SIMULATION STUDIES ON *DIGITARIA ERIANTHA* STEUD. SUBSP. *ERIANTHA* AT DIFFERING SOIL NITROGEN LEVELS.

BY

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DECLARATION

I declare this dissertation to be my own work. It has been submitted for the degree of Master of Science in Agriculture in the Department of Agrometeorology, University of the Orange Free State, Bloemfontein, South Africa. It has not been submitted for any degree in any other University or faculty.

M.D. HOWARD

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Note: Programme statements were expressed in the BASIC computer Language format.

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LIST OF SYMBOLS

SOIL PARAMETERS

CLAY	Average clay content of the A and B horizon of the soil	(%)
DRAIN1	Water drainage from soil level one	(mm)
DRAIN2	Water drainage from rest of soil profile	(mm)
DRAINP	Drainage coefficient (0.9)	(mm d^{-1})
FC1	Field capacity of soil level one 100 mm	(%)
FC2	Field capacity of remainder of soil profile	(%)
GWP	Soil water potential	(kPa)
HYCON	Hydraulic conductivity (0.01)	(mm d^{-1} kPa^{-1})
INFIL	Infiltration of water into soil	(mm)
PWP1	Permanent wilting point of soil level one	(%)
PWP2	Permanent wilting point of remainder of soil profile	(%)
RUNPAR	Run-off coefficient (0.1)	(mm d^{-1})
SDP	Effective root depth of pasture	(mm)
SDP1	Soil depth of level one	(100 mm)
SDP2	Soil depth of level two, remainder of profile	(mm)
SLWAT1(1)	Soil water content for soil profile one (100 mm)	(mm)
SLWAT2(1)	Soil water content for remainder of soil profile	(mm)
SLWP1(1)	Soil water of level one (1 st 100 mm)	(%)
SLWP2(1)	Soil water of remainder of profile	(%)
WHC1	Water holding capacity at field capacity 10 Kpa	(%)
WHC4	Water holding capacity at permanent wilting point 2440 Kpa	(%)
WHCTEMP	Water holding capacity from previous season	(%)

ENVIRONMENTAL PARAMETERS

AE	Actual evaporation	(mm d^{-1})
AMXT	Maximum air temperature	(°C)
AMNT	Minimum air temperature	(°C)
ATEMP	Average daily air temperature	(°C)
EE	Equilibrium evaporation	(mm d^{-1})
EVAP	Daily evaporation	(mm)

HUCRIT	Thermal period required to trigger next growth stage	(°C)
HUCRMN	Minimum value to which HUCRIT may be reduced by water stress	(°C)
PE	Potential evaporation	(mm d^{-1})
RAINF	Daily precipitation	(mm)
RFD	Radiant flux density	(J m^{-2} d^{-1})
SUN	Daily sunshine duration	(h)
SLVAP	Soil evaporation	(mm d^{-1})

PLANT PARAMETERS

AL	Leaf area index	
BCFUNC	Basal cover function	(%)
DBL	Leaf mass change demand at 100 % basal cover	(kg ha^{-1})
DMG	Daily dry matter gain	(kg ha^{-1})
GRSTGE	Growth stage	(1-5)
JDMAKS	Day on which maximum biomass is reached	(1-365)
LWP	Leaf water potential	(kPa)
PPRODO	Previous production	(kg ha^{-1})
PRVISC	Previous biomass production	(kg ha^{-1})
SPL	Specific leaf area	(kg ha^{-1})
TNEXT	Next growth stage	
TPMAKS	Maximum biomass production of previous season	(kg ha^{-1})
TRANS1	Daily transpiration from soil level one	(mm)
TRANS2	Daily transpiration from remainder of soil profile	(mm)
WPC	Wilting point capacity	(-1800 kPa)

PLANT COMPONENTS

BBL	Live leaf mass	(kg ha^{-1})
BBD	Dead leaf mass	(kg ha^{-1})
BCL	Live culm mass	(kg ha^{-1})
BCD	Dead culm mass	(kg ha^{-1})
BGL	Live grain mass	(kg ha^{-1})
BGD	Dead grain mass	(kg ha^{-1})

BSL	Live stubble mass	(kg ha^{-1})
BSD	Dead stubble mass	(kg ha^{-1})
BRL	Live root mass	(kg ha^{-1})
BRD	Dead root mass	(kg ha^{-1})
BL	Live leaf mass	(kg ha^{-1})
BD	Dead leaf mass	(kg ha^{-1})
CL	Live culm mass	(kg ha^{-1})
CD	Dead culm mass	(kg ha^{-1})
GL	Live grain mass	(kg ha^{-1})
GD	Dead grain mass	(kg ha^{-1})
RL	Live root mass	(kg ha^{-1})
RD	Dead root mass	(kg ha^{-1})
SL	Live stubble mass	(kg ha^{-1})
SD	Dead stubble mass	(kg ha^{-1})
BTB	Total above ground leaf biomass	(kg ha^{-1})
BTG	Total above ground grain biomass	(kg ha^{-1})
BTC	Total above ground culm biomass	(kg ha^{-1})
BTRO	Total root biomass	(kg ha^{-1})
BTS	Total above ground stubble biomass	(kg ha^{-1})
RES	Reserve pool for carbohydrate	(kg ha^{-1})

RATE PROCESS

DPROB	Desired proportion of DMG routed to leaf	(Partitioning factor)
DPROC	Desired proportion of DMG routed to culm	(Partitioning factor)
DPROG	Desired proportion of DMG routed to grain	(Partitioning factor)
DPROR	Desired proportion of DMG routed to root	(Partitioning factor)
DPROS	Desired proportion of DMG routed to stem	(Partitioning factor)
R(1)	Daily translocation rate to living leaves	(kg ha^{-1})
R(2)	Daily translocation rate to living stems	(kg ha^{-1})
R(3)	Daily translocation rate to living roots	(kg ha^{-1})
R(4)	Daily translocation rate to living culm	(kg ha^{-1})
R(5)	Daily translocation rate to living grain	(kg ha^{-1})

X(1)	Translocation rate to dead stems	(kg ha^{-1})
X(2)	Translocation rate to dead leaves	(kg ha^{-1})
X(3)	Translocation rate to dead roots	(kg ha^{-1})
X(8)	Translocation rate to dead grain	(kg ha^{-1})
X(9)	Translocation rate to dead culm	(kg ha^{-1})
X(4)	Translocation rate from dead grain to trash	(kg ha^{-1})
X(5)	Translocation rate from dead culm to trash	(kg ha^{-1})
X(6)	Translocation rate from dead stems to trash	(kg ha^{-1})
X(7)	Translocation rate from dead leaves to trash	(kg ha^{-1})
ITERM	Period over which mean determined	(1)
CUT	Cutting date of vegetation	(CUT)

SOIL NITROGEN

AN	Available inorganic nitrogen in soil	(kg ha^{-1})
ANC	Nitrogen content of soil water	(kg ha^{-1} mm^{-1})
CNR	C:N ratio	
CNRFOM	C:N ratio of fresh organic matter	
CNRHUM	C:N ratio of humus	
DECR	Decomposition rate of fresh organic matter	(d^{-1})
DMINR	Maximum rate of N-mineralization from humus	
DOYFERT	Day when fertilized	(DoyFert(i))
FCNR	C:N control function for decomposition	
FERTH4	Nitrogen in NH_4 form	(kg ha^{-1})
FERTO3	Nitrogen in NH_3 form	(kg ha^{-1})
FOM	Fresh organic matter	(kg ha^{-1})
HUM	Humus content of soil	(kg ha^{-1})
IFOM	Fresh organic matter in soil after last application	(kg ha^{-1})
L	Soil layer number	(1-2)
NFERT	Number of nitrogenous applications	
NFOM	Nitrogen content of fresh organic matter	(kg ha^{-1})
NH4	Ammonium content of soil	(kg ha^{-1})
NHUM	Humus in soil	(kg ha^{-1})
NIMMFOM	Nitrogen immobilization from fresh organic matter	(kg ha^{-1} d^{-1})
NINFLO	Nitrogen inflow in soil	(kg ha^{-1} d^{-1})

NIT	Nitrification rate	(kg ha^{-1} d^{-1})
NLEACH	Nitrogen leaching from soil	(kg ha^{-1} d^{-1})
NMASFLO	Nitrogen uptake as a result of mass flow	(kg ha^{-1} d^{-1})
NMINHUM	Nitrogen mineralization from humus	(kg ha^{-1} d^{-1})
NMINNET	Net nitrogen mineralization rate	(kg ha^{-1} d^{-1})
NO3	Nitrate content of soil	(kg ha^{-1})
NOUTFLO	Nitrate flow from a given soil layer	(kg ha^{-1} d^{-1})
PERC	Water flow from given soil layer	(mm d^{-1})
RDECR	Maximum fraction of organic matter decomposed	(kg ha^{-1} d^{-1})
TOTAN	Total available nitrogen in soil	(kg ha^{-1})

PLANT NITROGEN

COMP	Plant component (1 root, 2 culm, 3 leaf, 4 grain)	
FACN	Nitrogen control function for growth	
MASS	Plant component mass	(kg ha^{-1})
N	Nitrogen content of each plant component	(kg ha^{-1})
NC	Nitrogen concentration of each plant component	(kg kg^{-1})
NCMAX	Maximum nitrogen content of plant component	(kg kg^{-1})
NCMIN	Minimum nitrogen content of plant component	(kg kg^{-1})
NCOPT	Optimum nitrogen content of plant component	(kg kg^{-1})
NDEM	Nitrogen demand	(kg ha^{-1})
NDIFFLO	Nitrogen uptake by diffusion	(kg ha^{-1})
NDIFFLOO	Maximum nitrogen uptake by diffusion	(kg ha^{-1})
NUP	Nitrogen uptake	(kg ha^{-1} d^{-1})
NUPO	Maximum nitrogen uptake rate	(kg ha^{-1} d^{-1})
PAN	Plant available nitrogen	(kg ha^{-1})
TNDEM	Total plant nitrogen demand	(kg ha^{-1})
TPAN	Total plant nitrogen available for re-mobilization	(kg ha^{-1})

ENVIRONMENTAL FACTORS IN NITROGEN SUBROUTINE

FTMIN	Temperature control function for mineralization	
FWMIN	Water control function for mineralization	
T	Average daily soil temperature	(°C)

V	Soil water content	(mm m^{-1})
W	Soil water content	(mm)

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PREFACE

All the glory to our God almighty who reigns forever, Amen.

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In honour and praise

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May God's richest blessing be bestrewed upon you.

CHAPTER 1

INTRODUCTION

1.1 Description of the problem

Growth modelling entails multi-disciplinary investigations concerning:

- collection and classification of state-of-the-art knowledge,
- mathematical collation of such knowledge, and
- verification and validation of the algorithms produced from such information.

Algorithms are used to build a growth model and reflect the extent of present knowledge. Skoog (1955) concluded, "*We can claim to understand the plant when we can express it all in a mathematical model*". Since then, much literature has been published on the subject. Of particular relevance here, are the reviews by Van Veen & Frissel (1981), Van Keulen (1982), Van Keulen, Penning de Vries & Drees (1982). Booysen (1983), Fouché (1984), Van Keulen & Seligman, (1987) Du Pisani (1992) and Fouché (1992). Mostly, models have been developed for agronomic species. Southern African, grassland scientists have only really commenced work in this field over the past decade (De Jager, 1976; De Jager, Opperman & Booysen, 1980; Booysen, 1983; Fouché, 1984; Du Pisani, 1992 and Fouché, 1992).

Of particular interest is the PUTU 13 model used by Du Pisani (1992) to demonstrate the practical value of a grassland model in determining animal/veld performance under different stocking rates. This model was adapted from the PUTU 11 (Booysen, 1983; Fouché, 1984 and Fouché, 1992) which was based upon the original PUTU 2 climax grassland model developed by De Jager (unpublished monograph,1976).

Du Pisani (1992) further developed the PUTU 13 model to make possible the simulation of daily dry matter production of *Cenchrus ciliaris* L. cv. Molopo. Inability to simulate the influence of nitrogen on dry matter production however restricted the use of this model. PUTU 13 however did represent the first deterministic model developed for a subtropical dryland pasture and could well prove to be the basis for developing new models for other dryland cultivated pastures, e.g. *Anthephora pubescens, Digitaria eriantha, Eragrostis curvula, Medicago sativa* and *Sorghum almum*.

Numerous key questions arose following the work of Du Pisani (1992) viz. is it possible to :

1. use the PUTU 13 model as a basis for developing deterministic models for other dryland cultivated pasture such as *D. eriantha* ?
2. include a mechanistic computational procedure into the PUTU 13 model, which will enable simulation of the impact of nitrogen upon daily dry matter production ?
3. apply such model to solving questions as to how much and when to apply nitrogen ?

1.2 Objectives of the study

With these questions in mind, it was decided to:

- adapt PUTU 13 to simulate daily dry matter production of *D. eriantha*.
- build therein a routine accounting for the influence of nitrogen upon growth.
- validate the new model under different climatic and soil conditions, and
- undertake preliminary demonstration of the new model's suitability for determining nitrogen application strategies for different climatic scenarios.

1.3 Modelling approach

Throughout the thesis reference will be made to the scientific literature in the relevant sections as this becomes necessary. No separate literature study has been undertaken. Mathematical approaches towards crop growth modelling could involve the use of linear regression, stochastical or statistical techniques, or mechanistic procedures. Furthermore, plant growth modelling could take place at different levels (resolution) e.g. whole crop, plant organs, tissues, cells etc. (see Thornley & Johnson, 1990). The complexity of the modelling will depend on :

- the current state of knowledge,
- what data are available to compose and validate the model, and
- the accuracy required of the model output.

In this study, an intermediate level of modelling complexity was adopted. This entailed simplification of the PUTU 11 model and required the quantification of :

- growth and development in the plant organs i.e. roots, leaves, culm, stubble and seed, and
- the influence of daily status of radiation, temperature, precipitation and nitrogen on plant growth and development.

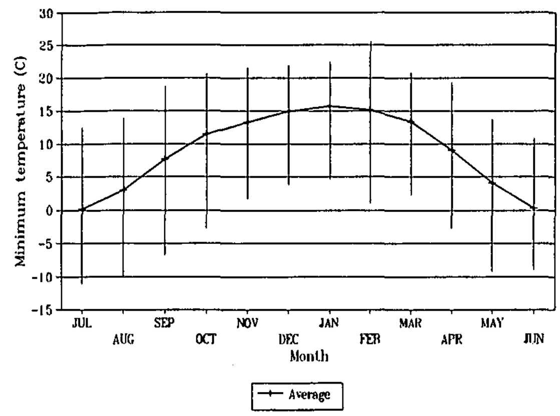
The model output was expected to be sensitive to differences in N-application rates of 20 kg N ha^{-1}. For modelling purposes, the study was restricted to use of available field data, which unfortunately were relatively few. The study thus represents a first attempt, but as the results will show, one offers much potential for future refinement and practical application.

1.4 Description of the study area

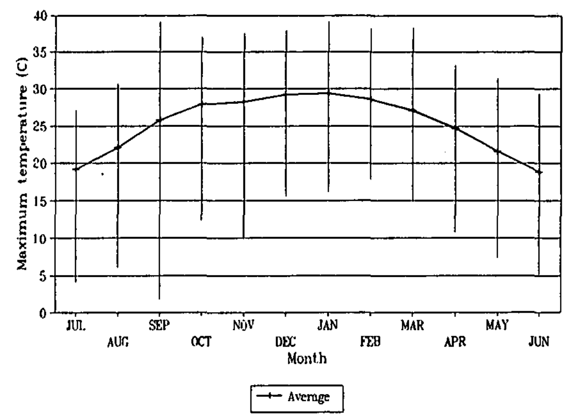
Data used to calibrate and validate the PUTU 13 model for *D. eriantha* were obtained for Pochefstroom from the High Veld Region Agriculture Development Institute. The experimental station is situated at 26° 44' latitude and 27° 05' longitude, 1345 m above sea-level. The data were collected by Dannhauser (1985), Dannhauser, Van Rensburg, Opperman & Van Rooyen (1987) and Dannhauser (1988).

1.4.1 Climate

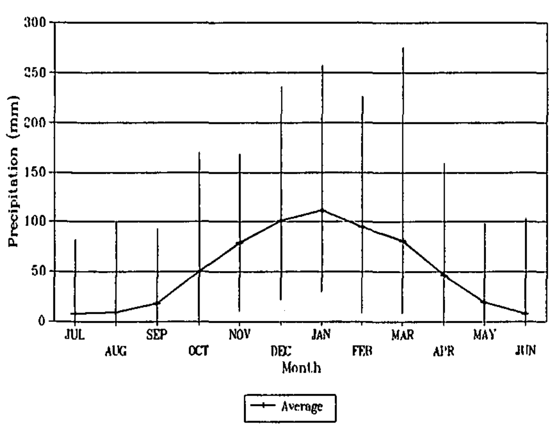
In general the temperature of Potchefstroom reflects cold to moderate winters with warm to hot summers (Figure 1.A & 1.B). The location receives a summer rainfall (Figure 1.C). with a long term mean precipitation of 625 mm per annum. The average daily sunshine duration varies between 8 and 10 hours (Figure 1.D) (Anonymous, 1986; Koch, 1988).



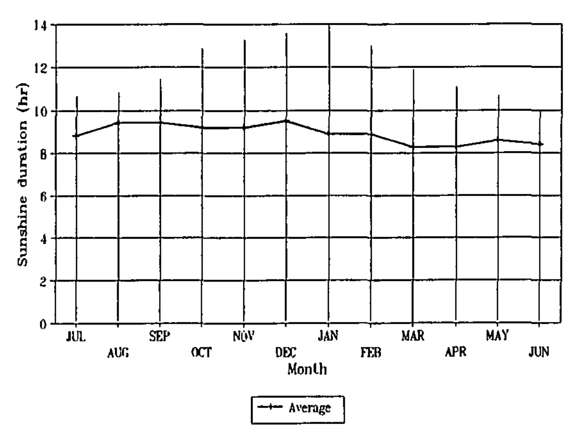
A. Mean daily minimum temperature



B. Mean daily maximum temperature



C. Mean monthly rainfall



D. Mean daily sunshine duration

Figure 1 Climatological characteristics of Potchefstroom with absolute daily extremes (I) and average values reported (Anonymous, 1986; Koch, 1988).

1.4.2 Soil

The soil profile can be characterized as a Westley form with a clay content of 25 %, soil depth of A & B horizon is 500 mm. This was covered by *D. eriantha* with an effective rooting depth of 300 mm. Results of soil analyses showed that the soil contained:

> pH(H_2O) = 6.4; pH(KCl) = 5.3; P = 35 and K = 62 ppm, respectively (Dannhauser, 1985).

CHAPTER 2

MODEL DESCRIPTION AND REFINEMENT

2.1 Choice of PUTU 13 as a basis

Certain factors were taken into account when considering models for possible refinement for use on cultivated pastures :

- the accessibility of source code and required level of complexity,
- the ease with which the new model may be interfaced with an animal production model such as STEER (Du Pisani, 1992), and
- compatibility of the fundamental structure of the basic model with the growth characteristics of a cultivated pasture such as *D. eriantha*.

The PUTU 13 model was selected as a basis for refinement due to the fact that both *C. ciliaris* and *D. eriantha* are all classified as subtropical dryland species and PUTU 13 had demonstrated reliability in the semi-arid regions of the Orange Free state. Fouché (1992) found with PUTU 11 for climax grassland that $R^2 = 0.92$ for total dry matter production simulated versus measured over 12 seasons. Furthermore, du Pisani (1992) found over 5 seasons that $R^2 = 0.96$ between measured and simulated yield for *C. ciliaris* (PUTU 13) and $R^2 = 0.86$ where measured animal mass was correlated against animal mass simulated using the STEER and PUTU 13 models.

