (WCLQT(I)-WCCR(I)) * RDNIL * 1000.)
        ELSE
          WACWC(I) = MAX(0., (WCLQT(I)-WCCR(I)) * TKLX(I) *
1000.)
        END IF
* ----- water availability taking into account root length (WARL,
   *
*       mm/d)
   *
        WARL(I)  = MXTRRL * RL(I)
* ----- water availability above the critical water content taking
   *
*       into account root length (MXWA, mm/d)
```

```
   *
       MXWA(I)  = MIN(WACWC(I), WARL(I))
       MXWAWS   = MXWAWS + MXWA(I)
* ----- reduction factor on water uptake (RFWU, -)
   *
       IF (.NOT.LVCGRS .AND. .NOT.LVCGDS) THEN
         RFWU(I) = 1.
       ELSE
         AVRFWU   = MAX(0.,
(WCLQT(I)-WCWPX(I))/(WCCR(I)-WCWPX(I)))
         RFWU(I)  = MIN(1., AVRFWU)
       END IF
* ----- effective root length (ERL, m/m2) per soil layer
   *
       ERL(I)   = RL(I) * RFWU(I)
* ----- cumulative effective root length (ERLB, m/m2)
   *
       ERLB     = ERLB + ERL(I)
50     CONTINUE

60     CONTINUE

* ----- water uptake per soil compartment (TRWL, mm/d)
   *
      DO 70, I=1,INLAYX
       IF (AVWU(I).EQ.1.) THEN
         IF (.NOT.LVCGRS .AND. .NOT.LVCGDS) RFWU(I)=1.
         TRWL(I) = TRWL(I) + TRADEF * ERL(I)/ERLB * RFWU(I)
* ----- boundary condition due to water availability
   *
         IF (TRWL(I).GT.WA(I)) THEN
           TRWL(I) = WA(I)
           AVWU(I) = 0.
         END IF
* ----- boundary condition due to maximum transpiration per unit
of    *
*      root length
   *
         IF (TRWL(I).GT.MXTRRL*RL(I)) THEN
           TRWL(I) = MXTRRL*RL(I)
           AVWU(I) = 0.
         END IF
       ELSE IF (AVWU(I).EQ.0.) THEN
```

```
          TRWL(I) = TRWL(I) + TRADEF * ERL(I)/ERLB * RFWU(I)
        END IF
* ----- water uptake in the rooted soil (TRW, mm/d)
   *
        TWE     = TWE + TRWL(I)
        IF (RFWU(I).LT.1.) AVWU(I)=0.
        AV1WU   = AV1WU + AVWU(I)
70      CONTINUE


* ----- loop for water compensation between soil layers
  *
      IF (MXWAWS.GE.TRADEF) THEN
        TRADEF = MAX(0., MTRANS-TWE)
        IF (TRADEF.GE.1.E-3 .AND. AV1WU.GT.0.) THEN
          TWE   = 0.
          AV1WU = 0.
          ERLB  = 0.
          DO 80 I=1,INLAYX
            IF (AVWU(I).EQ.1.) THEN
              ERLB = ERLB + ERL(I)
            ELSE
              RFWU(I) = 0.
              ERL(I)  = 0.
            END IF
80          CONTINUE
          GO TO 60
        END IF
      END IF

* ----- water uptake in the rooted soil (TRW, mm/d)
   *
      DO 90 I=1,INLAYX
        TRWL(I) = - TRWL(I)
90      CONTINUE


* ----- actual to potential transpiration ratio (TRANSR, -)
   *
      IF (LVCGRS .OR. LVCGDS) THEN
        IF (TRADEF.LT.1.E-3) THEN
          TRANSR = 1.
        ELSE
```

```
          TRANSR = TWE/MTRANS
          MTRANS = TWE
        END IF
      ELSE
        TRANSR = 1.
      END IF

* ----- water reduction factor for root extension (WRFRE, -)
    *
      WRFRE = RFWU(IN)

30    CONTINUE

* ----- reduction factor values when the growing cycle finish
    *
      IF (.NOT.LVCGRS .AND. .NOT.LVCGDS) THEN
        TRANSR = 1.
        WRFRE  = 1.
      END IF


*
-------------------------------------------------------------------- *
*             O u t p u t   o f   v a r i a b l e s
    *
*
-------------------------------------------------------------------- *



* ----- state variables and water stress factors
    *
      IF (OUTPUT .OR. TERMNL) THEN
        CALL OUTDAT (2,0,'TWA'   , TWA   )
        CALL OUTDAT (2,0,'TRANSR', TRANSR)
*         CALL OUTDAT (2,0,'WRFRE' , WRFRE )

* ------- variables for the sensitivity analysis
   *
        CALL OUTDAT (2,0,'MXTWT' , MXTWT )
        CALL OUTDAT (2,0,'MXTWE' , MXTWE )
        CALL OUTDAT (2,0,'MXTWU' , MXTWU )
        CALL OUTDAT (2,0,'MXTWD' , MXTWD )
        CALL OUTDAT (2,0,'TWT'   , TWT   )
```

```
        CALL OUTDAT (2,0,'TWS'   , TWS   )
        CALL OUTDAT (2,0,'TSWE'  , TSWE  )
        CALL OUTDAT (2,0,'TWU'   , TWU   )
        CALL OUTDAT (2,0,'TWD'   , TWD   )
        CALL OUTDAT (2,0,'CR'    , CR    )
        CALL OUTDAT (2,0,'CIR'   , CIR   )
        CALL OUTDAT (2,0,'SWT'   , SWT   )
        CALL OUTDAT (2,0,'SWE'   , SWE   )
        CALL OUTDAT (2,0,'SWU'   , SWU   )
        CALL OUTDAT (2,0,'SWD'   , SWD   )
*         CALL OUTDAT (2,0,'CRRS'  , CRRS  )
*         CALL OUTDAT (2,0,'CRDS'  , CRDS  )
*         CALL OUTDAT (2,0,'CRDP'  , CRDP  )
      END IF


*
-------------------------------------------------------------------- *
*                    I n t e g r a t i o n
   *
*
-------------------------------------------------------------------- *

     ELSE IF (ITASK.EQ.3) THEN
* ----- before crop emergence...
   *
      IF (ZRT .EQ. 0.) GO TO 100

* ----- deepest soil compartment where root growth takes place
(IN)    *
      DO 110 I=1,INLAYX-1
        IF (ZRT.GT.0. .AND. ZRT.LE.(DEPTH(1)+0.5*TKLX(1))) THEN
          IN = 1
        ELSE IF (ZRT.GT.(DEPTH(I)+0.5*TKLX(I)).AND.
     &           ZRT.LE.(DEPTH(I+1)+0.5*TKLX(I+1))) THEN
          IN = I+1
        END IF
110    CONTINUE

* ----- root penetration in the deepest soil compartment (RDNIL,
m)    *
      IF (IN.EQ.1) THEN
        RDNIL = ZRT
```

```
      ELSE
        RDNIL = ZRT-(DEPTH(IN-1)+0.5*TKLX(IN-1))
      END IF

* ----- maximum water availability (WA, mm) per soil layer and
total   *
*       water stored in the profile (TWS, mm)
    *
      TWA = 0.
      TWS = 0.
      DO 120 I=1,INLAYX
        IF (I.EQ.IN) THEN
          WA(I) = MAX(0., (WCLQT(I)-WCWPX(I)) * RDNIL * 1000.)
          TWA   = TWA + WA(I)
        ELSE
          WA(I) = MAX(0., (WCLQT(I)-WCWPX(I)) * TKLX(I) * 1000.)
          IF (I.LE.IN) TWA=TWA+WA(I)
        END IF
120     CONTINUE
      TWS = 0.
      DO 130 I=1,INLAYX
        WS   = MAX(0., WCLQT(I) * TKLX(I) * 1000.)
        TWS  = TWS + WS
130     CONTINUE

100     CONTINUE



* ----- seasonal transpiration (SWT, mm), soil evaporation (SWE,
mm)   *
*       and water drainage (SWD, mm)
    *
      IF (DRAICU .LT. AVTWD) THEN
        DWD = DRAICU - AVTWD
      ELSE
        DWD = 0.
      END IF
      AVTWD = DRAICU
      IF (LVCGRS .AND. SWITCH.NE.0) THEN
        CRRS   = 0.
        CIRRS  = 0.
        SWT    = 0.
        SWE    = 0.
```

```
       SWD    = 0.
       SWU    = 0.
       CRRS   = CRRS + RAIN
       CIRRS  = CIRRS + INRAIN
       SWT    = SWT + TWE
       SWE    = SWE - EVSW
       SWU    = SWT + SWE
       SWD    = SWD - DWD
       SWITCH = 0
      ELSE IF (LVCGRS.AND. SWITCH.EQ.0) THEN
       CRRS   = CRRS + RAIN
       CIRRS  = CIRRS + INRAIN
       SWT    = SWT + TWE
       SWE    = SWE - EVSW
       SWU    = SWT + SWE
       SWD    = SWD - DWD
      ELSE IF (LVCGDS .AND. SWITCH.NE.1) THEN
       CRDS   = 0.
       CIRDS  = 0.
       SWT    = 0.
       SWE    = 0.
       SWU    = 0.
       SWD    = 0.
       CRDS   = CRDS + RAIN
       CIRDS  = CIRDS + INRAIN
       SWT    = SWT + TWE
       SWE    = SWE - EVSW
       SWU    = SWT + SWE
       SWD    = SWD - DWD
       SWITCH = 1
      ELSE IF (LVCGDS .AND. SWITCH.EQ.1) THEN
       CRDS   = CRDS + RAIN
       CIRDS  = CIRDS + INRAIN
       SWT    = SWT + TWE
       SWE    = SWE - EVSW
       SWU    = SWT + SWE
       SWD    = SWD - DWD
      ELSE IF (.NOT.LVCGRS .AND. .NOT.LVCGDS .AND. SWITCH.NE.2)
THEN
       CRDP   = 0.
       SWT    = 0.
       SWE    = 0.
       SWD    = 0.
```

```
        SWT    = SWT + TWE
        CRDP   = CRDP + RAIN
        SWE    = SWE - EVSW
        SWD    = SWD - DWD
        SWITCH = 2
      ELSE IF (.NOT.LVCGRS .AND. .NOT.LVCGDS .AND.  SWITCH.EQ.2)
THEN
        SWT    = 0.
        SWE    = 0.
        SWD    = 0.
        CRDP   = CRDP + RAIN
        SWT    = SWT + TWE
        SWE    = SWE - EVSW
        SWD    = SWD - DWD
      END IF

* ----- total transpiration (TWT, mm), soil evaporation (TWE, mm)
   *
*       and water drainage (TWD, mm) per year
   *
      IF (IDOY.EQ.1) THEN
        MXTWT = TWT
        MXTWU = TWU
        MXTWE = TSWE
        MXTWD = TWD
        CR    = 0.
        CIR   = 0.
        TWT   = 0.
        TSWE  = 0.
        TWD   = 0.
        TWU   = 0.
        CR    = CR + RAIN
        CIR   = CIR + INRAIN
        TWT   = TWT + TWE
        TSWE  = TSWE - EVSW
        TWU   = TWU + TWE - EVSW
        TWD   = TWD - DWD
      ELSE IF (IDOY.NE.1) THEN
        CIR   = CIR + INRAIN
        CR    = CR + RAIN
        TWT   = TWT + TWE
        TSWE  = TSWE - EVSW
        TWU   = TWU + TWE - EVSW
```

```
        TWD   = TWD - DWD
      END IF
*
------------------------------------------------------------------- *
*                    T e r m i n a t i o n
   *
*
------------------------------------------------------------------- *

     ELSE IF (ITASK .EQ. 4) THEN

     END IF

     RETURN

     END
```

DRSAHE.FOR

```
*
--------------------------------------------------------------------- *
*  SUBROUTINE DRSAHE
     *
*
     *
*  Author : Daniel van Kraalingen
     *
*  Date   : December 1993
     *
*  Version: 1.1
     *
*
     *
*  Purpose: Tipping bucket water balance routine
     *
*
     *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)
     *
*  name   type meaning                                     units
class *
*  ----   ---- -------                                     -----
----- *
*  control
```

```
     *
*  ITASK   I4  determines action of routine                  -
 C,I  *
*  IUNIT   I4  unit number to be used, see file usage below   -
IN,C,I *
*  IUNLOG  I4  unit number in use for LOG FILE               -
IN,C,I *
*           = 0, no log file is used or assumed to exist
     *
*           > 0, error messages are written to log file
     *
*  FILIN   C*  name of file with soil data                  -
IN,C,I *
*  INLAYX  I4  number of layers as declared in calling program-
 IN   *
*
     *
*  time variables
     *
*  TIME    R4  simulation time                              d
 T,I  *
*  DELT    R4  time step                                    d
 T,I  *
*  OUTPUT  L4  Flag to indicate if output should be done      -
  I   *
*
     *
*  dynamic input
     *
*  EVSC    R4  potential evaporation rate                  mm/d
  I   *
*  RAIN    R4  rainfall / irrigation rate                  mm/d
  I   *
*  TRWL    R4  actual transpiration rate per layer         mm/d
  I   *
*
     *
*  soil description (available after initial call)
     *
*  INLAY   I4  number of layers specified in input file       -
  O   *
*  TKLX    R4  thickness of soil compartments                 m
IN,O  *
```

```
* ZRTMS   R4  maximum rooting depth as soil characteristic   -
 O   *
* WCADX   R4  volumetric water content airdry                -
IN,O  *
* WCWPX   R4  volumetric water content at wilting point      -
IN,O  *
* WCFCX   R4  volumetric water content at field capacity     -
IN,O  *
* WCSTX   R4  volumetric water content at saturation         -
IN,O  *
*
     *
* dynamic output
     *
* EVSW    R4  actual (realized) evaporation rate           mm/d
 O   *
* FLXQT   R4  layer boundary fluxes (rates)                mm/d
 O   *
* WCLQT   R4  volumetric soil water content per layer        -
 O   *
*
     *
* cumulated, derived and help variables
     *
* DRAICU  R4  cumulative drainage by drains                  mm
 O   *
* EVSWCU  R4  cumulative evaporation                         mm
 O   *
* INFCU   R4  cumulative infiltration                        mm
 O   *
* TRWCU   R4  cumulative transpiration                       mm
 O   *
* FLXCU   R4  cumulative flux for each layer boundary        mm
 O   *
*
     *
*----------------------------------------------------------------------*

      SUBROUTINE DRSAHE (ITASK , IUNIT , IUNLOG, FILIN, INLAYX,
     &                   TIME  , DELT  , OUTPUT, EVSC , RAIN  ,
TRWL,
     &                   INLAY , TKLX  , ZRTMS ,
     &                   WCADX , WCWPX , WCFCX , WCSTX,
```

```
     &                  EVSW  , FLXQT , WCLQT ,
     &                  DRAICU, EVSWCU, INFCU, TRWCU, FLXCU)

      IMPLICIT REAL (A-Z)

* --- formal parameters
      INTEGER ITASK, IUNIT, IUNLOG, INLAYX, INLAY
      CHARACTER FILIN*(*)
      LOGICAL OUTPUT

      REAL TIME  , DELT  , EVSC , RAIN , EVSW
      REAL DRAICU, EVSWCU, INFCU, TRWCU, ZRTMS

      REAL TRWL(INLAYX) , TKLX(INLAYX) , WCADX(INLAYX)  ,
WCWPX(INLAYX)
      REAL WCFCX(INLAYX), WCSTX(INLAYX), FLXQT(INLAYX+1),
WCLQT(INLAYX)
      REAL FLXCU(INLAYX+1)

* --- local variables

* --- control, switch, temporary and miscellaneous variables
      INTEGER IL, ITMP, NL
      INTEGER SWIT6, SWIT8, SWIT9
      REAL WCUM, WCUMO, TRW, FLOW, CAP, DRAIQT, WCUMCH, CHECK

* --- soil description arrays
      INTEGER IMNL
      PARAMETER (IMNL=10)
      INTEGER ITYL(IMNL)
      REAL TKL(IMNL)   , TYL(IMNL)  , DEPTH(IMNL)
      REAL WCAD(IMNL)  , WCWP(IMNL) , WCFC(IMNL) , WCST(IMNL)
      REAL WCLQTM(IMNL), WCLCH(IMNL), WCL(IMNL)

* --- variables for calculation of evaporation (modification May,
94)
      REAL VAR(IMNL), RESOIL(IMNL)
      REAL SUM, EES, EVSW2, EVSH, EVSD, RDSLR, DSLR

* --- variables for limitation soil evaporation effects until
*     a maximum depth
      INTEGER DLSE
      REAL MDSE, SD
```

```
* --- soil characteristics according to Rijtema/Driessen system
*     the number of soil types defined is NRDTYP
      INTEGER NRDTYP
      PARAMETER (NRDTYP=20)
      REAL MSWCAT(NRDTYP), WCSTT(NRDTYP), MSWCA(IMNL)

* --- soil characteristics according to Van Genuchten system
*     The number of soil types defined is NVGTYP
      INTEGER NVGTYP
      PARAMETER (NVGTYP=2)
      REAL VGWRT(NVGTYP), VGWST(NVGTYP), VGAT(NVGTYP),
VGNT(NVGTYP)
      REAL VGA(IMNL)    , VGR(IMNL)    , VGN(IMNL)
      REAL VGM, HLP1, WREL

* --- linear interpolation on user-defined log scale
      REAL PFWC00(IMNL), PFWC01(IMNL), PFWC02(IMNL), PFWC03(IMNL)
      REAL PFWC04(IMNL), PFWC05(IMNL), PFWC06(IMNL), PFWC07(IMNL)
      REAL PFWC08(IMNL), PFWC09(IMNL), PFWC10(IMNL)
      REAL PF(22)

* --- parameters for field capacity, wilting point and airdry
      REAL FIELD, WILTP, AIRDR
      PARAMETER (FIELD = 1.0E2, WILTP = 1.6E4, AIRDR = 1.0E7)

* --- functions
      REAL LINT, INTGRL

      REAL AVAIL(IMNL)

      SAVE

*     gamma, dimensionless (Rijtema/Driessen)
      DATA MSWCAT  /.0853, .0450, .0366, .0255, .0135, .0153,
.0243,
     $             .0299, .0251, .0156, .0186, .0165, .0164,
.0101,
     $             .0108, .0051, .0085, .0059, .0043, .0108/

*     saturated soil moisture content, dimensionless
(Rijtema/Driessen)
      DATA WCSTT   /.3950, .3650, .3500, .3640, .4700, .3940,
```

```
.3010,
    $            .4390, .4650, .4550, .5040, .5090, .5030,
.4320,
    $            .4750, .4450, .4530, .5070, .5400, .8630/

*     van Genuchten form:
*     TETA-r, dimensionless
      DATA VGWRT / 0.0448,  0.0000/
*     TETA-s, dimensionless
      DATA VGWST / 0.4012,  0.4505/
*     ALPHA in cm-1
      DATA VGAT  / 0.0036,  0.0067/
*     N, dimensionless
      DATA VGNT  / 1.5007,  1.2318/
*     end van Genuchten form

      IF (ITASK.EQ.1) THEN

         CALL RDINIT (IUNIT,IUNLOG,FILIN)

         CALL RDSINT ('NL',NL)
         IF (NL.GT.IMNL) CALL ERROR
     &      ('DRSAHE','too many layers defined in data file')
         INLAY = NL
         IF (INLAYX.LT.NL) CALL ERROR
     &      ('DRSAHE','too few layers in external arrays')

*        read thicknesses, and evaporation proportionality factor
         CALL RDFREA ('TKL', TKL, IMNL, NL)
         CALL RDSREA ('EES',EES)

*        read maximum depth affected by soil evaporation (mod.)
         CALL RDSREA ('MDSE', MDSE)

*        read switch
         CALL RDSINT ('SWIT9',SWIT9)
*        read type of moisture characteristic
         CALL RDSINT ('SWIT8',SWIT8)

         IF (SWIT9.EQ.1) THEN
*           moisture characteristics by user-defined parameters

            CALL RDFREA ('WCST' ,WCST ,IMNL,NL)
```

```
      IF (SWIT8.EQ.1) THEN

*       Driessen moisture characteristic
        CALL RDFREA ('MSWCA',MSWCA,IMNL,NL)
        DO 10 IL=1,NL
          WCFC(IL) = WCST(IL)*EXP (-MSWCA(IL)*LOG
(FIELD)**2)
          WCWP(IL) = WCST(IL)*EXP (-MSWCA(IL)*LOG
(WILTP)**2)
          WCAD(IL) = WCST(IL)*EXP (-MSWCA(IL)*LOG
(AIRDR)**2)
10      CONTINUE

      ELSE IF (SWIT8.EQ.2) THEN

*       Van Genuchten moisture characteristic
        CALL RDFREA ('VGA' ,VGA ,IMNL,NL)
        CALL RDFREA ('VGR' ,VGR ,IMNL,NL)
        CALL RDFREA ('VGN' ,VGN ,IMNL,NL)

        DO 20 IL=1,NL
          VGM = 1.-1/VGN(IL)

          HLP1     = (FIELD*VGA(IL))**VGN(IL)
          WREL     = (1.+HLP1)**(-VGM)
          WCFC(IL) = WREL*(WCST(IL)-VGR(IL))+VGR(IL)

          HLP1     = (WILTP*VGA(IL))**VGN(IL)
          WREL     = (1.+HLP1)**(-VGM)
          WCWP(IL) = WREL*(WCST(IL)-VGR(IL))+VGR(IL)

          HLP1     = (AIRDR*VGA(IL))**VGN(IL)
          WREL     = (1.+HLP1)**(-VGM)
          WCAD(IL) = WREL*(WCST(IL)-VGR(IL))+VGR(IL)
20      CONTINUE

      ELSE IF (SWIT8.EQ.3) THEN

*       linear interpolation on user-defined log scale

*       read pF values
        CALL RDFREA ('PFWC00',PFWC00,IMNL,NL)
```

```
      CALL RDFREA ('PFWC01',PFWC01,IMNL,NL)
      CALL RDFREA ('PFWC02',PFWC02,IMNL,NL)
      CALL RDFREA ('PFWC03',PFWC03,IMNL,NL)
      CALL RDFREA ('PFWC04',PFWC04,IMNL,NL)
      CALL RDFREA ('PFWC05',PFWC05,IMNL,NL)
      CALL RDFREA ('PFWC06',PFWC06,IMNL,NL)
      CALL RDFREA ('PFWC07',PFWC07,IMNL,NL)
      CALL RDFREA ('PFWC08',PFWC08,IMNL,NL)
      CALL RDFREA ('PFWC09',PFWC09,IMNL,NL)
      CALL RDFREA ('PFWC10',PFWC10,IMNL,NL)

*     set up relative moisture content values
      PF(2)  = 0.0
      PF(4)  = 0.1
      PF(6)  = 0.2
      PF(8)  = 0.3
      PF(10) = 0.4
      PF(12) = 0.5
      PF(14) = 0.6
      PF(16) = 0.7
      PF(18) = 0.8
      PF(20) = 0.9
      PF(22) = 1.0

*     fill array with pf values for subsequent soil
layers
      DO 30 IL=1,NL
        PF(1)  = PFWC00(IL)
        PF(3)  = PFWC01(IL)
        PF(5)  = PFWC02(IL)
        PF(7)  = PFWC03(IL)
        PF(9)  = PFWC04(IL)
        PF(11) = PFWC05(IL)
        PF(13) = PFWC06(IL)
        PF(15) = PFWC07(IL)
        PF(17) = PFWC08(IL)
        PF(19) = PFWC09(IL)
        PF(21) = PFWC10(IL)
        WCFC(IL) = WCST(IL)*MAX (0.01, LINT
(PF,22,FIELD))
        WCWP(IL) = WCST(IL)*MAX (0.01, LINT
(PF,22,WILTP))
        WCAD(IL) = WCST(IL)*MAX (0.01, LINT
```

```
(PF,22,AIRDR))
30          CONTINUE

         ELSE IF (SWIT8.EQ.4) THEN

*            user must specify pf-curve parameters to be read
*            and include error check
            CALL RDFREA ('WCFC',WCFC,IMNL,NL)
            CALL RDFREA ('WCWP',WCWP,IMNL,NL)
            CALL RDFREA ('WCAD',WCAD,IMNL,NL)

         ELSE
            CALL ERROR ('DRSAHE','Illegal SWIT8 value')
         END IF


      ELSE IF (SWIT9.EQ.2) THEN

*          physical properties from soil type number
         CALL RDFREA ('TYL',TYL,IMNL,NL)

         IF (SWIT8.EQ.1) THEN
*            Driessen moisture characteristic
            DO 40 IL=1,NL
               ITYL(IL) = NINT (TYL(IL))
               ITMP = ITYL(IL)
               WCST(IL) = WCSTT(ITMP)
               WCFC(IL) = WCST(IL)*EXP (-MSWCAT(ITMP)*LOG
(FIELD)**2)
               WCWP(IL) = WCST(IL)*EXP (-MSWCAT(ITMP)*LOG
(WILTP)**2)
               WCAD(IL) = WCST(IL)*EXP (-MSWCAT(ITMP)*LOG
(AIRDR)**2)
40          CONTINUE

         ELSE IF (SWIT8.EQ.2) THEN
*            Van Genuchten moisture characteristic
            DO 50 IL=1,NL
               ITYL(IL) = NINT (TYL(IL))
               ITMP = ITYL(IL)

               WCST(IL) = VGWST(ITMP)
               VGM      = 1.-1/VGNT(ITMP)
```

```
            HLP1    = (FIELD*VGAT(ITMP))**VGNT(ITMP)
            WREL     = (1.+HLP1)**(-VGM)
            WCFC(IL) =
WREL*(WCST(IL)-VGWRT(ITMP))+VGWRT(ITMP)

            HLP1    = (WILTP*VGAT(ITMP))**VGNT(ITMP)
            WREL     = (1.+HLP1)**(-VGM)
            WCWP(IL) =
WREL*(WCST(IL)-VGWRT(ITMP))+VGWRT(ITMP)

            HLP1    = (AIRDR*VGAT(ITMP))**VGNT(ITMP)
            WREL     = (1.+HLP1)**(-VGM)
            WCAD(IL) =
WREL*(WCST(IL)-VGWRT(ITMP))+VGWRT(ITMP)

50          CONTINUE
        ELSE
          CALL ERROR
   &          ('DRSAHE','SWIT8 wrong value ; should be 1 or
2')
        END IF
      ELSE

        CALL ERROR ('DRSAHE','SWIT9 wrong value ; should be 1
or 2')

      END IF

*       initial water contents
      CALL RDSINT ('SWIT6',SWIT6)

      IF (SWIT6.EQ.1) THEN

*         in hydrostatic equilibrium

        WRITE (*,'(2A,/,A)')
   &       ' WARNING from DRSAHE: initial soil moisture',
   &       ' in hydrostatic equilibrium',
   &       ' not implemented. Instead, field capacity is used.'
        IF (IUNLOG.GT.0) WRITE (IUNLOG,'(2A,/,A)')
   &       ' WARNING from DRSAHE: initial soil moisture',
   &       ' in hydrostatic equilibrium',
```

```
     &       ' not implemented. Instead, field capacity is used.'

