

# Rapports PSS N° 2

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

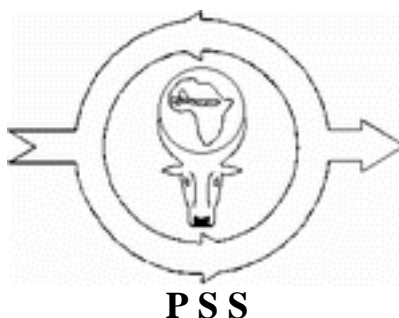
Projet de coopération scientifique

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

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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<sub>4</sub> 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<sub>4</sub> 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 lose 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-Saharan species (*Aristida pallida*, *Aristida papposa*, *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 led 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<sup>-1</sup>) 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):

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

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 <sup>1</sup>	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	Hagggar, 1970	283
Thies (Senegal)	14deg. 48' N	16deg. 57' W	300	Dieng <i>et al.</i> , 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:

$$\mathbf{DVR1 = A2 + B2 * DAYLP} \quad (3)$$

A2 and B2 are parameters (CROP.DAT file)

If the photoperiod is shorter than CRDAYL:

$$\mathbf{DVR1 = C2 + D2 * TMPA} \quad (2)$$

$$\mathbf{C2 = BTD / TUEA}$$

$$\mathbf{D2 = 1 / TUEA}$$

where, BTD is the base temperature for plant development, a value of 10 deg.C being used in other C<sub>4</sub> 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.*

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

$$\text{CRDAYL} = 12.84$$


---

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

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In this study, flowering date data refer to newly emerged crops. In Senegal, no differences 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:

$$\text{DVR1} = \text{SEDVS} / (\text{SEDRS} - \text{EMERGD}) \quad (4a)$$

before the onset of stem elongation in subsequent years:

$$\mathbf{DVR1 = SEDVS / (SEDRS - BGRS) (4b)}$$

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

$$\mathbf{DVR1 = (1 - SEDVS) / (FDRS - SEDRS) (4c)}$$

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:

$$\mathbf{VR1 = SEDVS / (SEDDS - BGDS) (5a)}$$

after the onset of stem elongation:

$$\mathbf{VR1 = (1 - SEDVS) / (FD DS - SEDDS) (5b)}$$

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<sup>-1</sup>) 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).

$$\mathbf{DVR2 = BT D / TUAM + 1 / TUAM * TMPA (6)}$$

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<sup>-1</sup>) is also temperature-dependent only.

$$\text{SSR} = \text{BTD} / \text{TUMD} + 1 / \text{TUMD} * \text{TMPA} \quad (7)$$

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<sup>-1</sup>) 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<sup>-1</sup>) 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<sup>-1</sup>) and Burkina Faso (3000-10 000 kg ha<sup>-1</sup>). 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<sup>-1</sup>) was considerably lower than that of the shoots (10 000-17 000 kg ha<sup>-1</sup>). 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<sup>2</sup> ground surface) is used instead of nitrogen content of leaves. Thus, the maximum rate of dry matter production (MXDMP, kg ha<sup>-1</sup> d<sup>-1</sup>) is calculated from daily incident global radiation (RDD, MJ m<sup>-2</sup> d<sup>-1</sup>) and the amount of nitrogen contained in the shoots with the equation:

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

where  $p$  is the initial shoot nitrogen use coefficient (grams of dry matter produced per day and per gram shoot nitrogen),  $\text{epsil}$  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<sup>-1</sup>), dry matter production (DMP, kg ha<sup>-1</sup> d<sup>-1</sup>) 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; Hagggar, 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<sub>4</sub> grass, are also similar to values of annual C<sub>4</sub> 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
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

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At Sotuba, after burning (January 1979), the aerial living biomass of *Andropogon gayanus* was slightly higher under optimum water supply (150 kg ha<sup>-1</sup> in March and 320 kg ha<sup>-1</sup> in June) than without irrigation (60 and 100 kg ha<sup>-1</sup>, 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 C<sub>4</sub> 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<sup>-1</sup> d<sup>-1</sup>) is calculated as follows:

$$\text{ADMP} = \text{DMP} * \text{MIN}(\text{TRANSR}, \text{RFCAAH}) \quad (9)$$

### 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<sub>4</sub> species (most of the perennial grasses of West Africa) is approximately 400 kg ha<sup>-1</sup> d<sup>-1</sup> (Lövenstein *et al.*, 1992), but the maximum growth rate reported (MXGRCCR, file CROP.DAT) of *Andropogon gayanus* grass was 305 kg ha<sup>-1</sup> d<sup>-1</sup> (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<sup>-1</sup> d<sup>-1</sup>) is calculated as:

$$\text{GRCR} = \text{MAX}[\text{MXGRCR}, \text{ADMP} + (\text{WCTSH} + \text{WCTRTR}) / \text{ASRQCR}] \quad (10)$$

where WCTSH (kg ha<sup>-1</sup> d<sup>-1</sup>) and WCTRTR (kg ha<sup>-1</sup> d<sup>-1</sup>) 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<sup>-1</sup> d<sup>-1</sup>) 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 arbitrarily 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<sup>-1</sup> d<sup>-1</sup> (Egunjobi, 1974) in the pre-anthesis phase and 20 kg ha<sup>-1</sup> d<sup>-1</sup> (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<sup>-1</sup> but under commercial conditions, seed production is in the range of 65-120 kg ha<sup>-1</sup> (Ferguson, 1990).