PUTU 13 has evolved as the latest in a series of crop growth models initiated in 1973 (see De Jager, 1974). Fouché (1992) chronicals the history of the development of the PUTU models.

In view of these facts, a new model PUTU 14 for *D. eriantha* was developed by appropriately simplifying and modifying PUTU 11 and 13 .

2.2 Model Structure

Fouché, De Jager & Booysen (1986) gave an overview of the typical structure of the PUTU models (see figure 2.1 for a schematic representation of the structure). A brief description of the PUTU 13 model will now be given. The source code for PUTU 14 is given in Appendix A. Where specific code statements are referred to the line numbers are given in parenthesis. A detailed description of the model is provided, which includes a relevant literature survey. This was done because no updated description of PUTU 11 and PUTU 13 exist and the work here reported represent a marked simplification of these models. In these models daily CO_2 assimilation is computed from weather variables and converted to dry matter (DMG) using the conversion factor 0.66 kg CH_2O/kg CO_2.

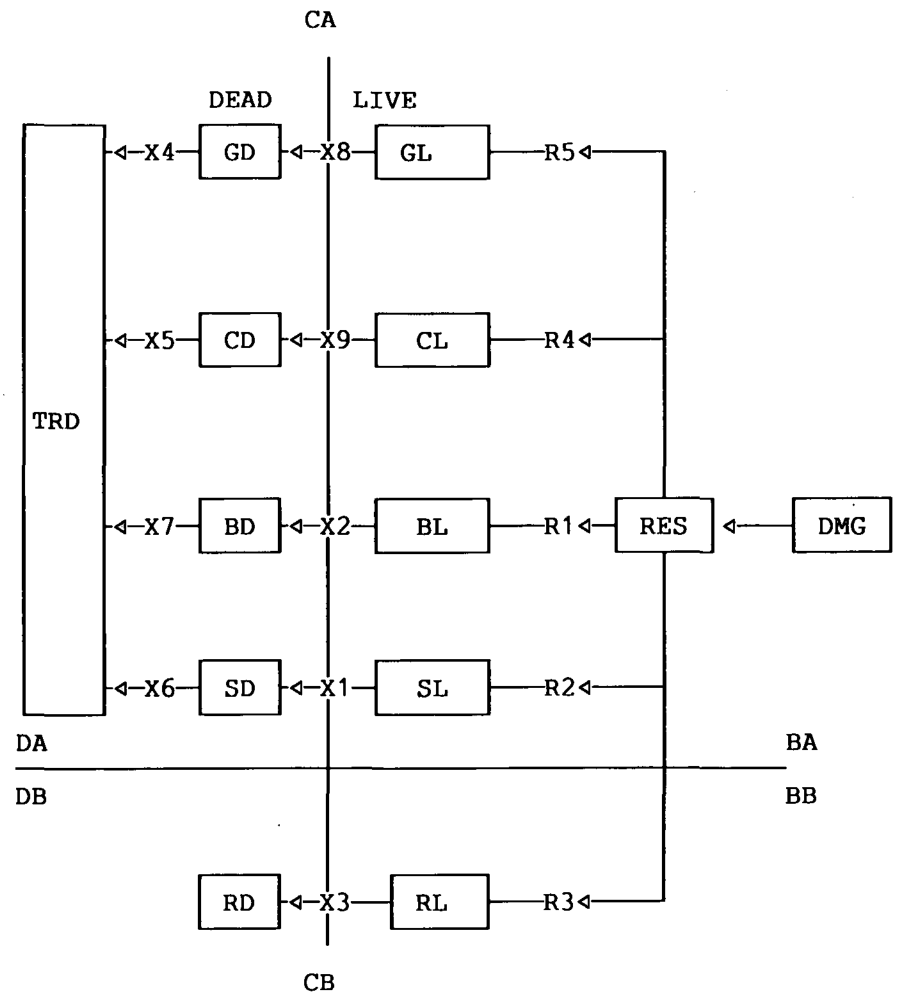


Figure 2.1 Schematic representation of the model structure for the PUTU family of models. The symbols are described in the text.

In Fig 2.1 the following symbols apply. Daily dry matter gain (DMG) from the assimilation process is routed to the reserve pool of carbohydrates (RES) (see [A, 419-423,434]. From this it is distributed among the different plant organs. Translocation rates of mobile carbohydrates to the living plant organs; grain (GL), culm (CL) , leaf (BL), stubble (SL) and root (RL) are quantified by parameters R5, R4, R1, R2 and R3, respectively. Due to senescence, biomass transfers from live to dead tissue. These translocation rates are accounted for by factors X8, X9, X2, X1 and X3 for grain (GD), culm (CD), leaf (BD), stubble (SD) and root (RD), respectively. With grassland the partitioning of dry matter is more important than is the case for most other species, because the storage of reserves can occur.

The amount of trash (TRD) is accumulated from each plant organ which dies at a rate determined by X4, X5, X7 and X6 , respectively.

Parameters CA, CB, BA, DA, BB and DB account for total above ground standing crop, below ground standing crop, above ground biomass, above ground dead biomass, root biomass and root dead biomass, respectively.

In PUTU 11 and 13, in order to make accounting for mutual shading and competition due to basal cover possible; an input parameter BCOVER = 10 (percent), is introduced, see [A,30 and 50]. This is then used to describe the influence of basal cover on competition (BCFUNC). Future work will hopefully formulate the relationship (BCFUNC) between competition effects and BCOVER which should not be a linear one. Up to the present however, the simple assumption BCFUNC = BCOVER / 100, see [A,50], was made. For convenience all computations were executed at 100 % basal cover and production status in each component simply obtained from the product of biomass and BCFUNC. Where cultivated pastures are concerned, a homogeneous nearly constant distribution is produced at the time of sowing. It was therefore decided to remove this complicated procedure in PUTU 14.

Since a summer crop is simulated in daily iterations, simulations commence on 1 July and end on 30 June of the following year. All the weather files are constructed accordingly and the day counter is J.

The various facets of the model will now be described.

2.3 Phenology

Seasonal plant development is related to physiological age and morphological appearance (Penning de Vries & Van Laar, 1982; Rimmington & Charles-Edwards, 1987; Thornley & Johnson, 1990). The prediction of phenological events in plants has been attempted as early as 1735 by Réamur as quoted by Van Keulen (1987).

Innes (1978) identified seven phenological events related to plant age. The PUTU family of models is capable of dividing the season into as many as nine different stages. The grassland models consider plant development in five categories, viz.

vegetative; reproductive; seed growth; seed fall and dormancy

Plant development is genetically determined, but regulated by external factors such as temperature and day length (Daubenmire, 1962; Innis, 1978; Angus, Mackenzie, Morton & Shafer, 1981; Penning de Vries & Van Laar, 1982; Van Keulen, 1987; Thornley & Johnson, 1990).

Plant development rate, is generally controlled by what is termed thermal period. These heat (temperature) sum formulae are commonly used to describe change from one phenological event to the next. Rimmington & Charles-Edwards (1987) described such process using :

$$v = Vr(1 + K\Delta T) \qquad [2.1]$$

where:

v = rate of phenological development (d^{-1})

Vr = development rate at a given reference temperature (d^{-1})

K = temperature coefficient ($^0C^{-1}$)

ΔT = difference between actual temperature experienced by the plant and the reference temperature (^0C)

Where rate of development $v(d^{-1})$ is defined as the fraction of the present growth stage through which the vegetation progresses during a given day. An example of the relationship between temperature and rate of development described by Eq. 2.1 is shown in figure 2.2

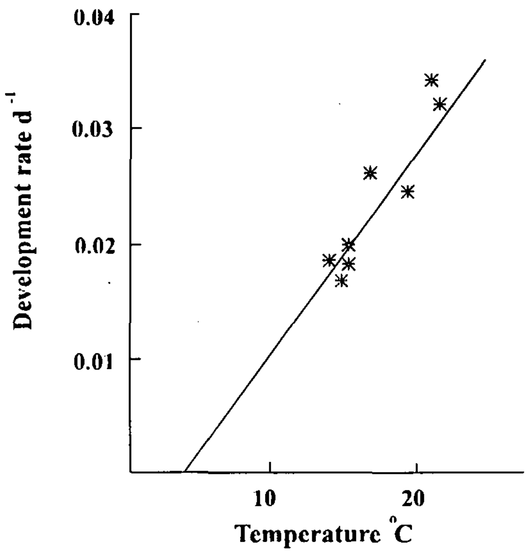


Figure 2.2 The relationship between plant development rate and prevailing temperature (after Van Keulen, 1987).

Eq. 2.1 may be rewritten in the form of the general day/degree expression, viz.

$$t_{AB} = a_n + b\sum\Delta t \qquad [2.2]$$

where, the summation takes place in daily increments. Furthermore t_{AB} is the time taken for the vegetation to progress between stages A and B and a_n and b are crop physiological constants. It is evident that t_{AB} is linearly related to the sum of the daily differences between the daily mean temperature experienced by the plant and the reference temperature (Charles-Edwards, Dooley & Rimmington, 1986).

The term $\sum\Delta t(d^0C)$ may simply be re-defined as the heat summation above a base temperature (at which development is zero) and then HU, or heat units, symbolizes what is termed thermal period.

The PUTU simulation models step from one growth stage to the next, when a minimum heat summation HUCRIT accrues to the plant:

Thermal period is computed by daily incrementation of an algorithm derived from Eq. 2.2, viz.

[A,127]	HU	= HU + ($TGROW_d$ - BO)	[2.3]
	HU	= thermal period (d°C)	
[A,124,325] where:	$TGROW_d$	= daily air temperature effective in the development process (°C)	
[A,32]	BO	= base air temperature below which no growth occurs (BO = 10 °C)	

In order to simulate the decreased plant development at extreme temperatures, Eq. 2.3 is subjected to two constraints, viz:

[A,126]	$TGROW_d$	= BO for (AMXT + AMNT)/2 $\leq$ BO, or
[A,125]	$TGROW_d$	= 30 for (AMXT + AMNT)/2 > 30.

AMXT and AMNT are daily maximum and minimum air temperature, respectively. When the thermal period, HU, in a given growth stage exceeds the HUCRIT corresponding to that growth stage, the model triggers progression to the next growth stage.

2.3.1 Growth stage one - Vegetative growth

No growth is assumed possible before photoperiod 31 st July [A,119]. The vegetation steps from vegetative to reproductive growth when it has received a thermal period HU〉 HUCRIT [A, 120]. The HUCRIT used in PUTU 11 for the vegetative growth stage is 250 (d°C) based upon a BO of 12 °C. Furthermore, PUTU 11 & 13 with BO = 12 °C, differs from PUTU 14 which has BO = 10 °C. The effect of drought on phenology is accounted for by shortening the duration (the thermal period required) in growth stages which experience drought. The critical thermal period is shortened according to :

[A,128]	HUCRIT	= HUCRIT - 10 * (100 - FW) / 100	[2.4]

FW is a growth limiting factor determined by plant water status. It will be described later. However HUCRIT may not become smaller than HUCRMN. When this occurs an assumption is made and HUCRIT is set equal to a minimum value HUCRMN (Appendix A, 129). For PUTU 13 and 14 the values of HUCRMN are 225 (d°C) and 230 (d°C), respectively.

Furthermore, when minimum daily minimum air temperature drops below 2 °C after 15 March, then reproductive growth commences :

[A,121]		IF	J	>	258 then 18	
[A,122]	18	IF	AMNT	≤	2 then terminate growth stage one	[2.5]
	where:		AMNT	=	minimum temperature (°C)	

2.3.2 Growth stage two - Reproductive growth

Triggers for the change from reproductive to seed growth are one of the following;

1. 25 days of reproductive growth for *Themeda-Cymbopogon* veld type (Fouché, 1992) 60 days of growth for *C. ciliaris* L. cv. Molopo (Du Pisani, 1992), or 30 days of growth for *D.eriantha*, and culm production must exceed 25 % of leaf biomass ;

[A,148]		CL	= (.25 * BL) AND J > MKOUNT	[2.6]
	where:	CL	= Live culm biomass (kg ha^{-1})	
[A,424]		BL	= Live leaf biomass (kg ha^{-1})	
		J	= days since July 1 st	
[A,146]		MKOUNT	= J + 30	

2. Reproductive growth may not endure for longer than 316 days of growth (i.e. beyond 15 May) [A,149] for *C. ciliaris* L. cv. Molopo (Du Pisani, 1992) and *D.eriantha,* or 258 growth days (15 March) for *Themeda-Cymbopogon* veld type (Fouché, 1992) and the daily minimum temperature drops below 2°C.

[A,149] J ≥ 316

2.3.3 Growth stage three - Seed formation

Triggers for the change to seed fall growth phase are :

[A,164] 1. 80 days (MKOUNT = 80) of seed formation for *D. eriantha*. It was 100 and 50 days for *C. ciliaris* L. cv. Molopo (Du Pisani, 1992) and *Themeda-Cymbopogon* veld type (Fouché, 1992), respectively, or

[A,168] 2. the growing season exceeds day J = 316 and

[A,170] 3. a minimum air temperature of 3, 2 and 2 °C is reached for *Themeda-Cymbopogon* veld type (Fouché, 1992) and *C. ciliaris* L. cv. Molopo (Du Pisani, 1992) and *D.eriantha*, respectively.

2.3.4 Growth stage four - Seed fall

Dormancy will commence when a minimum temperature of 3, 2 and 2 °C is reached for *Themeda-Cymbopogon* veld type (Fouché, 1992) and *C. ciliaris* L. cv. Molopo (Du Pisani, 1992), and *D.eriantha*, respectively [A,189].

2.3.5 General

The above approach is used to simulate phenological development in the PUTU grassland models. It is simple and makes possible describing different rates of change for each specie, provided its phenological characteristics are known. The differences between *D. eriantha, C. ciliaris* and *Themeda-Cymbopogon* veld type have been highlighted.

From an agricultural/ecological point of view the daily temperature extremes are most important. Particularly a minimum daily temperature of around 2 °C seems to be critical in grassland simulation models.

2.4 Leaf development

Leaf growth takes place during the vegetative growth phase. Environmental factors, such as temperature and water, control the rate of leaf development. Squire (1990) described a function where rate of leaf change increases linearly with temperature up to an optimum. This theory, as applied in the PUTU grassland models, has been extended (actually simplified) to cover cultivated pastures.

Squire (1990) expressed potential (no water or other stress) change in leaf (length) per unit time ($\delta l/\delta t$) as the product of the coefficient of thermal rate of expansion, P_ℓ, (units mm $(^0Cd)^{-1}$) and the difference between the temperature (T) and the base temperature (T_{br}), thus:

$$\delta l/\delta t = P_\ell (T-T_{br})$$

This equation has been adapted to calculate the daily biomass increment per unit ground area per unit time (DBL) written in the form :

[A,130]	DBL = BCON*($TGROW_d$ - BO) * FW/100	[2.7]
where:	DBL = daily increment in leaf biomass (kg ha^{-1} d^{-1})	
[A,123]	BCON = leaf biomass increment per unit ground area per unit time per unit temperature increment above a basal value (3.5 kg ha^{-1} d^{-1} $°C^{-1}$)	
[A,124,325]	$TGROW_d$ = daily air temperature effective in the leaf development process (°C)	
[A,32]	BO = base air temperature below which no growth occurs (BO = 10 °C)	
[A,83,85,357]	FW = growth limiting factor due to plant water status	

A description of how FW is computed will be given in Chapter 2.7.1. Leaf growth is constrained to a range of 10 °C and 30 °C (see A,125 and 126). Optimum growth rate will occur when $TGROW_d$ reaches 30 °C. If the value of $TGROW_d$ exceeds 30 °C then $TGROW_d$ is set equal to 30 °C, simulating optimal growth rate at temperatures higher than 30 °C. Furthermore, no leaf growth will occur when the temperature drops below 12 °C or 10 °C for *C.ciliaris* and *D.eriantha*, respectively (see Table 2.6). This leaf growth function could be modified in the future as additional information becomes available.

Furthermore, in PUTU 11 leaf development rate was initially taken as 20 % of the optimum rate until a leaf biomass of 2900 kg leaves ha^{-1} at 100% basal cover was reached (see, Fouché, 1992). For PUTU 13 and 14 this restriction was removed and the purely linear relationship Eq 2.7 adopted throughout the leaf development (vegetative) stage.

2.5 Dry matter assimilation

Photosynthesis is the process by which absorbed radiant energy is utilized by plant material to transform chemical energy. Essentially such process embodies diffusion of carbon dioxide (CO_2), water uptake (H_2O) and the release of oxygen (O_2). Feddes, Kowalik & Zaradny (1978) describe this as follows :

$$\underset{\text{(from soil)}}{2H_2O} + \underset{\text{(from atmosphere)}}{CO_2} \xrightarrow{\text{light}} \underset{\text{(to atmosphere)}}{O_2} + \underset{\text{(to plant)}}{(CH_2O)} + \underset{\text{(to atmosphere)}}{H_2O} \qquad [2.8]$$

The processes involved in the formation of carbohydrates are enzymatic, photochemical and biochemical i.e. carbon dioxide-assimilation, photo-respiration and carbohydrate-metabolism (Banner & Varner, 1965; Larcher, 1980; Paleg & Aspinall, 1981; Devlin & Whitham, 1983; Black & Vines, 1987; Jensen & Seftor, 1987; and Robinson, 1987). Carbohydrates act as an energy substrate in the plant and serve as building-blocks for newly formed tissues.

High resolution models have been developed to simulate assimilation and plant growth over the past two decades (see Table 2.1)

Table 2.1 Models which simulate certain photo- and biochemical events in various plant species.

Model name	Author	Crop
SORGF	Arkin, Vanderlip & Ritchie (1976)	Sorghum
SIMED	Shreiber, Miles, Holt & Bula (1978)	Grass
CANPAS	Fick (1980)	Rye grass
GOSSUM	Mckinion & Baker (1982)	Cotton
BACROS/PHOTON	Penning de Vries & Van Laar (1982)	Rhodes grass
SUCROS	Van Keulen et al (1982)	Wheat
PUTU	De Jager (1992)	Maize, Wheat Grassland
CERES-MAIZE	Jones & Kiniry (1986)	Maize

It is evident from Eq 2.8 that the rate of photosynthesis is determined by environmental factors such as: light, temperature, water, carbon dioxide and oxygen (Devlin & Whitham, 1983).

As early as 1860 Blackman, as quoted by Devlin & Whitham (1983) attempted to describe the control of photosynthetic rate by these factors. A typical control function is illustrated in Fig 2.3

In the PUTU grassland models, control of photosynthesis by the environmental elements is based upon the initial research of De Jager (1968). Here individual leaf gross photosynthetic rate was described in terms of incident radiant flux density, using a rectangular hyperbola given that the other environmental variables are not limiting photosynthesis i.e. they are at optimal value.

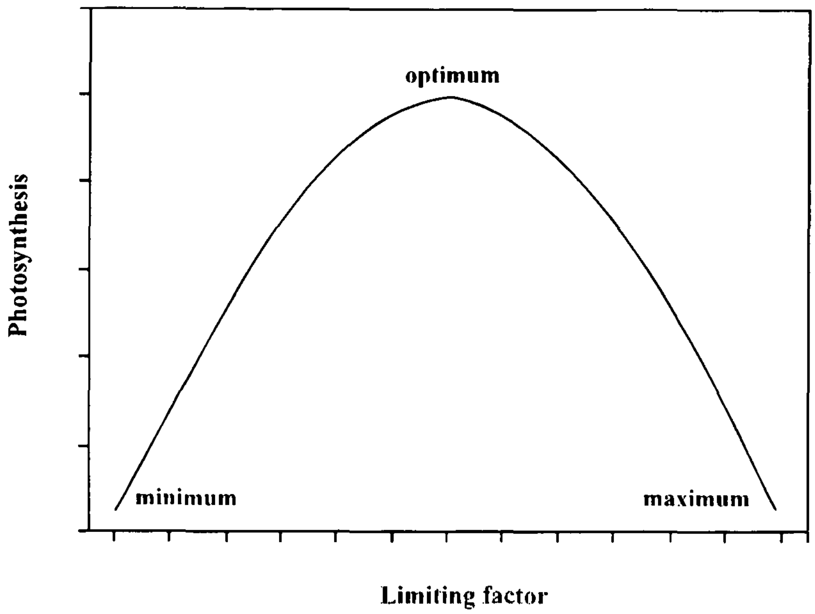


Figure 2.3 The relation between photosynthesis and some limiting factor as given by Devlin & Whitham (1983).