         DO 60 IL=1,NL
            WCLQTM(IL) = WCFC(IL)
60       CONTINUE

      ELSE IF (SWIT6.EQ.2) THEN

*        at observed moisture contents

         CALL RDFREA ('WCLQTM', WCLQTM, IMNL, NL)

         DO 70 IL=1,NL
            IF (WCLQTM(IL).GT.WCFC(IL)) THEN
               WRITE (*,'(2A)')
     &            ' WARNING from DRSAHE: initial soil moisture',
     &            ' content larger than field capacity'
               IF (IUNLOG.GT.0) WRITE (IUNLOG,'(2A)')
     &            ' WARNING from DRSAHE: initial soil moisture',
     &            ' content larger than field capacity'
               WCLQTM(IL) = WCFC(IL)
            ELSE IF (WCLQTM(IL).LT.WCAD(IL)) THEN
               WRITE (*,'(2A)')
     &            ' WARNING from DRSAHE: initial soil moisture',
     &            ' content less than air dry'
               IF (IUNLOG.GT.0) WRITE (IUNLOG,'(2A)')
     &            ' WARNING from DRSAHE: initial soil moisture',
     &            ' content less than air dry'
               WCLQTM(IL) = WCAD(IL)
            END IF
70       CONTINUE

      ELSE IF (SWIT6.EQ.3) THEN

*        at wilting point

         DO 80 IL=1,NL
            WCLQTM(IL) = WCWP(IL)
80       CONTINUE

      ELSE

         CALL ERROR ('DRSAHE',
```

```
     &      'SWIT6 wrong value ; should be 1, 2 or 3')

      END IF

*       end of reading from data file
      CLOSE (IUNIT)

*       calculate array with depths
      DEPTH(1) = 0.5*TKL(1)
      DO 90 IL=2,NL
        DEPTH(IL) = DEPTH(IL-1)+0.5*TKL(IL-1)+0.5*TKL(IL)
90     CONTINUE

*       maximum rooting depth as soil characteristic
      ZRTMS = DEPTH(NL)+0.5*TKL(NL)

*       Initialize remaining state variables
      WCUM = 0.
      DO 100 IL=1,NL
        WCLQT(IL) = WCLQTM(IL)
        WCUM      = WCUM+WCLQT(IL)*TKL(IL)*1000.
        FLXCU(IL) = 0.
        FLXQT(IL) = 0.
        AVAIL(IL) = 0.
100     CONTINUE

      FLXCU(NL+1) = 0.
      FLXQT(NL+1) = 0.

      EVSW   = 0.
      DRAICU = 0.
      EVSWCU = 0.
      RAINCU = 0.
      INFCU  = 0.
      TRWCU  = 0.
      DSLR   = 50.

*       copy soil description arrays to external arrays
      DO 110 IL=1,NL
        TKLX(IL)  = TKL(IL)
        WCADX(IL) = WCAD(IL)
        WCWPX(IL) = WCWP(IL)
        WCFCX(IL) = WCFC(IL)
```

```
          WCSTX(IL) = WCST(IL)
110       CONTINUE

*         set not used elements to zero
        DO 120 IL=NL+1,INLAYX
          TKLX(IL)  = 0.
          WCADX(IL) = 0.
          WCWPX(IL) = 0.
          WCFCX(IL) = 0.
          WCSTX(IL) = 0.
120       CONTINUE

*         Deeper layer affected by soil evaporation
        SD = 0.
        DO 130 IL=1, INLAYX
         SD = SD + TKLX(IL)
         IF (SD.GE.MDSE) THEN
           DLSE = IL
           GO TO 140
         END IF
130       CONTINUE
140       CONTINUE

      ELSE IF (ITASK.EQ.2) THEN

*         ================
*         Rate calculation
*         ================

*         determine rates of change of water balance

*         check: number of layers for external arrays is great
*         enough to hold data
        IF (INLAYX.LT.NL) THEN
          CALL ERROR
     &      ('DRSAHE','too few layers in external arrays')
        END IF

*         check: evaporation should be negative
        IF (EVSC.GT.0.) THEN
          WRITE (*,'(2A,/,2A)')
     &       ' WARNING from DRSAHE: potential soil evaporation',
     &       ' has positive sign !',
```

```
     &       '   To extract water from the soil,',
     &       ' the sign should be negative.'
          EVSC = 0.
        END IF

*       check: rainfall should be positive
        IF (RAIN.LT.0.) THEN
          WRITE (*,'(2A,/,2A)')
     &       ' WARNING from DRSAHE: rainfall',
     &       ' has negative sign !',
     &       '   To add water to the soil through rainfall,',
     &       ' the sign should be positive.'
          RAIN = 0.
        END IF

*       check: transpiration should be negative and 'available'
        DO 200 IL=1,NL
          IF (TRWL(IL).GT.0.) THEN
            WRITE (*,'(2A,/,2A)')
     &         ' WARNING from DRSAHE: transpiration',
     &         ' has positive sign !',
     &         '   To extract water from the soil,',
     &         ' the sign should be negative.'
            TRWL(IL) = 0.
          END IF

          IF (-DELT*TRWL(IL).GT.AVAIL(IL)) THEN
            WRITE (*,'(2A)')
     &         ' WARNING from DRSAHE: transpiration',
     &         ' not available in layer !'
            TRWL(IL) = -AVAIL(IL)/DELT
          ENDIF
200     CONTINUE


*       set rates of change to zero and make local water status
*       array equal to current water status, reset fluxes
        DO 220 IL=1,NL
          WCLCH(IL) = 0.
          WCL(IL)   = WCLQT(IL)
          FLXQT(IL) = 0.
220     CONTINUE
        FLXQT(NL+1) = 0.
```

```
*       cumulate transpiration
      TRW = 0.
      DO 230 IL=1,NL
        TRW = TRW+TRWL(IL)
230     CONTINUE

*       effectuate transpiration on local status array
      DO 240 IL=1,NL
        WCL(IL) = WCL(IL)+DELT*TRWL(IL)/(TKL(IL)*1000.)
        AVAIL(IL) = MAX
(0.,(WCL(IL)-WCAD(IL))*TKL(IL)*1000.)/DELT
240     CONTINUE



      INF   = MAX (0., RAIN)

      EVSH = MAX (EVSC, -AVAIL(1)-INF)
      EVSD = MAX (EVSC, 0.6*EVSC*(SQRT (DSLR+1.)-SQRT
(DSLR))-INF)

      IF (INF.GT.0.5) THEN
        EVSW2  = EVSH
        RDSLR = -(DSLR-1.)/DELT
      ELSE
        EVSW2  = EVSD
        RDSLR = 1.
      END IF

*       calculate array for exponential extinction of evaporation
      SUM = 0.
      DO 250 IL=1,NL
        IF (IL.LE.DLSE) THEN
          VAR(IL) = (AVAIL(IL)*DELT)*EXP(-EES*DEPTH(IL))
          SUM     = SUM+VAR(IL)
        ELSE
          VAR(IL) = 0.
        END IF
250     CONTINUE

*       effectuate evaporation on local status array and
calculate
*       the actual soil evaporation
```

```
      EVSW = 0.
      DO 260 IL=1,NL
        IF (SUM.GT.0.) THEN
*           water available somewhere in the profile
          RESOIL(IL) = EVSW2*VAR(IL)/SUM
          IF (-DELT*RESOIL(IL).GT.AVAIL(IL))
RESOIL(IL)=-AVAIL(IL)
          EVSW = EVSW+RESOIL(IL)
        ELSE
*           water not available in profile
          RESOIL(IL) = 0.0
        END IF
        WCL(IL) = WCL(IL)+DELT*RESOIL(IL)/(TKL(IL)*1000.)

260     CONTINUE

*       effectuate infiltration on local status array
*       nog een keer naar delt kijken
      FLOW = 0.
      IF (INF.GT.0.) THEN
        FLOW     = INF
        FLXQT(1) = FLOW
        DO 270 IL=1,NL
          CAP = (WCFC(IL)-WCL(IL))*TKL(IL)*1000.
          IF (CAP.LE.FLOW*DELT) THEN
*             water flow does not fit into compartment
            WCL(IL) = WCFC(IL)
            FLOW = FLOW-CAP/DELT
          ELSE
*             water flow does fit into compartment
            WCL(IL) = WCL(IL)+FLOW*DELT/(TKL(IL)*1000.)
            FLOW = 0.
          END IF
          FLXQT(IL+1) = FLOW
270       CONTINUE
      END IF
      DRAIQT = -FLOW

      WCUMCH = 0.
      DO 280 IL=1,NL
        WCLCH(IL) = (WCL(IL) - WCLQT(IL)) / DELT
*       rounded errors
        IF (WCL(IL).EQ.WCAD(IL)) THEN
```

```
           WCLCH(IL) = MIN(0.,-(WCLQT(IL)-WCAD(IL))/DELT)
           WCLQT(IL) = WCAD(IL)
         END IF
         WCUMCH = WCUMCH+WCLCH(IL)*TKL(IL)*1000.
280      CONTINUE

      IF (OUTPUT) THEN
*         output integrals
         CALL OUTDAT (2,0,'DRAICU',DRAICU)
         CALL OUTDAT (2,0,'EVSWCU',EVSWCU)
         CALL OUTDAT (2,0,'RAINCU',RAINCU)
         CALL OUTDAT (2,0,'TRWCU',TRWCU)
*          CALL OUTDAT (2,0,'WCUM',WCUM)
*          CALL OUTDAT (2,0,'DSLR',DSLR)
         CALL OUTARR ('WCLQT',WCLQT,1,NL)
*          CALL OUTARR ('FLXCU',FLXCU,1,NL+1)

*         output rates
*          CALL OUTDAT (2,0,'WCUMCH', WCUMCH)
*          CALL OUTDAT (2,0,'EVSH'  , EVSH  )
*          CALL OUTDAT (2,0,'EVSD'  , EVSD  )
*          CALL OUTDAT (2,0,'EVSW2' , EVSW2 )
         CALL OUTDAT (2,0,'TRW'   , TRW   )
         CALL OUTDAT (2,0,'EVSW'  , EVSW  )
*          CALL OUTARR ('FLXQT',FLXQT,1,NL+1)
*          CALL OUTARR ('WCLCH',WCLCH,1,NL)
*          CALL OUTARR ('RESOIL',RESOIL,1,NL)
      END IF

*       checks on calculated rate variables
      DO 290 IL=1,NL
         IF (RESOIL(IL).GT.0.) CALL ERROR
     &         ('RESOIL','evaporation rate greater than zero')
290      CONTINUE

    ELSE IF (ITASK.EQ.3) THEN

*       ===========
*       Integration
*       ===========

*       checks
      IF (INLAYX.LT.NL) CALL ERROR
```

```
    &      ('DRSAHE','too few layers in external arrays')
       WCUMO = WCUM

       DO 400 IL=1,NL
*          water content per layer

         IF (WCL(IL).EQ.WCAD(IL)) THEN
           WCLQT(IL) = WCAD(IL)
         ELSE
          WCLQT(IL) = INTGRL (WCLQT(IL), WCLCH(IL), DELT)
         END IF
         AVAIL(IL) = MAX
(0.,(WCL(IL)-WCAD(IL))*TKL(IL)*1000.)/DELT
400      CONTINUE

       DO 420 IL=1,NL+1
         FLXCU(IL) = INTGRL (FLXCU(IL), FLXQT(IL), DELT)
420      CONTINUE

       DRAICU = INTGRL (DRAICU, DRAIQT, DELT)
       EVSWCU = INTGRL (EVSWCU, EVSW  , DELT)
       RAINCU = INTGRL (RAINCU, RAIN  , DELT)
       INFCU  = INTGRL (INFCU , INF   , DELT)
       TRWCU  = INTGRL (TRWCU , TRW   , DELT)
       WCUM   = INTGRL (WCUM  , WCUMCH, DELT)
       DSLR   = INTGRL (DSLR  , RDSLR , DELT)

*       check on value of water content per layer
       DO 430 IL=1,NL
         CHECK = WCLQT(IL)/WCAD(IL)
         IF (CHECK .LT. (1.-1.E-5)) THEN
          WRITE (*,*) ' Error in DRSAHE.FOR :'
          WRITE (*,*) ' water content less than air dry'
          WRITE (*,*) 'IL',IL,'WCLQT(IL)',WCLQT(IL)
          WRITE (*,*) 'IL',IL,'WCAD(IL)',WCAD(IL)
          PAUSE
         END IF
         CHECK = WCLQT(IL)/WCFC(IL)
         IF (CHECK .GT. (1.+1.E-5)) THEN
          WRITE (*,*) ' Error in DRSAHE.FOR : '
          WRITE (*,*) 'water content greater than field
capacity'
          WRITE (*,*) 'IL',IL,'WCLQT(IL)',WCLQT(IL)
```

```
            WRITE (*,*) 'IL',IL,'WCFC(IL)',WCFC(IL)
            PAUSE
          END IF
430     CONTINUE

*       check on correctness of balance, use relative error
        CHECK = (WCUMO-WCUM)+DELT*(INF+DRAIQT+EVSW+TRW)
        IF (ABS (CHECK/(0.5*(WCUMO+WCUM))).GT.0.001) THEN
          WRITE (*,*) 'Error in DRSAHE.FOR :'
          WRITE (*,*) 'DRSAHE','water balance check exceeds
limit'
          WRITE (*,*) 'WCUMO',WCUMO,'WCCUM',WCUM,'INF',INF
          WRITE (*,*) 'DRAIQT',DRAIQT,'EVSW',EVSW,'TRW',TRW
          PAUSE
        END IF

      ELSE IF (ITASK.EQ.4) THEN
        CONTINUE
      ELSE
        CALL ERROR ('DRSAHE','wrong ITASK')
      END IF

      RETURN
      END
```

PETP.FOR

```
*
------------------------------------------------------------------ *
*
   *
*     P o t e n t i a l   e v a p o t r a n s p i r a t i o n
   *
*                        (PETP)
   *
* author  : J.G. Conijn
*
   *
* purpose : calculation of potential evaporation and transpiration
of  *
*           an herbaceous vegetation
   *
*
   *
```

```
* FORMAL PARAMETERS:  (I=input,O=output)
   *
* name   type meaning                                units
class *
* ----   ---- -------                                -----
----- *
* ITASK   I4  Task that subroutine should perform          -
 I  *
* OUTPUT  L4  Flag to indicate if output should be done      -
 I  *
* TERMNL  L4  Flag to indicate if simulation is to stop      -
I/O *
* TIME    R4  Time of simulation                          d
 I  *
* DOY     R4  Day of the year                             d
 I  *
* DELT    R4  Time step of integration                    d
 I  *
* DS0     R4  Daily extra-terrestrial radiation          J/m2/d
 I  *
* RDD     R4  Daily shortwave radiation                  J/m2/d
 I  *
* TMMN    R4  Daily minimum temperature                degrees C
 I  *
* TMMX    R4  Daily maximum temperature                degrees C
 I  *
* VP      R4  Early morning vapour pressure              kPa
 I  *
* WN      R4  Average wind speed                          m/s
 I  *
* KL      R4  PAR extinction coefficient of leaves          -
 I  *
* LAI     R4  Leaf area index                          m2/m2
 I  *
* DLAI    R4  Leaf area index of dead leaves           m2/m2
 I  *
* PTRANS  R4  Potential transpiration                    mm/d
 O  *
* EVSC    R4  Potential evaporation                      mm/d
 O  *
*
   *
* Warnings         : none
```

```
   *
* Subprograms called: PENMAN,OUTDAT
   *
* Functions called  : none
   *
* File usage        : none
   *
*----------------------------------------------------------------------*

      SUBROUTINE PETP(ITASK,OUTPUT,TERMNL,DELT,
     &              ELEV,ANGA,ANGB,DS0,RDD,TMMN,TMMX,VP,WN,
     &              KL,LAI,DLAI,PTRANS,EVSC)


      IMPLICIT  REAL (A-Z)

* --- formal parameters
      INTEGER ITASK
      LOGICAL OUTPUT,TERMNL
      REAL DELT,ELEV,ANGA,ANGB,DS0
      REAL RDD,TMMN,TMMX,VP,WN
      REAL KL,LAI,DLAI,EVSC,PTRANS

* --- local declarations
      REAL ATMTR,E0,ES0,ET0,EVAPR,EVAPD,
     &     RFCFS,RFCFC,RB,LHVP,EAC,DELTA,GAMMA,ALB,RNSC,
     &     E4,SUM,FRABS,
     &     PSE,PCE

      PARAMETER (E4 = 1.E4)

      SAVE

*
---------------------------------------------------------------------- *
*                   I n i t i l i z a t i o n
   *
*
---------------------------------------------------------------------- *

      IF (ITASK .EQ. 1) THEN

* ----- initial values
```

```
    *
      LAI   = 0.
      DLAI  = 0.



*
------------------------------------------------------------------ *
*                  R a t e   c a l c u l a t i o n
    *
*
------------------------------------------------------------------ *

     ELSE IF (ITASK .EQ. 2) THEN

* ----- evapotranspiration (PENMAN)
    *
      ATMTR = RDD / DS0
      IF (ATMTR .GT. 1.) THEN
        WRITE(*,*) 'RDD is greater than daily extraterrestrial
',
     &              'radiation DS0 !'
        WRITE(*,*) 'RDD = ',RDD,'  >  DS0 = ',DS0
        ATMTR = 1.
      END IF
      VP = VP * 10.
      CALL PENMAN (ELEV,ANGA,ANGB,ATMTR,TMMN,TMMX,RDD,WN,VP,
     &              E0,ES0,ET0,
     &              RFCFS,RFCFC,RB,LHVP,EAC,DELTA,GAMMA)
      VP  = VP / 10.
      E0  = 10. * E0
      ES0 = 10. * ES0
      ET0 = 10. * ET0

* ----- albedo of a vegetation/soil system for a herbaceous
    *
*      vegetation
    *
      SUM   = 0.7 * KL * LAI
      FRABS = 1. - EXP(-SUM)
      ALB   = RFCFS * (1. - FRABS) + RFCFC * FRABS

* ----- net absorbed radiation (mm/d)
    *
```

```
      RNSC = (RDD * (1. - ALB) - RB) / LHVP

* ----- radiation and drying power term of ET0 (mm/d)
   *
      EVAPR = (DELTA * RNSC) / (DELTA + GAMMA)
      EVAPD = (GAMMA * EAC) / (DELTA + GAMMA)

* ----- potential transpiration of the herbaceous vegetation
   *
*       (PTRANS, mm/d)
   *
      IF (LAI.GT.0.) THEN
        PTRANS =  FRABS * EVAPR + EVAPD * MIN(2., LAI)
      ELSE
        PTRANS = 0.
      END IF

* ----- potential evaporation (PSE, mm)
   *
      SUM  = 0.7 * KL * (LAI + DLAI)
      PSE  = (EVAPR + EVAPD) * EXP(-SUM)
      EVSC = -PSE

* ----- potential crop evapotranspiration (PCE)
   *
      PCE  = PSE + PTRANS

*
------------------------------------------------------------------- *
*              O u t p u t   o f   v a r i a b l e s
   *
*
------------------------------------------------------------------- *

      IF (OUTPUT .OR. TERMNL) THEN



* ------- rate variables
   *
        CALL OUTDAT (2,0,'PTRANS', PTRANS)
        CALL OUTDAT (2,0,'PSE'   , PSE   )
        CALL OUTDAT (2,0,'PCE'   , PCE   )
        CALL OUTDAT (2,0,'ES0'   , ES0   )
```

```
        CALL OUTDAT (2,0,'ET0'   , ET0   )
        CALL OUTDAT (2,0,'EVAPR' , EVAPR )
        CALL OUTDAT (2,0,'EVAPD' , EVAPD )


      END IF

*
------------------------------------------------------------------ *
*                   I n t e g r a t i o n
   *
*
------------------------------------------------------------------ *

     ELSE IF (ITASK .EQ. 3) THEN


     END IF

     RETURN

     END
```

PENMAN.FOR

```
*------------------------------------------------------------------*
*  SUBROUTINE PENMAN
  *
*  author : Daniel van Kraalingen
  *
*          based on an earlier version written by: Kees van
Diepen  *
*  date   : 9-JAN-1987
  *
*  purpose: This subroutine calculates potential evaporation
  *
*          according to Penman (1948).
  *
*
  *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)
  *
*  name    meaning                              units
```

```
class  *
*  ----    -------                         -----
-----  *
*  ELEV    Elevation of site                    m      I
  *
*  A       Coefficient of Angstrom formula         -      I
  *
*  B       Coefficient of Angstrom formula         -      I
  *
*  ATMTR   Atmospheric transmission                -      I
  *
*  TMIN    Minimum temperature during day          C      I
  *
*  TMAX    Maximum temperature during day          C      I
  *
*  AVRAD   Daily total global radiation       J/m2/d    I
  *
*  WIND    Average windspeed                     m/s     I
  *
*  VAP     Vapour pressure                      mbar     I
  *
*  E0      Potential evaporation of open water     cm/d     O
  *
*  ES0     Potential evaporation of soil        cm/d     O
  *
*  ET0     Potential evapotranspiration of crop     cm/d     O
  *
*
  *
*  FATAL ERROR CHECKS (execution terminated, message)
  *
*  condition
  *
*  ---------
  *
*  ATMTR < 0  or  ATMTR > 1
  *
*  TMIN > TMAX
  *
*  WIND < 0
  *
*  AVRAD < 0
  *
```

```
*
 *
*  WARNINGS (nonzero value of IWAR returned)
 *
*  condition                                    returned IWAR value
 *
*  ---------                                    -------------------
 *
*  AVRAD > 40,000,000 J m-2 d-1                          1
 *
*
 *
*  WARNINGS (with correction and message to the screen)
 *
*  condition
 *
*  ---------
 *
*  VAP > SVAP * 1.01 (entered vapour pressure > theor. saturated)
 *
*
 *
*  SUBROUTINES and FUNCTIONS called : LIMIT
 *
*
 *
*  FILE usage : none
 *
*----------------------------------------------------------------------*

      SUBROUTINE PENMAN (ELEV,A,B,ATMTR,TMIN,TMAX,AVRAD,WIND,VAP,
     $                   E0,ES0,ET0,
     $                   RFCFS,RFCFC,RB,LHVP,EAC,DELTA,GAMMA)


      IMPLICIT REAL (A-Z)

* --- Albedo for water surface, soil surface and canopy
      PARAMETER (REFCFW = 0.05)
      PARAMETER (REFCFS = 0.15)
      PARAMETER (REFCFC = 0.25)

* --- Latent heat of evaporation of water (J/kg=J/mm) and
```

```
*     Stefan Boltzmann constant (J/m2/d/K) Psychrometric
*     instrument constant (mbar K-1)
      PARAMETER (LHVAP = 2.45E6)
      PARAMETER (STBC  = 4.9E-3)
      PARAMETER (PSYCON= 0.000662)
      SAVE

* --- Different variable names used for communication with other
*     modules

      RFCFS = REFCFS
      RFCFC = REFCFC
      LHVP  = LHVAP

* --- Errors and warnings on some input variable ranges
      IF (ATMTR.LT.0..OR.ATMTR.GT.1.)
     &    CALL ERROR ('PENMAN','ATMTR<0 or >1')
      IF (TMIN.GT.TMAX) CALL ERROR ('PENMAN','TMIN > TMAX')
      IF (WIND.LT.0.)   CALL ERROR ('PENMAN','WIND < 0')
      IF (AVRAD.LT.0.)  CALL ERROR ('PENMAN','AVRAD < 0')

* --- Mean daily temperature and temperature difference (Celsius)
      TMPA = (TMIN+TMAX)/2.
      TDIF = TMAX-TMIN

* --- Coefficient Bu in wind function, dependent on
*     temperature difference

      BU = 0.54+0.35*LIMIT (0.,1.,(TDIF-12.)/4.)