#### 2.3.4.2. Growth rate of roots

Under potential growth conditions, the root growth rate (GRRT,  $\text{kg ha}^{-1} \text{d}^{-1}$ ) 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 accelerates 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  $240 \text{ kg ha}^{-1}$ ). 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 arbitrarily 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 senesce. 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 lose 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<sup>-1</sup> (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<sup>-1</sup> (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<sup>-1</sup> d<sup>-1</sup>) 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<sub>4</sub> 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<sup>-1</sup> (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; Hagggar, 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 ( $\text{cm}^3 \text{H}_2\text{O cm}^{-3} \text{soil}$ ) 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,  $\text{mm d}^{-1}$ ), actual rainfall minus run-off (or plus run-on), is calculated with an empirical relation as a function of daily rainfall (RAIN,  $\text{mm d}^{-1}$ ):

$$\text{INRAIN} = \text{MAX} [0, \text{RAIN1} * (\text{RAIN} - \text{RAIN2})] \quad (11)$$

RAIN1 (-) and RAIN2 ( $\text{mm d}^{-1}$ ) 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,  $\text{mm d}^{-1}$ ). Waterlogging conditions are not simulated.

### 2.8.1. Evapotranspiration

Potential evapotranspiration in the Sahel, calculated with Penman's formula, varies from less than 1800  $\text{mm yr}^{-1}$  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  $\text{mm d}^{-1}$  in the cool dry season and 6.5  $\text{mm d}^{-1}$  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<sup>-1</sup>) 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<sup>-1</sup>) 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<sup>2</sup> m<sup>-2</sup>), 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):

$$\text{EVSC} = \text{PET} * \text{EXP}(-.5*\text{SCC}) \quad (12)$$

Actual soil evaporation rate (EVSU, mm d<sup>-1</sup>) 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<sup>-1/2</sup>) is assumed to be equal to the product of 0.6 (d<sup>-1/2</sup>) 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<sup>-1</sup>) 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<sup>-1</sup> (Gregory *et al.*, 1978; Barraclough & Leigh, 1984). In West African conditions a higher value of 0.03 m d<sup>-1</sup> 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<sup>-1</sup>) 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:

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

where WSRT (kg ha<sup>-1</sup>) 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).*

Season	Measured		Simulated		
	rainy	dry	3	5	6
<b>RTDE (-)</b>					
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
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An average value of 100 m g<sup>-1</sup> (Siddique *et al.*, 1990) for the specific root dry matter is used to determine root length in each rooted layer (RL, m m<sup>-2</sup>).

### 2.8.1.3. Crop transpiration

Potential transpiration rate (MTRANS, mm d<sup>-1</sup>) is determined directly from daily dry matter production, taking into account nitrogen-limited conditions (DMP, g m<sup>-2</sup> d<sup>-1</sup>), 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):

$$\text{MTRANS} = \text{DMP} * \text{VPD} / (\text{WUEC} * 10) \quad (14)$$

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):

$$\text{MDT} = \text{TMMX} - 0.25 * (\text{TMMX} - \text{TMMN}) \quad (15)$$

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<sup>-3</sup> 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  $1.25 \text{ kg m}^{-1} \text{ d}^{-1}$  (Azam-Ali *et al.*, 1984) is used in the model to account for root density limitations.

The model treats each soil compartment individually 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,  $\text{cm}^3 \text{ H}_2\text{O cm}^{-3} \text{ soil}$ ) 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:

$$\mathbf{WCCR(I) = (1.-SDWF)*(WCFC(I)-WCWP(I))+WCWP(I)} \quad (16)$$

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

$$\mathbf{WACWC(I) = \text{MAX}(0., (WCLQT(I)-WCCR(I))*TKL(I)*1000)} \quad (17)$$

maximum water extractable by roots (WARL,  $\text{mm d}^{-1}$ ), obtained by multiplying the maximum transpiration rate per unit root length ( $\text{kg H}_2\text{O m}^{-1} \text{ root d}^{-1}$ ) by the root length (RL,  $\text{m m}^{-2}$ ):

$$\mathbf{WARL(I) = \text{MXTRRL}*RL(I)} \quad (18)$$

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

$$\mathbf{MXWA(I) = \text{MIN} (WACWC(I), WARL(I))} \quad (19)$$

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

$$\mathbf{RFWU(I) = \text{MIN}(1., \text{MAX}(0., (\text{WCLQT} - \text{WCWP(I)}) / (\text{WCCR(I)} - \text{WCWP(I)}))} \quad (20)$$