However, when temperature and plant water status were sub-optimal, they restricted growth, similarly to the relationship described by Fig 2.3. The original De Jager (1971a) results were eventually applied in a form where, F_w, the growth limiting factor due to plant water status, was described by a logistic function [A, 357] and, F_t, the growth limiting factor corresponding to temperature by a Gaussian function (De Jager, 1971b). Net photosynthetic rate was then expressed in terms of the product of a maximum radiation conversion coefficient and a light limiting factor derived from the rectangular hyperbola.

De Jager (1968) made the assumption that growth limiting factors could be mathematically combined in an overall growth limiting factor, F, using a law of independent mutual limitation (i.e. a multiplicative law), thus

$$F = \pi_i F_i \qquad [2.9]$$

Where i denotes over the range of relevant environmental limiting factors, viz radiation, temperature and plant water status. Thus Eq. 2.9 may be written:

$$F = F_q.F_t.F_w \qquad [2.10]$$

Where F_q, F_t and F_w are the growth limiting factor due to radiation, temperature and water, respectively. Thus, the net photosynthetic rate, P_l of individual leaves was expressed as

$$P_l = RCC.F \qquad [2.11]$$

or $$P_l = RCC.F_q.F_t.F_w. \qquad [2.12]$$

Values for the parameters used in the functions F_q, F_t and F_w are reported by De Jager (1971a) and De Jager (1971b) for *Lolium multiflorum, Lolium perenne* and *Paspalum dilatatum*.

Individual leaf photosynthesis

Notation :

The following symbol description will apply.

Variables:

RCC	= radiation-photosynthesis conversion coefficient (μg J^{-1})
P	= rate of net photosynthesis ($\mu g(CH_2O)\ m^{-2}\ J^{-1}$)
Q	= vertical component of radiant flux density (W m^{-2})
α	= leaf quantum yield, or photochemical efficiency 4 ($\mu gJ(CH_2O)\ J^{-1}$)
ϵ	= efficiency
a	= absorbtivity

Subscripts:

s	= level at radiation saturation
o	= maximum, or potential value
q	= radiation
ℓ	= an individual leaf
v	= a vegetative canopy

De Jager (1974) derived a simple leaf gross photosynthesis model based upon the following principles :

$$\lim_{Q \to 0} P_\ell = \alpha a_\ell Q$$

$$\lim_{Q \to \infty} P_\ell = P_{ls}$$

These may be combined simply to form a rectangular hyperbola as follows

$$1/P_\ell = 1/\ \alpha a_\ell Q + 1/P_{ls}$$

thus

$$P_\ell = P_{ls}Q/(P_{ls}/\alpha a_\ell + Q)$$

or

$$P_\ell = P_{ls}Q/(Q_B + Q) \qquad [2.13]$$

where $Q_B = P_{\ell s}/\ \alpha a_\ell$ [2.14]

Here, physically, Q_B is simply that radiant flux density at which one-half saturation leaf photosynthesis occurs. For convenient modelling purposes (as few as possible parameters); it is required to express photosynthetic rate as the product of a radiation conversion coefficient and incoming radiant flux density;

$$P_\ell = RCC.Q \qquad [2.15]$$

Now RCC may be evaluated in terms of the product of leaf quantum yield (α) and ϵ_q, a radiation use efficiency, which quantifies the efficiency with which incident radiation is used to fix CO_2. Thus, ϵ_q is defined as the fraction of incident radiation actually utilized in the photosynthetic process. Thus

$$RCC = \alpha\ \epsilon_q \qquad [2.16]$$

The radiation use efficiency ϵ_q may be derived from Eq 2.13 as follows. By definition, the absolute potential (maximum) leaf gross photosynthetic rate at a given radiant flux density, $P_{\ell o}$, will be given by :

$$P_{\ell 0} = \alpha a_\ell Q \qquad [2.17]$$

Radiation use efficiency for individual leaves during the photosynthetic process is by definition

$$\epsilon_q \quad = P_\ell/P_{\ell o} \qquad [2.18]$$

Now substituting from Eq 2.13 and Eq 2.17

$$\begin{aligned}\epsilon_q \quad &= P_{ls}Q/(Q_B + Q) \;/\; \alpha a_\ell Q \\ &= Q_B/(Q_B + Q) \qquad [2.19]\end{aligned}$$

P_ℓ may therefore be computed using Eq 2.15 and substituting for RCC estimated from Eq 2.16 and Eq 2.19. Thus

$$\begin{aligned}\mathrm{RCC} \quad &= \alpha\epsilon_q \\ &= \alpha\; Q_B/(Q_B + Q) \qquad [2.20]\end{aligned}$$

A worked example is useful for illustrating the fundamentals. From Eq 2.14

$$Q_B \quad = P_{ls}/\alpha a_\ell$$

For *Paspalum dilitatum* and *Lolium multiflorum* the values for $P_{\ell s}$ are 2400 $\mu g\ m^{-2}\ s^{-1}$ and 360 $\mu g\ m^{-2}\ s^{-1}$, respectively.

Thus for *Lolium multiflorum*

$$\begin{aligned}Q_B \quad &= 360\ \mu g\ m^{-2}\ s^{-1}(CH_2O)/(4\ \mu g\ J^{-1}\ 0.6) \\ &= 70\ W\ m^{-2}\end{aligned}$$

Note: $1\ \mu\ell(CO_2)\ m^{-2}\ s^{-1} \quad = 1.96 * 10^{-9}\ kg\ (CO_2)\ m^{-2}\ s^{-1}$

$$= 1.96\ \mu g\ (CO_2)\ m^{-2}\ s^{-1}$$

Leaf quantum yield, or α, is the initial slope of the radiant response curve for leaf net photosynthesis. For light energy it is around 12 $\mu g(CO_2)J^{-1}$ for most plant types (see Charles-Edwards et al 1986). In terms of dry matter, this is equivalent to $8\mu g(CH_2O)J^{-1}$. Note that 44 $\mu g(CO_2)$ will produce 33 $g(CH_2O)$ (0.68 $g(CO_2)\ g(CH_2O)^{-1}$), and when solar radiant flux density is considered in stead of light, this becomes 4 $\mu g(CO_2)J^{-1}$. Thus, leaf quantum yield, or photochemical efficiency, α has an upper limit of 4 $ug(CH_2O)J^{-1}$.

Canopy photosynthesis

A similar theory can be derived for a crop canopy by modifying Eq 2.15 and 2.16 for leaf area index

For a vegetative canopy using the same symbol definition:

$$P_v = RCC\ Q\ F$$

where, now $$F = F_v . F_t . F_w$$

F_v the fractional radiation interception, vegetative canopy is defined as i.e. the fraction of incident radiant flux density intercepted by foliage.

For a vegetative canopy, evaluation of RCC is complicated by having to integrate ϵ_q over canopy leaf area and the full range of incident radiant flux density. There are many examples of how this is done in the literature (Duncan, Loomis, Williams & Hanan; 1967). Thus, the photosynthetic rate of an element of leaf area, subjected a radiant flux density Q_i is given by

$$P_\ell = RCC_\ell\ Q_{\ell i}$$

$_\ell$ signifies finite element of leaf area, $_i$ signifies the class interval of radiant flux density to which the leaf is subjected.

The photosynthesis rate of an entire canopy, leaf area per unit square area is given by

$$\int_o^l = \int_o^l RCC_\ell \; Q_{\ell i}$$

$$\int_o^l RCC_\ell = \alpha \int_o^i \epsilon_{q_\ell}$$

$$\begin{aligned}
\epsilon_{q\ell} &= P_{\ell s} \,/\, P_\ell \\
&= P_{\ell s}\, Q_{\ell i} \,/\, (P_{\ell s} \,/\, \alpha a_\ell + Q_{\ell i}) / \alpha a_\ell \, Q_{\ell i} \\
&= (P_{\ell s} \,/\, \alpha a_\ell) \,/ (P_{\ell s} \,/\, \alpha a_\ell + Q_{\ell i}) \\
&= Q_B \,/ (Q_B + Q_{\ell i})
\end{aligned}$$

More conveniently, an equation for canopy photosynthesis may be developed analogously to the method used for an individual leaf. This is subject to assuming the canopy to be a single entity with overall definable properties. Such assumption has been called the conglomerate hypothesis (De Jager, 1974), or big leaf theory (see Monteith, 1975). In analogy with the development of Eq 2.13, the limits of vegetative canopy (with leaf area index $= \mathbb{L}$ and fractional interception F_v) gross photosynthesis, P_v, may be expressed

$$\underset{Q \to 0}{P_\ell} = \alpha a_\ell \, F_v Q$$

$$\underset{Q \to \infty}{P_v} = LP_{ls} = P_{vs}$$

Yielding $\quad P_v = P_{vs}\, Q \,/\, (Q_{Bv} + Q)$

where, now, $\quad Q_{Bv} = P_{vs} \,/\, \alpha \, a_\ell \, F_v$

Once again, similarly to Eq 2.19, it may be shown that

$$\epsilon_q = Q_{Bv}/(Q_{Bv} + Q) \qquad [2.21]$$

and $\quad P_v = RCC \; Q \qquad [2.22]$

where $\quad RCC = \alpha \, \epsilon_q$

In the early PUTU models Eq 2.22 was expressed

$$\begin{aligned}
P_v &= RCC \; Q \\
&= \alpha \, \epsilon_o \, Q
\end{aligned}$$

and the effect for plant water status and temperature (see Eq 2.12) accounted for using environmental growth limiting factors. Thus, by analogy, P_v may be expressed

$$P_v = \alpha\,[Q_{Bv} / (Q_{Bv} + Q)].\, F_v.\, F_t.\, F_w.\, Q$$
$$= \alpha\, \epsilon_q\, F_v.\, F_t.\, F_w.\, Q$$
$$= \alpha\, \epsilon_q\, F.\, Q$$

with $F = \pi_i\, F_i$

The coding of which (see Fouché, 1992) was

P = (EFFMAX*F/100)/100 * FE * RFDM

where FE = photochemical equivalent

RFDM = radiant flux density

EFFMAX = 3.51 * (VCS - 79.6114)

VCS = veld condition score

F = (FI/100)* (FT/100) * (FW/100) * 100

In the PUTU models the proportion of incoming radiation intercepted by the vegetation cover, the fractional interception, F_v, is computed from Campbell (1977) using:

$$F_v = 1 - \exp(-kL) \qquad [2.23]$$

where $k = 0.7$

In the case of row crops Charles-Edwards and Lawn (1984) suggest;

$$F_v = 2\,\beta\, F_{vo} / (1 + F_{vo}) \qquad [2.24]$$

where β is the proportion of ground surface area covered by the downward projection of the leaf canopy and F_{vo} is the proportion of the incident energy intercepted at the row centre around solar noon.

Pastures normally present a random distribution of basal cover which makes the former of these two equations the more suitable. This analysis of the impact of radiation, temperature and water constraints on photosynthetic rate, accounts for environmental limitation on vegetation growth rate. The formulation of the appropriate mathematical expressions used in the PUTU 14 model will now be given:

Fractional radiation interception, F_i, absorbed by the canopy is expressed using Eq 2.22:

[A,71]		AL	= BL / SPL		
[A,77]	thus:	FI	= (1 - EXP(- 0.7 * AL)) * 100		[2.25]
	where:	FI	= Fractional interception (%)		
[A,71]		AL	= Leave area index		
[A,424]		BL	= Live leaf mass	(kg ha^{-1})	
[A,32]		SPL	= Specific leaf area	(500 kg ha^{-1})	

Thus FI $\equiv$ F_v and Eq 2.24 differs from PUTU 13 in that the latter contained an adjustment (BCFUNC) for basal cover.

Formulation of RCC in PUTU 14 grassland

From Eq 2.21 it is evident that ϵ_q is a function of solar radiant flux density. Over weekly periods it has however been found to be reasonably constant because, in a given climate (locality), radiation over such periods during a growing season vary little (see De Jager & Venter, 1978). Because of this Monteith (1990) suggested that ϵ_q (actually RCC) is a conservative quantity. Based upon this argument it is logical to expect minor changes in RCC with locality and stage of growing season. These changes have been neglected in the PUTU models, but could form a basis for improvement in the future. This implies that the influence of construction and maintenance respiration is also accounted for in RCC.

The radiation-photosynthesis conversion coefficient, RCC, is defined as the amount of dry matter produced per unit of radiation intercepted by the foliage. The value off RCC for a wide range of crops is reported by Monteith (1990) to vary from 0.4 $\mu g\ J^{-1}$ to 1.5 $\mu g\ J^{-1}$. On the other hand, Jones & Kiniry (1986) use a value of (2.5 μg $CH_2O\ J^{-1}$) in CERES-MAIZE.

The early PUTU models (De Jager, 1976) utilized a value of $\alpha = 100 \mu g \ CO_2 \ J^{-1}$ for photosynthetically active radiation actually stored in the chloroplast. For such approach radiation use efficiency in terms of carbohydrate and total radiation for a full crop canopy is approximately $\epsilon_q = 2.7$ % yielding RCC = 2.7 $\mu g \ CH_2O \ J^{-1}$.

Such approach was adapted in PUTU 11 (see Fouché, 1992) where net photosynthesis was computed as gross photosynthesis less maintenance respiration and construction respiration, the latter two approximately 50 % of gross photosynthesis (CONS = 0.5), where

	P	= (EFFMAX*F/100)/100 * FE * RFDM
thus	CONS	= construction respiration (= 0.5)
where	COMM	= carbohydrate/CO_2 coefficient (= 0.68)
	DMG	= COMM * P * (1 - CONS)

In PUTU 14 quantum yield has been expressed in terms of the readily physically conseptualisable slope of photosynthesis curve at low radiation $\alpha = 4 \ \mu g \ CH_2O \ J^{-1}$. Thus an RCC of approximately unity would require an $\epsilon_q = 25$ % (De Jager, 1976).

In PUTU 14 construction respiration and maintenance respiration have been accounted for in RCC. Thus,

$$RCC = \alpha \epsilon_q$$

For grassland the assumption was made the $\epsilon_q = 77$ %, yielding

$$RCC = 4\ (77/100)$$
$$= 3.1 \ \mu g \ CH_2O \ J^{-1}$$

This operation takes place in

[A, 31] ALFA = 4 : EFFQ = 0.775 : RCC = ALFA * EFFQ and [A, 102] was modified so as to read

[A,102] $\quad P \quad = RCC * RFD * F / 100$

This algorithm can be reconciled with photosynthesis in the following manner.

Consider the alternative definition

$$RCC = \nabla W / \nabla Q$$

where ∇W is the gross amount of plant dry matter accumulated over a given period of time (here one day) and Q is the amount of solar energy intercepted during the same period, thus.

$$RCC = (\nabla_{pv} - \nabla_R).\ 0.68 / \nabla Q$$

where ∇_R denotes total respiration, and

R denotes dark respiration

Following Charles-Edwards et al (1986),

	∇_R	$= a_o \nabla_{pv} + b_1 \nabla Q$
where:	a_o	= construction respiration constant (0.14)
	a_1	= maintenance respiration constant (between 0.0143 and 0.0054)
	b_1	= empirical constant 0.4 $\mu g\ (CO_2)J^{-1}$ (in terms of light energy)
	N	= elemental nitrogen content of the plant
	b_o	= maintenance respiration constant
	∇_R	$= a_o\nabla_{pv} + a_1 W$
	∇_R	$= a_o\nabla_{pv} + b_o N$
	∇_R	$= a_o\nabla_{pv} + b_1 \nabla Q$
hence	RCC	$= \nabla_{pv}(1-a_o)/\nabla Q - b_1$

Charles-Edwards et al (1986) suggest that since b_1 has a magnitude of approximately 0.14 $\mu g\ (CH_2O)J^{-1}$ it could decrease total photosynthesis by only one-tenth and hence could be reasonably neglected. In early PUTU models maintenance respiration was however accounted for using the equation of McCree (1974) (see [A, 369] Fouché, 1992), thus

$$a_o = MAIN = (C30*(.044+.0019*TNITE+.001*TNITE^2*CLIVE)$$

Where nighttime temperature was estimated using the maximum temperature from the previous day (TMXPD) and the current day minimum (AMN(J), thus

$$TNITE = (TMXPD + AMN(J)) /4$$

This routine is still available in PUTU models, but has been neglected in the grassland PUTU 13 and PUTU 14 versions. Instead, construction respiration, a_o ∇_{pv}, and, accepting the conservativeness in ∇Q, its sum with maintenance respiration, is computed according to CONS = 0.5.

Computation of overall environmental limiting factor and plant daily dry matter gain

The existing Gaussian function for temperature, F_t, was retained, hence:

[A,325]	$ATEMP = (AMXT + AMNT) / 2$	
[A,79] thus:	$F_t = (EXP(-1 * ((ATEMP - 30)^2) / 360)) * 100$	[2.26]

As was the logistic control of water status on photosynthetic rate, F_w

[A,351-357]	$F_W = 1 / (1 + EXP[0.1*(WPC - LWP)])$	[2.27]
[A,83]	$F_W = FW * 100$	
[A,29] where:	WPC = Critical daily leaf water potential at which wilting commences (kPa)	
	LWP = Existing daily leaf water potential (kPa)	

Leaf water potential was computed using an empirical daily hydraulic conductivity, HYCON,

[A,349]	$LWP = E_o / HYCON$
where:	E_o = Potential evaporation (mm)
[A,33]	HYCON = Hydraulic conductivity (0.01 mm kPa^{-1})

The radiant flux density (RFD) effective in photosynthesis and evaporation is given by:

[A,332]	ALPHA	= 0.21	
[A,333]	BETHA	= 0.71	
[A,334]	DAYFRC	= SUN / DALEN(NMNTH)	
where:	DAYFRC	= Proportion of day with no cloud	
[A,69]	SUN	= Unclouded sunlight duration (h)	
[A,13,15-17]	DALEN(NMNTH)	= Maximum possible sunlight hours for month number NMNTH (h)	
[A,335]	ALPHA	= 0.29 for DAYFRC > .5	
[A,336]	BETHA	= 0.5 for DAYFRC > .5	
[A,337]	RFD	= SOLK * 10^6*(ALPHA + BETHA * DAYFRC)	[2.28]
where:	RFD	= Radiant flux density (J m^{-2} d^{-1})	

The solar constant, SOLK, is computed from:

[A,329]	X	= ((JDA + 10) / 365) * 360	
[A,330]	X	= X * 0.01745	
[A,331]	SOLK	= 30.85 + 12.65 * COS(X)	(MJ m^{-2} d^{-1})
	JDA	= Calender day counter from 1 st January	

Potential CH_2O assimilation (P = kg CH_2O ha^{-1} d^{-1}) is simulated as follows;

	P	= EFF/100 * FE * RFDM	(PUTU 11)	[2.29]
[A,102]	P	= RCC * RFD * (F / 100)	(kg m^{-2} d^{-1})(PUTU 14)	[2.30]
	RCC	= Radiation-photosynthesis conversion coefficient (μg J^{-1})		
thus:	P	= P * DALEN(NMNTH) * 3600 * 10^4	(PUTU 11)	[2.31]
[A,103]	P	= P * 10 (kg ha^{-1} d^{-1})	(PUTU 14)	[2.32]

The value of RCC in the PUTU 14 model is around 3, inferring a α = 4 μg J^{-1} and ϵ_q = 77 %. Charles-Edwards et al (1986) and Monteith (1990) reported RCC values of 1.3 μg J^{-1} and 1.5 μg J^{-1} respectively.