* --- Barometric pressure (mbar), Psychrometric constant (mbar/K)
      PBAR = 1013.*EXP(-0.034*ELEV/(TMPA+273.))
      GAMMA = PSYCON*PBAR

* --- Saturated vapour pressure according to equation
*     of Goudriaan (1977)
      SVAP = 6.11*EXP(17.4*TMPA/(TMPA+239.))

*      IF (VAP.GT.SVAP*1.01) CALL ERROR ('PENMAN','VAP > SVAP')
      IF (VAP .GT. SVAP) THEN
        WRITE(*,*) 'VP is greater than saturated VP ! '
        WRITE(*,*) 'VP = ',VAP,'  >  SVP = ',SVAP
        VAP = SVAP
```

```
      END IF

* --- Derivative of SVAP with respect to temperature, i.e. slope
of the
*     SVAP-temperature curve (mbar/K)
      DELTA = 239.*17.4*SVAP/(TMPA+239.)**2

* --- The expression n/N (RELSSD) from the Penman formula is
estimated
*     from the Angstrom formula: RI=RA(A+B.n/N) ->
n/N=(RI/RA-A)/B,
*     where AVRAD=RI and ANGOT=RA, the Angot radiation,

      RELSSD = LIMIT (0.,1.,(ATMTR-A)/B)

* --- Terms of the Penman formula, for water surface, soil
*     surface and canopy
*     Net outgoing long-wave radiation (J/m2/d) according
*     to Brunt (1932)

      RB  =
STBC*(TMPA+273.)**4*(0.56-0.079*SQRT(VAP))*(0.1+0.9*RELSSD)

* --- Net absorbed radiation, expressed in mm/d
      RNW = (AVRAD*(1.-REFCFW)-RB)/LHVAP
      RNS = (AVRAD*(1.-REFCFS)-RB)/LHVAP
      RNC = (AVRAD*(1.-REFCFC)-RB)/LHVAP

* --- Evaporative demand of the atmosphere (mm/d)
      EA  = 0.26*(SVAP-VAP)*(0.5+BU*WIND)
      EAC = 0.26*(SVAP-VAP)*(1.0+BU*WIND)

* --- Penman formula (1948), and conversion to cm/d
      E0  = 0.1*(DELTA*RNW+GAMMA*EA)/(DELTA+GAMMA)
      ES0 = 0.1*(DELTA*RNS+GAMMA*EA)/(DELTA+GAMMA)
      ET0 = 0.1*(DELTA*RNC+GAMMA*EAC)/(DELTA+GAMMA)

      RETURN
      END

ASTRO.FOR
*
---------------------------------------------------------------- *
```

```
*  SUBROUTINE ASTRO
   *
*
   *
*  Purpose: This subroutine calculates astronomic and
photoperiodical  *
*          daylength, diurnal radiation characteristics such as
the   *
*          daily integral of sine of solar elevation and solar
   *
*          constant.
   *
*
   *
*  Source : Simulation reports 27, Nov. 1992, CABO-DLO (SUCROS)
   *
*
   *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)
   *
*  name   type meaning                              units
class *
*  ----   ---- -------                              -----
----- *
*  IDOY    I4  Daynumber (Jan 1st = 1)                     -
 I  *
*  LATS    R4  Latitude of the site                  degrees
 I  *
*  SC      R4  Solar constant                       J m-2
s-1 O  *
*  DS0     R4  Daily extraterrestrial radiation          J m-2
d-1 O  *
*  SINLD   R4  Seasonal offset of sine of solar height       -
 O  *
*  COSLD   R4  Amplitude of sine of solar height             -
 O  *
*  DAYL    R4  Astronomic daylength (base = 0 degrees)       h
 O  *
*  DAYLP   R4  Photoperiodical daylength (base = 4 degrees)  h
 O  *
*  DSINB   R4  Daily total of sine of solar height           s
 O  *
*  DSINBE  R4  Daily total of effective solar height         s
```

```
 O  *
*
   *
*  FATAL ERROR CHECKS (execution terminated, message)
   *
*  condition: LAT > 67, LAT < -67
   *
*
   *
*  FILE usage : none
   *
*
------------------------------------------------------------------ *

      SUBROUTINE ASTRO (IDOY, LATS, SC , DS0, SINLD, COSLD,
     &                 DAYL, DAYLP, DSINB, DSINBE)
      IMPLICIT REAL (A-Z)

      INTEGER IDOY
      SAVE

*-----PI and conversion factor from degrees to radians
      PI    = 3.141592654
      RAD   = PI/180.

*-----check on input range of parameters
      IF (LATS.GT.67.)  STOP 'ERROR IN ASTRO: LATS> 67'
      IF (LATS.LT.-67.) STOP 'ERROR IN ASTRO: LATS>-67'

*-----declination of the sun as function of daynumber (IDOY)
      DEC   = -ASIN (SIN (23.45*RAD)*COS (2.*PI*(IDOY+10.)/365.))

*-----SINLD, COSLD and AOB are intermediate variables
      SINLD = SIN (RAD*LATS)*SIN (DEC)
      COSLD = COS (RAD*LATS)*COS (DEC)
      AOB   = SINLD/COSLD

*-----daylength (DAYL) and photoperiodical daylenght (DAYLP)
      DAYL   = 12.0*(1.+2.*ASIN (AOB)/PI)
      DAYLP  = 12.0*(1.+2.*ASIN((-SIN(-4.*RAD)+SINLD)/COSLD)/PI)
      DSINB  = 3600.*(DAYL*SINLD+24.*COSLD*SQRT (1.-AOB*AOB)/PI)
      DSINBE =
3600.*(DAYL*(SINLD+0.4*(SINLD*SINLD+COSLD*COSLD*0.5))+
```

```
    &        12.0*COSLD*(2.0+3.0*0.4*SINLD)*SQRT
(1.-AOB*AOB)/PI)

*-----solar constant (SC) and daily extraterrestrial radiation
(DS0)
      SC  = 1370.*(1.+0.033*COS (2.*PI*IDOY/365.))
      DS0 = SC*DSINB

      RETURN
      END
```

PGDM.FOR

```
* - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - *
*
    *
*                              PGDM
    *
*
    *
*
    *
* Author: Santiago Bonachela-Castano
    *
*
    *
* Date: January 1994 (final version, october, 1994)
    *
*
    *
* Purpose : dynamic of perennial grasses biomass: growth,
senescence,  *
*           recirculation of energy, etc.
    *
*
    *
* FORMAL PARAMETERS:  (I=input,O=output)
    *
* name   type meaning                                 units
class *
* ----   ---- -------                                 -----
----- *
```

```
* ITASK   I4  task that subroutine should perform           -
 I  *
* IUNITD  I4  unit that can be used for input files         -
 I  *
* IUNITO  I4  unit used for output file                     -
 I  *
* OUTPUT  L4  flag to indicate if output should be done      -
 I  *
* TERMNL  L4  flag to indicate if simulation is to stop      -
I/O *
* FILEI1  C*  name of species input file                    -
 I  *
* IDOY    I4  day number within year of simulation          d
 I  *
* DELT    R4  time step of integration                      d
 I  *
* RDD     R4  daily global incident radiation            J/m2/d
 I  *
* LATS    R4  latitude of the site                     degrees
 I  *
* TMMX    R4  daily maximum air temperature              degrees
C I  *
* TMMN    R4  daily minimum air temperature              degrees
C I  *
* VP      R4  daily vapour pressure early in the morning    kPa
 I  *
* DAYLP   R4  photosynthetic active photoperiod             h
 I  *
* IVSSC   I4  to select how simulation start: from sowing
   *
*             or from an established crop                   -
 I  *
* EMERG    L  to indicate the date of crop emergence        -
 I  *
* LATS    R4  latitude of the site                     degrees
 I  *
* WRFRE   R4  water reduction factor on root extension      -
 I  *
* TRANSR  R4  transpiration ratio                        mm/d
 I  *
* TWA     R4
* WERS    R4
* RFSGWS  R4  water stress reduction factor on shoot growth  -
```

```
 I  *
* MTRANS  R4  maximum transpiration rate                  mm/d
 O  *
* INLAYX  I4  number of soil layers                        -
 I  *
* WCLQT   R() actual water content per soil layer         cm3/cm3
 I  *
* WCWPX   R() water content at wilting pint (soil layer)  cm3/cm3
 I  *
* TKLX    R() thickness of soil layers                     m
 I  *
* LAI     R4  leaf area index                              m2/m2
 O  *
* DLAI    R4  leaf area index of dead plant                m2/m2
 O  *
* ZRT     R4  root depth                                   m
 O  *
* LVCS     L  to indicate when crop simulation occurs        -
 O  *
* LVCGRS   L  to indicate crop growth in the rainy season    -
 O  *
* LVCGDS   L  to indicate crop growth in the dry season      -
 O  *
*
   *
* Fatal error checks: ABS(CHKPBB) > 1.E-3
   *
* Warnings          : CRSRT > MXCRS
   *
* Subprograms called: RDINIT, RDSREA, RDSINT, RDAREA
   *
* Functions used    : LINT, INSW, INTGRL, ABS, REAL, INT
   *
* File usage        : FILEI1 (CONTROL.DAT)
   *
*  ---------------------------------
-- *

      SUBROUTINE PGDM (ITASK,IUNITD,IUNITO,OUTPUT,TERMNL,FILEI1,
     &                 IDOY,DELT,RDD,TMMX,TMMN,VP,DAYLP,
     &                 IVSSC,EMERG,RFIBWS,LATS,
     &                 WRFRE,TRANSR,TWA,MTRANS,
     &                 INLAYX,WCLQT,WCWPX,TKLX,
```

```
     &              LAI,DLAI,ZRT,LVCS,LVCGRS,LVCGDS,
     &              WSH,WSRT)

      IMPLICIT REAL (A-Z)

* --- formal parameters
*
      INTEGER ITASK,IUNITD,IUNITO,IDOY,IVSSC
      LOGICAL OUTPUT,TERMNL,EMERG,LVCGRS,LVCGDS,LVCS
      CHARACTER FILEI1*(*)
      INTEGER INLAYX
      REAL WCLQT(INLAYX),WCWPX(INLAYX),TKLX(INLAYX)
      REAL MTRANS

* --- local declarations
*
      INTEGER INTBMX,IFBSHN,IRDSHN,IRDRTN,ISHNRS,ISHNDS,IVSCNS,
     &       IFMHCN,IMHDBN,IWSESS,IWSERS,IGRSHN,ISSAN,ISDSAN,
     &       BG,BGDS,DBRR,IBR,DGSE,TCSS,SD,TCCS,LDRT,DFAR,
     &       TCCDWE,TCCDRE,IVRT,TCRTDS,TCRTRS,DNCC,EMERGD,
     &       FDRS,IMXNCS,IMNNCS,IMNNCR,INARTN,I,I1

      LOGICAL
LVCDRS,LVCDDS,LVCDP,LVRSVP,SWITCH,SWITC1,SWITC2,SWITC3,
     &       LVEX,EXPDVS,SDEX,SPROUT,LVSS,LVDMA

      PARAMETER(TINY = 1.E-10)
      PARAMETER(INTBMX = 40)

      REAL
FBSHTB(INTBMX),RDSHTB(INTBMX),RDRTTB(INTBMX),GRSHTB(INTBMX),
     &
WSESST(INTBMX),WSERST(INTBMX),SHNRST(INTBMX),SHNDST(INTBMX),
     &
FMHCTB(INTBMX),MHDBTB(INTBMX),SDSATB(INTBMX),SSATB(INTBMX),
     &
MXNCST(INTBMX),MNNCST(INTBMX),TMNNCR(INTBMX),NARTTB(INTBMX)
      REAL AVVP(10), AVDMP(10)

      SAVE
```

```
*
---------------------------------------------------------------- *
*
   *
*               I n i t i a l i z a t i o n
   *
*
   *
*
---------------------------------------------------------------- *

     IF (ITASK .EQ. 1) THEN

     CALL RDINIT (IUNITD,IUNITO,FILEI1)


* - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - *
*                  P A R A M E T E R S
   *
*
   *

*    B e g i n n i n g   o f   c r o p   s i m u l a t i o n:
   *

* --- integer variable that indicates whether crop simulation
start    *
*     from sowing or from an stablished crop;
   *
     IF (IVSSC.EQ.0) THEN
       CALL RDSINT ('SD'    , SD    )
       CALL RDSREA ('IWSHS' , IWSHS )
       CALL RDSREA ('IWRTS' , IWRTS )
     ELSE IF (IVSSC.EQ.1) THEN
       CALL RDSREA ('IWSH ' , IWSH  )
       CALL RDSREA ('IWDSH' , IWDSH )
       CALL RDSREA ('IWRT ' , IWRT  )
       CALL RDSREA ('IWDRT' , IWDRT )
       CALL RDSREA ('IWRS ' , IWRS  )
       CALL RDSREA ('IZRT1 ', IZRT1 )
       ZRT = IZRT1
     END IF
```

```
* --- initial value of intermediate logical variables;
   *
     SWITCH = .FALSE.
     SWITC1 = .FALSE.
     SWITC3 = .FALSE.

* --- initial values of a logical variable used to trigger the
onset   *
*     crop simulation.
   *
     LVCS   = .FALSE.

* --- initial values:
   *
     SWITC2 = .TRUE.
     LVRSVP =.TRUE.
     BGDS   = 0
     IBR    = 0


*     D r y   m a t t e r   p r o d u c t i o n:
   *

* --- initial shoot N use coefficient g/(g.d);
   *
     CALL RDSREA ('P'     , P     )

* --- initial radiation use coefficient g/MJ;
   *
     CALL RDSREA ('EPSIL' , EPSIL )

* --- water use efficiency coefficient;
   *
     CALL RDSREA ('WUEC'  , WUEC  )

* --- initial value of cumulative radiation                  .
   *
     CRDD = 0.

* --- initial values
   *
     DMP    = 0.
```

```
      ADMP   = 0.
      NCSH   = 0.
      ANSH   = 0.
      ANRT   = 0.
      ANCR   = 0.
      AVANSH = 0.
      A1GRSH = 0.
      AVSGND = 0.
      MXNCSH = 0.
      MNNCSH = 0.
      MNNCRT = 0.
      GRNSH  = 0.


*     G r o w t h:
   *

* --- maximum growth rate of the crop;
   *
      CALL RDSREA ('MXGRCR', MXGRCR )

* --- time constant for crop sprouting (TCCS, d);
   *
      CALL RDSINT ('TCCS'  , TCCS  )

* --- maximum value of the root:shoot ratio for new root growth;
   *
      CALL RDSREA ('CSHRTR', CSHRTR )

* --- critical water availability for starting a new crop cycle;
   *
      CALL RDSREA ('CRWARC', CRWARC )

* --- critical transpiration ratio for crop assimilation;
   *
      CALL RDSREA ('CRTRCT', CRTRCT )

* --- critical and maximum vapour pressure deficits (kPa) for
   *
*     crop assimilation;
   *
      CALL RDSREA ('CRVPD' , CRVPD  )
      CALL RDSREA ('MXVPD' , MXVPD  )
```

```
* --- critical vapour pressure (kPa) for the end of the rains
    *
*     (CRVPER, kPa);
    *
      CALL RDSREA ('CRVPER', CRVPER )

* --- fraction of root biomass allocated to reserves (FRBART, -);
    *
      CALL RDSREA ('FRBARS', FRBARS )

* --- multiplicative factor used to define a threshold value of
    *
*     shoot nitrogen concentration below which shoot growth rate
is    *
*     reduced (TSNCSG, -);
    *
      CALL RDSREA ('TSNCSG', TSNCSG )

* --- multiplicative factor used to define a threshold value of
    *
*     shoot nitrogen concentration below which dry matter
production   *
*     is reduced (TSNCDM, -);
     *
      CALL RDSREA ('TSNCDM', TSNCDM )

* --- maximum root depth by soil limitation (RDMSOL, m);
    *
      CALL RDSREA ('RDMSOL', RDMSOL )

* --- potential rate of root extension (PRRE, m/d);
    *
      CALL RDSREA ('PRRE'  , PRRE   )

* --- biomass remaining during the dormant phase.
    *
      CALL RDSREA ('SHBDP' , SHBDP  )

* --- root depth at the beginning of the rainy season
    *
      CALL RDSREA ('IZRTR', IZRTR )
```

```
* --- initial values:
   *
     GRSH   = 0.
     GRRT   = 0.
     GRRS   = 0.
     WRT    = 0.
     WSRT   = 0.
     WRS    = 0
     WSH    = 0.
     WCR    = 0.
     WSB    = 0.
     TDM    = 0.
     TDMP   = 0.
     MXWCR  = 0.
     MXWSH  = 0.
     MXWRT  = 0.
     MXTDM  = 0.
     AVMRRC = 0.
     AVGRRT = 0.
     AV1GRR = 0.
     FBSH   = 0.
     FBRT   = 0.
     RFSGND = 1.
     TRANSR = 1.
     WRFRE  = 1.
     RFCAAH = 1.
     RFSGWS = 1.
     RFLWU  = 1.
     MTRANS = 0.
     RER    = 0.
     LVDMA  = .FALSE.

*     N i t r o g e n:
   *


* --- integer variable to select crop nitrogen supply (-);
   *
     CALL RDSINT ('IVSCNS', IVSCNS )

* --- fraction of crop nitrogen allocated to the roots (FCNART,
-);    *
*     CALL RDSREA ('FCNART', FCNART )
```

```
* --- time coefficient (d) for shoot death due to nitrogen
deficiency  *
      CALL RDSREA ('TCSDND', TCSDND )



*     C r o p   s u r v i v a l
    *


* --- time constant for crop death due to water or reserves
    *
*     exhaustion;
    *
      CALL RDSINT ('TCCDWE' , TCCDWE)
      CALL RDSINT ('TCCDRE' , TCCDRE)

* --- initial values of auxiliar variables
    *
      AVCDWE = 0.
      AVCDRE = 0.




*     S e n e s c e n c e:
    *


* --- fraction of carbohydrates withdrawn from the plant
    *
*     (FCW..);
    *
      CALL RDSREA ('FCWSH', FCWSH)
      CALL RDSREA ('FCWRT', FCWRT)

* --- relative death rate of old roots when the reserves have been
    *
*     depleted (RDRRTC, kg/kg/d)
    *
      CALL RDSREA ('RDRRTC', RDRRTC)

* --- initial values:
    *
      WDSH   = 0.
      WDCR   = 0.
      WDRT   = 0.
```

```
      DRSH   = 0.
      DRSH1  = 0.
      DRSH2  = 0.
      DRSHEX = 0.
      DRRT   = 0.
      DRRT1  = 0.
      DRRT2  = 0.
      DRRT3  = 0.
      ADWSSH = 0.
      ADWSRT = 0.
      CWDSH  = 0.
      CWDRT  = 0.
      WOSRT  = 0.
      WOSH2  = 0.
      WSH2   = 0.
      WORT2  = 0.
      WRT2   = 0.
      WOSHDE = 0.
      LWSH   = 0.
      LWRT   = 0.
      MXWCRD = 0.
      MXWSHD = 0.
      MXWRTD = 0.


*     R e s e r v e s   m o b i l i z a t i o n:
   *

* --- relative growth rate of shoots and roots used to determine
   *
*     their potential growth rates in the phase of reserve
   *
*     remobilization;
   *
      CALL RDSREA ('RGRSH' , RGRSH  )
      CALL RDSREA ('RGRRT' , RGRRT  )

* --- time coefficient for reserve remobilization;
   *
      CALL RDSINT ('TCRTRS', TCRTRS )
      CALL RDSINT ('TCRTDS', TCRTDS )

* --- weight of reserves mobilised in the first growing day
```

```
(WRMFD,    *
*     kg/ha);
    *
      CALL RDSREA ('WRMFD' , WRMFD  )

* --- variable used to trigger reserves mobilization.
    *
      IVRT  = 0

* --- maximum amount of assimilates remobilisated (MXAR, kg/ha/d)
    *
      CALL RDSREA ('MXAR'   , MXAR   )

* --- maximum growth rate of reserves (kg/ha/d)
    *
      CALL RDSREA ('MXGRRS' , MXGRRS )

* --- maximum and minimum concentration of reserves in the roots
    *
*     (MXCRS and MNCRS, kg/kg)
    *
      CALL RDSREA ('MXCRS'  , MXCRS  )
      CALL RDSREA ('MNCRS'  , MNCRS  )

* --- initial values:
    *
      LDRT   = 0
      RTRT   = 0.
      RTSH   = 0.
      WCWSH  = 0.
      WCWRT  = 0.
      WCTSH  = 0.
      WCTRT  = 0.
      CRSRT  = 0.



*     E x p l o i t a t i o n
    *


* --- time constant for shoots senescence after exploitation
    *
      CALL RDSINT ('TCSS', TCSS)
```

```
* --- maximum height of the canopy in the rainy and dry season (m)
   *
     CALL RDSREA ('MXHCRS', MXHCRS)
     CALL RDSREA ('MXHCDS', MXHCDS)

* --- initial values of auxiliar variables for shoot death after
   *
*     exploitation.
   *
     SDEX   = .FALSE.
     WOSHDE = 0.
     WSHE   = 0.
     WSHRE  = 0.
     WDSHRE = 0.
     WDSHE  = 0.
     HCC    = 0.
     MHDB   = 0.


*     R e s p i r a t i o n:
   *

* --- growth respiration coefficient of the plant (ARG..);
   *
     CALL RDSREA ('ASRQSH' , ASRQSH)
     CALL RDSREA ('ASRQRT' , ASRQRT)
     CALL RDSREA ('ASRQSO' , ASRQSO)
     ASRQCR = 1.5

* --- temperature reference for maintenance respiration (TREF) and
   *
*     factor accounting for increase of maintenance respiration
with   *
*     a 10 C rise temperature (Q10)
   *
     CALL RDSREA ('TREF' , TREF )
     CALL RDSREA ('Q10'  , Q10  )

* --- maintenance respiration coefficient for the plant;
   *
     CALL RDSREA ('MAINSH' , MAINSH )
     CALL RDSREA ('MAINRT' , MAINRT )
     CALL RDSREA ('MAINSO' , MAINSO )
```

```
* --- reduction factor for maintenance respiration during the crop
   *
*     dormant phase.
   *
      CALL RDSREA ('RFMR'   , RFMR   )

* --- initial values
   *
      MRRCR  = 0.