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

$$\mathbf{TRWL(I) = MTRANS * ERL(I) / ERLB * RFWU(I)} \quad (21)$$

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

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,  $\text{mm d}^{-1}$ ). 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 Environment (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 approaches 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 EDDS = 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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## Rapports PSS No 2

### Appendix A: List of variable acronyms PGWA model

A auxiliary variable to calculate flowering date d PENMAN  
A1 parameter used in the flowering date equation d PGPHE  
A1GRRS auxiliary variable used to calculate rate of reserves growth  
kg ha-1 PGDM =  
A1GRSH auxiliary variable used in the calculation of shoot growth  
rate kg ha-1 PGDM =  
A1MRRC auxiliary variable used to calculate rate of maintenance  
crop respiration kg ha-1 d-1 PGDM =  
A1SDND auxiliary 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 auxiliary variable used to calculate water stress effects on  
root senescence - PGDM =  
ADWSSH auxiliary variable used to calculate water stress effects on  
shoot senescence - PGDM =  
AIRDR parameter for airdry m<sup>3</sup> m<sup>-3</sup> 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 Ångström equation - MODELS  
PETP  
ANGB parameter of the Ångström 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 auxiliar 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 auxiliary variable used to estimate growth rate of structural roots kg ha-1 d-1 PGDM =

AVGRSH auxiliary variable used to estimate growth rate of shoots kg ha-1 d-1 PGDM =

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

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

AVMHDB auxiliary variable to estimate maximum height of dead shoots m PGDM =

AVMRRC auxiliary 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

AVRFRWU auxiliary variable used to calculate a reduction factor affecting water uptake - PGWU =

AVRTRT auxiliary variable used to calculate reserve translocation to roots kg ha-1 PGDM =

AVRTSH auxiliary variable used to calculate reserve translocation to shoots kg ha-1 PGDM =

AVSDND auxiliary variable used to calculate the date of shoot death (nitrogen limitation) - PGDM =

AVSE1 auxiliary variable used to separate dead and living shoots removed by exploitation - PGDM =

AVSE2 auxiliary variable used to separate dead and living shoots removed by exploitation m2 PGDM =

AVSE3 auxiliary 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 auxiliary 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<sup>-2</sup> 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<sup>-1</sup> 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 m<sup>3</sup> m<sup>-3</sup> 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<sup>-1</sup> PGDM =

CWDSH cumulative weight of dead shoots kg ha<sup>-1</sup> PGDM =

CWRT auxiliary variable used to calculate cumulative weight of roots kg ha<sup>-1</sup> PGWU =

CWSEDS threshold value of aboveground biomass from which exploitation occur

in the dry season kg ha<sup>-1</sup> PGEXP

CWSERS threshold value of aboveground biomass from which exploitation occur

in the rainy season kg ha<sup>-1</sup> PGEXP

CWV concentration of water vapour kg m<sup>-3</sup> 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 saturated 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 m<sup>2</sup> m<sup>-2</sup> 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<sup>-1</sup> d<sup>-1</sup> 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<sup>-1</sup> d<sup>-1</sup> PGDM =

DRRT1 death rate of roots in the growth phase kg ha<sup>-1</sup> d<sup>-1</sup> PGDM =

DRRT2 death rate of roots in the shoots death phase kg ha<sup>-1</sup> d<sup>-1</sup>



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

DSLRL 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 auxiliary 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  $\text{m}^2 \text{ha}^{-1}$  PETP =

EA isothermal evaporation  $\text{mm d}^{-1}$  PENMAN =

EAC evaporative demand of the atmosphere  $\text{mm d}^{-1}$  PENMAN =  
PETP

ECTTB table of epidermical transpiration as a function of living biomass  $\text{mm d}^{-1}$  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  $\text{m}^{-1}$  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  $\text{MJ}^{-1}$  PGDM

ERL effective root length per soil layer  $\text{m m}^{-2}$  PGWU =

ERLB cumulative effective root length  $\text{m m}^{-2}$  PGWU =

ERS variable used to know whether or not exploitation occur in the rainy growth phase - PGEXP

ES0 potential evaporation of soil  $\text{mm d}^{-1}$  PENMAN =  
PETP =

ET0 potential evapotranspiration  $\text{mm d}^{-1}$  PENMAN =  
PETP =

ETRANS epidermical transpiration  $\text{mm d}^{-1}$  PGWU =

EVAPD drying power term of ET0  $\text{mm d}^{-1}$  PETP =

EVAPR radiation term of ET0  $\text{mm d}^{-1}$  PETP =

EVSC potential soil evaporation rate  $\text{mm d}^{-1}$  DRSAHE =  
PETP =  
MODELS