Results from the PUTU 13 and PUTU 14 model suggest that this approach towards simulating dry matter assimilation is reliable (see Fouché, 1992, Du Pisani, 1992 and the present study). Furthermore it suggests similarities in the growth patterns between *C. ciliaris* L. cv. Molopo and *D. eriantha*. This was the main reason for the belief that PUTU grassland models, especially PUTU 13 are capable of simple adaptation to the simulation of dry matter assimilation in other subtropical dryland pastures. Little change in Eq 2.31 need be made.

As explained, gross photosynthesis in PUTU 11 and PUTU 13 is reduced by construction and maintenance respiration (taken to be 50% of gross photosynthesis) and calculated in kg ha^{-1} at 100% basal cover (see Eq 2.29, 2.30, 2.31 and 2.32). Here RCC = $\alpha\epsilon_q$ = 3.1 μg CH_2O J^{-1} In PUTU 14 this was simplified to express net photosynthesis as

[A,103]	P	= RCC * 10	(kg ha^{-1} d^{-1})
with	RCC	= $\alpha\epsilon_q$	
		= 4 * 77/100	

this simplified calibration. By trial and error for ϵ_q *D. eriantha* was found to be 77 %. The value of ϵ_q is in *arte fact* of the expressions utilized for factors F_v, F_i F_w and particularly F_t. Thus the constant α which will have to be determined empirically for any new specie which is to be modelled. Expressing P as in Eq 2.31 does however simplify evaluation of ϵ_q.

Re-inclusion of conservation and maintenance respiration would probably improve the equation somewhat. The simplistic approached developed here does however form a convenient basis for refinement and indicates the expected magnitude of the significant variables.

2.6 Carbohydrate translocation

For the translocation rate of carbohydrates to the different organs, viz; root, stubble, culm, leaf and seed, Booysen (1983), Fouché et al (1986), in PUTU 11 accepted carbohydrate to be a source sink driven relationship. In PUTU 14 this was simplified using the theory of Furniss (1982). PUTU 11 assumed that carbohydrate translocation to different plant organs, is driven by the ratio of the existing mass of the given organ to the total plant mass and that the mass in each plant organ strives to attain an optimal proportion of the total plant biomass. The translocation of carbohydrate according to this law is illustrated in Fig 2.4. A maximum translocation rate is imposed for each growth stage and translocation only proceeds if sufficient reserves are available. This hypothesis was successfully adopted and tested in the PUTU 11 model (Fouché et al 1986; Fouché, 1992).

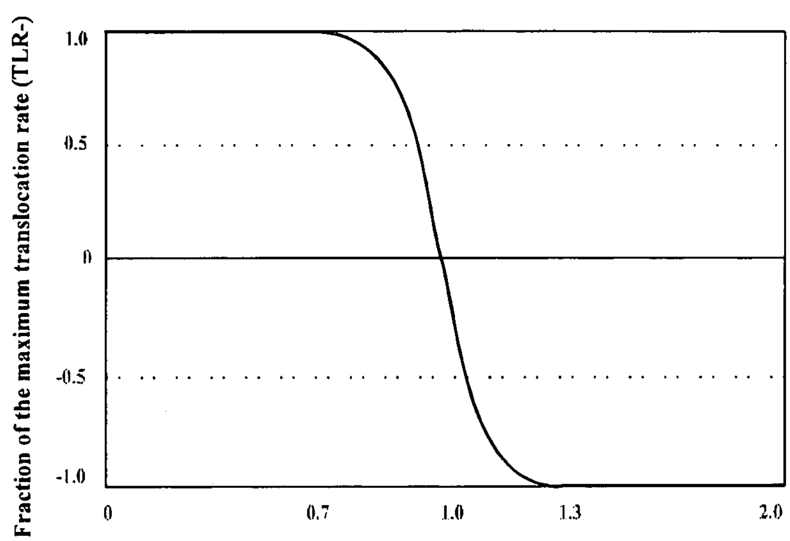


Figure 2.4 Typical relationship between the fraction of the maximum translocation rate and the desired proportion of plant mass shortage (Fouché, et al 1986).

When developing PUTU 14 the mode of partitioning of dry matter assimilate was changed. This represent one of the major changes made to the model.

Squire (1990) modelled dry matter partitioning to the different plant components as follows. Let, W_0, be the dry mass of the plant at growth initiation. Then during a period of growth, t_w, dry mass change can be represented as the product of the corresponding growth rate of the whole plant (Γ) and a partitioning factor, p. Mass of a plant structure or component, W_s is given by:

$$W_s = p\Gamma t_w \qquad [2.33]$$

and the current mass of a given plant component, W_s, maybe related to the mass of the whole plant, W_t, after a given time t_w; as follows:

$$W_s = p(W_t - W_o)$$

The Squire(1990) theory has been implemented in the PUTU 14 model. The partitioning factors, p, or daily PROportion of assimilate routed to root, stem, leaf, culm and grain are coded DPROR, DPROS, DPROB, DPROC and DPROG, respectively. Each partitioning factor changes from one growth stage to the next, according to Fig 2.5.

Reproductive Growth (Stage 2)

Culm	Leaf	Stubble
0.2	0.3	0.1
Root 0.4		

Seed Growth (Stage 3)

Culm	Leaf	Stubble	Grain
0.34	0.17	0.2	0.09
Root 0.3			

Seed fall and dormant (Stage 4,5)

Culm	Leaf	Stubble
0.3	0.1	0.1
Root 0.5		

Figure 2.5 Partitioning factor for dry matter assimilate (kg ha^{-1} d^{-1}) in the different growth stages. For the status variables culm, leaf, stubble, grain and root.

In the model, DPROR, DPROS, DPROB, DPROC and DPROG are set to either zero or the values given in Fig 2.5 at the commencement of each growth stage.

The algorithms for the partitioning of daily dry matter gain, DMG (kg ha^{-1} d^{-1}), actually evaluate the amount of carbohydrate (kg ha^{-1} d^{-1}) sent to the different plant organs. These parameters are R(1), R(2), R(3), R(4) and R(5) as defined in Fig 2.1

[A,414]	R(1)	= DBL
[A,415]	R(2)	= DPROS * DMG
[A,416]	R(3)	= DPROR * DMG
[A,417]	R(4)	= DPROC * DMG
[A,418]	R(5)	= DPROG * DMG

remembering:

[A,104]	DMG	= P * FACN (kg ha^{-1} d^{-1})
where	FACN	= nitrogen deduction factor in leaf (see Chapter 2.7.2)

In contrast PUTU 11 and PUTU 13 computed partitioning at 100% basal cover and hence in PUTU 14 the BCFUNC term could be removed from the equations corresponding to these.

Due to senescence, live tissue mass is transferred to dead tissue. Parameters X2, X1, X3, X9 and X8 are defined as the daily rate of senescence and they differ according to growth stage. The values for the leaf, stubble, root, culm and grain components, respectively are given in Table 2.2

Similarly to dry matter partitioning, the values of the senescence factors are set at the commencement of each growth stage. In principle, the rate of senescence is assumed to be directly proportional to the current live mass of the relevant component and the senescence factors for, for example, the vegetative growth stage X1, X2, and X3 are defined:

[A,132]	X(1)	= 0.001 * SL	for stem
[A,133]	X(2)	= 0.001 * BL	for leaf
[A,134]	X(3)	= 0.001 * RL	for root

Table 2.2 Senescence factors accounting for the daily transfer of mass (kg ha^{-1} d^{-1}) from living plant structures to dead tissue in the different growth stages. (Source code statement numbers are given in parenthesis).

Plant Structure	Growth stage				
	Vegetative	Reproductive	Seed	Seed fall	Dormant
Stubble (X1)	0.001 [A,132]	0.001 [A,152]	0.002 [A,171]	0.002 [A,190]	0.020 [A,205]
Leaves (X2)	0.001 [A,133]	0.001 [A,153]	0.002 [A,172]	0.010 [A,191]	0.200 [A,206]
Root (X3)	0.001 [A,134]	0.001 [A,154]	0.003 [A,173]	0.003 [A,192]	0.003 [A,207]
Grain (X8)			0.150 [A,174]	0.500 [A,200]	0.500 [A,200]
Culm (X9)			0.001 [A,175]	0.050 [A,201]	0.250 [A,201]

The current status of living tissue mass (kg ha^{-1} d^{-1}) for leaf, stubble, root, grain and culm are denoted by parameters, BL, SL, RL, GL and CL (see, Section 2.2). Live mass balances (kg ha^{-1}) are computed in daily iterations using the following :

[A,424]	BL	= BL + R(1) - X(2)	leaf
[A,426]	SL	= SL + R(2) - X(1)	stem
[A,432]	RL	= RL + R(3) - X(3)	root
[A,430]	GL	= GL + R(5) - X(8)	grain
[A,428]	CL	= CL + R(4) - X(9)	culm

Furthermore dead tissue mass is transferred to trash, TRD, at rates determined by X7, X6, X4 and X5 for leaf, stubble, grain and culm, respectively (see, Section 2.2). These rates also differ for each growth stage (Table 2.3)

Table 2.3 Trash factors for the transfer of dead tissue to trash, in the different growth stages. (Source code reference are given in parenthesis).

Plant Structure	Growth Stage		
	Seed	Seed fall	Dormant
Stubble (X6)	0.001 [A,176]	0.005 [A,198]	0.500 [A,210]
Leaves (X7)	0.001 [A,177]	0.005 [A,199]	0.005 [A,211]
Grain (X4)		0.300 [A,193-196]	0.500 [A,208]
Culm (X5)		0.005 [A,197]	0.002 [A,209]

The trashing rates (kg ha^{-1} d^{-1}) in the dormant growth stage for SD, BD, GD and CD (see, Section 2.2) are as follows;

[A,208]	X(4)	= 0.5 * GD	grain
[A,209]	X(5)	= 0.002 * CD	culm
[A,210]	X(6)	= 0.005 * SD	stem
[A,211]	X(7)	= 0.005 * BD	leaf

Use of this transfer matrix X permits daily computation of the standing dead mass balance (kg ha^{-1}). The actual gain in dead tissues due to senescence for plant organs, stubble, leaf grain, and culm are defined as:

[A,425]	BD	= BD + X(2) - X(7)	leaf
[A,427]	SD	= SD + X(1) - X(6)	stem
[A,429]	CD	= CD + X(9) - X(5)	culm
[A,431]	GD	= GD + X(8) - X(4)	grain
[A,433]	RD	= RD + X(3)	root

The amount of trash accumulated (kg ha^{-1} d^{-1}) is constituted of the sum of the daily transfers of mass from the different plant organs ;

[A,435] TRD $= TR + X(4) + X(5) + X(6) + X(7)$

2.7 Soil mass balances

2.7.1 Water balance

Water is indispensable to the growth, development and maintenance of vegetation. A schėmatic representation of the different components involved in the water balance of a vegetative surface are given in Fig 2.6

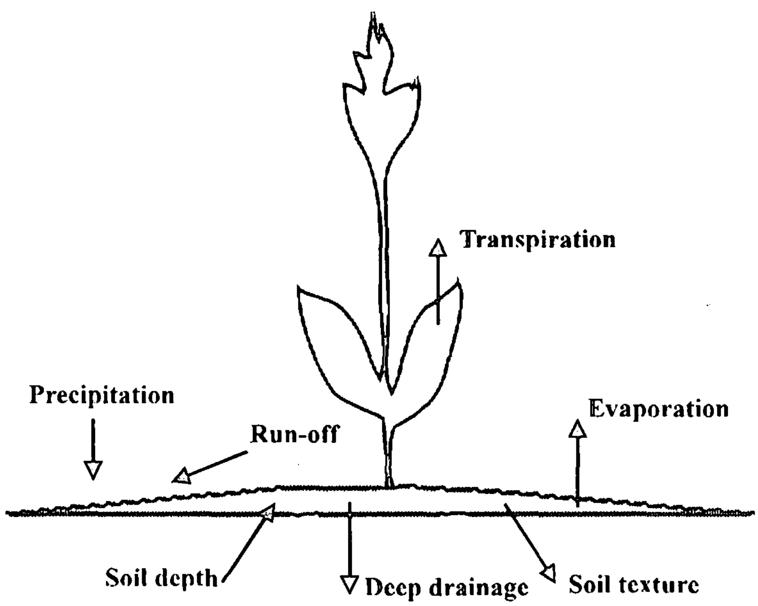


Figure 2.6 Components of the water balance model at a vegetative surface.

Stochastical and Markov matrix simulation of surface balances whereby one variable (rainfall) was measured and the rest simulated have been attempted (Richardson, Hanson & Huber, 1987). Other models have concentrated on only certain components. Such as for example, the equations for determining the effective rainfall (Snyman & Van Rensburg, 1986), evapotranspiration (Makink & van Heemst, 1975) and soil moisture status (Renard, Shirley, Williams & Nicks (1987). Since weather determines the ultimate control on plant water use and growth, most operational models seek to use weather data input to simulate these aspects. The most important component is evapotranspiration, about which much has been written pertaining to grassland (De Jager et al, 1980; Hayes, O'Rourke, Terjung, & Todhunter, 1982; Van Keulen, 1982; Wight, Hanson & Whitmer, 1984; Wight, Hanson & Cooley, 1986; Wight & Hanson, 1988).

Wisiol (1987) reviewed eight equations with reference to the water balance and plant production. Most important was the equation of Penman (1948) later modified by Monteith (1965) as quoted by Thornley & Johnson (1990). The formulation of this, known as the Penman-Monteith equation is as follows;

$$E = \frac{s \oint N + \lambda \gamma G_a \Delta P_{va}}{\lambda[s + \gamma(1 + G_a / G_c)]} \qquad [2.34]$$

where:

E = Transpiration (mm d^{-1})

$\oint N$ = Energy available for evaporation (J m^{-2} d^{-1})

ΔP_{va} = Vapour density deficit (kg m^{-3})

G_c, G_a = Canopy and boundary layer conductances (m s^{-1})

λ, γ, s = Physical parameters (MJ kg^{-1}, kg m^{-3} K^{-1}, kg m^{-3} K^{-1}; respectively)

In the PUTU grassland models the Priestley-Taylor variant of this equation is used. When wind and atmospheric vapour measure are available Eq 2.34 is used.

The potential short grass evaporation rate in mm d^{-1}, E_o, is estimated using the Priestley- Taylor equation modified for high temperatures (see De Jager, 1992). Thus the normal expression

$$E_o = 1/\lambda[\Delta/(\Delta + \gamma)]1.28(R_n - G)$$

reads $E_o = 1/\lambda[\Delta/(\Delta + \gamma)]1.28[0.63RFD]$ for $T_{mx} < 20$ °C

or $E_o = 1/\lambda[\Delta/(\Delta + \gamma)][1.28 + 0.08(T_{mx} - 20)][0.63RFD]$ for $T_{mx} > 20$ °C

where: λ = the coefficient of latent heat of evaporation at constant temperature (2.45 MJ kg^{-1} or 2450 J g^{-1})

Δ	= the slope of the saturation vapour pressure temperature curve (kPa °C^{-1})
γ	= the psychometric constant (kPa °C^{-1})
T_{mx}	= daily maximum air temperature (°C^{-1})
R_n	= net radiant flux density (W m^{-2})
G	= soil heat flux (W m^{-2})
RFD	= Radiant flux density (W m^{-2})

In the PUTU 14 model, the algorithms for the Priestley-Taylor formula are:

[A,342]		PE = PECONS * EE	[2.35]
	where:	PECONS = Parameter in the Priestley-Taylor formula	
		EE = Equilibrium evaporation (mm d^{-1})	
[A,339]		PECONS = 1.28 for AMXT < 20 °C	
	or:		
[A,340]		PECONS = 1.28 + 0.08 * (AMXT -20) for AMXT > = 20 °C	
[A,341]		EE = GS * 0.63 * RFD / 2.45	
	where:	GS = Δ / (Δ + γ) and is given by	
[A,326]		GS = 0.4019914+).01725101*ATEMP-0.0001485* $ATEMP^2$	
		RFD = Radiant flux density (W m^{-2})	

Soil properties like depth and texture determine the amount of water stored in the soil profile as well as the availability of the water for plant growth and production (Hillel, 1977). To simulate growth and production these factors need to be taken into account. Most of all, the water balance equations have to be properly calibrated and validated.

De Jager <u>et</u> <u>al</u> (1980), illustrated the usefulness of the water stress function, F_w, in the PUTU 11 grassland simulation model for assessing production potential in grassland. Snyman (1982) compared results given by PUTU 11 with measured Et/E_0-coefficients. He concluded that the PUTU grassland simulation model, accurately simulates soil water status.

The depth of the rooting zone (SDP = 300 mm here) is an important input parameter. Computation proceeds in two layers, the surface layer being SDP1 = 100 mm [A, 38]. In PUTU 11, Booysen (1983) and Fouché (1984, 1992) simulated the soil water retention curve using the method originally developed by De Jager (1976) for PUTU 2. For the PUTU 13 and 14 models the soil moisture potential (GWP) is simulated following the work of Campbell (1977). The author and Fouché (1992) computed this as follows;

[A,324]	GWP	= -1500 * (WJ / WHC4) ^ M1	[2.36a]
where:			
[A,44]	M1	= (LOG(10) - LOG(1500)) / (LOG(WHC1) - LOG(WHC4))	
[A,404]	WJ	= SLWAT(J+1)*100 current day soil water content (%)	
[A,27]	WHC1	= water holding capacity at 10 kPa (%)	
[A,28]	WHC4	= water holding capacity at 2440 kPa (%)	
[A,401]	SLWAT(J + 1)	= soil water content of the previous day (mm)	

Both WHC1 and WHC4 are calculated from the clay content of the soil, using the Hudson equation as quoted by De Jager, van Zyl, Kelbe & Singels (1987).

This differs markedly from PUTU 11 where an exponential spline function is used. Four splines apply and the computational procedure is here included for comparative purposes.

```
                    WJ    = SLWAT(J) / SDP * 100
                    AI1   = ((log(2440)-log(148.1))/(WHC3-WHC4)
                    AI2   = ((log(148.1)-log(22.1))/(WHC2-WHC3)
                    AI3   = ((log(22.1)-log(10))/(WHC1-WHC2)
     where:         WJ    = % Soil moisture
                    SDP   = Soil depth (mm)
               if   WJ    > = WHC3 then             go to A
                    WST   = WHC4 : GWPST = 24.4
                    COEF  = -1 * AI1                go to C
A              if   WJ    > = WHC2 then             go to B
                    WST   =  WHC3 : GWPST =  1.48
                    COEF  =  -1 * AI2          go to C
B                   WST   =  WHC2 : GWPST =  .22
                    COEF  =  -1 * AI3
```

thus:

```
C                ARGU  =  COEF * (WJ-WST)                    [2.36b]
                 GWP   =  GWPST * EXP(ARGU)                  [2.36c]
                 GWP   =  GWP * (-100)
```

The difference between the retention curves of PUTU 11 and PUTU 14 is illustrated in Fig 2.7. It is evident that only at soil moisture percentages lower than 5 %, do soil water potentials differ. The simulation in PUTU 14 is preferred, because the manner in which it is constructed ensures reliability at the dry end of the water content range.