* --- initial values:
   *
      WATCH  = 0.
      EMERGD = 0


*  - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - *
*
   *
*                F U N C T I O N S
   *

* --- biomass allocated to plant components (FB..)
   *
      CALL RDAREA ('FBSHTB', FBSHTB, INTBMX, IFBSHN)

*     maximum shoot growth rate;
   *
      CALL RDAREA ('GRSHTB', GRSHTB, INTBMX, IGRSHN)

*     relative death rates of plant components (RDR..);
   *
      CALL RDAREA ('RDSHTB', RDSHTB, INTBMX, IRDSHN)
      CALL RDAREA ('RDRTTB', RDRTTB, INTBMX, IRDRTN)

*     water stress effects on the relative death rates;
   *
      CALL RDAREA ('WSESST', WSESST, INTBMX, IWSESS)
      CALL RDAREA ('WSERST', WSERST, INTBMX, IWSERS)

*     fraction of the maximum height of crop canopy (FMHC..);
```

```
*
      CALL RDAREA ('FMHCTB', FMHCTB, INTBMX, IFMHCN)

*     dead biomass height as a function of DVS;
*
      CALL RDAREA ('MHDBTB', MHDBTB, INTBMX, IMHDBN)

*     actual nitrogen accumulated in the shoots (kg ha-1)
*
      CALL RDAREA ('SHNRST', SHNRST, INTBMX, ISHNRS)
      CALL RDAREA ('SHNDST', SHNDST, INTBMX, ISHNDS)

*     maximum and minimum shoot nitrogen concentration (kg kg-1)
*
      CALL RDAREA ('MXNCST', MXNCST, INTBMX, IMXNCS)
      CALL RDAREA ('MNNCST', MNNCST, INTBMX, IMNNCS)

*     minimum root nitrogen concentration in the (kg kg-1)
*
      CALL RDAREA ('TMNNCR', TMNNCR, INTBMX, IMNNCR)

*     nitrogen allocated to the roots (-)
*
      CALL RDAREA ('NARTTB', NARTTB, INTBMX, INARTN)

*     specific shoot area as function of DVS
*
      CALL RDAREA ('SSATB' , SSATB,  INTBMX, ISSAN )
      CALL RDAREA ('SDSATB', SDSATB, INTBMX, ISDSAN)


      CLOSE (IUNITD,STATUS='DELETE')


* --- c r o p   s p r o u t i n g
*
      CALL PGCR (ITASK,IUNITD,IUNITO,FILEI1,TERMNL,INLAYX,TKLX,
     &           WCLQT,WCWPX,IVSSC,EMERG,SPROUT,IZRT,RFIBWS)
      IF (EMERG) EMERGD=IDOY

* --- initial values:
*
      CDMP = 0.
```

```
      DO 10 I=1,10
       AVVP(I)  = 0.
       AVDMP(I) = 0.
10    CONTINUE

* --- beginning of regular rains
   *
      CALL PGRAIN (ITASK,IUNITD,IUNITO,FILEI1,IDOY,DFAR,DBRR)

* --- development stage (DVS)
   *
      TMPA = (TMMX + TMMN) * 0.5
      CALL PGPHE (ITASK,IUNITD,IUNITO,FILEI1,OUTPUT,TERMNL,
     &           IDOY,DELT,BG,TMPA,DAYLP,TRANSR,LVEX,LVCS,
     &           LATS,CRTRCT,LVCGRS,LVCDRS,LVCGDS,
     &           LVCDDS,LVCDP,SEDVS,FDRS,LVSS,AVSS,DNCC,
     &           SSS,SSR,EXPDVS,DVR,DVS)

* --- exploitation of crop forage
   *
      CALL PGEXP(ITASK,IUNITD,IUNITO,FILEI1,IDOY,
     &          WSH,DVS,SSS,LVCS,LVCGRS,LVCDRS,
     &          LVCGDS,LVCDDS,LVCDP,HCC,LVEX,HE)


*
---------------------------------------------------------------- *
*
   *
*               R a t e   c a l c u l a t i o n
   *
*
   *
*
---------------------------------------------------------------- *

      ELSE IF (ITASK .EQ. 2) THEN

* --- height of canopy (HCC, m);
   *
      IF (LVCGRS) THEN
        IF (DVS.EQ.0.) AVHCRS=MXHCRS
        HCCRS = AVHCRS * LINT(FMHCTB,IFMHCN,DVS)
```

```
      HCC   = HCCRS
    ELSE IF (LVCGDS) THEN
      IF (DVS.EQ.0.) AVHCDS=MXHCDS
      HCCDS = AVHCDS * LINT(FMHCTB,IFMHCN,DVS)
      HCC   = HCCDS
    ELSE IF (WSH.EQ.0.) THEN
      HCC = 0.
    ELSE
      AVHCRS = 0.
      AVHCDS = 0.
    END IF

* --- development rate (DVR)
  *
    TMPA = (TMMX + TMMN) * 0.5
    CALL PGPHE (ITASK,IUNITD,IUNITO,FILEI1,OUTPUT,TERMNL,
   &          IDOY,DELT,BG,TMPA,DAYLP,TRANSR,LVEX,LVCS,
   &          LATS,CRTRCT,LVCGRS,LVCDRS,LVCGDS,
   &          LVCDDS,LVCDP,SEDVS,FDRS,LVSS,AVSS,DNCC,
   &          SSS,SSR,EXPDVS,DVR,DVS)

* --- onset of growth and development simulation
  *
    IF (.NOT. LVCS) GO TO 110



*  - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - *
*
  *
* --- E x p l o t a t i o n
  *

* --- maximum height of dead shoots (MHDB, m);
  *
    IF (WDSH.GT.0.) THEN
      IF (LVCGRS.AND.DVS.EQ.0..AND.IDOY.LT.FDRS) AVMHDB=0.
      MHDB   = MAX(AVMHDB, HCC*LINT (MHDBTB,IMHDBN,DVS))
    ELSE
      MHDB   = 0.
      AVMHDB = 0.
    END IF
```

```
* --- exploitation
  *
    IF (LVEX) THEN

* ----- date of biginning of a new growth cycle after exploitation
  *
     IF (EXPDVS) THEN
       DGSE = BG
     ELSE
       DGSE = 0
     END IF

* ----- fraction of living and dead above ground biomass removed
by    *
*      clipping or grazing (FLBRE and FDBRE).
  *
     FSBRE = MAX (0.,(HCC-HE)/(HCC+TINY))
     IF (LVCDRS) THEN
       IF (SSS.EQ.1.) THEN
         WDSHRE = FSBRE * WDSH
         WSHRE  = 0.
         HCC    = HE
         MHDB   = HE
       ELSE
         WDSHRE = FSBRE * WDSH
         WSHRE  = MIN (FSBRE*WSH, WSH-SHBDP)
         HCC    = HE
         MHDB   = HE
       END IF
     ELSE IF (HE.GE.HCC) THEN
       WSHRE  = 0.
       WDSHRE = 0.
     ELSE IF (HE.GE.MHDB) THEN
       WSHRE  = FSBRE*WSH
       WDSHRE = 0.
       HCC    = HE
       FLBRE  = 1.
       FDBRE  = 0.
       AVMHDB = MHDB
     ELSE IF (HE.LT.MHDB) THEN
       AVSE1  = WDSH/WSB
       AVSE2  = (MHDB-HE)**2
       AVSE3  = MHDB**2
```

```
        FLBRE  = 1. - AVSE1*AVSE2/AVSE3 - HE/HCC
        FDBRE  = AVSE1*AVSE2/AVSE3
        WSHRE  = FLBRE*WSB
        HCC    = HE
        MHDB   = HE
        AVMHDB = MHDB
        IF (WSHRE.GT.WSH) THEN
          WSHRE = WSH
          IF (.NOT.LVCDRS) WRITE (*,*) 'ERROR: WSHRE .GT. WSH'
          PAUSE
        END IF
        WDSHRE = FDBRE*WSB
        IF (WDSHRE.GT.WDSH) THEN
          WSHRE = WSH
          WRITE (*,*) 'ERROR: WDSHRE.GREATER THAN WDSH'
          PAUSE
        END IF
      END IF
    ELSE
      FSBRE  = 0.
      FLBRE  = 0.
      FDBRE  = 0.
      WSHRE  = 0.
      WDSHRE = 0.
    END IF

* --- effects of exploitation on maximum height of canopy;
  *
    IF (LVCGRS) THEN
      IF (LVEX) THEN
        AVHCRS = MAX((1.-DVS)*AVHCRS, 0.25*MXHCRS)
      END IF
    ELSE IF (LVCGDS) THEN
      IF (LVEX) THEN
        AVHCDS = MAX((1.-DVS)*AVHCDS, 0.25*MXHCDS)
      END IF
    END IF

* - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - *
*
  *
* --- D r y  m a t t e r   p r o d u c t i o n
```

```
    *

* --- dry matter production as a function of cumulative shoot
    *
*     nitrogen (g N per m2 ground surface);
    *
* --- actual dry matter production (ADMP, kg/ha/d);
    *
      IF (LVCGRS .OR. LVCGDS) THEN
        ADMP = DMP * MAX(0.,MIN(TRANSR, RFCAAH))
      ELSE
        ADMP = 0.
      END IF

*  - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - *
*
    *
*     S e n e s c e n c e
    *
*
    *
*     Senescence of perennial grass shoots starts around the
    *
*     onset of stem elongation stage (SESDVS, plant.dat).
    *
*     Death rate of shoots and roots (DR.., kg/ha/d) are
calculated     *
*     as the weight of living plant components (W.., kg/ha) times
    *
*     their relative death rates (RDR.., tables in plant.dat). The
    *
*     entire shoot and part of the root system is assumed to die
    *
*     after crop maturity (DVS=2 ).
    *
*     The relative death rates could be enhanced by water stress
    *
*     and nutrient deficiencies (tables in plant.dat).
    *
*
    *
* --- relative death rates of shoots and roots (RDR..);
```

```
   *
     IF (LVCGRS .OR. LVCGDS) THEN
       RDRSH = LINT(RDSHTB,IRDSHN,DVS)
       RDRRT = LINT(RDRTTB,IRDRTN,DVS)

* ----- water stress effects on the relative death rate of shoots
   *
*       (WSESSH) and roots (WSERST) as a function of accumulated
days  *
*       of water stress (ADWSSH and ADWSRT, d)
   *
       IF (DVS.GT.0. .AND. DVS.LE.2.) THEN
         WSESSH  = LINT(WSESST, IWSESS, ADWSSH)
         RDRSH   = MIN(1., RDRSH + WSESSH)
         WSESRT  = LINT(WSERST, IWSERS, ADWSRT)
         RDRRT   = MIN(1., RDRRT + WSESRT)
       END IF

* ----- death rate of shoots remaining after exploitation;
   *
       IF (SDEX) THEN
         IF (WOSHDE.LT.10.) THEN
           DRSHEX = WOSHDE
           WOSHDE = 0.
         ELSE
           DRSHEX = WOSHDE / TCSS
           WOSHDE = WOSHDE-DRSHEX*DELT
           IF (WOSHDE.LT.0.) THEN
             DRSHEX = (DRSHEX+WOSHDE)/DELT
             WOSHDE = 0.
           END IF
         END IF
         IF (WOSHDE.EQ.0.) SDEX=.FALSE.
       ELSE
          DRSHEX = 0.
       END IF

* ----- death rate of shoots and roots during growing phases
(DR..).   *
       IF (DVS.GT.0. .AND. DVS.LE.2.) THEN
         DRSH1  = RDRSH * WSH + DRSHEX
         DRRT1  = RDRRT * WRT
       ELSE
```

```
        DRSH1 = 0.
        DRRT1 = 0.
      END IF
    ELSE
      DRSH1 = 0.
      DRRT1 = 0.
    END IF

* --- death rate of shoots and roots after growing phases (DR..).
*
    IF (SSS.GE.0. .AND. SSS.LT.1.) THEN
      IF (WOSH2.GT.0.) THEN
        DRSH2 = MIN (WOSH2/DELT, SSR*WSH2)
        WOSH2 = WOSH2 - DRSH2*DELT
      ELSE
        DRSH2 = 0.
        WOSH2 = 0.
        WSH2  = 0.
      END IF
      IF (WORT2.GT.0.) THEN
        DRRT2 = MIN (WORT2/DELT, SSR*WRT2)
        WORT2 = WORT2 - DRRT2*DELT
      ELSE
        DRRT2 = 0.
        WORT2 = 0.
        WRT2  = 0.
      END IF
    ELSE
      WOSH2 = 0.
      WSH2  = 0.
      WORT2 = 0.
      WRT2  = 0.
      DRSH2 = 0.
      DRRT2 = 0.
    END IF

*     structural roots dying after crop reserves are used
*
    IF (LVCGRS .AND. WOSRT.GT.0.) THEN
      IF (WRS/WSRT .LE. MXCRS) THEN
        DRRT3 = MAX(0., 3*RDRRTC*WOSRT)
        IF (WOSRT.LE.10.) DRRT3=WOSRT
        WOSRT = MAX(0., WOSRT-DRRT3)
```

```
        END IF
      ELSE IF (LVCGRS) THEN
        DRRT3 = 0.
      ELSE IF ((LVCDP.OR.LVCGDS) .AND. WSRT.GT.1500.) THEN
        IF (WRS/WSRT.LE.MXCRS) THEN
          AVWDRT = MAX (0., WSRT - WRS/MXCRS)
          AVWDRT = MAX (0., AVWDRT - DRRT3*DELT)
          IF (AVWDRT.LE.1.) THEN
            DRRT3 = MAX (0., AVWDRT)
          ELSE
            DRRT3  = MAX (0., RDRRTC * AVWDRT)
          END IF
        END IF
      ELSE
        DRRT3  = 0.
      END IF

      DRSH = DRSH1 + DRSH2
      DRRT = DRRT1 + DRRT2 + DRRT3

      IF (WRS/WSRT.GE.MXCRS) THEN
        DRRT  = 0.
        DRRT1 = 0.
        DRRT2 = 0.
        DRRT3 = 0.
      END IF

* - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - *
*      A c c u m u l a t i o n   o f   a s s i m i l a t e s
   *
*    a n d   n u t r i e n t s   f r o m   d e a d   p l a n t s
   *
*
   *
*    Before dead leave and stems fall on the soil, some
assimilates   *
*    and nutrients could be translocated to other plant parts
   *
*    depending on their growth demands.
   *

* --- withdrawal of carbohydrates from shoots and roots;
```

```
   *
     IF (LVCGRS .OR. LVCGDS .OR. LVCDRS .OR. LVCDDS) THEN
       WCWSH = DRSH * FCWSH
       WCWRT = DRRT * FCWRT
     ELSE
       WCWSH = 0.
       WCWRT = 0.
     END IF

* --- remobilization of carbohydrate reserves to other plant
   *
*     components. During crop senescence after the growing phases,
   *
*     it is assumed that these carbohydrates are used for
maintenance  *
*     respiration
   *
     IF (LVCGRS .OR. LVCGDS) THEN
       WCTSH = WCWSH
       WCTRT = WCWRT
     ELSE
       WCTSH = 0.
       WCTRT = 0.
     END IF



*  - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - *
*     G r o w t h
   *
*
   *
*     Under potential growth conditions, growth of shoots and
roots   *
*     is defined as a function of the crop development stage
(FB..).  *
*     But the biomass allocation could be modified either by
   *
*     enviromental constrains such as water shortage and nutrient
   *
*     deficiencies or by crop management.
   *
```

```
* --- actual growth rates: crop (GRCR) and plant components (GR..)
   *
     IF (LVCGRS .OR. LVCGDS) THEN
       IF (TRANSR.LT.1.) THEN
         RFSGWS = MAX(0., 0.9*TRANSR)
       ELSE
         RFSGWS = 1.
       END IF
       FBSH   = LINT (FBSHTB, IFBSHN, DVS)
       FBRT   = 1. - FBSH
       ASRQCR = FBSH*ASRQSH + FBRT*ASRQRT
       IF (ADMP+(WCTSH+WCTRT)/ASRQCR .GT. MXGRCR) THEN
         ADMP = MAX (0.,MXGRCR-(WCTSH+WCTRT)/ASRQCR)
         DMP  = ADMP/MAX(TINY,MIN(RFCAAH,TRANSR))
       END IF
       PGRCR  = DMP*RFCAAH + (WCTSH+WCTRT)/ASRQCR
       GRCR   = ADMP+(WCTSH+WCTRT)/ASRQCR
       PGRSH  = FBSH * PGRCR
       GRSH   = RFSGWS * PGRSH
       GRRT   = GRCR - GRSH
     ELSE
       RFSGWS = 1.
       GRCR   = 0.
       GRSH   = 0.
       GRRT   = 0.
       AVGRRS = 0.
     END IF

     IF (LVCGRS .OR. LVCGDS) THEN
* ----- root growth rate could be limited by a minimum nitrogen
   *
*      concentration in the roots
   *
       MNNCRT = LINT(TMNNCR, IMNNCR, DVS)
       ANCR   = ANSH + ANRT
       FCNART = LINT(NARTTB, INARTN, ANCR)
       ANRT   = INSW(1.-DVS,ANRT,ANSH*FCNART/(1.-FCNART))
       NCRT   = ANRT/WRT
       IF (NCRT.LT.MNNCRT .AND. DVS.GE.0.2) THEN
         GRRT = 0.
         GRSH = GRCR
       END IF
* ----- root growth rate could be limited by a maximum shoot to
```

```
root   *
*      ratio (-)
    *
       SHRTR  = WSH/WSRT
       IF (SHRTR.LE.CSHRTR .AND. LVDMA) THEN
         GRRT = 0.
         GRSH = GRCR
       END IF
* ----- shoot growth rate could be limited by a low shoot nitrogen
    *
*      concentration
    *
       AVSGND = MIN(0.006, TSNCSG*MNNCSH)
       IF (DVS.LT.2. .AND. NCSH.LT.AVSGND) THEN
         RFSGND = MIN(1.,1.-
MIN(0.9,(AVSGND-NCSH)/(AVSGND-MNNCSH)))
         A1GRSH = GRSH
         GRSH   = RFSGND*GRSH
         IF ((NCRT.LT.MNNCRT .AND. DVS.GE.0.2)  .OR.
     &        (SHRTR.LE.CSHRTR .AND. LVDMA)) THEN
           GRRT = 0.
         ELSE
           GRRT = GRRT + MAX (0., A1GRSH-GRSH)
         END IF
       ELSE
         GRRT   = GRRT
         RFSGND = 1.
       END IF
       A1GRRS   = MAX(0., GRCR-GRRT-GRSH)
* ----- shoot growth rate could be limited by a maximum growth
rate    *
*      rate (kg/ha/d)
    *
       MXGRSH = MAX(0.,LINT (GRSHTB, IGRSHN, DVS))
       IF (GRSH.GT.MXGRSH) THEN
         GRSH   = MXGRSH
         A1GRRS = MAX(0., GRCR-GRSH-GRRT)
       END IF
* ----- once translocation of reserves to new rooted shoots during
   *
*      regrowt stop, non-structural carbohydrates are again
stored   *
       AVGRRS = 0.
```

```
      A2GRRS = 0.
      IF (DVS.GT.0. .AND. AVGRRS.EQ.0. .AND. IVRT.EQ.0 .AND.
    &     GRRT.GT.0. .AND. CRSRT.LT.MXCRS) THEN
        A2GRRS = FRBARS * GRRT
        GRRT   = MAX(0., GRRT-A2GRRS)
      END IF

* ----- if the demand for shoots and roots growth are met, the
   *
*      remaining assimilates are allocated to reserves
   *
      AVGRRS  = MAX(0., A1GRRS+A2GRRS)
      IF (AVGRRS.GT.MXGRRS) THEN
        AVGRRS = MXGRRS
        ADMP = MAX(0.,GRSH+GRRT+AVGRRS-(WCTSH+WCTRT)/ASRQCR)
        DMP  = ADMP/MAX(TINY,MIN(RFCAAH,TRANSR))
        GRCR = ADMP+(WCTSH+WCTRT)/ASRQCR
      END IF
      IF (AVGRRS.LT.1.E-7) AVGRRS=0.
      IF (DVS.GT.1.) THEN
        IF (DMP.LT.IDMP) THEN
          RFLWU = MIN(1.,MAX(0.,DMP/IDMP))
        ELSE
          RFLWU = 1.
        END IF
      ELSE
        RFLWU = 1.
      END IF
     END IF



* - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - *
*    R o o t   e x t e n s i o n
    *
*
    *
* --- root extension rate (RER, m/d)
    *
     IF (ZRT.LT.RDMSOL .AND. (LVCGRS .OR. LVCGDS)
    &    .AND. (GRRT.GT.0. .OR. RTRT.GT.0.)) THEN
      RER   = INSW(DVS-2.,PRRE*WRFRE,0.)
      RER   = MIN(RER, RDMSOL-ZRT)
```

```
    ELSE
      RER   = 0.
    END IF



* - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - *
*                T r a n s l o c a t i o n  o f
    *
*         a s s i m i l a t e s   a n d   n u t r i e n t s
    *
*
    *
*    At the beginning of a each new crop cycle the initial weight
    *
*    of shoots and roots (these only at the beginning of the
rainy    *
*    season) is determined by available reserves.
    *
*    Reserves translocation supplies for some days (TCRT) the
    *
*    the assimilates required for potential growth rate of shoots
    *
*    and roots. Assimilates remobilization is zero under water
    *
*    stress.
    *
*
    *
* --- reserve translocation
    *
    IF (IVRT.EQ.2 .AND. (LVCGRS .OR. LVCGDS)) THEN
      PGRSH = 0.
      PGRRT = 0.
      IF (TRANSR.LT.1.) THEN
        RTSH = 0.
        RTRT = 0.
      ELSE IF (CRSRT.LT.MNCRS .AND. LVCGDS) THEN
        RTSH = 0.
        RTRT = 0.
        IVRT = 0
        LDRT = 0
```

```
    ELSE
     PGRSH = WSH * (EXP(RGRSH*DELT)-1.)/DELT
     PGRRT = WRT * (EXP(RGRRT*DELT)-1.)/DELT
     IF (GRSH.LT.PGRSH) THEN
      AVRTSH = MIN (MXAR*ASRQSH,(PGRSH-GRSH)*ASRQSH)
      RTSH   = MIN (WRS*0.5, AVRTSH)
     ELSE
      RTSH   = 0.
      AVRTSH = 0.
     END IF
     IF (GRRT.LT.PGRRT) THEN
      AVRTRT = MIN (MXAR*ASRQRT,(PGRRT-GRRT)*ASRQRT)
      RTRT   = MIN (WRS*0.5, AVRTRT)
     ELSE
      AVRTRT = 0.
      RTRT   = 0.
     END IF
    END IF
    IF (IDOY.EQ.LDRT) IVRT = 0
   ELSE IF (IVRT.EQ.1 .AND. (LVCGRS .OR. LVCGDS)) THEN
    PGRSH = WSH * (EXP(RGRSH*DELT)-1.) / DELT
    IF (GRSH.LE.PGRSH) THEN
     AVRTSH = MIN (MXAR,(PGRSH-GRSH)*ASRQSH*TRANSR)
     RTSH   = MIN (WRS, AVRTSH)
     RTRT   = 0.
    ELSE
     AVRTSH = 0.
     AVRTRT = 0.
     RTSH   = 0.
     RTRT   = 0.
    END IF
    IF (IDOY.EQ.1 .AND. LDRT.GE.365) LDRT=LDRT-365
    IF (IDOY.EQ.LDRT) IVRT = 0
   ELSE
    AVRTSH = 0.
    AVRTRT = 0.
    PGRSH  = 0.
    PGRRT  = 0.
    RTSH   = 0.
    RTRT   = 0.
    IVRT   = 0
    LDRT   = 0
   END IF
```

```
* ---------------------------------
-- *
*   M a i n t e n a n c e   r e s p i r a t i o n
   *
*
   *
* --- Maintenance respiration losses start to be simulated at the
   *
*    end of the growing cycle. Hereafter, the carbohydrate
reserves   *
*    are used in the maintenance respiration and the crop biomass
   *
*    decreases. At the end of each growing cycle, assimilates
from    *
*    the remaining senescent plant parts are assumed to cover
   *
*    maintenance respiration requirements.
   *
*    Maintenance respiration rates of shoots (MRRSH, kg/ha/d),
   *
*    roots (MRRSR) and reserves (MRRRS).
   *
*     - MAINSH, maintenance respiration coefficient for shoots
   *
*     - MAINRT, maintenance respiration coefficient for roots
   *
*     - MAINSO, maintenance respiration coefficient for reserves
   *
*     - TREF, reference temperature for maintenance respiration
   *
*
   *
* --- rates of maintenance respiration
   *
      IF (LVCDP) THEN
       MRRSH = MAINSH * WSH  * Q10**((TMPA-TREF)/10.)
       MRRRS = MAINSO * WRS  * Q10**((TMPA-TREF)/10.)
       MRRRT = MAINRT * WRT  * Q10**((TMPA-TREF)/10.)
       MRRSH = MRRSH*RFMR
       MRRRT = MRRRT*RFMR
       MRRRS = MRRRS*RFMR
      ELSE
```

```
      MRRSH = 0.
      MRRRT = 0.
      MRRRS = 0.
    END IF

* --- rate of crop maintenance respiration
  *
    IF (LVCDP) THEN
      MRRCR  = MRRSH + MRRRT + MRRRS
      AVMRRC = MRRSH + MRRRT + MRRRS
    ELSE IF (.NOT.LVCGRS .AND. .NOT.LVCGDS) THEN
      MRRCR  = WCWSH + WCWRT
      AVMRRC = 0.
    ELSE
      MRRCR  = 0.
      AVMRRC = 0.
    END IF
    A1MRRC = 0.
    IF (LVCDP) THEN
      IF (WRS.LE.1.) MRRCR=WRS
      IF (MRRCR.GT.WRS) THEN
        A1MRRC = MAX (0.,WRS-(RTSH+RTRT)+AVGRRS*ASRQCR)
        IF (MRRCR.GT.A1MRRC) MRRCR=A1MRRC
      END IF
    END IF