EVSD soil evaporation rate as function of DSLR  $\text{mm d}^{-1}$  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 m<sup>3</sup> m<sup>-3</sup> 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 compartments) -  
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 compartments - 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 established crop kg ha-1

PGDM

IWDSH initial weight of dead shoot of an established crop kg ha-1

PGDM

IWRS initial weight of reserves of and established crop kg ha-1

PGDM

IWRT initial weight of roots of an established 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 established 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 m<sup>2</sup> m<sup>-2</sup> 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 =

LVCCDS 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 identify 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 identify 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

LVRVVP 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<sup>-1</sup> d<sup>-1</sup> PGDM =

LWSH rate of losses of shoots kg ha<sup>-1</sup> d<sup>-1</sup> PGDM =

MAINRT maintenance respiration coefficient of roots kg CH<sub>2</sub>O PGDM

MAINSH maintenance respiration coefficient of shoots kg CH<sub>2</sub>O PGDM

MAINSO maintenance respiration coefficient of storage organs kg

CH<sub>2</sub>O 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 remobilised 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 weight of the crop in the rainy season kg ha-1 PGDM  
=  
MXWCRD maximum weight of the crop in the dry season kg ha-1 PGDM =  
MXWRT maximum weight of roots in the rainy season kg ha-1 PGDM =  
MXWRD maximum weight of roots in the dry season kg ha-1 PGDM =  
MXWSH maximum weight of shoots in the rainy season kg ha-1 PGDM =  
MXWSHD maximum weight 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  $\text{g g}^{-1} \text{d}^{-1}$  PGDM  
PBAR barometric pressure mbar PENMAN =  
PBRs possible date of onset of regular rains d PGRAIN =  
PCE potential crop evapotranspiration  $\text{mm d}^{-1}$  PETP =  
PCRS auxiliary variable used to calculate concentration of reserves  
  
 $\text{kg kg}^{-1}$  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  $\text{kg ha}^{-1} \text{d}^{-1}$  PGDM =  
PGRRT potential growth rate of roots  $\text{kg ha}^{-1} \text{d}^{-1}$  PGDM =  
PGRSH potential growth rate of shoots  $\text{kg ha}^{-1} \text{d}^{-1}$  PGDM =  
PI ratio of circumference to diameter of a circle (3.141592654) -  
ASTRO =  
PRRE potential rate of root extension  $\text{m d}^{-1}$  PGDM  
PSE potential evaporation  $\text{mm d}^{-1}$  PETP =  
PSYCON psychrometric instrument constant  $\text{mbar K}^{-1}$  PENMAN =  
PTRANS potential transpiration  $\text{mm d}^{-1}$  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

RDSLRL rate of change in number of days since last rain (DSLRL) -  
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 accounting 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 describing the extinction coefficient of the

exponential function used to  
simulated root distribution in the soil - PGWU =  
RTDEDS parameter describing 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 switth -

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 auxiliary variable used to trigger crop regrowth - PGDM =

WCAD water content at airdry m<sup>3</sup> m<sup>-3</sup> DRSAHE =

WCADX volumetric water content airdry m<sup>3</sup> m<sup>-3</sup> 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  $\text{m}^3 \text{m}^{-3}$  DRSAHE =

WCFCX volumetric water content at field capacity  $\text{m}^3 \text{m}^{-3}$  DRSAHE =  
MODELS  
PGWU

WCL intermediate value of volumetric water content per soil  
compartment  $\text{m}^3 \text{m}^{-3}$  DRSAHE =

WCLCH rate of change of water content per soil compartment (array)

mm d-1 DRSAHE =

WCLQT initial volumetric water content per soil compartment  $\text{m}^3 \text{m}^{-3}$

DRSAHE =

MODELS

PGCR

PGDM

PGWU

WCLQTM intermediate value of WCLQT (volumetric water content per  
soil compartment)  $\text{m}^3 \text{m}^{-3}$  DRSAHE =

WCR weight of living crop  $\text{kg ha}^{-1}$  PGDM =

WCST volumetric water content at saturation  $\text{m}^3 \text{m}^{-3}$  DRSAHE =

WCSTT volumetric soil moisture content at saturation in Driessen  
eq. (standard set)  $\text{m}^3 \text{m}^{-3}$  DRSAHE =

WCSTX global equivalent of volumetric water content at saturation  
 $\text{m}^3 \text{m}^{-3}$  DRSAHE =

MODELS

WCTRT weight of carbohydrate reserves translocated to roots  $\text{kg}$   
 $\text{ha}^{-1}$  PGDM =

WCTSH weight of carbohydrate reserves translocated to shoots  $\text{kg}$   
 $\text{ha}^{-1}$  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  $\text{m}^3 \text{m}^{-3}$  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 exploited kg ha-1 PGDM =