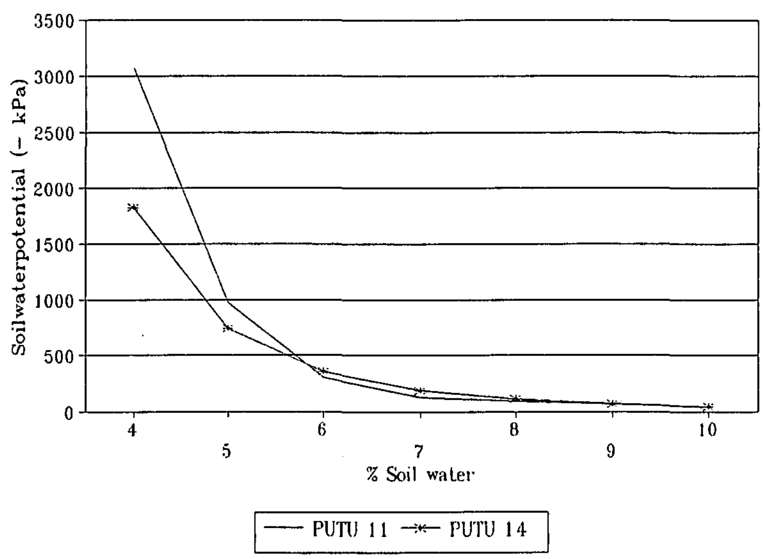


Figure 2.7

Difference in calculated soil water potential between the PUTU 11 and PUTU 13 and PUTU 14 simulation models.

The daily soil water balance is computed using the finite layer (reservoir) cascade technique. Firstly, only when the soil water content, in the surface layer SLWAT1(J) exceeds the field capacity of that level ,FC1, will access water drain (DRAIN1) to the second soil layer. If the soil water content in the rest of the soil profile, SLWAT2(J), exceeds the field capacity, FC2, of this layer, then only will deep drainage take place out of the root zone, DRAIN2. This water is lost to the vegetation. These processes are simulated as follows:

[A,375,376]	SLWAT1(J)	= SLWAT1(J) + RAINF + IRRIG - TRANS1 - SLVAP (mm)
Should	SLWAT1(J) > FC1 then	
[A,383]	DRAIN1	= (SLWAT1(J) - FC1)* DRN1P (mm)
[A,382]	DRN1P	= 1 rate of drainage parameter
[A,67]	RAINF	= Daily Precipitation (mm)
	IRRIG	= Irrigation (mm)
[A,371]	TRANS1	= Daily transpiration (mm)
[A,370]	SLVAP	= Soil vaporation (mm)

Finally, the soil water content in the surface layer is computed

[A,385]	SLWAT1(J)	= SLWAT1(J) - DRAIN1

A similar process occurs in the second layer, viz.

[A,386]	SLWAT2(J)	= SLWAT2(J) + DRAIN1 - TRANS2
[A,389] should	SLWAT2(J) > FC2 then	
[A,390]	DRAIN2	= (SLWAT2(J) - FC2) * DRAINP
where,		
[A,33]	DRAINP	= 0.9
[A,391]	DRAIN2	= 0 for DRAIN2 < = 0
[A,392]	SLWAT2(J)	= SLWAT2(J) - DRAIN2

For grass species with shallow roots, which effectively saturate the root zone, this simple model has shown to be reliable (Fouché, 1992; du Pisani; 1992).

Soil evaporation and transpiration rate

The rate of evaporation from the soil surface and transpiration are computed following, De Jager, Van Zyl, Bristow & Van Rooyen (1982).

First the proportion of potential evapotranspiration used in transpiration, B, is determined using an empirical relationship;

[A,346-348]	B	= (0.1 + (AL / 3) * 0.9)
[A,371]	TRANS1	= B * FW * PE

Daily potential plant evaporation is assumed equal to the difference between PE and transpiration, TRANS. Thereafter evaporation from the soil surface SLVAP is assumed to decay exponentially (as quantified by FG the drying parameter) with time since the previous wetting event of > 5 mm, CNT(J + 1).

[A,361-364]	FG	= EXP(-0.5 * CNT(J + 1)
[A,370]	SLVAP	= (1 - B) * FG * PE

The surface soil layer however is not allowed to dry below permanent wilting point of layer one, PWP1, in which case it is constrained by;

[A,373]	SLVAP	= SLWAT1(J) - PWP1
[A,371]	TRANS1	= B * FW * PE

Run-off is computed using a simple run-off routine described by Jones & Kiniry (1986) [A, 365 - A, 369]. It is important that each of these components appear in the soil water balance calculations.

2.7.2 Nitrogen balance

Haynes (1986) reviewed factors involved in the nitrogen balance of an ecosystem (see Fig 2.8). Nitrogen mineralization, -immobilization, -leaching and -uptake are factors involved in the maintenance and balance of such an ecosystem. The rate of these processes are however dependant on external factors i.e. temperature, carbon to nitrogen ratio in the soil organic matter, water penetration, nitrogen demand and rate of nitrogen application.

A mechanistic simulation of N-mineralization, N-immobilization, N-leaching, N-uptake and distribution through the plant was included in the PUTU 14 model. Singels & Manley (1991) gave detailed reasons for choosing the model of Seligman & Van Keulen (1981) and Van Keulen & Seligman (1987).

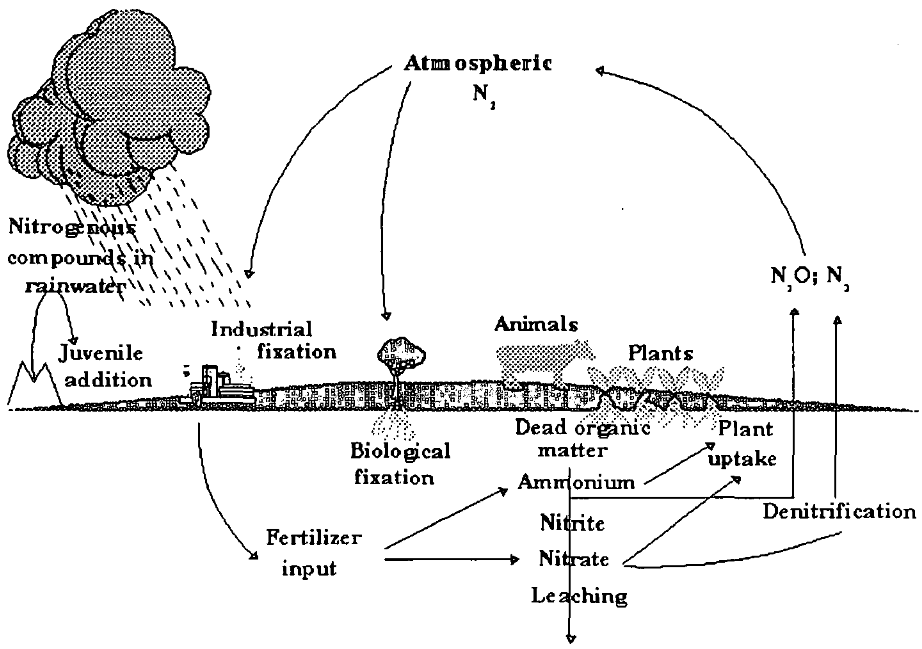


Figure 2.8 Nitrogen balance in an ecosystem (Haynes, 1986)

It was found to operate reliable for wheat (Singles & Manley; 1991). A brief description of this model and the processes simulated in the soil-plant system will now be given. As far as possible, shortcomings will also be highlighted. Computer code for the soil - and plant nitrogen balance is available in Appendix B and C, respectively.

Soil Nitrogen balance

Plant and animal residues decompose and make N available (mineralization) to the vegetation. This assists recirculation of carbon (CO_2) to the atmosphere (Haynes, 1986). The decomposition of fresh organic matter thus has an impact on maintaining a nitrogen balance (Floate, 1981; Woodmanse, Vallis & Mott, 1981). Factors that influence the rate of decomposition are temperature (Alexander, 1977) and soil water (Wilson & Griffin, 1975) and C/N ratio of organic matter (Aber & Melillo, 1980). Models simulating this process have been reviewed by Frissel & Van Veen (1981) and De Willegen & Neeteson (1985)

The model takes external rate limiting factors for temperature (FTMIN), soil water (FWMIN) and carbon/nitrogen ratio in the organic matter (FCNR) into account when simulating the decomposition rate of organic matter, or mineralization (DECR). The fundamental algorithm is;

[A,18]	DECR	= RDECR(L) * FTMIN * FWMIN * FCNR (d^{-1})
where:	DECR	= decomposition rate of fresh organic matter (d)
[B,9-1]	RDECR(L)	= maximum fraction of organic matter decomposed (0.8, 0.05, 0.0095 kg $ha^{-1}d^{-1}$, depending on the FOM(L)/IFOM(L) ratio defined below)
[B,12]	FTMIN	= 1/(1 + EXP(-0.15 * (T(L) -16)))
[B,13]	FWMIN	= 1 / (1* EXP(-GWP/1500))
[B,15]	CNR	= C:N ratio
[B,16-17]	FCNR	= EXP(-0.693 * (CNR -25) / 25)
[B,22]	FOM(L)	= fresh organic matter in soil layer L (kg ha^{-1})
[A,452]	IFOM(L)	= initial amount of fresh organic matter in soil layer L ($kgha^{-1}$)
[A,445]	T(L)	= average daily soil temperature in layer L (°C)
[A,324]	GWP	= soil water potential (kPa)

The expression [B,13] for FWMIN represents a marked change from the function used by Singels & Manley (1991). It appeared that the exponential function for describing water limitations on mineralization rate, better quantified these process in the current PUTU 14 model. The original expression read;

	FWMIN	= ((V(L)-V15(L))*.5/(V01(L)-V15(L)*.5)
where	V(L)	= soil water content (mm m^{-1})
	V01(L)	= Soil water content at -10 kPa (mm m^{-1})
	V15(L)	= Soil water content at -1500 kPa (mm m^{-1})

Graphical representations of factors FTMIN, FWMIN and FCNR on the decomposition rate of organic matter are given in Fig 2.9 - 2.11, respectively.

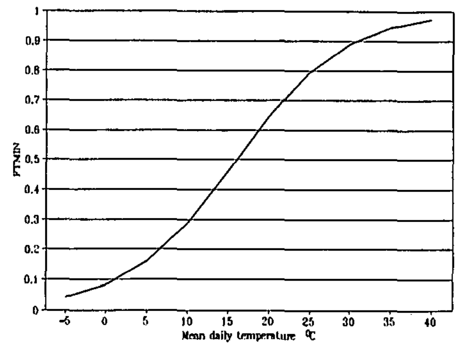


Figure 2.9 Relationship between mean daily soil temperature and a function describing how temperature limits mineralization rate.

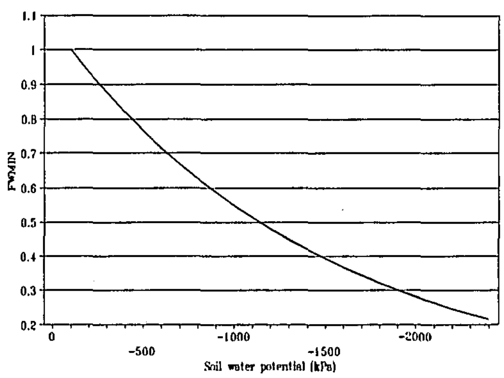


Figure 2.10 Relationship between soil water potential and the function for describing how soil water limits the rate of mineralization

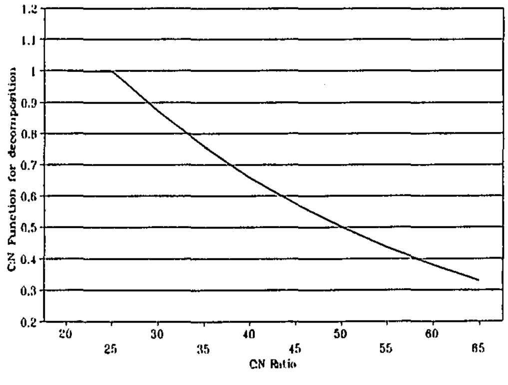


Figure 2.11 Relationship between C:N ratio and the function describing how C:N ratio limits rate of decomposition of organic matter.

N-mineralization from fresh organic matter and stable organic matter (humus) are computed by factors NMINFOM(L) and NMINHUM(L), respectively; in the following manner:

[B,19]	NMINFOM(L)	= NFOM(L) * DECR
[B,24]	NMINHUM(L)	= NHUM(L) * DMINR * FWMIN * FTMIN

where,

NFOM(L)	= nitrogen in fresh organic matter for soil layer L (kg ha^{-1})
NHUM(L)	= nitrogen in humic fraction for soil layer L (kg ha^{-1})
DMINR	= relative decay rate of humus ($8.3 * 10^{-5}$)

Nitrogen immobilization rate from fresh organic matter is given by NIMMFOM(L), and thus net mineralization rate NMINNET(L), and computed, thus:

[B,20]	NIMMFOM(L)	= DECR * FOM(L) * 0.02
[B,25]	NMINNET(L)	= .8*NMINFOM(L) + NMINHUM(L)-NIMMFOM(L)

Once NMINNET(L) exceeds zero, nitrogen is mineralized and added to the ammonium fraction NH4(L). However, nitrogen can also be immobilized into the organic fraction. This phenomena will take place when NMINNET(L) drops below zero [B, 25-28).

Indications that nitrogen in the form of NH_4^+ nitrifies to NO_3^- have been reported by Van Veen & Frissel (1981,1982) and Haynes (1986). Lees & Quatel (1946) as quoted by Kruh & Segal (1980) and Hagin & Welte (1984) used the following equation to describe such nitrification rate;

$$\mathrm{LOG}\ \frac{(NO_3^-)_N}{M - (NO_3^-)_N} = K\,(t - t_{1/2})$$

where,

K	= constant
M	= asymptotic value of $(NO_3^-)_N$
$t_{1/2}$	= time when $(NO_3^-)_N$ = M/2

In the PUTU 14 model, this process is simulated by a simple nitrification routine for each soil layer, which states that 25 % of NH_4^+ nitrifies per day [B, 32-37] (see Singels & Manley, 1991).

The balance between the loss of nitrogen through leaching in rain water and the nitrogen applied determine the amount of nitrogen available for dry matter production, AN(L), and thus daily dry matter gain [B, 50-54). The mineral nitrate status of the soil profile ANC(L) is determined as follows:

[B,51]	AN(L)	= ((NO3(L)-1) + (NH4(L)-1)*.9)
[B,53]	ANC(L)	= AN(L) / W(L)

where,

AN(L)	= available inorganic nitrogen in the soil for soil layer L (kg ha^{-1})
ANC(L)	= Nitrate content of soil water for layer L (kg ha^{-1} mm^{-1})

Mineralization rate of organic matter is not only a function of the environmental factors. The amount and concentration of stable organic matter HUM(L) and fresh organic matter FOM(L) present in the soil also greatly influence mineralization rate. In this study these values were guesstimated, because of lack of information. This must be remembered should any application of these results be contemplated.

Unfortunately microbial biomass could not be incorporated in the present model. Van Keulen (1982) listed the problems preventing this. Studies to investigate the influence of microbial population size for decomposing organic matter under dryland conditions with species like *D. eriantha* etc. are required.

Exponential relationships for FTMIN and FCNR and FWMIN are here assumed. Whether these hold true under different climate and soil conditions are debatable.

Plant Nitrogen balance

Nitrogen uptake (NUP) by the vegetation is extracted from the transpiration flux of water (TNFLO). It is further influenced by the maximum nitrate uptake rate which the canopy can accommodate (NUPO), the demand for nitrogen from the vegetation (TNDEM), and the amount of soil nitrogen available to the plant for the growth process (TOTAN). Once these are accounted for, nitrate will be withdrawn from the soil [C, 56-

62] and distributed amongst the plant organs in proportion to there relative mass and demand for nitrate. Thus by the law of the minimum;

[C,43-47]	NUP	= MIN(TNFLO,NUPO,TNDEM,TOTAN)
where,		
	COMP	= subscript referring to the different plant components root(1),culm(2) and leaf(3) (kg ha^{-1})
[C,42]	TNFLO	= TNMASFLO + TNDIFFLO
[C,23]	NUPO	= 6*(1-EXP(-.005*(TOTMASS(2) + TOTMASS(3))))
[C,19]	NDEM(COMP)	= TOTMASS(COMP)*(NCMAX(COMP)-NC(COMP))/2
[C,21]	TNDEM	= ΣNDEM(COMP)* EOSF
[C,35]	TOTAN	= AN(L)
[C,24-30]	TNMASFLO	= nitrate due to mass flow (kg ha^{-1} d^{-1})
[C,38]	TNDIFFLO	= nitrate flow by diffusion (kg ha^{-1})
	TOTMASS(COMP)	= mass in different organs (kg ha^{-1})
[C,17]	EOSF	= factor preventing uptake after maturity

Nitrogen distribution amongst the plant organs is a function of individual plant organ demand for nitrogen in relation to the total demand and the uptake rate, hence:

[C,63]	DN(COMP)	= NDEM(COMP)/TNDEM*NUP
[C,64]	N(COMP)	= N(COMP) + DN(COMP)
[C,65]	NC(COMP)	= N(COMP)/TOTMASS(COMP)
where,		
	DN(COMP)	= fraction of nitrogen distributed to plant organ COMP (kg ha^{-1})
	N(COMP)	= nitrate content for root, culm and leaf, respectively (kg ha^{-1})
	NC(COMP)	= nitrate concentration for root, culm and leaf, respectively (kg kg^{-1})

Once simulation of the reproductive growth has been initiated, seed growth commences. The availability of nitrate for the production and formation of seeds depends on;

- the nitrogen demand created by the seeds DN(4), and
- the nitrogen status in the individual plant organs PAN(COMP) (for root, culm and leaf).

Demand set by the seeds DN(4) depends upon the mass of the seeds (TOTMASS(4)), the difference between the optimum and current nitrate concentration (ONC- NC(4)) in the seeds and a reduction factor reflecting nitrogen deficiency in the leaves (RFNS) [C, 55-60].

If the current nitrogen concentration in a given plant organ exceeds the limit set for that organ, then nitrate will be available for growth of seeds. Plant available nitrate PAN(COMP) is a function of:

[C,66] PAN(COMP) = (NC(COMP)-NCMIN(COMP))*TOTMASS(COMP)

where,

NCMIN(COMP) = Minimum nitrogen concentration for root, culm and leaf, respectively (kg kg^{-1})

Withdrawal of nitrogen from plant organs to meet the demand by seed is then computed,

[C,70] DN(COMP) = DN(4) * PAN(COMP)/TPAN (kg kg^{-1})

thus,

[C,71] N(COMP) = N(COMP) - DN(COMP)

where,

TPAN = Total plant available nitrogen for distribution to the seeds (kg ha^{-1})

Nitrogen distribution to the seeds in growth stage four has been modified from the function used by Singels & Manley (1991) in a wheat model to the approach used by Seligman & Van Keulen (1980), viz

DN(4) = MIN(NTRANSMAX, NDEM(4) (Singels & Manley; 1991) to

DN(4) = TOTMASS(4) * (ONC - NC(4)) * RFNS (Seligman & Van Keulen, 1980)

To compute the growth limiting factor due to the nitrate status in the leaves (FACN) for processes such as dry matter assimilation; the following equation applies;

[C,76] FACN = (NC(3)-NCMIN(3))/(NCOPT(3)-NCMIN(3))

where:

NC(3)	= nitrate concentration in the leaves (kg kg^{-1})
NCMIN(3)	= minimum nitrate concentration in the leaves (kg kg^{-1})
NCOPT(3)	= optimum nitrate concentration in the leaves (kg kg^{-1}) Currently assumed to 80 % of the maximum nitrogen concentration in the leaves.

Daily dry matter gain (DMG) is then expressed as the product of CO_2 assimilation and the growth limiting factor due to nitrogen status of the leaves (FACN).

The Van Keulen & Seligman (1987) model here employed, is a first attempt which could be refined.

Certain principal questions still remain to be answered, such as for example

1. What is the true maximum and minimum nitrogen concentration in the different plant organs for *D. eriantha* ?
2. How do these concentrations change with growth stage from vegetative through to dormancy ?
3. Living and dead tissue mass were lumped for each plant organ. To what extent can nitrogen be withdrawn from dead material ?
4. To what extent does the nitrogen content in the leaves of *D. eriantha* influence dry matter production? and
5. Does the seed withdraw all nitrogen available for seed growth. Since the importance of seed formation in perennial dryland cultivated pasture is merely for reproduction. While seed production constitutes the economic product of annual species such as maize and wheat.