* --- root growth reallocation for matching the maximum reserve
  *
*     concentration
  *
    AVGRRT = 0.
    AVCRS  = 0.
    AVCRS  = (WRS+AVGRRS*ASRQCR-AVMRRC)/(WSRT+GRRT)
    IF (AVGRRS.GT.0. .AND. AVCRS.GT.MXCRS .AND.
   &    NCRT.GT.MNNCRT) THEN
      AVGRRT = (WRS+AVGRRS*ASRQCR-AVMRRC-MXCRS*(WSRT+GRRT))*
   &           ASRQCR/(ASRQCR+MXCRS)
      AVGRRT = AVGRRT/ASRQCR
      IF (AVGRRT.GE.AVGRRS) THEN
        AVGRRT = AVGRRS
        AVGRRS = 0.
      ELSE
        AVGRRS = MAX(0., AVGRRS-AVGRRT)
```

```
      END IF
      GRRT   = MAX(0., GRRT+AVGRRT)
      AVGRRT = 0.
    ELSE IF (AVGRRS.GT.0. .AND. AVCRS.GT.MXCRS .AND.
   &    NCRT.LE.MNNCRT) THEN
      ADMP   = ADMP - AVGRRS
      DMP    = ADMP/MAX(TINY,MIN(RFCAAH,TRANSR))
      GRCR   = GRCR - AVGRRS
      AVGRRS = 0.
      IF (DVS.GT.1.) THEN
        IF (DMP.LT.IDMP) THEN
          RFLWU = MIN(1.,MAX(0.,DMP/IDMP))
        ELSE
          RFLWU = 1.
        END IF
      ELSE
        RFLWU = 1.
      END IF
    END IF

*
----------------------------------------------------------------- *
*                     OUTPUT OF RESULTS
   *
*
----------------------------------------------------------------- *

    IF (OUTPUT .OR. TERMNL) THEN

* ----- weather variables
   *
*       CALL OUTDAT (2, 0, 'VP'    , VP     )
*       CALL OUTDAT (2, 0, 'TMPA'  , TMPA   )

* ----- time variables
   *
*       CALL OUTDAT (2, 0, 'IYEAR' , REAL())

* ----- state variables
   *
      CALL OUTDAT (2, 0, 'WCR'   , WCR   )
      CALL OUTDAT (2, 0, 'WSH'   , WSH   )
      CALL OUTDAT (2, 0, 'WRT'   , WRT   )
```

```
      CALL OUTDAT (2, 0, 'WRS'   , WRS   )
*       CALL OUTDAT (2, 0, 'ZRT'   , ZRT   )
*       CALL OUTDAT (2, 0, 'WSRT'  , WSRT  )
*       CALL OUTDAT (2, 0, 'WSHE'  , WSHE  )
*       CALL OUTDAT (2, 0, 'WDSHE' , WDSHE )
*       CALL OUTDAT (2, 0, 'WDSH'  , WDSH  )
*       CALL OUTDAT (2, 0, 'WSB'   , WSB   )
*       CALL OUTDAT (2, 0, 'WDRT'  , WDRT  )
*       CALL OUTDAT (2, 0, 'CWDRT' , CWDRT )
*       CALL OUTDAT (2, 0, 'CWDSH' , CWDSH )
*       CALL OUTDAT (2, 0, 'LAI'   , LAI   )
*       CALL OUTDAT (2, 0, 'DLAI'  , DLAI  )

* ----- variables for the sensitivity analysis
   *
      CALL OUTDAT (2, 0, 'MXWCR' , MXWCR )
      CALL OUTDAT (2, 0, 'MXWSH' , MXWSH )
      CALL OUTDAT (2, 0, 'MXWRT' , MXWRT )
*       CALL OUTDAT (2, 0, 'MXWCRD', MXWCRD)
*       CALL OUTDAT (2, 0, 'MXWSHD', MXWSHD)
*       CALL OUTDAT (2, 0, 'MXWRTD', MXWRTD)
*       CALL OUTDAT (2, 0, 'MXTDM' , MXTDM )


* ----- rate variable
    *
       CALL OUTDAT (2, 0, 'DMP'   , DMP   )
       CALL OUTDAT (2, 0, 'MTRANS', MTRANS)
       CALL OUTDAT (2, 0, 'VPD'   , VPD   )
       CALL OUTDAT (2, 0, 'ADMP'  , ADMP  )
       CALL OUTDAT (2, 0, 'RFLWU' , RFLWU )

     END IF

110   CONTINUE

*
-------------------------------------------------------------------- *
*
   *
*                 I n t e g r a t i o n
   *
*
```

```
    *
*
------------------------------------------------------------------ *

      ELSE IF (ITASK .EQ. 3) THEN

* --- indicator of onset of the rainy season
    *
      IF (IVSSC.LE.1 .AND. .NOT.LVCS .AND. DBRR.EQ.0) THEN
        CALL PGRAIN (ITASK,IUNITD,IUNITO,FILEI1,IDOY,DFAR,DBRR)
      ELSE IF (IVSSC.EQ.2 .AND. IDOY.EQ.2) THEN
        CALL PGRAIN (ITASK,IUNITD,IUNITO,FILEI1,IDOY,DFAR,DBRR)
      END IF

* --- indicator of end of the rainy season (defined by the vapour
    *
*     pressure)
    *
      CVP = 0.
      DO 210, I=1,10
        I1 = 10-I+1
        IF (I1.EQ.1) THEN
          AVVP(1) = VP
          CVP     = CVP + AVVP(1)
        ELSE
          AVVP(I1) = AVVP(I1-1)
          CVP      = CVP + AVVP(I1)
        END IF
210   CONTINUE
      MVP = CVP/10.
      IF (IDOY.EQ.(DBRR-2) .AND. IDOY.LE.(DBRR+20)) THEN
        LVRSVP = .TRUE.
      ELSE IF (IDOY.GT.DBRR .AND. MVP.GE.CRVPER) THEN
        LVRSVP = .TRUE.
      ELSE
        LVRSVP = .FALSE.
      END IF

* --- simulation could start from:
    *
*     - sowing;
    *
*     - an established crop (in the dry season)
```

```
   *
* --- onset of crop growth in the first year of simulation
   *
      IF (IVSSC.EQ.0) THEN
        IF (EMERG) THEN
          BG     = IDOY
          LVCS   = .TRUE.
          DVS    = 0.
          LVCGRS = .TRUE.
          EMERG  = .FALSE.
        END IF
      ELSE IF (IVSSC.EQ.1) THEN
        IF (.NOT.LVCS) THEN
          IF (TWA .LE. CRWARC) THEN
            LVCDP = .TRUE.
            LVCS  = .TRUE.
            BGDS  = 0
          ELSE IF (BGDS.EQ.0) THEN
            BGDS  = IDOY+TCCS
          END IF
        END IF
        IF (TWA .GT. CRWARC) THEN
          IF (IDOY.EQ.365 .AND. BGDS.GT.365) THEN
            BGDS = BGDS - 365
          ELSE IF (IDOY.EQ.366) THEN
            BGDS = BGDS + 365
            IF (IDOY.EQ.BGDS) THEN
              LVCS   = .TRUE.
              LVCGDS = .TRUE.
              LVCDP  = .FALSE.
              DVR    = 0.
              DVS    = 0.
              BG     = BGDS
              IVRT   = 1
              BGDS   = 0
              MRRCR  = 0.
              AVMRRC = 0.
            ELSE
              BGDS = BGDS - 366
            END IF
          ELSE IF (IDOY.EQ.BGDS) THEN
            LVCS   = .TRUE.
```

```
        LVCGDS = .TRUE.
        IVRT   = 1
        BG     = BGDS
        DVR    = 0.
        DVS    = 0.
        BGDS   = 0
        MRRCR  = 0.
        AVMRRC = 0.
      END IF
    ELSE
      BGDS = 0
    END IF
  END IF

* ---------------------------------
-- *
*
  *
*   O n s e t  o f  a  n e w  c r o p  c y c l e s
  *

* --- a new crop cycle, triggered by water stored in the soil,
  *
*    could start in the dry season...
  *
  IF (LVCDP .AND. IVSSC.EQ.2 .AND. SWITC2) THEN
    IF (TWA.GE.CRWARC .AND. BGDS.EQ.0) THEN
      BGDS = IDOY + TCCS
    END IF
    IF (TWA.GE.CRWARC) THEN
      IF (IDOY.EQ.365 .AND. BGDS.GT.365) THEN
        BGDS = BGDS - 365
      ELSE IF (IDOY.EQ.366) THEN
        BGDS = BGDS + 365
        IF (IDOY.EQ.BGDS) THEN
          LVCGDS = .TRUE.
          LVCDP  = .FALSE.
          DVR    = 0.
          DVS    = 0.
          BG     = BGDS
          IVRT   = 1
          BGDS   = 0
          MRRCR  = 0.
```

```
          AVMRRC = 0.
          SWITC2 = .FALSE.
        ELSE
          BGDS   = BGDS - 366
        END IF
      ELSE IF (BGDS.EQ.IDOY) THEN
        LVCGDS = .TRUE.
        LVCDP  = .FALSE.
        DVR    = 0.
        DVS    = 0.
        BG     = BGDS
        IVRT   = 1
        BGDS   = 0
        MRRCR  = 0.
        AVMRRC = 0.
        SWITC2 = .FALSE.
      ELSE IF (TWA.LT.CRWARC) THEN
        SSS    = -1.
        LVCDP  = .TRUE.
        BGDS   = 0
      END IF
    END IF
    WATCH = 0.
  END IF

* --- a new crop cycle could also be triggered by rain...
*

  IF (IVSSC.GE.1 .AND. .NOT.LVCGRS .AND. .NOT.LVCDRS) THEN
    SPROUT = .FALSE.
    WATCH = WATCH + 1.
    IF ((IDOY.GE.DBRR .OR. WATCH.GT.10.) .AND. .NOT.SPROUT
   &       .AND. (WRS.GT.0. .OR. LVCGDS)) THEN
      CALL PGCR
(ITASK,IUNITD,IUNITO,FILEI1,TERMNL,INLAYX,TKLX,
   &              WCLQT,WCWPX,IVSSC,EMERG,SPROUT,IZRT,RFIBWS)
    END IF
    IF (SPROUT .AND. IBR.EQ.0) THEN
      WATCH = 0.
      IBR    = IDOY
      BGDS   = 0
    END IF
    IF (IBR.GT.0) THEN
```

```
      IF (IDOY.EQ.365 .AND. IBR.GT.365) THEN
        IBR = IBR - 365
      ELSE IF (IDOY.EQ.366) THEN
        IF (IDOY.EQ.IBR) THEN
          SWITCH =.TRUE.
        ELSE
          IBR    = IBR - 366
        END IF
      ELSE IF (IBR.EQ.IDOY) THEN
        SWITCH =.TRUE.
      END IF
    END IF
  END IF
  IF (IDOY.GE.DBRR .AND. LVRSVP .AND. SWITCH) THEN
    SWITCH = .FALSE.
    SPROUT = .FALSE.
    IF (LVCDP) THEN
      LVCGRS = .TRUE.
      SWITC2 = .TRUE.
      BG     = IBR
      IBR    = 0
      DVR    = 0.
      DVS    = 0.
      IVRT   = 2
      LVCDP  = .FALSE.
      MRRCR  = 0.
      AVMRRC = 0.
      WOSRT  = MAX (0., WSRT)
    ELSE IF (LVCGDS) THEN
      LVCGDS = .FALSE.
      LVCGRS = .TRUE.
      SWITC2 = .TRUE.
      AVSS   = 0.
      BG     = IBR
      IBR    = 0
      DVR    = 0.
      DVS    = 0.
      IVRT   = 2
      WOSRT  = MAX (0., WSRT)
    ELSE IF (LVCDDS) THEN
      LVCGRS = .TRUE.
      SWITC2 = .TRUE.
      BG     = IBR
```

```
        IBR    = 0
        DVR    = 0.
        DVS    = 0.
        IVRT   = 2
        WOSRT  = MAX (0., WSRT)
      END IF
    ELSE IF (SWITCH) THEN
      SWITCH = .FALSE.
      SPROUT = .FALSE.
      IF (LVCDP) THEN
        LVCGDS = .TRUE.
        BG     = IBR
        IBR    = 0
        DVR    = 0.
        DVS    = 0.
        IVRT   = 2
        LVCDP  = .FALSE.
        MRRCR  = 0.
        AVMRRC = 0.
      ELSE IF (LVCDDS) THEN
        LVCGDS = .TRUE.
        BG     = IBR
        IBR    = 0
        DVR    = 0.
        DVS    = 0.
        IVRT   = 2
      ELSE IF (LVCGDS .AND. (IDOY.GE.DFAR .AND. IDOY.LT.DBRR))
THEN
        IBR    = 0
        IVRT   = 1
        SWITC3 = .TRUE.
      ELSE
        IBR    = 0
      END IF
    END IF

* --- a new crop cycle could start after exploitation...
 *
    IF (IDOY.EQ.DGSE .AND. EXPDVS) THEN
      IF (TWA.GE.CRWARC) THEN
        IVRT  = 1
        IF (IDOY.LT.DBRR .OR. .NOT.LVRSVP) THEN
          LVCGRS =.FALSE.
```

```
          LVCGDS =.TRUE.
          DVR    = 0.
        END IF
      ELSE
        IF (LVCGRS) LVCGRS=.FALSE.
        IF (LVCGDS) LVCGDS=.FALSE.
        LVCDP = .TRUE.
        DVR   = 0.
      END IF
    END IF

* --- shoot death due to nitrogen deficiency
   *
    IF (LVCGRS .OR. LVCGDS) THEN
      IF (DVS.EQ.0.) THEN
        AVSDND = 0.
      ELSE
        IF (AVSDND.GT.TCSDND) DVR = MAX(0., 2.-DVS)
      END IF
    END IF

* --- logical variable to indicate that exploitation has occurred
   *
    IF (DVS.EQ.2. .AND. LVCGRS) LVDMA=.FALSE.

* --- development stage (DVS)
    CALL PGPHE (ITASK,IUNITD,IUNITO,FILEI1,OUTPUT,TERMNL,
   &          IDOY,DELT,BG,TMPA,DAYLP,TRANSR,LVEX,LVCS,
   &          LATS,CRTRCT,LVCGRS,LVCDRS,LVCGDS,
   &          LVCDDS,LVCDP,SEDVS,FDRS,LVSS,AVSS,DNCC,
   &          SSS,SSR,EXPDVS,DVR,DVS)


*  - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - *
*
   *
*             I n i t i a l   C o n d i t i o n s
   *

* --- initial translocation of reserves
   *
    IF ((DVS.EQ.0. .OR. SWITC3) .AND. IVSSC.GE.1) THEN
```

```
      IF (IVRT.GE.1) THEN
        IF (SWITC3) SWITC3=.FALSE.
        IF (LVCGRS) THEN
          LDRT  = IDOY + TCRTRS
        ELSE IF (LVCGDS) THEN
          LDRT  = IDOY + TCRTDS
        END IF
      END IF
      CRSRT = WRS/(WSRT+TINY)
      IF (IVRT.EQ.2 .AND. LVCGDS) THEN
        IF (CRSRT.LT.MNCRS) THEN
          RTSH  = 0.
          RTRT  = 0.
        ELSE
          RTSH  = MIN (WRS*0.5, WRMFD*RFIBWS)
          RTRT  = MIN (WRS*0.5, WRMFD*RFIBWS)
        END IF
        RFIBWS  = 1.
      ELSE IF (IVRT.EQ.1) THEN
        IF (CRSRT.LT.MNCRS) THEN
          RTSH  = 0.
        ELSE
          RTSH  = MIN (WRS, WRMFD*RFIBWS)
        END IF
        RFIBWS  = 1.
        RTRT    = 0.
      ELSE
        RTSH    = 0.
        RTRT    = 0.
      END IF
    END IF

* --- initial weight of shoots and roots
*
    IF (DVS.EQ.0. .AND. IVSSC.EQ.0) THEN
      WSH    = IWSHS * RFIBWS
      WDSH   = 0.
      WRT    = IWRTS * RFIBWS
      RFIBWS = 1.
      WDRT   = 0.
      WSRT   = WRT
      WRS    = 0.
      WDRT   = 0.
```

```
    WCR    = WSH + WRT
    IVSSC  = 2
   ELSE IF (IVSSC.EQ.1) THEN
    IF (LVCS) THEN
     WSH   = IWSH + RTSH/ASRQSH
     WRS   = IWRS - RTSH
     WRT   = IWRT
     WDSH  = IWDSH
     WDRT  = IWDRT
     WSRT  = WRT - WRS
     WCR   = WSH + WRT
     HCC   = 0.05
     IVSSC = 2
    END IF
   END IF

   IF (.NOT.LVCS) GO TO 220

*  - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - *
*
  *
*    S e n e s c e n c e
  *
*
  *
* --- loss of biomass of shoots and roots (LW..);
  *
   LWSH = MAX(0., DRSH - WCWSH)
   LWRT = MAX(0., DRRT - WCWRT)

* --- dead biomass of the crop during the cropping year (WD..);
  *
   IF (LVEX) WDSH=MAX(0., WDSH - WDSHRE)
   IF (LVCGRS .AND. DVS.EQ.0.) THEN
    WDSH = 0.
    WDRT = 0.
    WDCR = 0.
   ELSE
    WDSH = MAX(0., WDSH + LWSH * DELT)
    WDRT = MAX(0., WDRT + LWRT * DELT)
   END IF
   IF (DVS.EQ.2. .AND. LVCGRS) THEN
```

```
      END IF
*     cumulative dead biomass of the crop  (CWD..);
    *
      CWDSH = MAX(0., CWDSH + (LWSH - WDSHRE) * DELT)
      CWDRT = MAX(0., CWDRT + LWRT * DELT)

*     accumulated days of water stress for shoots (ADWSSH),
    *
*     and roots senescence (ADWSRT).
    *
      IF (DVS.EQ.0.) THEN
        ADWSSH = 0.
        ADWSRT = 0.
      ELSE IF (DVS.GT.0. .AND. DVS.LT.2.) THEN
        IF (WSH.GT.0.) THEN
          ADWSSH = MAX(0.,(ADWSSH + 2. * (0.3 - TRANSR) * DELT))
        ELSE
          ADWSSH = 0.
        END IF
        IF (WRT.GT.0.) THEN
          ADWSRT = MAX(0.,(ADWSRT + 2. * (0.3 - TRANSR) * DELT))
        ELSE
          ADWSRT = 0.
        END IF
      ELSE
        ADWSSH = 0.
        ADWSRT = 0.
      END IF

* --- growth rate of reserves
    *
      GRRS = AVGRRS*ASRQCR

*  - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - *
*
    *
*                    D r y   M a t t e r
    *

* --- living plant biomass (W..)
    *
      AVGRSH = GRSH + RTSH/ASRQSH - DRSH - WSHRE
```

```
      WSH    = MAX(0., INTGRL(WSH, AVGRSH, DELT))
      AV1GRR = GRRS - (RTSH+RTRT+AVMRRC)
      WRS    = MAX(0., INTGRL(WRS, AV1GRR, DELT))
      AVGRRT = GRRT + RTRT/ASRQRT - DRRT
      WSRT   = MAX(0., INTGRL(WSRT, AVGRRT, DELT))
      WRT    = MAX(0., WSRT + WRS)

* --- living and dead forage exploitated (WSHE and WDSHE, kg/ha)
*
      WSHE   = MAX(0., INTGRL(WSHE, WSHRE, DELT))
      WDSHE  = MAX(0., INTGRL(WDSHE, WDSHRE, DELT))


* --- dry matter production as a function of cumulative shoot
*
*     nitrogen (g N per m2 ground surface)
*
      IF (LVCGRS .OR. LVCGDS) THEN
* ----- shoot nitrogen (kg/ha)
*
        AVANSH = ANSH
        MXNCSH = LINT (MXNCST, IMXNCS, DVS)
        MNNCSH = LINT (MNNCST, IMNNCS, DVS)
        IF (LVCGRS) THEN
          IF (IVSCNS.EQ.0) THEN
            ANSHRS = LINT (SHNRST, ISHNRS, DVS)
          ELSE IF (IVSCNS.EQ.1) THEN
            AVDNCC = REAL(DNCC)
            ANSHRS = LINT (SHNRST, ISHNRS, AVDNCC)
            ANSHDS = LINT (SHNDST, ISHNDS, AVDNCC)
          END IF
        ELSE IF (LVCGDS) THEN
          AVDNCC = REAL(DNCC)
          ANSHDS = LINT (SHNDST, ISHNDS, AVDNCC)
        END IF
        IF (LVCGRS) THEN
          ANSH = ANSHRS
        ELSE IF (LVCGDS) THEN
          ANSH = ANSHDS
        END IF
        IF (DVS.EQ.0.) AVANSH=ANSH
        NCSH = ANSH/WSH
        IF (DVS.LE.1. .AND. NCSH.GT.MXNCSH) THEN
```

```
        ANSH = MIN (ANSH, WSH*MXNCSH)
      END IF

* ----- radiation RDD  (from J m-2 d-1 to MJ m-2 d-1)
  *
      RDD   = RDD*1.E-06
* ----- cumulative radiation (MJ m-2)
  *
      CRDD  = INTGRL(CRDD, RDD, DELT)
* ----- shoot nitrogen (g N per m2 ground surface)
  *
      NSH   = MAX(0., ANSH/10.)
* ----- growth per unit rad and unit shoot N (g g-1/(MJ m-2))
  *
      IF (DVS.LE.1.) THEN
        RNEFF = (P/RDD)*(1.-EXP(-EPSIL*RDD/(P*NSH+TINY)))
      ELSE IF (DVS.GT.1.) THEN
        RNEFF = (0.5*P/RDD)*(1.-EXP(-EPSIL*RDD/(P*NSH+TINY)))
      END IF
* ----- output: overall shoot N use efficiency (g g-1 d-1)
  *
      NUE   = RNEFF*RDD
* ----- output: overall radiation use efficiency (g MJ-1)
  *
      RUE   = RNEFF*NSH
* ----- dry matter production (kg ha-1 d-1)
  *
      IF ((LVCGRS .OR. LVCGDS) .AND. DVS.EQ.0.) THEN
        SWITC1 = .TRUE.
      ELSE IF (.NOT.LVCGRS .AND. .NOT.LVCGDS) THEN
        SWITC1 = .FALSE.
      END IF
      IF (DVS.LE.2.) THEN
        MXDMP   = 10.*RNEFF*RDD*NSH
        AVNCSH  = MIN(0.006, TSNCDM*MNNCSH)
        IF (NCSH.LT.MNNCSH .AND. DVS.GT.0.) THEN
          DMP = 0.
        ELSE IF (NCSH.LE.AVNCSH .AND. DVS.GT.0.) THEN
          GRNSH = MAX(0.,ANSH-AVANSH)/DELT
          DMP   = MIN(MXDMP,GRNSH/MNNCSH)
        ELSE
          DMP   = MXDMP
        END IF
```

```
        CDMP = 0.
        DO 230 I=1, 5
          I1 = 5-I+1
          IF (DVS.GE.0. .AND. DMP.GT.0. .AND. SWITC1) THEN
            AVDMP(I) = DMP
            CDMP     = CDMP + AVDMP(I)
            IF(I.EQ.5) SWITC1=.FALSE.
          ELSE
            IF (I1.EQ.1) THEN
              AVDMP(1)  = DMP
              CDMP      = CDMP + AVDMP(1)
            ELSE
              AVDMP(I1) = AVDMP(I1-1)
              CDMP      = CDMP + AVDMP(I1)
            END IF
          END IF
230     CONTINUE
        IF (NCSH.LE.AVNCSH .AND. DVS.GT.0.) THEN
          DMP = CDMP/5.
        END IF
      ELSE
        MXDMP = 0.
        DMP   = 0.
      END IF

* ----- shoot death due to nitrogen deficiency
  *
      IF ((LVCGRS .OR. LVCGDS) .AND. DMP.EQ.0.) THEN
        A1SDND = 1.
      ELSE IF (LVCGDS .AND. DMP.GT.0.) THEN
        A1SDND = -1.
      ELSE IF (LVCGRS .AND. DMP.GT.0.) THEN
        IF (DVS.GT.1.) THEN
          A1SDND = -1.
        ELSE
          A1SDND = 0.
          AVSDND = 0.
        END IF
      ELSE
        A1SDND =  0.
      END IF
      AVSDND   = MAX(0., AVSDND+A1SDND)
```

```
* ----- crop assimilation could stops under severe water stress;
   *
      IF (TRANSR.LE.CRTRCT) THEN
        MXDMP = 0.
        DMP   = 0.
      END IF

* ----- crop assimilation could be reduced by low air humidity;
   *
      CWV    = (273.+TMMN)/(0.217*VP*10.)
      MDT    = TMMX - 0.25*(TMMX-TMMN)
      MVPDT  = 0.1 * (273.+MDT)/(0.217*CWV)
      MSVPDT = 0.1 * 6.11 * EXP(17.47*MDT/(239.+MDT))
      VPD    = MSVPDT - MVPDT
      IF (VPD.LE.CRVPD) THEN
        RFCAAH = 1.
      ELSE IF (VPD.GT.CRVPD .AND. VPD.LE.MXVPD) THEN
        RFCAAH = MIN(1., (1.- (VPD-CRVPD)/(MXVPD-CRVPD)))
      ELSE IF (VPD.GT.MXVPD) THEN
        RFCAAH  = 0.
      END IF
     ELSE
      CRDD  = 0.
      MXDMP = 0.
      DMP   = 0.
     END IF
     IDMP = DMP

* --- maximum transpiration rate as a function of the actual dry
   *
*    matter production (MTRANS, mm/d);
   *
     MTRANS = RFLWU * DMP * VPD / (WUEC * 10.)