WDSHRE weight of dead shoot removed by exploitation kg ha-1 d-1

PGDM =

WILTP parameter for wilting point m<sup>3</sup> m<sup>-3</sup> DRSAHE =

WIND local equivalent of WN m s<sup>-1</sup> PENMAN

WN average wind speed m s<sup>-1</sup> 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

## A - 12, Appendix A: List of variable acronyms PGWA model

variable description unit module(s)

## Appendix A: List of variable acronyms PGWA model, A - 11

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](mailto: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 RDFFROM (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

\* --- photosynthetic 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

\*

----- \*

\*  
\*  
\* Regrowth (sprouting) and emergenc  
e \*  
\* of perennial grasses  
\*  
\* 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 compartments - I
*
* TKLX R() thickness of soil compartments m I
*
* IVSSC I to indicate if the simulation starts
*
* from sowing or from an established 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

\*

-----\*

\*

\*

\* Beginning of regular rains

\*

\*

\*

\* 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 pluies 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

\* --- Initialization

\*

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.
```

\* --- calculation

\*

```
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 = PBR5
  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

\*

-----\*

\*

\*

\* Water uptake of perennial grasses

\*  
\*  
\*  
\* (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 \*

\*    d i s t r i b u t i o n   i n   t h e   r o o t e d   s o i l

\*

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
```

```
* Functions
```

```
*
```

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

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

```
*      Output of variables
*
*
----- *
```

```
* ----- 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.

EVSU = 0.  
DRAICU = 0.  
EVSUCU = 0.  
RAINCUCU = 0.  
INFCUCU = 0.  
TRWCUCU = 0.  
DSLRCU = 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 (DSLRL+1.)-SQRT
(DSLRL))-INF)

IF (INF.GT.0.5) THEN
    EVSW2 = EVSH
    RDSLRL = -(DSLRL-1.)/DELT
ELSE
    EVSW2 = EVSD
    RDSLRL = 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,'RAINCUCU',RAINCUCU)

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

\* CALL OUTDAT (2,0,'WCUM',WCUM)

\* CALL OUTDAT (2,0,'DSLRCU',DSLRCU)

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)
```

```
DSLRL = INTGRL (DSLRL , RDSLRL , 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+EVSU+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,'EVSU',EVSU,'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.

\*

----- \*

\*                   Rate calculation

\*

----- \*

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)

\*

$$\text{RNSC} = (\text{RDD} * (1. - \text{ALB}) - \text{RB}) / \text{LHVP}$$

\* ----- radiation and drying power term of ET0 (mm/d)

$$\text{EVAPR} = (\text{DELTA} * \text{RNSC}) / (\text{DELTA} + \text{GAMMA})$$
$$\text{EVAPD} = (\text{GAMMA} * \text{EAC}) / (\text{DELTA} + \text{GAMMA})$$

\* ----- potential transpiration of the herbaceous vegetation

\* (PTRANS, mm/d)

IF (LAI.GT.0.) THEN

$$\text{PTRANS} = \text{FRABS} * \text{EVAPR} + \text{EVAPD} * \text{MIN}(2., \text{LAI})$$

ELSE

$$\text{PTRANS} = 0.$$

END IF

\* ----- potential evaporation (PSE, mm)

$$\text{SUM} = 0.7 * \text{KL} * (\text{LAI} + \text{DLAI})$$
$$\text{PSE} = (\text{EVAPR} + \text{EVAPD}) * \text{EXP}(-\text{SUM})$$
$$\text{EVSC} = -\text{PSE}$$

\* ----- potential crop evapotranspiration (PCE)

$$\text{PCE} = \text{PSE} + \text{PTRANS}$$

\*

----- \*

\* Output of variables

\* ----- \*

\* ----- \*

----- \*

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)

$$\text{DELTA} = 239. * 17.4 * \text{SVAP} / (\text{TMPA} + 239.) ** 2$$

\* --- The expression n/N (RELSSD) from the Penman formula is estimated

\* from the Angstrom formula:  $\text{RI} = \text{RA}(\text{A} + \text{B} \cdot \text{n}/\text{N}) \rightarrow$

$$\text{n}/\text{N} = (\text{RI}/\text{RA} - \text{A})/\text{B},$$

\* where  $\text{AVRAD} = \text{RI}$  and  $\text{ANGOT} = \text{RA}$ , the Angot radiation,

$$\text{RELSSD} = \text{LIMIT}(0., 1., (\text{ATMTR} - \text{A})/\text{B})$$

\* --- Terms of the Penman formula, for water surface, soil

\* surface and canopy

\* Net outgoing long-wave radiation (J/m<sup>2</sup>/d) according

\* to Brunt (1932)

$$\text{RB} =$$

$$\text{STBC} * (\text{TMPA} + 273.) ** 4 * (0.56 - 0.079 * \text{SQRT}(\text{VAP})) * (0.1 + 0.9 * \text{RELSSD})$$