2.8 Calibration of the PUTU 14 model for *D. eriantha*

2.8.1 Method

Accepted modelling procedures prescribe the use of independent data sets for calibration and validation. Field data procurable (from Dannhauser; 1985) on *D. eriantha* for the 1978/79 season were selected for calibration. Data obtained during the 1979/80 season and data obtained during the 1981/82, 1982/83 and 1983/84 season on both an Avalon and Valsriver soil were used for validation of the refined PUTU 14 model (see Chapter 3).

The simplifications and modifications brought about to the model are detailed in the preceding sections of Chapter 2. The PUTU 14 including these refinements was then calibrated by trial and error. The 1978/79 season proved to be particularly appropriate for this purpose as it was a season in which water limited production, thereby providing a thorough test of the water stress routine.

2.8.2 Results

The parameters calibrated and values obtained are given in Table 2.6, which indicates changes from the values used in PUTU 13. The realistic shape of the simulations obtained in Quadrants A and B in Fig 2.12 verify the functioning of PUTU 14, as does the good agreement between final yields illustrated in Quadrant C.

On this evidence, the model verification and calibration of PUTU 14 may be deemed to have been successful. The data available were few and hence use of the standard statistical test of significance (correlation coefficient, mean square error etc. or even the boot strapping techniques) have limited value. For interest, comparison of simulated versus measured yields for the n = 3 sets of data are given in Table 2.4.

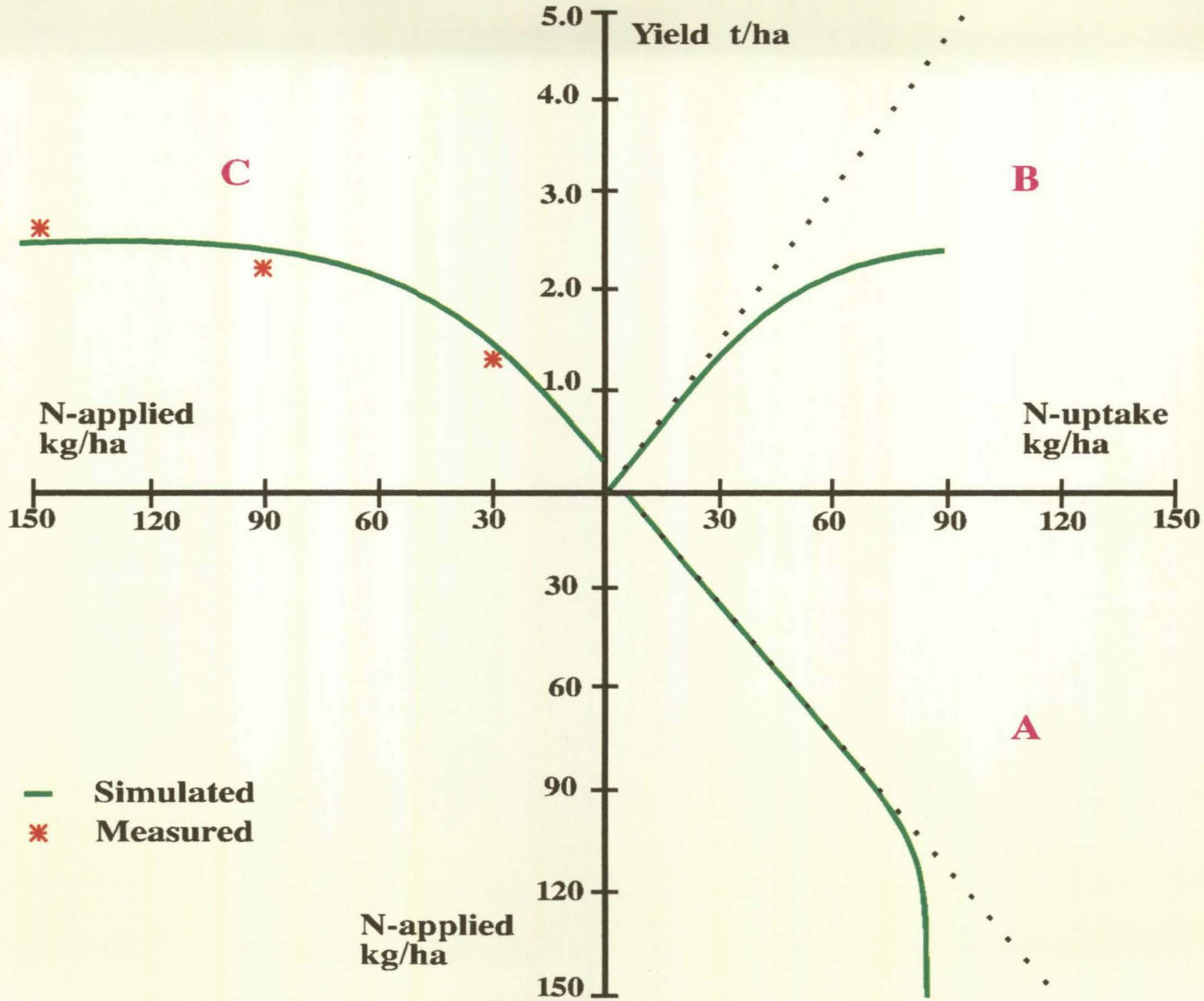


Figure 2.12 Simulated nitrogen applied, simulated N-uptake, simulated production and measured final yields at three N-levels for the 1978/79 growing season at Potchefstroom.

Statistical analyses

Results of the statistical tests undertaken during calibration are given in Table 2.4.

Table 2.4 Model performance during calibration (1978/79) on a Westley soil (n = 3). MAE = mean absolute error, RMSE = root mean square error, $RMSE_s$ = systematic error, $RMSE_u$ = unsystematic error, D = Wilmott index of agreement and r^2 = coefficient of determination.

Soil Type	MAE t ha^{-1}	RMSE t ha^{-1}	$RMSE_s$ t ha^{-1}	$RMSE_u$ t ha^{-1}	D	r^2	Slope through origin
Westley	0.066	0.077	0.04	0.06	0.99	0.98	0.98

Indication of the good agreement between measured and simulated yield are given by the low MAE and RMSE. The MAE and RMSE are 0.06 and 0.07 t ha^{-1}, respectively. Which is relatively small by modelling standards.

Both the Wilmott index of agreement (D) (Wilmott, 1982) and the coefficient of determination (r^2) approach unity. This is not surprising in view of the view data sets (n = 3).

2.8.3 Discussion

Rainfall

From Table 2.5 it is clear that only September, October and May had more rain than the long term mean for 1978/79. The annual total rainfall was 435.8 mm, or 70 % of normal (625 mm). Furthermore, apart from the early season, 1978/79 was a poor growing season in which water stress probably occurred, making this season ideal for calibration of water stress on growth.

Table 2.5 Mean monthly rainfall (mm) for the Agriculture Development Institute of Potchefstroom in relation to the monthly mean for 1978/1979.

Growth season	Month												
	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Total
1978/79	0	7.5	23.3	83.7	16.7	79.6	84.6	54.5	34.4	17.2	33.4	1	435.8
% of Mean	0	80	119	148	20	83	72	61	46	29	233	17	70

Dry matter gain

The rates of dry matter assimilation and therefore daily dry matter production differ greatly from specie to specie. The new expression for

[A,105] $P = RCC * RFD * (F / 100)$

included in PUTU 14 accommodates construction and maintenance differently to the previous models. The value of RCC = 3.1 $\mu g\ J^{-1}$ does however seem to provide reliable growth simulation of *D. eriantha*.

Phenology

The most marked changes came in the phenological controls. These are listed in Table 2.6. Such specie differences were to be expected.

The change in BO from 12 °C for *C. ciliaris* to 10 °C for *D. eriantha* mean that the latter reaches the reproductive stage considerably quicker than the former. Furthermore, since the adaptation for the latter for water stress permits HUCRMN to decrease to only 230 °C rather than 225 °C shows that *D. eriantha* is less adaptable to

Table 2.6 New values of variables resulting from the calibration of PUTU 14 on 1978/79 season data.

GROWTH PROCESS	GROWTH STAGE	VARIABLE	UNITS	PUTU 13	PUTU 14	LINE
Phenology	1	HUCRMN	°C	225	230	129
	1	BO	°C	12	10	89
	1					126
	1					127
	1					130
	2	MKOUNT	d	60	30	146
	3	MKOUNT	d	100	80	164
	1	BCON	kg ha^{-1}(d °C)$^{-1}$	2.0	3.5	130
Dry matter assimilation	1-4	RCC	µg J^{-1}	3.5	3.1	102
Translocation rate	2	DPROC		0.25	0.2	417
	3	DPROG		0.05	0.09	418
	3	DPROC		0.41	0.34	417
Growth limiting factor	1-4	COEF	kPa^{-1}	0.5	0.1	352

water stress than is *C. ciliaris*. It is also a shorter season specie as illustrated by shortening of the MKOUNT routines.

By a process of trial and error, the rate of change of phase from reproductive to seed formation and seed formation to seed fall were determined. These values were fixed at 30 days of reproductive growth and 80 days of seed formation, after which seed fall was initiated. Furthermore, when a minimum temperature of 2 °C was reached, dormancy commenced and carbohydrate translocation is terminated.

Use of a respectively slow and rapid leaf development phases with, BCON = 0.8 and BCON = 2 kg ha^{-1} (d °C)$^{-1}$ appeared (see Booysen; 1983) to overestimate leaf mass. Adoption of BCON = 3.5 kg ha^{-1} (d °C)$^{-1}$ during the vegetative growth stage of *D. eriantha* yielded good results. This single linear growth rate should be tested on other species.

Reproductive growth, seed and seed fall phases

During these three phases, carbohydrate is translocated to the different plant organs in accordance with preferred proportions. These factors differ from growth stage to growth stage. A comparison between the rate of translocation to the different plant organs for *D. eriantha* and *C. ciliaris* are given in Table 2.6. From this it is obvious how the translocation rate between leaf and culm were adjusted. It was assumed that *D. eriantha* requires a higher leaf : culm ratio than *C. ciliaris*.

Factor limiting rate of mineralization of humic compounds due to plant water status

The equation suggested by Singels & Manley (1991) is given in Section 2.7.2. This equation was replaced by [B, 13] in Section 2.7.2. It's accuracy is verified by the realistic cut-off in simulated and measured yield obtained during the 1978/79 growing season, see Quadrant C in Fig 2.12

Nitrogen distribution to seed

The demand for nitrogen in seeds is controlled by several factors. Singels & Manley (1991) suggested that a maximum nitrogen translocation rate to the seeds (NTRANSMA X) and the demand for nitrogen in the seeds (NDEM(4)) regulates the distribution process. These two factors are functions of :

1. The nitrogen turnover in the vegetative parts,
2. Plant available nitrogen,
3. Fraction of nitrogen in vegetative parts available for distribution,
4. Temperature control of translocation to seed
5. Maximum nitrogen demand by the seed.

These controls seem to be realistic for crop models for maize and wheat, but uncertain for perennial dryland cultivated pastures. The availability of nitrogen for distribution to seed is however of primary concern. Algorithm, RFNS, [C, 54 and 56] apparently accommodates the process adequately. Only when nitrogen is available, then does distribution to the seed take place.

CHAPTER 3

VALIDATION OF THE PUTU 14 MODEL

3.1 Introduction

Extensive work has been done by Dannhauser (1985) on *D. eriantha*. Essentially this work endeavoured to assess the feasibility of cultivating *D.eriantha* in the Western Transvaal of Southern Africa. The results however, have never been applied in deterministic models.

Data obtained on a Westley soil included two growth seasons 1978/79, 1979/80 where 3 nitrogen fertilization rates; 30 kg N ha^{-1} + 10 kg P ha^{-1}, 90 kg N ha^{-1} + 10 kg P ha^{-1} and 150 kg N ha^{-1} + 10 kg P ha^{-1} were applied. Although nitrogen and phosphate were applied, the soil profile (Chapter 1) clearly indicates that existing phosphate was adequate to satisfy the demands of *D. eriantha*. Data from the 1979/80 season was used to validate the model, together with data from an Avalon and Valsrivier soil for seasons 1981/82, 1982/83 and 1983/84 with N-application of 60 kg N ha^{-1} + 10 kg P ha^{-1} and 120 kg N ha^{-1} + 20 kg P ha^{-1}, respectively in each year (see Dannhauser; 1985 and Dannhauser, van Rensburg, Opperman & Van Rooyen, 1987).

3.2 Results and discussion

Rainfall

Annual rainfall for 1979/80 may be compared to the long term mean rainfall in Table 3.1. An annual rainfall of 714.4 mm, or 114 % of normal (625 mm) was reported, with 6 out of the 12 months recording more rain than the long term mean.

Table 3.1 Mean monthly rainfall (mm) for the Agriculture Development Institute of Potchefstroom in relation to the monthly long term mean for 1979/1980.

Growth season	Month												
	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Total
1979/80	7.2	84.7	58.3	136.8	81.8	62.0	125.8	112.4	17.9	23.5	4.0	0.0	714.4
% of Mean	191	853	297	241	99	64	107	126	24	40	28	0	114

The 1979/80 season was well endowed with rainfall (114 % of normal). Thus, this fortunately offered an ideal base for testing the nitrogen limitation mechanism of the model.

Yield comparison 1979/80

Yields obtained for *D. eriantha* during 1978/79 (calibration season) and 1979/80 on a Westley soil were 2445 and 5167 kg ha^{-1}, respectively (Dannhauser, 1985). Due to the favourable rainfall, the latter growing season yielded approximately 2700 kg ha^{-1} more than the former. Results obtained with the PUTU 14 model accurately simulated this tendency (see Fig 3.1)

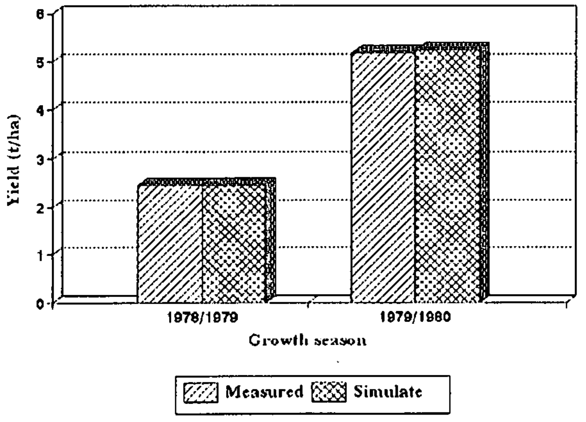


Figure 3.1 Comparison of measured and simulated yields for the 1978/80 and 1979/80 growth seasons.

Regrettably no serial harvesting was undertaken so it was not possible to test the growth pattern simulated by the model through the season.

These comparisons however does suggest reliability of the PUTU 14 model for simulating yield for *D. eriantha*. Significantly, it appears to take into account the affect of natural physical environment (particular water see Section 2.7.1) and nitrogen. The nitrogen balance model incorporated into the PUTU 14 model seems to account for nitrogen balance influences, both in the soil as well as in the plant.

N-distribution

Results of measured and simulated yields at 30, 90 and 150 kg N ha^{-1} obtained during the 1978/1979 growing season for a Westley soil are given Fig 2.12. The decided limitation due to water stress at high nitrogen levels is apparent. Results from the 1979/1980 growing season are shown in Fig 3.2. By contrast measured yields obtained with 30, 90 and 150 kg applied nitrogen ha^{-1} showed a steady increase from 1456, through 3302 to 5167 kg ha^{-1} (see Quadrant C; Fig 3.2). The model predicted this change in biomass production well, giving 1484, 3437 and 4930 kg ha^{-1} (see Quadrant B; Fig 3.2). Nitrogen limitation still prevailed even when 150 kg nitrogen ha^{-1} was applied, as simulated and measured yields were still increasing almost linearly (Quadrant A; Fig 3.2) with applied nitrogen. A tendency to simulate moderate nitrogen stress is apparent from the slight curve in the simulation curve in Quadrant C, Fig 3.2.

Validation on all soils and seasons

Model performance was studied under conditions prevailing on the Western Transvaal of Southern Africa, using the results provided by Dannhauser (1985) and Dannhauser et al (1987).

Effective rooting depth was taken as 1200 mm and 1000 mm for the Avalon and Valsrivier soil, respectively, while clay content of A and B horizon was taken as 15 %

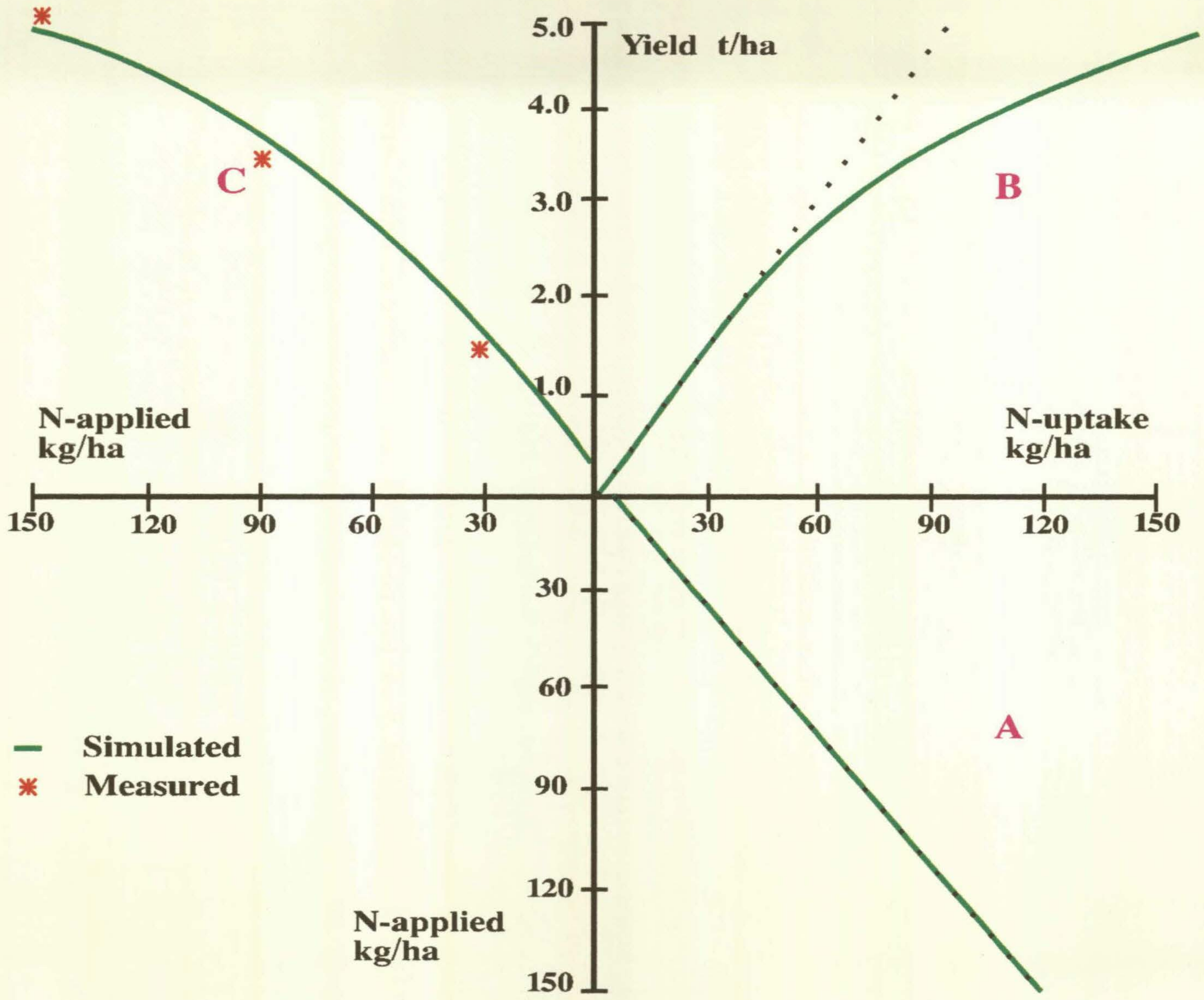


Figure 3.2 Simulated nitrogen applied, simulated N-uptake, simulated production and measured final yields at three N-levels for the 1979/80 growing season at Potchefstroom.

and 35 %. Initial soil water conditions in 1981/82 were assumed the same for both soils at 19.7 and 23.5 % for the two soil layers respectively. In subsequent seasons the soil water content as simulated at the end of the previous season was carried over to the next. The statistical analyses comparing model output to measured yield on three soil types is given in Table 3.2 and Fig 3.3; 3.4 and 3.5.