*  - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - *
*
   *
*    R o o t   D e p t h
   *

* --- root depth (m)
   *
```

```
     IF (DVS.GT.0. .AND. DVS.LT.2.) THEN
       ZRT = INTGRL (ZRT, RER, DELT)
     END IF
220   CONTINUE


* --- initial conditions at the beginning of a new crop cycle
    *
*     after exploitation
    *
     IF (LVEX .AND. EXPDVS) THEN
       SDEX = .TRUE.
       IF (DVS.EQ.0.) THEN
         WOSHDE = WSH
       ELSE IF (DVS.GT.0.) THEN
         WOSHDE = MIN(1.,(1.-DVS/SEDVS)) * WSH
       END IF
     END IF

*  - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - *
*
    *
*                 L e a f   A r e a   I n d e x
    *

* --- leaf area index of green and dead leaves
    *
     SSHA  = LINT(SSATB,ISSAN,DVS)
     SDSHA = LINT(SDSATB,ISDSAN,DVS)
     IF (LVCGRS .OR. LVCGDS) THEN
       LAI  = WSH * SSHA
       DLAI = WDSH * SDSHA
     ELSE
       LAI  = 0.
       DLAI = (WDSH+WSH) * SDSHA
     END IF

* --- seasonal biomass (W..)
    *
     WCR  = WSH + WRT
     IF (DVS.EQ.0.) THEN
       WDSH = 0.
```

```
        WDRT = 0.
      END IF
      WDCR = WDSH + WDRT
      WSB  = WDSH + WSH
      IF (LVEX) THEN
        TDMP = TDM - WDSHRE
      ELSE
        TDMP = TDM
      END IF
      TDM  = WCR + WDCR
      IF (LVCGRS .AND. DVS.EQ.0.) THEN
        MXWCR = 0.
        MXWSH = 0.
        MXWRT = 0.
        IF (WCR.GT.MXWCR) MXWCR=WCR
        IF (WSH.GT.MXWSH) MXWSH=WSH
        IF (WRT.GT.MXWRT) MXWRT=WRT
      ELSE IF (LVCGRS) THEN
        IF (WCR.GT.MXWCR) MXWCR=WCR
        IF (WSH.GT.MXWSH) MXWSH=WSH
        IF (WRT.GT.MXWRT) MXWRT=WRT
      ELSE IF (LVCGDS .AND. DVS.EQ.0.) THEN
        MXWCRD = 0.
        MXWSHD = 0.
        MXWRTD = 0.
        IF (WCR.GT.MXWCRD) MXWCRD=WCR
        IF (WSH.GT.MXWSHD) MXWSHD=WSH
        IF (WRT.GT.MXWRTD) MXWRTD=WRT
      ELSE IF (LVCGDS) THEN
        IF (WCR.GT.MXWCRD) MXWCRD=WCR
        IF (WSH.GT.MXWSHD) MXWSHD=WSH
        IF (WRT.GT.MXWRTD) MXWRTD=WRT
      END IF

      IF (IDOY.EQ.1) THEN
        MXTDM = 0.
        IF (TDM.GT.MXTDM) MXTDM=TDM
      ELSE
        IF (TDM.GT.MXTDM) MXTDM=TDM
      END IF

* --- biomass balance check (CHKPBB < 0.001)
    *
```

```
      ASRQCR = FBSH*ASRQSH + FBRT*ASRQRT

      IF (LVCS .AND. ASRQCR.GT.0. .AND. ASRQRT.GT.0.) THEN
        IF (DVS.EQ.0.) THEN
          BALANS = TDM - TDMP
        ELSE
          IF (GRRS.GT.0.) THEN
            CORF = GRRS-(GRRS/ASRQCR)
          ELSE
            CORF = 0.
          END IF
          BALANS = (ADMP + (WCTSH+WCTRT)/ASRQCR + CORF +
     &             (RTSH/ASRQSH+RTRT/ASRQRT) - WSHRE -
     &             (WCTSH+WCTRT+RTSH+RTRT+MRRCR)) * DELT
        END IF
        CHKPBB = (TDM - TDMP - BALANS) / TDMP

        IF (ABS(CHKPBB) .GT. 1.E-3) THEN
          WRITE(*,*) ' Fatal error in PGDM.FOR :',
     &            ' CHKPBB exceeds limit (1.E-3)'
          WRITE(*,*) ' CHKPBB = ', CHKPBB
          TERMNL = .TRUE.
        END IF
      END IF

* --- biomass reserve concentration in the roots (RECRT)
    *
      IF ((WRT-WRS).GT.0.) THEN
        CRSRT = WRS / (WRT - WRS)
      END IF
* --- check upon reserve concentration
    *
      IF (CRSRT .GT. 1.2*MXCRS) THEN
        WRITE(*,*) ' Warning in PGDM.FOR :',
     &          ' CRSRT exceeds max. concentration'
        WRITE(*,*) ' CRSRT, MXCRS = ', CRSRT,MXCRS
      END IF



* --- severe water stress ends the growing cycle
    *
      IF (LVSS .AND. DVS.EQ.2.) THEN
        IF (LVCGRS) THEN
```

```
        LVCGRS = .FALSE.
        LVCDRS = .TRUE.
      ELSE IF (LVCGDS) THEN
        LVCGDS = .FALSE.
        LVCDDS = .TRUE.
      END IF
    END IF

* --- calculation of crop biomass to die after a growing cycle
finish  *
    IF ((LVCDRS .OR. LVCDDS) .AND. SSS.EQ.0.) THEN
      WSH2  = MAX (0., WSH-SHBDP)
      WOSH2 = WSH2
    END IF
    IF (LVCDRS .AND. SSS.EQ.0.) THEN
      PCRS = WRS / WSRT
      IF (PCRS.GE.MXCRS) THEN
        WRT2 = 0.
      ELSE
        WRT2  = MAX(0., MIN((WSRT-WRS/MXCRS),WSRT-1500.))
      END IF
      WORT2 = WRT2
    END IF

* --- exploitation of forage
  *
    CALL PGEXP(ITASK,IUNITD,IUNITO,FILEI1,IDOY,
   &          WSH,DVS,SSS,LVCS,LVCGRS,LVCDRS,
   &          LVCGDS,LVCDDS,LVCDP,HCC,LVEX,HE)

* --- logical variable to indicate that exploitation has occurred
  *
    IF (LVEX .AND. LVCGRS) LVDMA=.TRUE.

* --- finish conditions due to water depletion or reserves
exhaustion  *
    IF (LVCS .AND. TWA.EQ.0.) THEN
      AVCDWE = AVCDWE + 1.
      IF (INT(AVCDWE).EQ.TCCDWE) THEN
        TERMNL = .TRUE.
        WRITE(*,*) ' Water availability depleted',
   &              ' Most perennial grasses tussocks die'
      END IF
```

```
      ELSE
        AVCDWE = 0.
      END IF
      IF (LVCDP .AND. WRS.EQ.0.) THEN
        AVCDRE = AVCDRE + 1.
        IF (INT(AVCDRE).EQ.TCCDRE) THEN
          TERMNL = .TRUE.
          WRITE(*,*) ' Reserves exhausted',
     &              ' Most perennial grasses tussocks die'
        END IF
      ELSE
        AVCDRE = 0.
      END IF


*
----------------------------------------------------------------- *
*                  T E R M I N A T I O N
   *
*
----------------------------------------------------------------- *

      END IF

      RETURN

      END

PGPHE.FOR
*
----------------------------------------------------------------- *
*
   *
*   P h e n o l o g y   o f   p e r e n n i a l   g r a s s e s
   *
*                        (PGPHE)
   *
*
   *
*  author: Santiago Bonachela-Castano
   *
*
   *
```

```
*   date:   January 1994
    *
*
    *
*   purpose: this routine simulates the phenological development
of    *
*   perennial grasses; basically, the programme estimates the
dates    *
*   of the the main development stages and simulates the effects
of    *
*   forage exploitation on crop phenology.
    *
*
    *
*
    *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)
    *
*  name   type meaning                                units
class *
*  ----   ---- -------                                -----
----- *
*  ITASK   I4  task that subroutine should perform          -
 I  *
*  IUNITP  I4  unit of input file with plant data           -
 I  *
*  IUNITO  I4  unit of output file                          -
 I  *
*  FILEI1  C*  name of file with plant data                 -
 I  *
*  OUTPUT  L4  flag to indicate if output should be done    -
 I  *
*  TERMNL  L4  flag to indicate if simulation is to stop    -
I/O *
*  IDOY    I4  day number                                   d
 I  *
*  DELT    R4  time step of integration                     d
 I  *
*  BG      I4  day of beginning of a new crop cycle         d
O/I *
*  TMPA    R4  daily mean temperature                       C
 I  *
*  DAYLP   R4  photoperiodical daylenght                    h
```

```
 I  *
*  LVCS     L  crop growth simulation                    -
 I  *
*  LATS    R4  latitude of simulation site               degrees
 O  *
*  CRTRCT  R4  critical transpiration ratio for crop growth  -
 I  *
*  TRANSR  R4  transpiration ratio                        -
 I  *
*  LVEX     L  to indicate when exploitation occur          -
 I  *
*  LVCGRS   L  a crop growth phase in the rainy season       -
O/I *
*  LVCGDS   L  a crop growth phase in the dry season         -
O/I *
*  LVCDRS   L  a crop death phase after the rainy season     -
O/I *
*  LVCDDS   L  a crop death phase after a growth cycle in
   *
*           the dry season                               -
O/I *
*  SEDVS   R4  phenological stage value at onset of the
   *
*           stem elongation stage                        -
 O  *
*  FDRS    R4  flowering date in the rainy season           d
 O  *
*  LVSS     L  to indicates whether or not death of shoots
   *
*           is going to occur                            -
 O  *
*  AVSS    R4  auxiliar variables used to trigger shoot
   *
*           senescence                                   -
 O  *
*  DNCC    I4  time duration of each crop growth cycle       d
 O  *
*  SSS     R4  crop senescence stage                      -
 O  *
*  SSR     R4  crop senescence rate                       1/d
 O  *
*  EXPDVS   L  to indicate ehether or not exploitation is
   *
```

```
*           going to affect DVS                        -
 O  *
*  DVR     R4  development rate                        1/d
 O  *
*  DVS     R4  development stage                        -
 O  *
*
   *
*
   *
*  routines called : OUTDAT,RDINIT,RDSREA,RDAREA
   *
*                  RDFINT, PGDR
   *
*  functions called: REAL
   *
*  file usage      : IUNITD, IUNITO
   *
*
---------------------------------------------------------------- *

     SUBROUTINE PGPHE (ITASK,IUNITD,IUNITO,FILEI1,OUTPUT,TERMNL,
    &              IDOY,DELT,BG,TMPA,DAYLP,TRANSR,LVEX,LVCS,
    &              LATS,CRTRCT,LVCGRS,LVCDRS,LVCGDS,
    &              LVCDDS,LVCDP,SEDVS,FDRS,LVSS,AVSS,DNCC,
    &              SSS,SSR,EXPDVS,DVR,DVS)

     IMPLICIT REAL (A-Z)

* --- formal parameters
   *
     INTEGER ITASK,IUNITD,IUNITO,IDOY,BG,FDRS,DNCC
     LOGICAL OUTPUT,TERMNL,LVEX,EXPDVS
     LOGICAL LVCS,LVCDP,LVCGRS,LVCDRS,LVCGDS,LVCDDS,LVSS
     CHARACTER*(*) FILEI1
     REAL DAYLP,TMPA,TRANSR,CRTRCT,SEDVS,DVS,DVR,SSS,SSR

* --- local declarations
   *
     PARAMETER (TINY=1.E-4)
     INTEGER DCGS,IVPRS,IVPDS,BGDS,SED,FD,
    &       SEDRS,SEDDS,FDDS,TCWSCD,IDOY1
     LOGICAL LVCC,SWITCH,SWITC1
```

```
* --- PGDR subroutine
   *
     INTEGER DMXD,DMND

     SAVE


*
----------------------------------------------------------------- *
*                  I n i t i a l i z a t i o n
   *
*
----------------------------------------------------------------- *

     IF (ITASK.EQ.1) THEN

     CALL RDINIT (IUNITD, IUNITO, FILEI1)


* --- Different approaches for simulation of crop development:
   *
*
   *
*     integer variable to select the crop development approach
   *
*     in the rainy season (IVPRS):
   *
*       - IVPRS=0, flowering and stem elongation dates (FDRS and
   *
*         SEDRS);
   *
*       - IVPRS=1, SEDRS and parameter values (A1, B1, C1) to
   *
*         calculate FDRS = A1+B1*LATS+C1*LONGS;
   *
*       - IVPRS=2, parameter values (A2, B2) to calculate DVR=A2+
   *
*         B2*DAYLP and critical daylength (CRDAYL, h).
   *
     CALL RDSINT ('IVPRS'  , IVPRS  )
     IF (IVPRS.EQ.0) THEN
       CALL RDSINT ('FDRS' ,  FDRS  )
```

```
      CALL RDSINT ('SEDRS',  SEDRS )
    ELSE IF (IVPRS.GE.1) THEN
      CALL RDSREA ('A1'  , A1  )
      CALL RDSREA ('B1'  , B1  )
      CALL RDSREA ('C1'  , C1  )
      CALL RDSREA ('LONGS', LONGS)
      CALL RDSINT ('SEDRS',  SEDRS )
    ELSE IF (IVPRS.EQ.2) THEN
      CALL RDSREA ('CRDAYL', CRDAYL )
      CALL RDSREA ('A2'    ,  A2    )
      CALL RDSREA ('B2'    ,  B2    )
    END IF
    IF (IVPRS.EQ.2) THEN
      CALL RDSREA ('DVRC'  , DVRC   )
      CALL RDSREA ('CRDAYL', CRDAYL )
      CALL RDSREA ('A2'    ,  A2    )
      CALL RDSREA ('B2'    ,  B2    )
    END IF

* --- integer variable used to select the crop simulation approach
   *
*    in the dry season (IVPDS):
   *
*     - IVPDS=0, if SWITC1 =.FALSE.
   *
*              there is no frowering or stem elongation;
   *
*              flowering and stem elongation dates in the
   *
*              rainy season are used for the dry season;
   *
*              if SWITC1 =.TRUE.
   *
*              flowering and stem elongation dates (FDDS and
   *
*              SEDDS);
   *
*     - IVPDS=2, parameter values (A2, B2) to calculate DVR=A2+
   *
*       B2*DAYLP, critical daylength (CRDAYL, h) and development
   *
*       stage rate when daylenth is increasing (DVRC, 1/d).
   *
```

```
      CALL RDSINT ('IVPDS' , IVPDS )
      IF (IVPDS.EQ.0) THEN
        SWITC1 = .TRUE.
        CALL RDSINT ('FDDS' ,  FDDS  )
        CALL RDSINT ('SEDDS',  SEDDS )
      ELSE IF (IVPDS.EQ.2) THEN
        SWITC1 = .FALSE.
        CALL RDSREA ('DVRC'  , DVRC   )
        CALL RDSREA ('CRDAYL', CRDAYL )
        CALL RDSREA ('A2'    ,  A2    )
        CALL RDSREA ('B2'    ,  B2    )
      ELSE
        SWITC1 = .FALSE.
      END IF

* --- base temperature for crop development (BTD, C)
    *
      CALL RDSREA ('BTD'  , BTD   )

* --- thermal units ( C d) from emergence to anthesis of the crop
    *
      CALL RDSREA ('TUEA' , TUEA  )

* --- thermal units ( C d) from anthesis to maturity of the crop
    *
      CALL RDSREA ('TUAM' , TUAM  )

* --- thermal units ( C d) from maturity to complete death of the
    *
*     seasonal above ground biomass of the crop
    *
      CALL RDSREA ('TUMDRS', TUMDRS )
      CALL RDSREA ('TUMDDS', TUMDDS )

* --- phenological stage value (-) for the beginning of the stem
    *
*     elongation stage
    *
      CALL RDSREA ('SEDVS', SEDVS )



* --- exploitation effects on DVS:
    *
```

```
*      - EXPDVS, logical variable that indicates whether or not
    *
*        exploitation will affect crop development
    *
*      - LVCC, logical variable to trigger a new crop cycle after
    *
*        exploitation
    *
      EXPDVS = .FALSE.
      LVCC   = .FALSE.
      DVSEX  = 0.

* --- Water stress effects on DVS:
    *
*      - LVSS, logical variable that indicates whether or not
    *
*        shoots death is going to occur
    *
*      - AVSS and AVSS1 auxiliar variables used to trigger
    *
*        shoot senescence
    *
*      - TCWSCD, integer variable used to define the maximum time
    *
*        interval without transpiration, after which the above
    *
*        ground biomass dies
    *
      CALL RDSINT ('TCWSCD', TCWSCD )
      LVSS   = .FALSE.
      AVSS   = 0.
      SWITCH = .TRUE.

* --- initial values of logical variables:
    *
*     LVCGRS, LVCDRS, LVCGDS and LVCDDS are logical variables used
    *
*     to distinguish among growth, death and dormant phases within
    *
*     the rainy and the dry season
    *
      LVCDP  = .FALSE.
      LVCGRS = .FALSE.
```

```
      LVCDRS = .FALSE.
      LVCGDS = .FALSE.
      LVCDDS = .FALSE.

* --- initial value of development stage (DVS, -), shoot
senescence    *
*     stage (SSS, -), the number of days once crop simulation have
    *
*     started and LVEX
    *
      DVS    = -1.
      SSS    = 0.
      DVR    = 0.
      DVR1   = 0.
      DVR2   = 0.
      SSR    = 0.
      DNCC   = 0
      DCGS   = 0
      LVEX   = .FALSE.
      BG     = 0

      CLOSE (IUNITD, STATUS='DELETE')


*
------------------------------------------------------------------- *
*              R a t e   c a l c u l a t i o n
    *
*
------------------------------------------------------------------- *


      ELSE IF (ITASK.EQ.2) THEN

* --- dates when the main phenological stages occur
   *
      IF (SWITCH) THEN
        IF (IVPRS.LE.1 .OR. IVPDS.LE.1) SED=SEDRS
        IF (IVPRS.EQ.0.) THEN
          FD   = FDRS
        ELSE
          FDRS = INT(A1+B1*LATS+C1*LONGS)
          FD   = FDRS
```

```
      END IF
    END IF

* --- subroutine PGDR is used to calculate cumulative daylength
   *
*     reduction (ADR, h) from maximum daylenth (DMXD, d) to
fowering   *
*     date (FDRS, d). Date of minimum daylenth is also calculated
   *
    IF (SWITCH) THEN
      CALL PGDR (LATS,FDRS,MXDAYL,DMXD,DMND,ADR)
      SWITCH = .FALSE.
    END IF

* --- before simulation of crop growth start...
  *
    IF (.NOT. LVCS) THEN
      DVR = 0.
      SSR = 0.
    END IF

    IF (.NOT. LVCS) GO TO 10

* --- effects of forage exploitation on DVS...
 *
    IF (LVEX .AND. (LVCGRS .OR. LVCGDS)) THEN
      IF (DVS.LT.SEDVS) THEN
        EXPDVS = .FALSE.
        DVS    = DVS
      ELSE IF (DVS.GE.SEDVS .AND. DVS.LT.1.) THEN
        EXPDVS = .TRUE.
        DVSEX  = (1.-DVS) * (SEDVS/(1.-SEDVS))
        DVS    = DVSEX
      ELSE IF (DVS.GE.1.) THEN
        EXPDVS = .TRUE.
        DVS    = 0.
      END IF
    ELSE IF (LVEX .AND. (LVCDRS .OR. LVCDDS)) THEN
      EXPDVS = .FALSE.
      DVS    = 2.
    ELSE IF (LVEX .AND. LVCDP) THEN
      EXPDVS = .FALSE.
      DVS    = 2.
```

```
      ELSE
        EXPDVS = .FALSE.
        DVSEX  = 0.
      END IF

* --- LVCC, logical variable to trigger a new crop cycle after
   *
*     exploitation
   *
      IF (EXPDVS) LVCC=.TRUE.

* --  date of the onset of a new crop cycle after exploitation
   *
      IF (EXPDVS .AND. DVS.EQ.0.) THEN
        BG  = IDOY + 1
      ELSE IF (EXPDVS .AND. DVS.EQ.DVSEX) THEN
        BG  = IDOY + 1
      END IF



*  - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - *
*
   *
* --- d e v e l o p m e n t   r a t e s  (1/d)
   *
*
   *
      IF (LVCDP .OR. LVCC) THEN
        DVR = 0.
      ELSE IF (LVCGRS .AND. DVS.LT.1. .AND. IVPRS.LE.1) THEN
        IF (BG.LT.SED) THEN
          IF (DVS.LT.SEDVS) THEN
            IF (IDOY.EQ.SED) THEN
              DVR1 = MAX (0.,SEDVS-DVS)
            ELSE
              DVR1 = MAX (0.,(SEDVS-DVS)/(SED-IDOY))*TRANSR
            END IF
            IF (IDOY.LT.BG) DVR1=0.
          ELSE IF (DVS.GE.SEDVS) THEN
            DVR1   = (1.-SEDVS)/(FD-SED)
          END IF
        ELSE IF (BG.GE.SED) THEN
```

```
      DVR1  = (1.-DVSEX)*((MXDAYL-DAYLP)/ADR)
      IF (IDOY.LT.BG) DVR1=0.
    END IF
    DVR2 = 0.
    DVR  = DVR1
    DVR  = MIN (1.-DVS,DVR1)
  ELSE IF (LVCGRS .AND. DVS.LT.1. .AND. IVPRS.EQ.2) THEN
    IF (IDOY.GT.DMXD) THEN
      IF (DAYLP .LE. CRDAYL) THEN
        DVR1  = MAX(0.,-BTD/TUEA+TMPA/TUEA)
      ELSE IF (DAYLP .GT. CRDAYL) THEN
        DVR1  = MAX(0.,A2+B2*DAYLP)
      END IF
    ELSE
      DVR1  = DVRC
    END IF
    DVR2 = 0.
    DVR  = DVR1
  ELSE IF (LVCGRS .AND. DVS.LT.2.) THEN
    DVR1 = 0.
    DVR2 = MAX (0., -BTD/TUAM+TMPA/TUAM)*(2.-TRANSR)
    DVR  = MIN (2.-DVS,DVR2)
  ELSE IF (LVCGRS .AND. DVS.EQ.2.) THEN
    DVR1 = 0.
    DVR2 = 0.
    DVR  = 0.
    SSS  = 0.
  ELSE IF (LVCGDS .AND. DVS.LT.1. AND. IVPDS.LE.1) THEN
    IF (DVS.LT.0.) THEN
      DVR = 0.
    ELSE IF (DVS.EQ.0.) THEN
      IF (SWITC1) SED=SEDDS
      IF (SWITC1) FD=FDDS
      BGDS = BG
      IF (BG.GE.SED) BG=BG-365
      IF (IDOY.LE.365) BGDS=0
    END IF
    IF (DVS.LT.SEDVS) THEN
      IF (IDOY.EQ.SED) THEN
        DVR1 = MAX (0.,SEDVS-DVS)
      ELSE
        IF (IDOY.GE.SED) THEN
          IDOY1 = IDOY-365
```

```
        ELSE
          IDOY1 = IDOY
        END IF
        DVR1  = MAX (0.,(SEDVS-DVS)/(SED-IDOY1))*TRANSR
      END IF
      IF (IDOY.LT.BGDS) DVR1=0.
    ELSE IF (DVS.GE.SEDVS) THEN
      DVR1 = (1.-SEDVS)/(FD-SED)
    END IF
    DVR2 = 0.
    DVR  = DVR1
  ELSE IF (LVCGDS .AND. DVS.LT.1. .AND. IVPDS.EQ.2) THEN
    IF (DVS.LT.0.) THEN
      DVR = 0.
    ELSE IF (DVS.GE.0.) THEN
      IF (BG.GT.DMXD) THEN
        IF (DAYLP .LE. CRDAYL) THEN
          DVR1  = MAX(0.,-BTD/TUEA+TMPA/TUEA)
        ELSE IF (DAYLP .GT. CRDAYL) THEN
          DVR1  = MAX(0.,A2+B2*DAYLP)
        END IF
      ELSE
        DVR1  = DVRC
      END IF
    END IF
    DVR  = DVR1
    DVR2 = 0.
  ELSE IF (LVCGDS .AND. DVS.GE.1. .AND. DVS.LT.2.) THEN
    DVR1 = 0.
    DVR2 = MAX (0., -BTD/TUAM+TMPA/TUAM)*(2.-TRANSR)
    DVR  = MIN(2.-DVS, DVR2)
  ELSE IF (LVCGDS .AND. DVS.EQ.2.) THEN
    DVR2 = 0.
    DVR  = DVR2
    SSR  = 0.
  ELSE
    DVR  = 0.
  END IF


*  - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - *
*
```

```
   *
* --- E f f e c t s   o f   w a t e r   s t r e s s   o n   D V S
   *
*
   *
     IF (LVCGRS .OR. LVCGDS) THEN
       IF (DVS.EQ.0.) THEN
         AVSS  = 0.
         AVSS1 = 0.
       ELSE IF (TRANSR.EQ.1. .AND. AVSS.GT.0.) THEN
         AVSS1 = -1.
       ELSE IF (TRANSR.LE.CRTRCT) THEN
         AVSS1 = 1.
       ELSE IF (TRANSR .LE. 0.75) THEN
         AVSS1 = 1. * MAX (0., (1.-TRANSR))
       ELSE IF (TRANSR.GT.0.75 .AND. TRANSR.LT.1.) THEN
         AVSS1 = 0.
       END IF
       AVSS = MAX (0., AVSS+AVSS1)
       IF (AVSS.GE.TCWSCD) THEN
         LVSS = .TRUE.
         AVSS = 0.
       END IF
     ELSE
       AVSS = 0.
     END IF

*  - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - *
*
   *
* --- s h o o t   s e n e s c e n c e   r a t e   (1 / d)
   *
*
   *
     IF (LVCDRS .AND. (SSS.GE.0. .AND. SSS.LT.1.)) THEN
       SSR = MAX(0., MIN(1.-SSS,-BTD/TUMDRS+TMPA/TUMDRS))
     ELSE IF (LVCDRS .AND. SSS.EQ.1.) THEN
       SSR = 0.
     ELSE IF (LVCDDS .AND. (SSS.GE.0. .AND. SSS.LT.1.)) THEN
       SSR = MAX(0., MIN(1.-SSS,-BTD/TUMDDS+TMPA/TUMDDS))
     ELSE IF (LVCDDS .AND. SSS.EQ.1.0) THEN
       SSR = 0.
```

```
      ELSE
        SSR = 0.
      END IF


10    CONTINUE


*
------------------------------------------------------------------- *
*       O u t p u t   o f   s t a t e s   a n d   r a t e s
    *
*
------------------------------------------------------------------- *

      IF (OUTPUT .OR. TERMNL) THEN

* --- states variables
    *

* ----- development stage (-)
      *
        CALL OUTDAT (2, 0, 'DVS'    , DVS     )

* ----- duration of crop growth simulation (DCGS, d)
      *
        CALL OUTDAT (2, 0, 'DCGS', REAL(DCGS) )

* ----- duration of a new crop growth cycle (DNCC, d)
      *
        CALL OUTDAT (2, 0, 'DNCC', REAL(DNCC) )

      END IF


*
------------------------------------------------------------------- *
*                   I n t e g r a t i o n
    *
*
------------------------------------------------------------------- *
```

```
      ELSE IF (ITASK.EQ.3) THEN


      IF (.NOT. LVCS) GO TO 100

* --- a new crop cycle after exploitation
   *
      IF (IDOY.EQ.BG) LVCC=.FALSE.

* - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - *
*
   *
* --- d e v e l o p m e n t   s t a g e   (DVS, -)
   *

      IF (LVCDP) THEN
        DVS    = 2.
      ELSE IF (LVCGRS .AND. (DVS.GE.0. .AND. DVS.LT.2.)) THEN
        DVS    = INTGRL(DVS,DVR,DELT)
      ELSE IF (LVCGRS .AND. DVS.EQ.2.) THEN
        LVCGRS = .FALSE.
        LVCDRS = .TRUE.
        SSS    = 0.
        DVS    = 2.
      ELSE IF (LVCGDS .AND. (DVS.GE.0. .AND. DVS.LT.2.)) THEN
        DVS = INTGRL(DVS,DVR,DELT)
      ELSE IF (LVCGDS .AND. DVS.EQ.2.0) THEN
        LVCGDS = .FALSE.
        LVCDDS = .TRUE.
        SSS    = 0.
        DVS    = 2.
      ELSE
        DVS    = 2.
      END IF

* - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - *
*
   *
* --- s h o o t  s e n e s c e n c e  s t a g e
   *
*
```

```
 *
  IF (LVCDP) THEN
    SSS    = -1.
  ELSE IF (LVCDRS .AND. (SSS.GE.0. .AND. SSS.LT.1.)) THEN
    SSS    = INTGRL(SSS,SSR,DELT)
  ELSE IF (LVCDRS .AND. SSS.EQ.1.) THEN
    LVCDRS = .FALSE.
    LVCDP  = .TRUE.
    SSS    = -1.
  ELSE IF (LVCDDS .AND. (SSS.GE.0. .AND. SSS.LT.1.)) THEN
    SSS = INTGRL(SSS,SSR,DELT)
  ELSE IF (LVCDDS .AND. SSS.EQ.1.0) THEN
    LVCDDS = .FALSE.
    IF (.NOT.LVCGDS .AND. .NOT.LVCGRS) LVCDP=.TRUE.
    SSS    = -1.
  ELSE
    SSS    = -1.
  END IF


* - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - *
*
 *
* --- E f f e c t s   o f   w a t e r   s t r e s s   o n   D V S
 *

  IF (LVSS .AND. (LVCGRS .OR. LVCGDS)) THEN
    SSS  = 0.
    DVS  = 2.
    DVR  = 0.
    SSR  = 0.
  ELSE
    LVSS = .FALSE.
  END IF

* --- cycle duration (DNCC, d)
 *
  IF (DVS.EQ.0. .AND. (LVCGRS .OR. LVCGDS)) THEN
    DNCC = 1
  ELSE IF (LVCGRS .OR. LVCGDS) THEN
    DNCC = DNCC + 1
  ELSE
```

```
      DNCC = 0
    END IF

* --- duration of crop growth simulation period (DCGS, d)
  *
    DCGS  = DCGS + 1

100   CONTINUE

*
--------------------------------------------------------------------- *
*                  T e r m i n a t i o n
    *
*
--------------------------------------------------------------------- *

    END IF

    RETURN

    END

*
--------------------------------------------------------------------- *
*                         PGDR
    *
*
    *
*
    *
*  authors: Santiago Bonachela-Castano
    *
*
    *
*  date   : November 1993
    *
*
    *
*  purpose: to calculate the cumulative daylength reduction from
    *
*          maximum daylength date to flowering date in the rainy
    *
*          season
```

```
    *
*
    *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)
    *
*
    *
*  name   type   meaning                                units
class    *
*  ----   ----   -------                                -----
-----    *
*
    *
*  LATS     R4   latitude of the simulation site       degrees   I
    *
*  FDRS     I4   flowering date during the rainy season   d      I
    *
*  MXDAYL   R4   maximum value of the photoperiodically
    *
*                active daylength                       h      O
    *
*  DMXD     I4   day of maximum daylength               d      O
    *
*  DMND     I4   day of minimum daylength               d      O
    *
*  ADR      R4   cumulative daylength reduction
    *
*                from DMD to FDRS                       h      O
    *
*
    *
*
    *
*  subroutines and functions called : ASTRO
    *
*  FILE usage : none
    *
*
---------------------------------------------------------------------- *

      SUBROUTINE PGDR (LATS,FDRS,MXDAYL,DMXD,DMND,ADR)

* --- formal arguments
```

```
     *
      IMPLICIT REAL (A-Z)
      INTEGER FDRS,DMXD,DMND

* --- local declarations
     *
      INTEGER IDOY

      SAVE

* --- initial values of local variables
     *
      MNDAYL = 24.
      MXDAYL = 0.
      DAYLF  = 0.
      ADR    = 0.

* --- maximum value of the photoperiodically active daylength
     *
*     (MXDAYL, h) during the year and occurrence date (DMXD, d).
     *
*     Minimum value of photoperiodically active daylength (MNDAYL,
h)   *
*     and occurrence date (DMND, d)
     *
      DO 10  IDOY=1, 365
        CALL ASTRO (IDOY, LATS, SC, DS0, SINLD, COSLD,
     &              DAYL, DAYLP, DSINB, DSINBE)
        IF (DAYLP.GT.MXDAYL) THEN
          MXDAYL = DAYLP
          DMXD   = IDOY
        ELSE IF (DAYLP.LT.MNDAYL) THEN
          MNDAYL = DAYLP
          DMND   = IDOY
        END IF

* ----- daylength at the day of flowering (DAYLF, h)
     *
        IF (IDOY.EQ.FDRS) DAYLF = DAYLP

* ----- accumulation of daylength reduction per day (h) from
maximum    *
*       daylength date (DMD, d) to flowering date (FDRS, d)
```

```
 *
      IF (IDOY.GE.DMXD .AND. IDOY.LE.FDRS) THEN
        DR = (MXDAYL-DAYLP)
      ELSE
        DR = 0.
      END IF
      ADR = ADR + DR

10    CONTINUE

      RETURN

      END
```

PGEXP.FOR

```
*
------------------------------------------------------------------- *
*
   *
*        F o r a g e   e x p l o i t a t i o n   o f
   *
*            p e r e n n i a l   g r a s s e s
   *
*                      (PGEXP)
   *
*
   *
*   author: Santiago Bonachela-Castano
   *
*
   *
*   date: February, 1994
   *
*
   *
*   purpose: this routine indicates the exploitation dates and the
   *
*   heigth of crop cutting.
   *
*
   *
*
   *
```

```
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)
   *
*  name   type meaning                                units
class *
*  ----   ---- -------                                -----
----- *
*  ITASK   I4  task that subroutine should perform          -
 I  *
*  IUNITD  I4  unit of input file with plant data           -
 I  *
*  IUNITO  I4  unit of output file                          -
 I  *
*  FILEI1  C*  name of file with plant data                 -
 I  *
*  IDOY    I4  day number                                   d
 I  *
*  WSH     R4  weigth of shoots                             kg/ha
 I  *
*  DVS     R4  development stage                            -
 I  *
*  SSS     R4  shoot senescence stage                       -
 I  *
*  LVCS     L  to indicate when crop simulation occurs      -
 I  *
*  LVCGRS   L  a crop growth cycle in the rainy season      -
 I  *
*  LVCDRS   L  a shoot death phase after the rainy season   -
 I  *
*  LVCGDS   L  a crop growth cycle in the dry season        -
 I  *
*  LVCDRS   L  a shoot death phase after the a growth cycle
   *
*              in the dry season                            -
 I  *
*  LVCDP    L  a dormant phase in the dry season            -
 I  *
*  HCC     R4  heigth of the crop                           m
 I  *
*  LVEX     L  to u=indicate when exploitation occur        -
 O  *
*  HE      R4  height of exploitation                       m
 O  *
*
```

```
   *
*
   *
*  Routines called   : OUTDAT, RDINIT, RDSINT, RDSREA, RDAREA
   *
*  Funtions called   : REAL
   *
*  File usage        : FILEI1
   *
*
------------------------------------------------------------------ *



      SUBROUTINE PGEXP (ITASK,IUNITD,IUNITO,FILEI1,IDOY,
     &                  WSH,DVS,SSS,LVCS,LVCGRS,LVCDRS,
     &                  LVCGDS,LVCDDS,LVCDP,HCC,LVEX,HE)

      IMPLICIT REAL (A-Z)

* --- formal parameters
      INTEGER ITASK,IUNITD,IUNITO,IDOY
      LOGICAL LVEX
      LOGICAL LVCS,LVCGRS,LVCDRS,LVCGDS,LVCDDS,LVCDP
      CHARACTER FILEI1*(*)
      REAL WSH,DVS,SSS,HE

* --- local parameters
      INTEGER INTBMX
      PARAMETER (INTBMX = 10)
      INTEGER EXPTYP,EDRS,EDDS,ERS,EDS,
     &        IERS1,IERS,NERS,IEDS1,IEDS,NEDS,
     &        AVDE,I,EDAYRS,EDAYDS,AVCL1,AVCL2
      LOGICAL SWITC1,SWITC2
      REAL DVSERS(INTBMX),DVSEDS(INTBMX)

      SAVE



*
------------------------------------------------------------------ *
*                 I n i t i a l i z a t i o n
   *
*
```

```
---------------------------------------------------------------- *

     IF (ITASK.EQ. 1) THEN

     CALL RDINIT (IUNITD,IUNITO,FILEI1)

*  - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - *
*
   *
*    P a r a m e t e r s
   *

* --- the model assumes that burning, mechanical cutting or
grazing    *
*     of the vegetation occurs when the entire shoot biomass
produced  *
*     during the rainy season die (LVCDRS = .TRUE. and SSS.EQ.1.).
   *
*     After burnig almosts all the above ground biomass is
assummed    *
*     to desappear.
   *
*     Exploitation type at this stage is selected with the integer
   *
*     variable EXPTYP:
   *
*      - EXPTYP = 0, burning
   *
*      - EXPTYP = 1, cutting or grazing; height of cutting is
   *
*                   selected with HEC (m)
   *

     CALL RDSINT ('EXPTYP' , EXPTYP )
     IF (EXPTYP.EQ.1) CALL RDSREA ('HEC  ', HEC  )

* --- Exploitation of forage could be simulated with three
   *
*     options:
   *
*      - by introducing the date of the first exploitation, the
   *
```

*   the time interval between two exploitations and total
*
*   number of them;
*
*   - exploitation is going to occur when the above ground
*
*   biomass reaches a critical value;
*
*   - by introducing the development stage at which
exploitation   *
*   is going to occur and the total number of them.
*
*
*
*   The choice among these aproaches is carried out with the
*
*   integer variables EDRS (rainy season) and EDDS (dry season):
*
*   - EDRS = 0 or EDDS = 0, for the date approach;
*
*   - EDRS = 1 or EDDS = 1, for the biomass approach;
*
*   - EDRS = 2 or EDRS = 2, for the phenological approach (in
*
*   the dry season only when phenology is simulated).
*

* --- rainy season:
*
*
*
*   - ERS (-), integer variable used to define whether or not
*
*   exploitation occur during the crop growing phase:
*
*   - ERS = 0, exploitation does not occur;
*
*   - ERS = 1, exploitation does occur;
*
*   - HERS (m), real variable used to define the height above
*
*   the soil of clipping or grazing;

```
    *
*
    *
*      when EDRS = 0
    *
*        - IERS1 (d), variable used to define the time interval
    *
*          for the first exploitation after BGRS;
    *
*        - IERS (d), variable used to define the time interval
    *
*          between two exploitations;
    *
*        - NERS (-), variable used to define the total number of
    *
*          crop exploitation;
    *
*
    *
*      when EDRS = 1
    *
*        - CWSERS (kg/ha), variable used to define the critical
    *
*          above ground biomass which trigger exploitation;
    *
*
    *
*      when EDRS = 2
    *
*        - DVSERS (-), array of development stages when forage
    *
*          exploitation occur;
    *

* --- dry season:
    *
*
    *
*      - EDS (-), integer variable used to define whether or not
    *
*        exploitation occurs during this time period:
    *
*        - EDS = 0, exploitation does not occur
```

```
    *
*       - EDS = 1, exploitation does occur
    *
*
*     - HEDS (m), integer variable used to define the height
    *
*       above the soil of clipping or grazing
    *
*
    *
*     when EDDS = 0
    *
*       - IEDS1 (d), variable used to define the date of the
first    *
*         forage exploitation after BGDS;
    *
*       - IEDS (d), variable used to define the time interval
    *
*         between two exploitations;
    *
*       - NEDS (-), variable used to define the total number of
    *
*         crop exploitation;
    *
*
    *
*     when EDRS = 1
    *
*       - CWSEDS (kg/ha), variable used to define the critical
    *
*         above ground biomass which trigger exploitation;
    *
*
    *
*     when EDDS = 2
    *
*       - DVSEDS (-), array of development stages when forage
    *
*         exploitation occur;
    *

      CALL RDSINT ('ERS' , ERS )
      CALL RDSINT ('EDS' , EDS )
```

```
      IF (ERS.EQ.0 .AND. EDS.EQ.0) GO TO 10

      IF (ERS.EQ.1) THEN
        CALL RDSINT ('EDRS' , EDRS )
        CALL RDSREA ('HERS' , HERS )
        IF (EDRS.EQ.0) THEN
          CALL RDSINT ('IERS1'  , IERS1  )
          CALL RDSINT ('IERS'   , IERS   )
          CALL RDSINT ('NERS'   , NERS   )
        ELSE IF (EDRS.EQ.1) THEN
          CALL RDSREA ('CWSERS' , CWSERS )
        ELSE IF (EDRS.EQ.2) THEN
          CALL RDFREA ('DVSERS' , DVSERS, INTBMX, INTBMX)
        END IF
      ELSE IF (EDS.EQ.1) THEN
        CALL RDSINT ('EDDS' , EDDS )
        CALL RDSREA ('HEDS' , HEDS )
        IF (EDDS.EQ.0) THEN
          CALL RDSINT ('IEDS1'  , IEDS1  )
          CALL RDSINT ('IEDS'   , IEDS   )
          CALL RDSINT ('NEDS'   , NEDS   )
        ELSE IF (EDRS.EQ.1) THEN
          CALL RDSREA ('CWSEDS' , CWSEDS )
        ELSE IF (EDDS.EQ.2) THEN
          CALL RDFREA ('DVSEDS' , DVSEDS, INTBMX, INTBMX)
        END IF
      END IF

10    CONTINUE

      CLOSE (IUNITD, STATUS='DELETE')

* --- initial values of:
   *
*     - HE (m), height of exploitation;
   *
*     - LVEX, logical variable to indicate whether or not
   *
*       exploitation occur;
   *
*     - SWITC1 and SWITC2, intermediate variables
   *
```

```
      HE      = 10.
      LVEX    = .FALSE.
      SWITC1  = .TRUE.
      SWITC2  = .TRUE.
      AVCL1   = 0.
      AVCL2   = 0.
      AVDE    = 0.
      HCC     = 0.
      EDAYRS  = 0
      EDAYDS  = 0

*
----------------------------------------------------------------- *
*                    I n t e g r a t i o n
   *
*
----------------------------------------------------------------- *

      ELSE IF (ITASK.EQ.3) THEN

* --- before simulation of crop growth start...
   *
      IF (.NOT.LVCS) GO TO 100

* --- exploitation during the growing phases (rainy or dry
seasons)    *
      IF (ERS.EQ.0 .AND. EDS.EQ.0) GO TO 110

* - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - *
*
   *
*    E x p l o t a t i o n   i n   t h e   r a i n y   s e a s o
n    *

      IF (EDRS.EQ.0 .OR. EDRS.EQ.2) THEN

* ----- calendar for exploitation
   *
        IF (LVCGRS .AND. DVS.GE.0. .AND. .NOT.SWITC1) THEN
          EDAYRS = EDAYRS + 1
        ELSE IF (LVCGRS .AND. DVS.EQ.0. .AND. SWITC1) THEN
          SWITC1  = .FALSE.
```

```
        EDAYRS  = 1
        AVCL1   = 1
        AVCL2   = 1
      ELSE IF (LVCGDS .OR. LVCDP) THEN
        SWITC1 = .TRUE.
        EDAYRS = EDAYRS + 1
      END IF
    END IF

*     crop growth in the rainy season
*
    IF (LVCGRS .AND. ERS.EQ.1 .AND. EDRS.EQ.0) THEN
      AVCL1 = MIN (AVCL2,NERS)
      DO 120 I=AVCL1, NERS
        AVDE = IERS1+(I-1)*IERS
        IF (EDAYRS.EQ.AVDE) THEN
          AVCL2 = AVCL1 + 1
          HE    = HERS
          IF (HE.LT.HCC) LVEX=.TRUE.
          GO TO 140
        ELSE
          LVEX = .FALSE.
          HE   = 10.
          GO TO 140
        END IF
120     CONTINUE
    ELSE IF (LVCGRS .AND. ERS.EQ.1 .AND. EDRS.EQ.1) THEN
      IF (WSH.GE.CWSERS) THEN
        HE   = HERS
        IF (HE.LT.HCC) LVEX =.TRUE.
      ELSE
        LVEX = .FALSE.
        HE   = 10.
      END IF
    ELSE IF (LVCGRS .AND. ERS.EQ.1 .AND. EDRS.EQ.2) THEN
      AVCL1 = MIN (AVCL2,INTBMX)
      DO 130 I=AVCL1, INTBMX
        IF (DVSERS(I).EQ.0.) GO TO 140
        IF (DVS.EQ.DVSERS(I)) THEN
          AVCL2 = AVCL1 + 1
          HE    = HERS
          IF (HE.LT.HCC) LVEX=.TRUE.
        ELSE
```

```
          LVEX = .FALSE.
          HE   = 10.
          GO TO 140
        END IF
130     CONTINUE
      ELSE IF ((LVCGDS.OR.LVCDP) .AND. DVS.EQ.0. .AND. ERS.EQ.1)
THEN
        IF(LVEX) LVEX=.FALSE.
      END IF
140   CONTINUE



* - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - *
*
   *
*    E x p l o t a t i o n   i n   t h e   d r y   s e a s o n
   *

      IF (EDDS.EQ.0) THEN

* ----- beginning of the first growing cycle
   *
        IF (LVCGDS .AND. DVS.EQ.0. .AND. SWITC2) THEN
          SWITC2 = .FALSE.
          EDAYDS = 1
          AVCL1  = 1
          AVCL2  = 1
        ELSE IF ((LVCGDS.OR.LVCDDS.OR.LVCDP) .AND. EDAYDS.GT.0)
THEN
          EDAYDS = EDAYDS + 1
        ELSE
          IF (LVCGRS) SWITC2=.TRUE.
          EDAYDS = 0
        END IF

      END IF

*     dry growing season
   *
      IF (LVCGDS .AND. EDS.EQ.1 .AND. EDDS.EQ.0) THEN
        AVCL1 = MAX (AVCL2,NEDS)
        DO 150 I=AVCL1, NEDS
```

```
        AVDE = IEDS1+(I-1)*IEDS
        IF (EDAYDS.EQ.AVDE) THEN
          AVCL2 = AVCL1 + 1
          HE    = HEDS
          IF (HE.LT.HCC) LVEX=.TRUE.
          GO TO 170
        ELSE
          LVEX = .FALSE.
          HE   = 10.
          GO TO 170
        END IF
150     CONTINUE
      ELSE IF (LVCGDS .AND. ERS.EQ.1 .AND. EDRS.EQ.1) THEN
        IF (WSH.GE.CWSEDS) THEN
          HE   = HEDS
          IF (HE.LT.HCC) LVEX=.TRUE.
        ELSE
          LVEX = .FALSE.
          HE   = 10.
        END IF
      ELSE IF (LVCGDS .AND. EDS.EQ.1 .AND. EDRS.EQ.2) THEN
        AVCL1 = AVCL2
        DO 160 I=AVCL1, INTBMX
          IF (DVSEDS(I).EQ.0.) GO TO 170
          IF (DVS.EQ.DVSEDS(I)) THEN
            AVCL2 = AVCL1 + 1
            HE    = HEDS
            IF (HE.LT.HCC) LVEX=.TRUE.
          ELSE
            LVEX = .FALSE.
            HE   = 10.
            GO TO 170
          END IF
160     CONTINUE
      END IF
170   CONTINUE

110   CONTINUE

* --- burning, mechanical clipping or grazing during the dry
season    *
      IF (LVCDRS .AND. SSS.EQ.1.) THEN
        LVEX   = .TRUE.
```

```
        IF (EXPTYP.EQ.0) HE=0.01
        IF (EXPTYP.EQ.1) HE=HEC
      ELSE IF (LVCDDS .OR. LVCDP) THEN
        LVEX   = .FALSE.
      END IF

100   CONTINUE

      END IF

      RETURN

      END
```

Appendix B: PGWA modules (DRSAHE.FOR), B - 37

B - 40, Appendix B: PGWA modules (PETP.FOR)

Appendix B: PGWA modules (PETP.FOR), B - 39

B - 42, Appendix B: PGWA modules (PENMAN.FOR)

Appendix B: PGWA modules (PENMAN.FOR), B - 41

B - 43, Appendix B: PGWA modules (ASTRO.FOR)

Appendix B: PGWA modules (ASTRO.FOR), B - 45

B - 68, Appendix B: PGWA modules (PGDM.FOR)

Appendix B: PGWA modules (PGDM.FOR), B - 69

B - 78, Appendix B: PGWA modules (PGPHE.FOR)

Appendix B: PGWA modules (PGPHE.FOR), B - 77

B - 84, Appendix B: PGWA modules (PGEXP.FOR)

Appendix B: PGWA modules (PGEXP.FOR), B - 83

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Appendix C: PGWA data files

Table des matières

CROP.DAT
SOIL.DAT
TIMER.DAT
CONTROL.DAT

CROP.DAT

```
*----------------------------------------------------------------------*
*
    *
*         Crop data file to be used by PGWL routine of FSE 2.0
    *
*
    *
*----------------------------------------------------------------------*