\* --- Net absorbed radiation, expressed in mm/d

$$\text{RNW} = (\text{AVRAD} * (1. - \text{REFCFW}) - \text{RB}) / \text{LHVAP}$$

$$\text{RNS} = (\text{AVRAD} * (1. - \text{REFCFS}) - \text{RB}) / \text{LHVAP}$$

$$\text{RNC} = (\text{AVRAD} * (1. - \text{REFCFC}) - \text{RB}) / \text{LHVAP}$$

\* --- Evaporative demand of the atmosphere (mm/d)

$$\text{EA} = 0.26 * (\text{SVAP} - \text{VAP}) * (0.5 + \text{BU} * \text{WIND})$$

$$\text{EAC} = 0.26 * (\text{SVAP} - \text{VAP}) * (1.0 + \text{BU} * \text{WIND})$$

\* --- Penman formula (1948), and conversion to cm/d

$$\text{E0} = 0.1 * (\text{DELTA} * \text{RNW} + \text{GAMMA} * \text{EA}) / (\text{DELTA} + \text{GAMMA})$$

$$\text{ES0} = 0.1 * (\text{DELTA} * \text{RNS} + \text{GAMMA} * \text{EA}) / (\text{DELTA} + \text{GAMMA})$$

$$\text{ET0} = 0.1 * (\text{DELTA} * \text{RNC} + \text{GAMMA} * \text{EAC}) / (\text{DELTA} + \text{GAMMA})$$

RETURN

END

ASTRO.FOR

\*

----- \*



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 daylength (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)

$$SC = 1370.*(1.+0.033*COS (2.*PI*ID0Y/365.))$$

$$DS0 = SC*DSINB$$

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



```
*
-----*
*
*      Initialization
*
*
*
*
-----*
```

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

```
CALL RDINIT (IUNITD,IUNITO,FILEI1)
```

```
* -----*
--*
*      PARAMETERS
*
*
*
*
* Beginning of crop simulation:
*
```

```
* --- integer variable that indicates whether crop simulation
start *
```

```
* from sowing or from an established 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.

LVRSP = .TRUE.

BGDS = 0

IBR = 0

\* Dry matter production:

\*

\* --- 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.

\* Growth:

\*

\* --- 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.

\* Nitrogen:

\*

\* --- 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 ('TCSNDND', TCSNDND )

\* Crop survival

\*

\* --- time constant for crop death due to water or reserves

\*

\* exhaustion;

\*

CALL RDSINT ('TCCDWE' , TCCDWE)

CALL RDSINT ('TCCDRE' , TCCDRE)

\* --- initial values of auxiliary variables

\*

AVCDWE = 0.

AVCDRE = 0.

\* Senescence:

\*

\* --- 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.

\* Reserves mobilization:

\*

\* --- 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 remobilised (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, IWSEERS)

\* 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')

\* --- crop sprouting

\*

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)
```

```
*
```

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

```
*
```

```
*
```

```
* Rate calculation
```

```
*
```

```
*
```

```
*
```

```
*
```

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

```
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 beginning 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
```

\* -----

--\*

\*

\*

\* --- Dry matter production

\*

\* --- dry matter production as a function of cumulative shoot

\*

\* nitrogen (g N per m<sup>2</sup> 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
```

```
* -----
*
* Accumulation of assimilates
*
* and nutrients from dead plants
*
*
* 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

\* -----

-- \*

\* Growth

\*

\*

\*

\* 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, TSNCSTG*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
*
* regrowth 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
```

\* -----

--\*

\* Root extension

\*

\*

\*

\* --- 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*DELTA)-1.)/DELTA
  PGRRT = WRT * (EXP(RGRRT*DELTA)-1.)/DELTA
  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*DELTA)-1.) / DELTA
  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
```

```
* -----  
*  
* Maintenance respiration  
*  
*  
* --- 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
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, 'YEAR' , 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, 'MXWRD' , MXWRD )  
\* 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

LVRSP = .TRUE.

ELSE IF (IDOY.GT.DBRR .AND. MVP.GE.CRVPER) THEN

LVRSP = .TRUE.

ELSE

LVRSP = .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
```

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

```
- - *
```

```
*
```

```
*
```

```
* Onset of a new crop cycles
```

```
*
```

```
* --- 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.
```

```
AVMRRRC = 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)
```

\* -----

--\*

\*

\*

\* Initial Conditions

\*

\* --- 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
```

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

```
- - *
```

```
*
```

```
*
```

```
* Senescence
```

```
*
```

```
*
```

```
*
```

```
* --- 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..);

\*

$CWDSH = \text{MAX}(0., CWDSH + (LWSH - WDSHRE) * \text{DEL T})$

$CWDRT = \text{MAX}(0., CWDRT + LWRT * \text{DEL T})$

\* 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 =  $\text{MAX}(0., (ADWSSH + 2. * (0.3 - \text{TRANSR}) * \text{DEL T}))$

ELSE

ADWSSH = 0.