Field studies, under dryland conditions in respect of nitrate uptake, nitrification, humufication, nitrogen leaching etc, were not undertaken. Thus, it was not possible to test any of the soil nitrogen outputs obtained from the model.

Table 3.2 Model performance and test for Westley (n=3), Avalon (n=6) and Valsrivier (n=6) soils at various N-levels and data from all three lumped together (n=15). MAE = mean absolute error, RMSE = root mean square error, $RMSE_s$ = systematic error, $RMSE_u$ = unsystematic error, D = Wilmott index of agreement and r^2 = coefficient of determination.

Soil Type	n	MAE t ha^{-1}	RMSE t ha^{-1}	RMSEs t ha^{-1}	RMSEu t ha^{-1}	D	r^2	Slope through origin
Westley	3	0.23	0.15	0.11	0.11	0.99	0.99	0.98
Avalon	6	0.89	0.51	0.02	0.51	0.96	0.85	0.98
Valsrivier	6	0.43	0.72	0.58	0.41	0.94	0.89	0.78
Lumped	15	0.35	0.56	0.26	0.50	0.96	0.88	0.90

The resullts attained with the lumped data reflect an accurate validation of the PUTU 14 model. The MAE is low 0.35 t ha^{-1}; as are RMSE, $RMSE_s$ and $RMSE_u$. The coefficient of determination (r^2 = 0.88) is highly acceptable.

The lumped data (n = 15) from all three soils are presented in the scatter diagram in Fig 3.3.

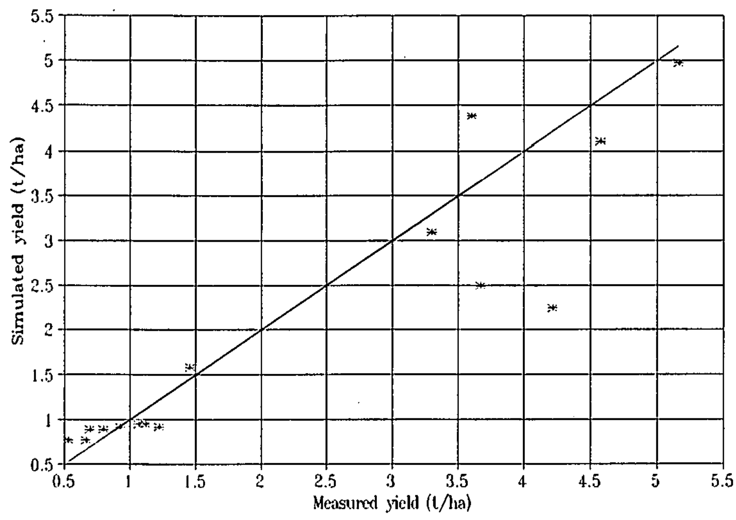


Figure 3.3 Comparison of measured and simulated yield attained for a Westley, Avalon and Valsrivier soil.

Westley soil

Evidence of good agreement between measured and simulated yield is given by MAE and RMSE of less than 0.23 t ha^{-1} for the Westley soil. The $RMSE_s$ and $RMSE_u$ are small by modelling standards and nearly equal, indicating good model performance with little systematic error.

Both the Wilmott index of agreement (D) and the coefficient of determination (r^2) approach unity for the Westley soil because the data sets are few (n = 3).

Avalon soil

Model estimation between measured and simulated yield are less than 0.65 t ha^{-1}, indicating a poor fit. Both the Wilmott index of agreement (D) and the coefficient of determination (r^2) are 0.80, or higher. Results from Fig 3.4 depict poor prediction of yields at 60 kg N ha^{-1} in only the 1981/82 season.

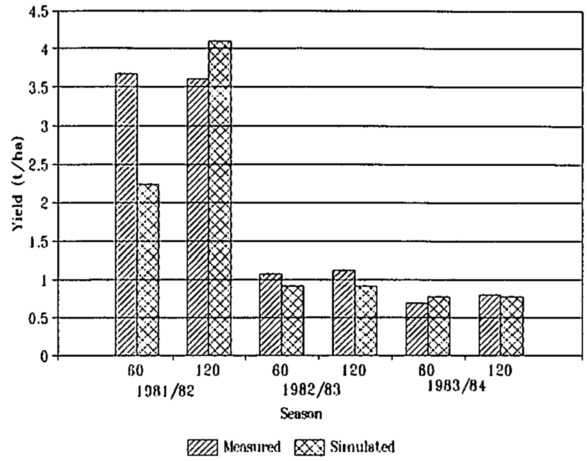


Figure 3.4 Measured and simulated yield for Avalon soil at different soil N-levels for 1981/82, 1982/83 and 1983/84 season.

Valsrivier soil

Model performance tests indicated a reasonable to poor model fit in these conditions. The MAE and RMSE of 0.43 t ha^{-1} and 0.72 t ha^{-1} approach acceptability. Both the r^2 and D value were higher than 0.89. Once again the agreement (see Fig 3.5) was adversely affected by only the 60 kg N ha^{-1} treatment in the 1981/82 season.

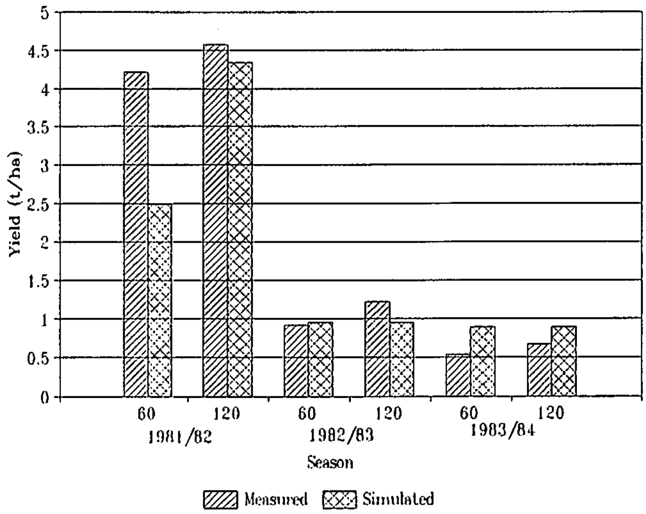


Figure 3.5 Measured and simulated yields on a Valsrivier soil at different soil N-levels for 1981/82, 1982/83 and 1983/84 season.

To conclude, it appears as though the soil N-balance yields were poorly modelled during the 1981/82 seasons at N-application rates of 60 kg N ha^{-1}. This was probably due to using too low soil N-levels at the start of the season (7.5 kg N ha^{-1}). In Fact, when a higher value of 120 kg N ha^{-1} was subsequently substituted, this discrepancy was eliminated. In this regard, Rethman (1987) has indicated the differences in dry matter yield in *D. eriantha* attainable in seasons subsequent to seasons fertilized at different levels of nitrogen. These quantities are essential when modelling the nitrogen balance is undertaken.

Although phosphorus was applied, it appeared in any event to have been optimal. It is important to quantify low levels of phosphorus as this could seriously reduce growth rate.

CHAPTER 4

MODEL APPLICATIONS

4.1 Introduction

Nitrogen application rates need to be chosen according to expected seasonal plant growth, which is primarily determined by rainfall and to a lesser extent existing soil nitrate levels. Due to the unpredictability and variability in rainfall (see Fig 4.1 for Potchefstroom), there is always a certain amount of climatic risk involved in applying nitrate. In poor rainfall years over application occurs and in good rainy seasons under application.

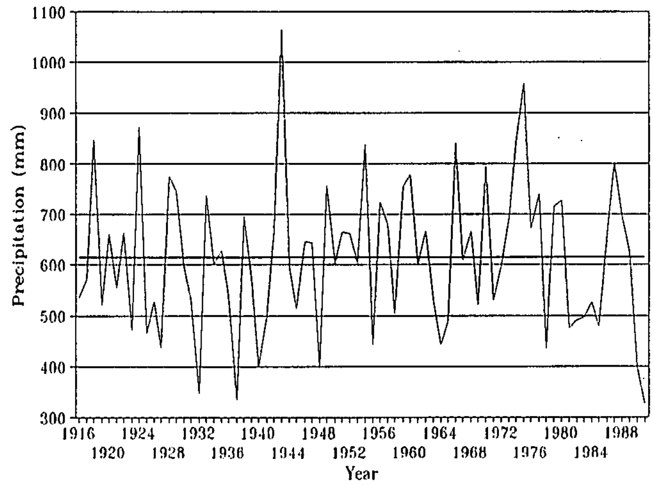


Figure 4.1 Variation in annual rainfall for period 1916 to 1990 at Potchefstroom.

To diminish this risk, solutions are required for questions such as:

1. What is the influence of climatic regime upon yield response to both level and time of nitrogen application ?
2. How may climatic risk at different nitrogen application rates be quantified ?

Both these questions deal with the optimization of nitrogen application rate and climatic risk.

Five growing season rainfall scenarios were selected, viz. bad, poor, moderate, good and wet, in which to assess the influence of timing and level of N-application. These scenarios were defined as periods receiving monthly and seasonal rainfall totals not exceeding what has occurred 10; 30; 50; 70 or 90 percent of the time in the past.

Composite rainfall scenarios

In order to investigate the above two questions, it was necessary to create the five rainfall scenarios bad through wet as defined above. The method of Fouché (1992) was followed. Herein cumulative probability functions of rainfall were established for each month of the year. From these it was possible to extract the monthly totals of rainfall not exceeded 10, 30, 50, 70 or 90 % of the time. These totals are given in Table 4.1. The years in which these totals occurred appear in Table 4.2. Taking the daily rainfall values for these particular months, composite years were constructed with expected monthly and seasonal totals not exceeded 10, 30, 50, 70 or 90 % of the time. Data from these five composites were then used for running the model to estimate yields for bad through wet scenarios.

Table 4.1 Monthly total rainfall (mm) with the given chances of non-exceedance (cumulative probability) for Potchefstroom.

Scenarios	Cumulative Probability %	Month												
		Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Total
Bad	10	0	0	0	15.4	24.2	47.8	50.8	45.4	26.1	4.6	0.0	0.0	214.3
Poor	30	0	0	3.4	29.9	62.6	72.1	89.4	71.0	62.0	21.8	5.3	0.0	417.5
Moderate	50	1.7	1.8	9.5	48.8	90.8	102.6	115.6	88.3	80.6	40.9	11.4	3.0	595.0
Good	70	7.4	11.3	31.6	70.8	110.5	125.8	143.6	128.6	116.8	84.1	33.4	11.9	875.8
Wet	90	32.5	30.7	58.3	106.4	149.7	163.8	188.4	179.5	167.7	105.8	54.8	19.4	1257.2

Table 4.2 Years in which the monthly rainfall totals given in Table 4.1 occurred at Potchefstroom.

Scenarios	Cumulative Probability %	Month											
		Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
Bad	10	1935	1933	1946	1968	1950	1957	1960	1971	1940	1920	1991	1936
Poor	30	1974	1970	1963	1931	1988	1988	1958	1918	1989	1939	1921	1986
Moderate	50	1942	1983	1984	1928	1976	1941	1945	1929	1985	1922	1970	1975
Good	70	1923	1984	1921	1964	1928	1969	1957	1974	1928	1924	1978	1949
Wet	90	1952	1943	1979	1982	1980	1973	1976	1959	1944	1942	1962	1925

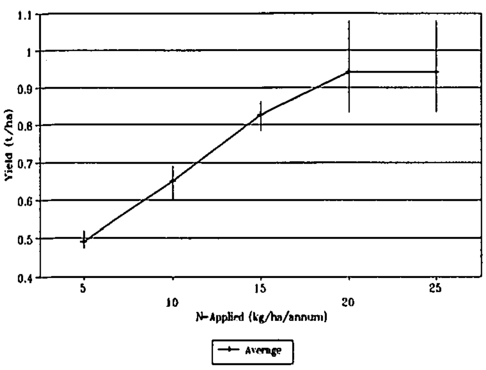
Three dates for applying nitrogen were investigated for each application level. These dates were: 1st September (1), 1st November (2) and 1st January (3).

Table 4.3 Rate of N-application.

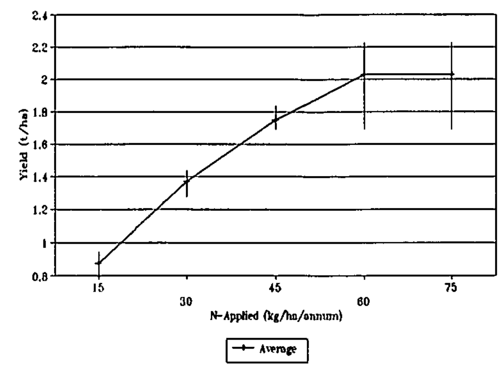
Scenarios	Nitrogen applied (kg ha^{-1})
Bad	5,10,15,20,25
Poor	15,30,45,60,75
Moderate	25,50,75,100,125
Good	35,70,105,140,170
Wet	60,120,180,240,300

4.2 Interaction between climate and nitrogen application

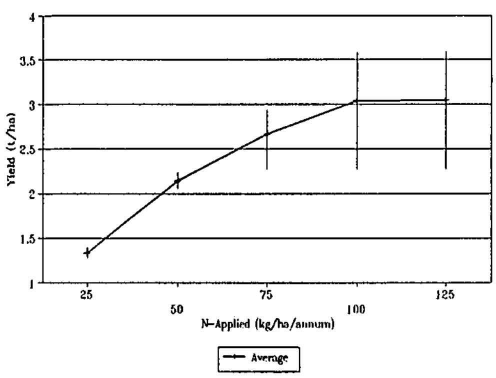
The PUTU 14 model was used to simulate expected yields for the five different climatic regimes, bad through wet at each of the application rates detailed in Table 4.3. Results for each of these simulations are given in Appendix D(1-5). Fig 4.2 (A-E) illustrate the influence of these various climatic regimes and N-application rates upon yield.



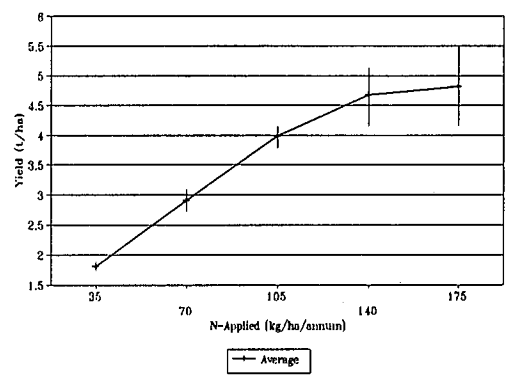
A. Bad



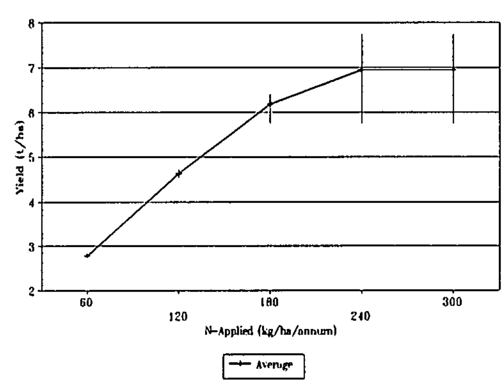
B. Poor



C. Moderate

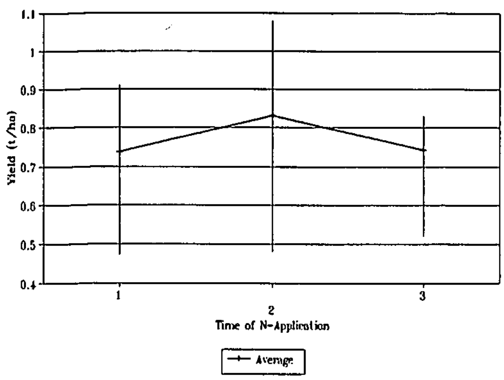


D. Good

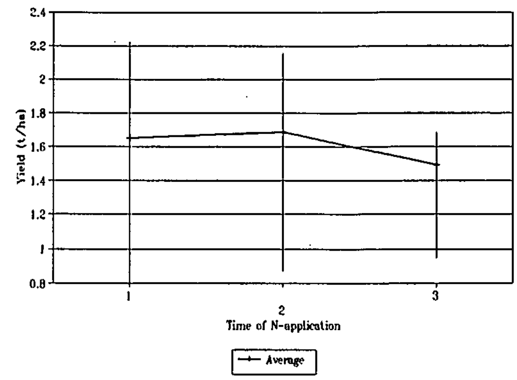


E. Wet

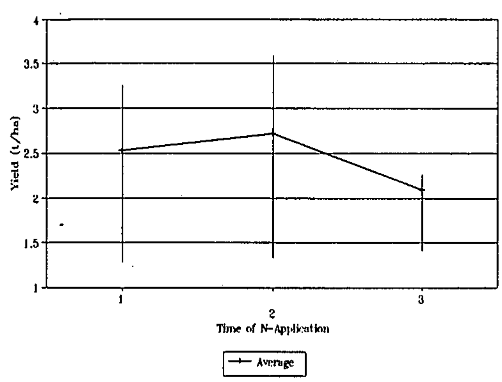
Figure 4.2 Influence of various climatic regimes and N-application rate on yield. The bars indicate the range in yield obtained as a result of different time of application.



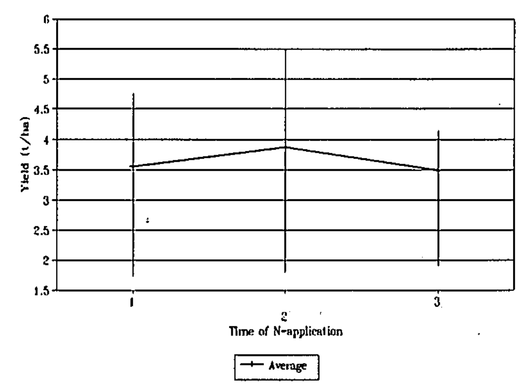
A. Bad



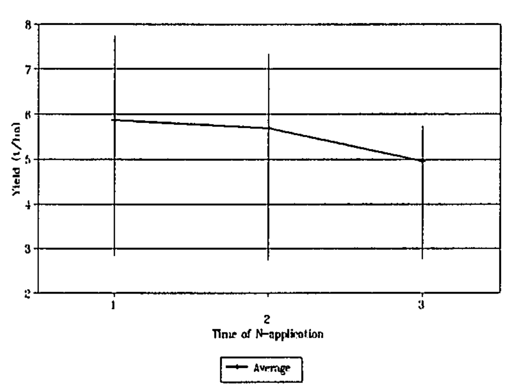
B. Poor



C. Moderate



D. Good



E. Wet

Figure 4.3 **Influence of various climatic regimes and time of N-application on yield. The bars indicate the range in yield obtained as a result of the different levels of applied nitrogen.**

From these figures optimum nitrate levels for each of the five scenarios could be established. These were for optimum yields of 0.9; 2.0; 3.0; 4.7 and 7.0 t ha^{-1}, respectively.