* -------------------  M o d e l s   m o d u l e
--------------------- *

* characteristics of the site
    *
  ANGA   = 0.25        ! site-specific Angstrom-coefficients for
  ANGB   = 0.45        ! for Mali
  ELEV   = 275.        ! for Niono (Mali)

* rain infiltrated (run off or run on)
    *
  RAINF1 =  0.2
  RAINF2 =  10.        ! mm


* -----------   C r o p   g r o w t h   m o d u l e  (PGCG)
-------- *

* sowing date and initial conditions at sowing year
    *
  SD    = 161          ! day
```

IWSHS = 3. ! kg/ha
IWRTS = 3. ! kg/ha

* initial conditions from an established crop
*
IWSH = 10. ! kg/ha
IWRT = 4000. ! kg/ha
IWDSH = 0. ! kg/ha
IWDRT = 0. ! kg/ha
IWRS = 1000. ! kg/ha
IZRT1 = 1.8 ! m

* D r y m a t t e r p r o d u c t i o n:
*

* initial shoot N use coefficient
*
P = 7.25 ! g/(g.d)
* radiation effectivity coefficient
*
ALPHA = 0.0 ! d.m2/MJ
* initial global radiation use coefficient
*
EPSIL = 1.8 ! g/MJ
* water use efficiency factor Pa;
*
WUEC = 11.8
* integer variable to select how shoot nitrogen data are supplied:
*
* IVSCNS=0, as a function of DVS
*
*
* IVSCNS=1, as a function of julian days
*
*
IVSCNS = 0

* shoot nitrogen (kg/ha) as a function of DVS
*
* N'TARLA low fertility
SHNRST = 0.,0.08, 0.2,27., 0.5,50.2, 1.,56.2, 1.5,29.7,2.,15.3
SHNDST = 0.,0.03, 30.,1.5, 40.,1.5, 100.,1.0, 300.,1.

* maximum nitrogen concentration in the shoots as a function of
DVS   *
  MXNCST = 0.0,0.035, 0.35,0.030, 1.0,0.012, 2.0,0.01
* minimum nitrogen concentration in the shoots as a function of
DVS   *
  MNNCST = 0.0,0.01, 0.35,0.007, 1.0,0.0048, 2.0,0.003
* minimum nitrogen concentration in the roots (kg kg-1) as a
function *
* of DVS
    *
  TMNNCR = 0.0,0.005, 0.35,0.005, 1.0,0.0045, 2.0,0.004
* multiplicative factor used to define a threshold value of shoot
    *
* nitrogen concentration below which shoot growth rate is reduced
    *
  TSNCSG = 1.10
* multiplicative factor used to define a threshold value of shoot
    *
* nitrogen concentration below which dry matter production is
reduced *
  TSNCDM= 1.05
* fraction of crop nitrogen allocated to the roots (NARTTB, -) as
a   *
* function of the total nitrogen in the crop (ANCR, kg/kg)
    *
  NARTTB = 0.0,0.32, 50.,0.30, 75.,0.28, 150.,0.18,
          200.,0.16, 300.,0.12
* critical transpiration ratio for crop assimilation
    *
  CRTRCT = 0.10   ! -
* reduction factor for low air humidity
    *
  CRVPD = 3.   ! kPa
  MXVPD = 5.   ! kPa

* G r o w t h
    *

* maximum growth rate of a perennial grass crop
    *
  MXGRCR = 305.   ! kg/ha/d

```
* partitioning parameters
   *
  FBSHTB = 0.00,0.50, 0.10,0.70, 0.20,0.75, 0.35,0.80,
         0.50,0.90, 1.00,0.95, 1.80,1.00, 2.50,1.00
* maximum growth rate of shoots
   *
  GRSHTB = 0.0,260., 0.9,260., 1.0,260., 1.1,20., 1.990,20.,
         2.000,0., 2.500,0.
* critical water availability for new aboveground growth
   *
  CRWARC  = 25.          ! mm
* time coefficient (d) for shoot death due to nitrogen deficiency
*
  TCSDND  = 25.
* fraction of biomass remaining during the dormant phase
   *
  SHBDP = 10.            ! -
* fraction of root biomass allocated to reserves (FRBARS, -);
*
  FRBARS = 0.15          ! -
* root growth
   *
  PRRE   = 0.03          ! m/d
  CSHRTR = 0.5           ! ratio
  RDMSOL = 2.0           ! m
* leaf area parameters
   *
  SSATB  = -1.00,0.00, -0.00001,0.00, 0.00,0.0012, 0.35,0.0008,
          0.9, 0.00025, 1.00,0.0001, 1.10,0.00003,
2.00,0.000005
  SDSATB = -1.00,0.00, -0.00001,0.00, 0.00,0.0012, 1.,0.0012,
          1.5,0.0012, 2.0,0.0001
* critical values of vapour pressure used to estimate the end of
the   *
* the rainy season
   *
  CRVPER = 2.3           ! kPa



* C r o p   s u r v i v a l
   *
```

* time constant for crop death due to water and reserves
exhaustion   *
  TCCDWE = 8
  TCCDRE = 8

* S e n e s c e n c e
    *

* relative death rates
    *
  RDSHTB = 0.0000,0.000, 0.3500,0.000, 0.4000,0.0005,
1.0000,0.001,
          1.3000,0.005, 1.8000,0.015, 2.0000,0.02, 2.0001,0.000,
          2.5000,0.000
  RDRTTB = 0.0000,0.000, 1.0000,0.000, 1.3000,0.003, 1.8000,0.007,
          2.0000,0.01, 2.0001,0.000, 2.5000,0.000
* water stress effects on relative death rates
    *
  WSESST = 0.0,0.000, 4.0,0.000, 10.0,0.01, 20.0,0.01, 500.0,0.015
  WSERST = 0.0,0.000, 4.0,0.000, 10.0,0.005, 20.0,0.01,
500.0,0.015
* relative death rate of old structural roots
    *
  RDRRTC = 0.03

* M o b i l i z a t i o n o f a s s i m i l a t e s a n d
    *
* n u t r i e n t s
    *

* translocation parameters
    *
  FCWSH = 0.1   ! %
  FCWRT = 0.1   ! %
* weight of reserves mobilised in the first growing day
    *
  WRMFD = 20.   ! kg/ha
* reserves mobilization
    *
  TCRTRS = 10   ! d
  TCRTDS = 3   ! d

```
 MXAR   = 20.            ! kg/ha
* maximum growth rate of reserves
   *
 MXGRRS = 15.            ! kg/ha/d
* maximum concentration of reserves
   *
 MXCRS = 0.3             ! kg/kg
* minimum concentration of reserves
   *
 MNCRS = 0.05            ! kg/kg
* relative growth rates of shoots and roots
   *
 RGRSH = 0.44
 RGRRT = 0.44


* R e s p i r a t i o n
   *

* growth respiration parameters
   *
 ASRQRT = 1.444; ASRQSH = 1.488
 ASRQSO = 1.415
* maintenance respiration parameters
   *
 Q10    = 2.   ; TREF = 25.
 MAINSH = 0.015
 MAINRT = 0.015
 MAINSO = 0.010
* reduction factor for maintenance respiration
   *
 RFMR   = 0.05


*  E x p l o i t a t i o n
   *

* hight of crop canopy
   *
 FMHCTB = 0.00,0.00, 0.35,0.50, 1.00,1.00, 2.50,1.00
 MHDBTB = 0.00,0.00, 0.30,0.25, 1.00,0.50, 2.00,1.00, 2.50,0.00
* maximum crop height
   *
```

```
 MXHCRS = 2.5          ! m
 MXHCDS = 1.           ! m
* time constant for shoot senescence
   *
 TCSS   = 10



* ------------  P h e n o l o g y   m o d u l e  (PGPHE)
------------ *

* variable for selection of development approach
   *
 IVPRS  = 0
 IVPDS  = 2
* flowering date N'Tarla
   *
 FDRS   = 285          ! day
* flowering date Niono
   *
*  FDRS   = 275          ! day
* stem elongation date
   *
 SEDRS  = 235          ! day
* parameters for geographical approach
   *
 A1     = 351.8        ! day
 B1     = -05.7        ! day/degrees
 C1     = -0.7         ! day/degrees
* N'Tarla (Mali) station
   *
 LATS   = 12.35        ! degrees
 LONGS  =  5.42        ! degrees
* parameters for photothermic approach
   *
 CRDAYL = 12.84        ! h
 A2     =  0.49458     ! day-1
 B2     = -0.03659     ! (day*h)-1
* constant development rate during the dry season
   *
 DVRC   =  0.0001      ! day-1
* base temperature for development
   *
 BTD    = 10.          ! øC
```

* thermal sum from emergence to anthesis
 *
 TUEA = 900. ! øC day
* thermal sum from anthesis to maturity
 *
 TUAM = 1000. ! øC day
* thermal sum from maturity to complete senescence of the shoots
 *
 TUMDRS = 600. ! øC day
 TUMDDS = 200. ! øC day
* numeric value for the onset of stem elongation stage
 *
 SEDVS = 0.35 ! -
* integer variable used to define the maximum duration under water
 *
* stress conditions, after which the above ground biomass dies
 *
 TCWSCD = 25 ! day

* --- F o r a g e e x p l o i t a t i o n m o d u l e (PGEXP)
 -- *

* type of exploitation when the entire shoot biomass produced
during *
* the rainy season die (0 for burning and 1 for cutting or
grazing; *
 EXPTYP = 1 ! -
* height of cutting when the entire shoot biomass produced during
the *
* rainy season die (only for EXPTYP=1)
 *
 HEC = 0.2 ! m
* variable used to know whether or not exploitation will occur: 1
for *
* exploitation and 0 for not
 ERS = 0
 EDS = 0
* variable used to select how the time of exploitation is given to
the *
* model: date approach for EDRS=0 or EDDS=0; critical biomass
approach *
* for EDRS=1 or EDDS=1; and the phenological approach for EDRS=2

```
or    *
* EDRS=2
    *
  EDRS   = 0              ! -
  EDDS   = 0              ! -
* days interval for the first exploitation
    *
  IERS1  = 60             ! day
  IEDS1  = 0              ! day
* days interval between two exploitations after the first one
    *
  IERS   = 80             ! day
  IEDS   = 0              ! day
* total number of exploitations;
    *
  NERS   = 2              ! -
  NEDS   = 0              ! -
* variable used to define the critical above ground biomass which
    *
* trigger exploitation;
    *
  CWSERS = 0.             ! kg/ha
  CWSEDS = 0.             ! kg/ha
* variable used to define the height above the soil of clipping or
    *
* grazing;
    *
  HERS   = 0.1            ! m
  HEDS   = 0.             ! m
* array of development stages when forage exploitation occur;
    *
  DVSERS = 10*0.0         ! -
  DVSEDS = 10*0.0         ! -



* ---  B e g i n n i n g   o f   r a i n s  m o d u l e  (PGRAIN)
--- *

* time constant for calculation of beginning of the regular rains
    *
  TCRD1  = 20
  TCRD2  =  5
* rains values for calculation of beginning of the regular rains
```

```
   *
  RAIN1  = 25.
  RAIN2  = 20.
  RAIN3  = 25.


* ---------- W a t e r   u p t a k e  m o d u l e  (PGWU)
---------- *

* extinction coefficient for visible and near infrared radiation
   *
  KL     = 0.70           ! -
* specific root weight
   *
  SRTW   = 100.           ! m/g
* maximum transpiration rate per unit of root length
   *
  MXTRRL = 0.00125        ! kg/m/d
* parameter in the exponential function used to simulated root
   *
* distribution in the rooted soil
   *
  RTDERS = 6.             ! -
  RTDEDS = 3.             ! -
* soil water depletion factor for crop transpiration
   *
  SWDFTB = 0.,0.9, 2.,0.9, 5.,0.65, 6.,0.55, 8.,0.5,
         9.,0.48, 10.,0.45
* table of epidermal transpiration as a function of living shoots
   *
  ECTTB = 0.00,0.01, 100.,0.05, 30000.,0.3


* -  S pr o u t i n g  a n d  e m e r g e n c e  m o d u l e
(PGCS)  - *

*  initial root depth at crop emergence
   *
   IZRTS  = 0.10          ! m
*  initial root depth at crop sprouting
   *
   IZRTR  = 0.25          ! m
*  soil depth for crop germination and sprouting
```

```
   *
  SDCG   = 0.1           ! m
  SDCS   = 0.2           ! m
*  critical water content for crop germination and crop sprouting
   *
  CRWCCG = 1.3           ! -
  CRWCCS = 1.3           ! -
*  time constant for crop emergence, emergence failure,
   *
*  crop sprouting and sprouting failure
   *
  TCCE   = 8             ! d
  TCCS   = 4             ! d
  TCEF   = 6             ! d
  TCSF   = 4             ! d

SOIL.DAT
NL = 10
TKL = 0.02, 0.18, 5*0.2, 0.4, 2*0.2              !  units: m
MDSE =  0.5                                      !  units: m
SWIT9 = 1
SWIT8 = 4
SWIT6 = 2
EES = 20. ! M-1

* sandy soil (Nara)
WCST = 10*0.3
WCFC = 10*0.15
WCWP = 10*0.02
WCAD = 10*0.007
WCLQTM = 0.007,0.01,3*0.02,0.04,0.04,0.05,0.06,0.08

* loamy soil
*WCST = 10*0.40
*WCFC = 10*0.22
*WCWP = 10*0.07
*WCAD = 10*0.02
*WCLQTM = 0.02,0.06,3*0.07,0.08,0.08,0.10,0.11,0.12

* clay soil
*WCST = 10*0.40
*WCFC = 10*0.35
*WCWP = 10*0.16
```

```
*WCAD = 10*0.06
*WCLQTM = 0.06,0.07,3*0.16,0.18,0.20,0.22,0.25,0.28

TIMER.DAT
*---------------------------------------------------------------------*
*
    *
* Timer data file to be used by FSE 2.0
    *
*
    *
*---------------------------------------------------------------------*

*
* Weather data specification

*    PC : C:\SYS\WEATHER\
*    VAX: <diskname>:[<account>.SYS.WEATHER]
*    MAC: HD40:WEATHER:
*
* WEATHER_DATA:

*

WTRDIR = ' '              ! Directory of weather data
CNTR   = 'MLI'            ! Country of weather data
ISTN   = 45               ! Station number of weather data
IFLAG  = 1101             ! Indicates where weather error and
warnings
                          ! go (1101 means errors and warnings to
log
                          ! file, errors to screen, see FSE
manual)


* Time control variables

IYEAR  = 1993             ! Start year of simulation
STTIME = 1.               ! Start day of simulation
FINTIM = 360.             ! Finish time of simulation
DELT   = 1.               ! Time step of integration
```

```
* Output variables

PRDEL  = 5.              ! Time between consecutive outputs to
file,
                    ! (when PRDEL=0, no output is
generated,
                    ! when PRDEL is very large (i.e.
10000.)
                    ! only initial and terminal output is
                    ! generated
IPFORM = 4             ! Format of output file:
                    !    0 = no output table,
                    !    4 = normal table,
                    !    5 = tab-delimited (Excel),
                    !    6 = TTPLOT format
COPINF = 'N'           ! Switch variable what should be done
with
                    ! the inputfiles:
                    !   'N' = do not copy inputfiles into
                    !         outputfile,
                    !   'Y' = copy inputfiles into
outputfile
DELTMP  = 'N'           ! Switch variable what should be done
with
                    ! the temporary output file:
                    !   'N' = do not delete,
                    !   'Y' = delete



* Optional output variables

PRSEL = 'DNCC','DVS','WCR','WSH','WRT','<TABLE>',
      'DNCC','WSRT','WRS','WERS','TWA','<TABLE>',
      'DNCC','SWT','SWE','SWD','CRRS','<TABLE>',
      'DNCC','CR','TWT','TSWE','TWD','<TABLE>',
      'DNCC','MXTWU','MXTWT','MXTWE','MXTWD','<TABLE>',
      'DNCC','TWS','DMP','CIR','EVSW','<TABLE>',
      'DNCC','MTRANS','ADMP','VPD','<TABLE>'
*       'DNCC','ZRT','MXWCR','MXWSH','MXWRT','<TABLE>',
*       'DNCC','DMP','MXWRTD','MXWSHD','MXTDM','<TABLE>',
*       'DNCC','TWE','EVSW','LAI','DLAI','<TABLE>',
*       'VPD1','MTRANS','VPD','RFCAWS','RFSGWS'
*       'DNCC','WDSHE','WSHE','WDSH','WDRT','<TABLE>',
```

```
*       'DNCC','ERCCCU','CRDS','CRDP','LAI','<TABLE>',
*       'DNCC','WCLQT(2)','WCLQT(3)','WCLQT(4)','WCLQT(6)','
<TABLE>',
*       'DNCC','WCLQT(8)','WCLQT(10)','<TABLE>',
                    ! Selection of variables that are
printed in
                    ! the output table. If PRSEL is
inactive all
                    ! variables are printed, otherwise only
those
                    ! that are specified after PRSEL. The
string
                    ! '<TABLE>' means that variables listed
to
                    ! the left are put in one table.
* IOBSD  = 1992,182, 1992,194
                    ! List of observation data for which
output
                    ! is required. The list should consist
of
                    ! pairs of <year>,<day> combinations.


* specific variables for perennial grasses model
IVSSC = 1       ! starting point (sowing or an stablished crop)

CONTROL.DAT
*--------------------------------------------------------------------*
* File names to be used by FSE 2.0
   *
*
   *
* The input files (except FILEIR) may may used in reruns.
   *
* Up to five input data files may be used (FILEI1-5)
   *
*--------------------------------------------------------------------*

  FILEON = 'RES.DAT'       ! Normal output file
  FILEOL = 'MODEL.LOG'     ! Log file
  FILEIR = 'RERUNS.DAT'    ! Reruns file
  FILEIT = 'TIMER.DAT'     ! File with timer data
  FILEI1 = 'CROP.DAT'      ! First input data file
```

```
  FILEI5 = 'SOIL.DAT'      ! Fifth input data file

* FILEI2 = ' '             ! Second input data file (not used)
* FILEI3 = ' '             ! Third input data file (not used)
* FILEI4 = ' '             ! Fourth input data file (not used)
```

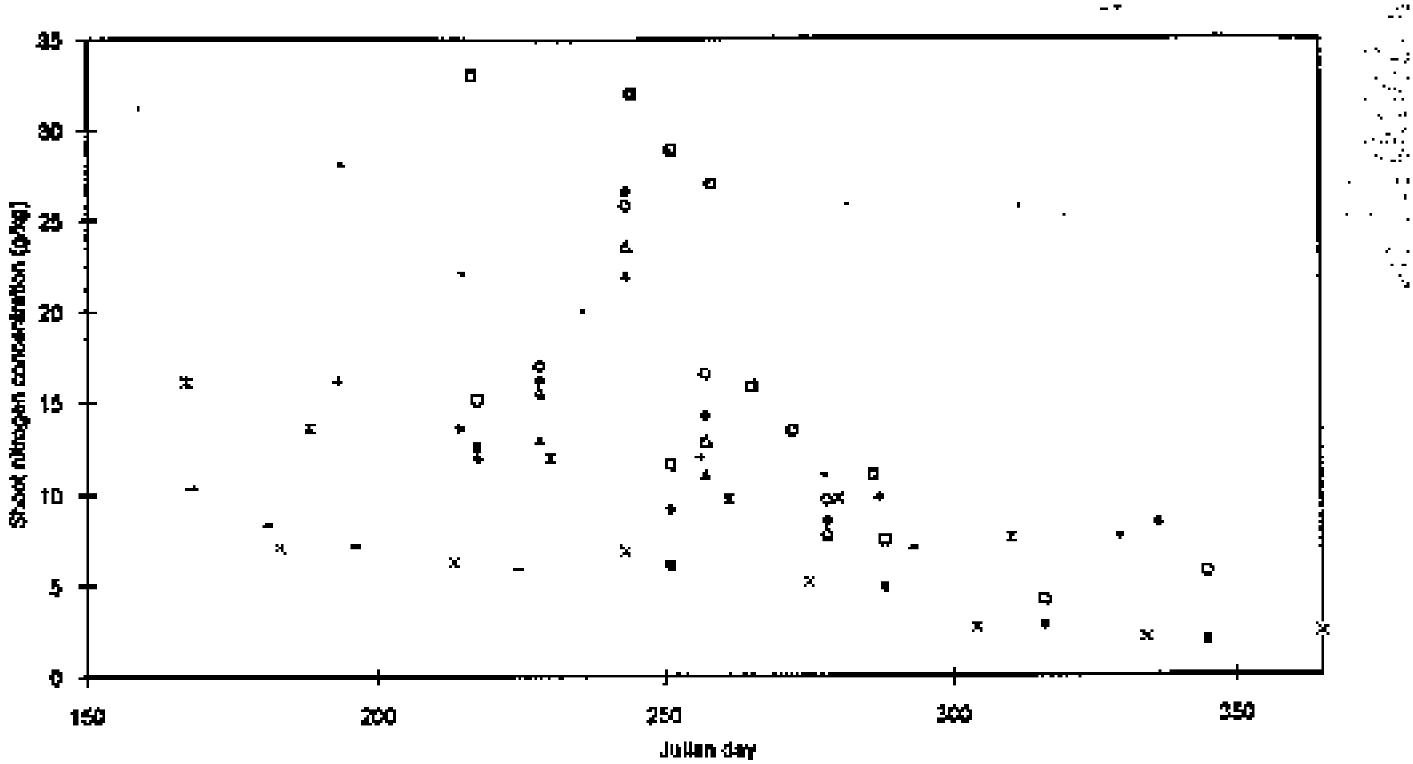

Figure 1. Maximum and minimum shoot nitrogen in Andropogon gayanus.

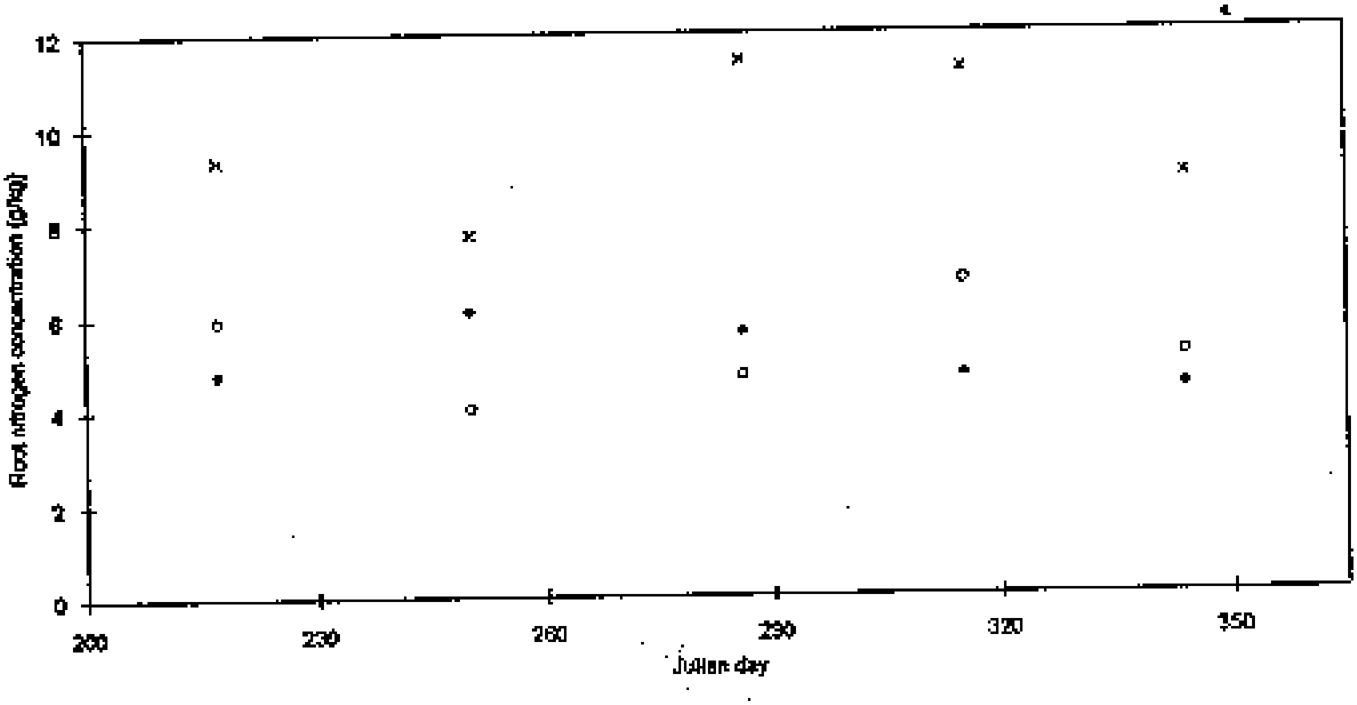

Figure 2. Maximum and minimum root nitrogen in Andropogon gayanus.