END IF

IF (WRT.GT.0.) THEN

ADWSRT =  $\text{MAX}(0., (ADWSRT + 2. * (0.3 - \text{TRANSR}) * \text{DEL T}))$

ELSE

ADWSRT = 0.

END IF

ELSE

ADWSSH = 0.

ADWSRT = 0.

END IF

\* --- growth rate of reserves

\*

$GRRS = \text{AVGRRS} * \text{ASRQCR}$

\* -----

-- \*

\*

\*

\* Dry Matter

\*

\* --- living plant biomass (W..)

\*

$\text{AVGRSH} = \text{GRSH} + \text{RTSH} / \text{ASRQSH} - \text{DRSH} - \text{WSHRE}$

```
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 exploited (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 m<sup>2</sup> 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
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.)

\* -----

- - \*

\*

\*

\* Root Depth

\*

\* --- 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
```

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

```
- - *
```

```
*
```

```
*
```

```
* Leaf Area Index
```

```
*
```

```
* --- 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.
  MXWRD = 0.
  IF (WCR.GT.MXWCRD) MXWCRD=WCR
  IF (WSH.GT.MXWSHD) MXWSHD=WSH
  IF (WRT.GT.MXWRD) MXWRD=WRT
ELSE IF (LVCGDS) THEN
  IF (WCR.GT.MXWCRD) MXWCRD=WCR
  IF (WSH.GT.MXWSHD) MXWSHD=WSH
  IF (WRT.GT.MXWRD) MXWRD=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 (RECR)

\*

```
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
*
*           ( P G P H E )
*
*
*
*   a u t h o r :   S a n t i a g o   B o n a c h e l a - C a s t a n o
*
*
*
```



\* 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 daylength 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 flowering 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')

\*

----- \*

\* Rate calculation

\*

\*

----- \*

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 daylength (DMXD, d) to  
flowering \*

\* date (FDRS, d). Date of minimum daylength 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
```

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

```
- - *
```

```
*
```

```
*
```

```
* --- development rates (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=FDSDS
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
```

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

```
*
* --- Effects of water stress on DVS
*
*
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
```

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

```
-- *
```

```
*
```

```
*
```

```
* --- shoot senescence rate (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
```

```
*  
-----*  
*   Output of states and rates  
*  
*  
-----*
```

```
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.

\* -----

--\*

\*

\*

\* --- development stage (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

\* -----

--\*

\*

\*

\* --- shoot senescence stage

\*

\*

\*

```
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
```

\* -----

- - \*

\*

\*

\* --- Effects of water stress on 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

\*

----- \*

\*                    P G D R

\*

\*

\*

\*

\*

\* 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
```

```
*  
-----*  
*  
*  
*   Forage exploitation of  
*  
*   perennial grasses  
*  
*   (PGEXP)  
*  
*  
*  
* author: Santiago Bonachela-Castano  
*  
*  
*  
* date: February, 1994  
*  
*  
*  
* purpose: this routine indicates the exploitation dates and the  
*  
* height 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

\*  
----- \*

Initialization

\*  
\*

----- \*

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

```
CALL RDINIT (IUNITD,IUNITO,FILEI1)
```

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

```
* - - *
```

```
* 
```

```
* 
```

```
* Parameters
```

```
* 
```

```
* --- 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 disappear.
```

```
* 
```

```
* 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 approaches 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 EDDS = 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.LVCDDP) .AND. DVS.EQ.0. .AND. ERS.EQ.1)
THEN
    IF(LVEX) LVEX=.FALSE.
    END IF
140  CONTINUE
```

```
* -----
-- *
*
*
*  Explotation in the dry season
*
```

```
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.LVCDDP) .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
```

B - 10, Appendix B: PGWA modules (PGWA.FOR)

Appendix B: PGWA modules (PGWA.FOR), B - 11

Appendix B: PGWA Fortran modules, B - 1

B - 8, Appendix B: PGWA modules (PGWA.FOR)

Appendix B: PGWA modules (PGWA.FOR), B - 7

B - 12, Appendix B: PGWA modules (MODELS.FOR)

Appendix B: PGWA modules (MODELS.FOR), B - 11

B - 16, Appendix B: PGWA modules (PGCR.FOR)

Appendix B: PGWA modules (PGCR.FOR), B - 15

B - 18, Appendix B: PGWA modules (PGRAIN.FOR)

Appendix B: PGWA modules (PGRAIN.FOR), B - 19

B - 26, Appendix B: PGWA modules (PGWU.FOR)

Appendix B: PGWA modules (PGWU.FOR), B - 27

B - 36, Appendix B: PGWA modules (DRSAHE.FOR)



- 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

## Rapports PSS No 2

### 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

\* Dry matter production:

\*

\* 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<sup>-1</sup>) 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

\* Crop survival

\*

\* time constant for crop death due to water and reserves

exhaustion \*

TCCDWE = 8

TCCDRE = 8

\* Senescence

\*

\* 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

\* Mobilization of assimilates and

\*

\* nutrients

\*

\* 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. ! °C



\* thermal sum from emergence to anthesis

\*

TUEA = 900. ! °C day

\* thermal sum from anthesis to maturity

\*

TUAM = 1000. ! °C day

\* thermal sum from maturity to complete senescence of the shoots

\*

TUMDRS = 600. ! °C day

TUMDDS = 200. ! °C 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

\* --- Forage exploitation module (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 ! -

\* --- Beginning of rains module (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.

\* ----- Water uptake module (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

\* - Sprouting and emergence module  
(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','MXWRD','MXWSD','MXTDM','<TABLE>',
- \* 'DNCC','TWE','EVSW','LAI','DLAI','<TABLE>',
- \* 'VPD1','MTRANS','VPD','RFAWS','RFGWS'
- \* '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)

B - 84, Appendix B: PGWA modules (PGEXP.FOR)

Appendix B: PGWA modules (PGEXP.FOR), B - 83

Appendix C: PGWA data files, C - 1

C - 6, Appendix C: data files (CROP.DAT)

Appendix C: data files (CROP.DAT), C - 5

C - 10, Appendix C: data files (TIMER.DAT)

Appendix C: data files (TIMER.DAT), C - 9





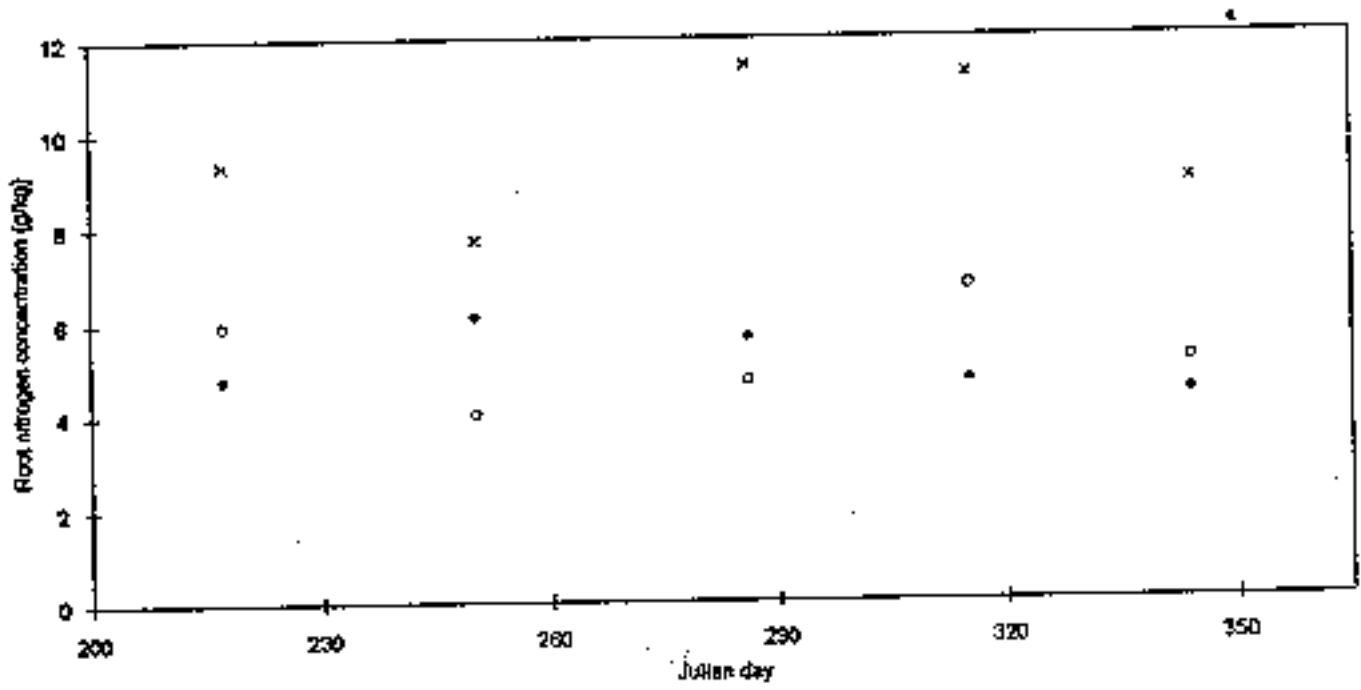


Figure 2. Maximum and minimum root nitrogen in *Andropogon gayanus*.