As far as timing of N-application is concerned (Fig 4.3), it is evident that the late (3) N-applications, restricted growth, irrespective of the type of year experienced. There was however a wide range in simulated yields as the level of N-application changed (see bars in Fig 4.3). This implies that the time of N-application is dependent upon the pattern of vegetative growth. An early N-application could result in a loss of N either through leaching or an inability of the plant to immobilize N for growth throughout the rest of the growing season. It appears that a mid-season application (2) could prove to be the best time for applying nitrogen. By comparison, Dannhauser (1988) found a N-application during December to January to be the best.

4.3 Optimization of nitrogen application and climatic risk

Climatic risk is here defined (de Jager, pers. comm.) as the chance of non-realisation of a given yield due to the weather conditions prevailing during the growing season. It is evident that this is equivalent to the cumulative probability of occurrence of a given yield and is obtainable from the cumulative distribution function, CDF (see de Jager and Singels 1990).

Simulations were carried out using actual weather data for the period 1916-1991 at various soil-N levels (0, 30, 60, 90, 120 and 150 kg N ha^{-1} $annum^{-1}$). The results for Potchefstroom are given in Appendix D.6. In order to calculate the level of climatic risk, (cumulative probability of yields at different soil N levels) the techniques of Doll & Orazem (1984) are required. For first order stochastic dominance (SD) a cumulative distribution function (CDF) lying to the right of another will reflect less climatic risk than the other.

Because grassland pastures utilize (in vegetative growth) virtually every drop of water received, the CDF in Fig 4.4 are the same at low yield levels. This is an interesting phenomenon peculiar to grassland perhaps not previously appreciated.

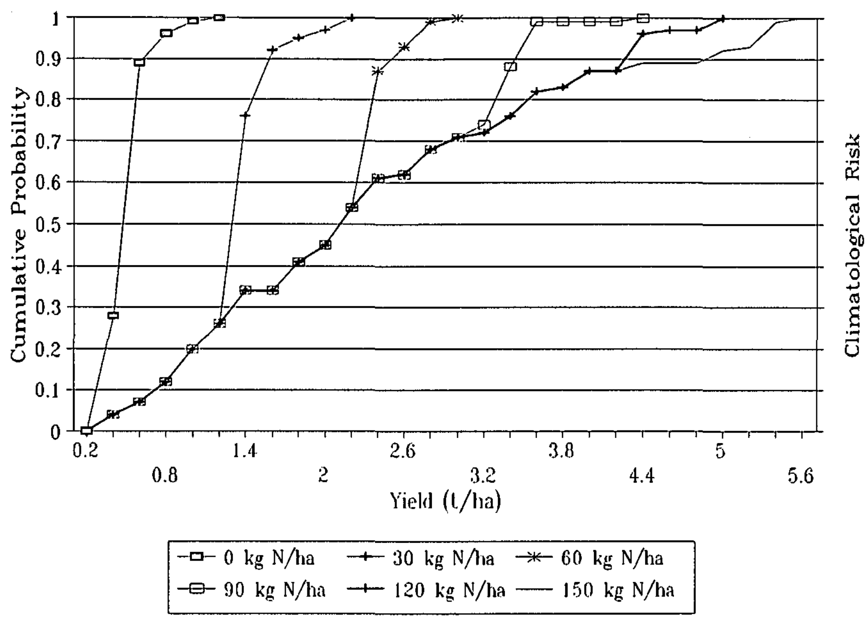


Figure 4.4 Climatic risk — , the cumulative distribution function of simulated yield for different soil N-levels.

Simulated yields with increasing levels of N from Fig 4.4 and Table 4.4 clearly indicate that :

1. As might be expected, climatic risk is decreased, with increased N-fertilization, and of course, so would gross margin as well, and
2. Higher standard deviation and range between high and low simulated yields, but lower coefficients of variation, occur.

Table 4.4 Average, Median, Standard deviation, Low and High values simulated for Potchefstroom from 1916-1991, at different N-levels.

Description	N(0)	N(30)	N(60)	N(90)	N(120)	N(150)
Average	469.7	1433.7	2029.5	2266.9	2363.7	2389.9
Median	435.3	1621.8	2100.9	2100.9	2100.9	2100.9
Standard deviation	145.9	458.2	952.3	1273.0	1458.0	1523.2
Low	243.9	268.0	268.0	268.0	268.0	268.0
High	1041.4	2228.9	3710.7	4863.3	5830.8	6705.6

From Table 4.4 it is also evident that except for levels of 30 and 60 kg N ha^{-1} applied, the median yields are always below average simulated yields, indicating that less years occur with above than below average yield. Furthermore for a probability of 0.5, that is 1 out of 2 years a yield of about 2.2 t ha^{-1} could be expected with an application of 60 kg N ha^{-1} (see Fig 4.4 and Fig 4.5).

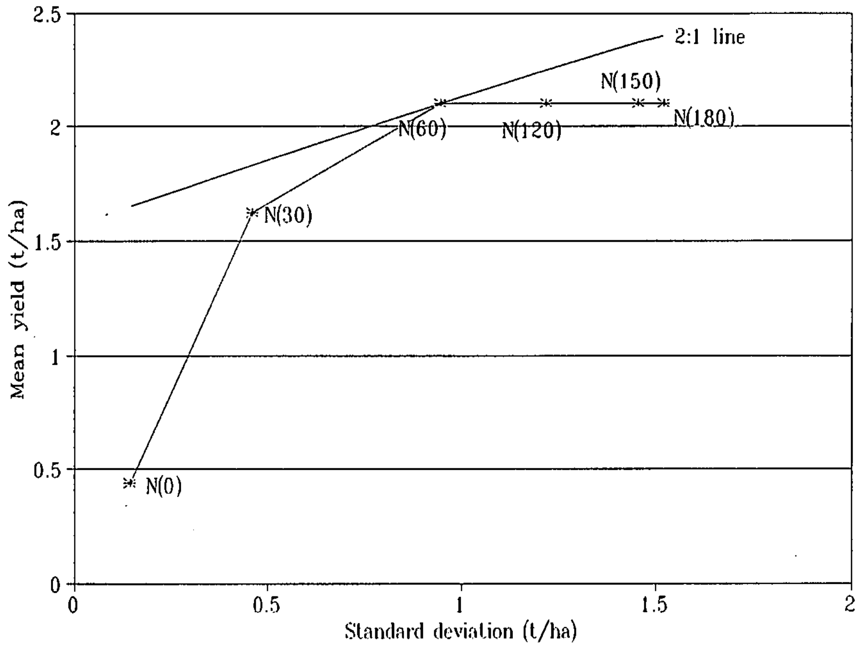


Figure 4.5 The expected outcome-variance space - A. Plot of mean yield against standard deviation at differing N-applications. A 2:1 line is also indicated. Data for all 76 seasons was included.

It is a simple matter to construct an expected yield-variance diagram (E-V space), where variance is quantified using the standard deviation of yields obtained at the various N-levels. Such E-V space is illustrated in Fig 4.5. Wafula, McCown & Keating (1992) suggest that as a rule of thumb, risk averse entrepreneurs will prefer strategies found on the 2:1 line. In Potchefstroom this would be 60 and 30 kg N ha^{-1} with preference for the former.

Lastly, a parameter for estimating possible improved yield (P) at a given N-application is defined as:

The chance of realising an improved yield above the yield corresponding to that attained with a lower N-application rate.

Thus, where:

n - Total number with simulated yields (n = 75 seasons)

N_h - Number of seasons in which an increased yield would result were a higher N-application used.

$$P = \frac{N_h}{n}.$$

From Fig 4.6, the highest P occurred when N-application was increased from 0 - 30 kg ha^{-1} (P = 0.32) which was virtually the same for an increment from 30 - 60 kg ha^{-1} (P = 0.27). Thereafter the P = 0.11 for each subsequent increment in the level of N.

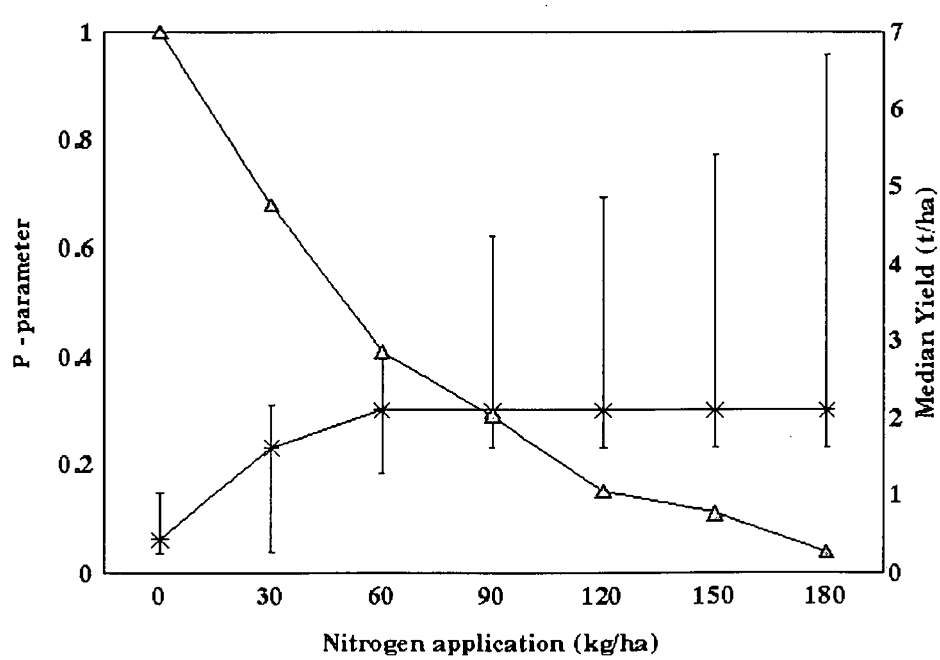


Figure 4.6 Chance of realising an increased yield were a higher N-application utilized (△) and the mean yield (*) at given nitrogen application rates. The bars indicate the range (maximum - minimum) in yields due to seasonal weather variability.

CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1 Introduction

The need for a simulation model for cultivated pasture, particularly *Digitaria eriantha,* for the RSA has become urgent. Furthermore, since previous grassland simulation models have not included soil nitrogen subroutines. This too has become a priority. With a view to producing such model and refining former simulation exercises; numerous key questions have been identified. For example, would it be possible to use the PUTU 13 type of model for *Cenchrus ciliarus* as a basis for developing a new model for *Digitaria eriantha*, would it be possible to include a nitrogen subroutine into such model and apply it to determine efficient fertilizer strategies (how much and when nitrogen should be applied).

Objectives

Bearing this in mind, the objectives of the present study were to :

- adapt the PUTU 13 model for simulation of the growth and development of *Digitaria eriantha*.
- Include a nitrogen subroutine into this model and validate it, and
- Demonstrate the suitability of the new model for determining nitrogen strategies given a long series of weather data.

5.2 Method

General model development

The work was carried out in the Potchefstroom area, using yields of *D. eriantha* collected by Dannhauser (1985). A literature survey was included, where applicable in the body of the thesis, as this facilitated model description. A detailed model description was undertaken which outlined how the PUTU 2, 11 and 13 models were refined to produce the new model PUTU 14 for *D. eriantha*.

The changes to these earlier models were highlighted. The entire functioning of the model was carefully explained. The source of the equations utilized was given, thereby meeting an urgent need of scientists interested in developing the model further.

New mathematical functions developed, included;

- Use of a constant leaf development rate in place of the rapid and slow phases used in the previous grassland models.
- Expressing photosynthetic rate in terms of the product of radiation-photosynthesis conversion coefficient and incident radiant flux density.
- Where the previous grassland models considered 100% basal cover which was later graded down according to a basal cover function; the new PUTU 14 has no such option. Where cultivated pastures are concerned a uniform cover is usually established and such operation is not nescesary.
- Where previously translocation was based on a source-sink relationship; in the new model a constant proportion of daily dry matter assimilation is partitioned to each plant organ.

The growth processes simulated in each of five growth stages consisted of carbon dioxide assimilation, translocation, senescence and death. The five growth stages defined were vegetative, reproductive, seed, seed fall and dormancy.

Water and carbohydrate mass balances are computed in each growth stage. The water balance remained virtually unchanged from previous PUTU models, use being made of the finite reservoir cascade technique. This process is clearly described in the text.

An innovation is a new exponential function for the water retention curve. It is calculated using a modified Campbell (1977) equation which is now common in all PUTU models.

Modelling soil nitrogen

The nitrogen subroutine was taken from Singels & Manley (1991). Briefly this entails:

The computation of the fresh organic matter decomposition rate which is a function of an empirical maximum rate, temperature, soil water status and the C:N ratio. A modified water status function is included in the new model. The mineralisation rate of organic matter is taken as a function of a given empirical decay rate, temperature, water and nitrogen content in the humic fraction of the soil. Nitrogen immobilization is calculated similarly to the above, but at a rate approximately 2% thereof. The nitrogen balance is computed according to a logarithmic theory of van Keulen & Seligman (1987). The calculations accommodate losses due to leaching.

Modelling Plant nitrogen

In the plant, N-uptake is regulated according to the law of the minimum. Nitrogen flow is proportional to transpiration flow, a potential uptake rate which is a function of the mass in each relevant organ and a rate of demand. Nitrogen mass balance is calculated for each organ on a daily basis.

5.3 Calibration

Calibration was conducted on three sets (different N-levels) of data collected in the 1978/79 season. The major input parameter changes from values applicable to PUTU 11 and 13 were the following:

- The base for calculating thermal period, which was changed from 12°C to 10°C.
- The minimum decrement in thermal period accounting for adaptation to water

stress was changed from 230 d°C to 225 d°C.

- The duration of the reproductive period was altered from 60 to 30 days and the seed

  formation period from 100 to 80 days.
- The minimum temperature for growth of 2°C seems as applicable to *D. eriantha* as it is to the former species.
- Furthermore, the rate constants (proportions) for partitioning of dry matter were determined for *D. eriantha* for all growth stages.
- The constant in the argument of the exponential water stress factor was altered from its previous value of 0.5 to the 0.1 used in PUTU 14.

5.4 Validation

The model was validated on data collected in 1979/80 season and the 1981/82, 82/83 and 83/84 seasons. A total of 15 sets of data were available for three different soil types. The significant tests of accuracy undertaken were the Wilmott coefficient of agreement (D), the coefficient of determination r^2, mean absolute error (MAE), the root mean square error (RMSE), systematic ($RMSE_s$) and unsystematic ($RMSE_u$).

Values obtained during validation were

$D = 0.96$; $r^2 = 0.88$; $MAE = 0.35$; $RMSE = 0.56$; $RMSE_s = 0.26$ and $RMSE_u = 0.50$.

These testify to an accurate model.

5.5 Application of the model

The model was run on 75 years of weather data for the period 1916 to 1991 at Potchefstroom on a Westley soil. Seasonal yields were calculated for each growing season and used to determine the most suitable nitrogen strategy for Potchefstroom. The optimum N-level obtained from these data for each of the seasonal scenarios defined as bad, poor, moderate, good and wet were determined. The most favourable time of application was found to be 1 November. It was further demonstrated how N-applications could diminish climatic risk. Furthermore, use was made of the expected yield-variance space from which it was found that a risk averse entrepreneur would prefer a nitrogen application of 60 kg/ha.

A new parameter for estimating the chance of an improved yield resulting from an incremented nitrogen application was defined. This potential for improving yield of a given N-application (*P*) was evaluated. The highest P occurred when N-application was increased from 0 - 30 kg ha^{-1} (P = 0.32) and was virtually the same for an increment from 30 - 60 kg ha^{-1} (P = 0.27). Thereafter P = 0.11 approximated for each subsequent level of N.

The variability in yield due to weather fluctuations at each N-level was determined and the highest expected variation was found to occur at N-applications of 180 kg ha^{-1}. The potential yield at Potchefstroom for each nitrogen application was also determined. This was taken as the median yield. It varied between 1.14 and 2.1 t ha^{-1} according to the level of nitrogen fertilization. Whereas, median yield ceased to improve with N-applications greater than 60 kg N ha^{-1}, average yields did reflect a slight increase at higher N-levels.

While the analysis was expressed in terms of yield, the results could very easily be expressed in terms of gross margin which would have great economic significance.

5.6 Conclusion

It may be concluded that the functioning of a new model for *D. eriantha* (PUTU 14), which contains a nitrogen sub-routine, how it was developed and how it differs from the previous grassland models upon which it was based, has been fully described. The model was calibrated and then validated on independent data.

The model was applied to calculating the potential (median) yield for Potchefstroom at different levels of nitrogen and the variation therein brought about by variability in climate.

The model was applied to demonstrate how climatic risk may be diminished by increased nitrogen fertilization.

The potential for improving yield by incrementing nitrogen applied level was also determined.

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APPENDIX A

Source code for the PUTU 14 model (*Digitaria eriantha*)

```
DECLARE SUB PLANTN (J, BRL, BCL, BBL, BGL, BRD, BCD, BBD, BGD,
             TRANS1, TRANS2, ANC(), AN(), V(), V15(), NO3(), NH4(),
             TAVE, FW, N(), BO, FACN, GRSTGE, TOTMASS(), NDEM(),
             NCMAX(), NC(), TOTAN, TPAN, TNFLO, TNMASFLO, TOTNUP)

DECLARE SUB SOILN (J, BRL, BCL, BBL, BGL, BRD, BCD, BBD, BGD, TRANS1,
             TRANS2, V(), V01(), V15(), ANC(), NO3(), NH4(), W01(),
             W(), IFOM(),  FOM(), T(), INFIL, PERC(), DoyToFert(),
             FERTO3(), FERTH4(), TAVE, GWP, N(), BO, FACN, GRSTGE,
             TOTMASS(), NFERT, FTMIN, FWMIN, CNR, FCNR, DECR, RDECR(),
             NMINFOM(), NFOM(), NIMMFOM(), NMINHUM(), NHUM(), DMINR,
             NMINNET(), HUM(), NIT(), NOUTFLO(), NLEACH, AN(), NDEM(),
             NCMAX(), NC(), TOTAN, TPAN, TNFLO, TNMASFLO)


NA$ = "C:\QB45\WEER\PCH79.TXT"

'----------------------------------------------------------------------
' PROGRAM PUTU 14  DIGITARIA ERIANTHA MODEL  VERSION 1       JUNE 1993
'----------------------------------------------------------------------

DIM TP(300), PRVISC(300), PPRODO(300), MAXPROD(300), CNT(370)
DIM D(300), DATE(300), TPCUT(100), RTRIM(370), DALEN(13), DAE(13)
DIM SLWAT1(367), SLWAT2(367), SLWAT(367)

DIM ANC(2), NO3(2), NH4(2), IFOM(2), FOM(2), T(2)
DIM DoyFert(2), FERTO3(2), FERTH4(2)
DIM RDECR(2), NMINFOM(2), NFOM(2), NIMMFOM(2), NMINHUM(2), NHUM(2)
DIM NMINNET(2), HUM(2), NIT(2), NOUTFLO(2)
DIM AN(2), NDEM(4), NCMAX(4), NC(4), N(4)

CLS

DATA 10.5,11.1,11.9,12.8,13.6,14.0,13.8,13.1,12.3,11.4,10.7,10.3,10.3
DATA 31,31,30,31,30,31,31,28,29,31,30,31,30

      FOR i = 1 TO 13
          READ DALEN(i)
      NEXT i
      FOR i = 1 TO 13
          READ DAE(i)
      NEXT i

     ' ***************   GROWTH STAGE DEFINITION  *****************
     STAGE$(1) = "VEGETATIVE"
     STAGE$(2) = "REPRODUCTIVE"
     STAGE$(3) = "SEED"
     STAGE$(4) = "SEEDFALL"
     STAGE$(5) = "DORMANT"

     ' ********************  INPUT VALUES  ************************
     CLAY = 25: SDP = 300
     WHC1 = (.138 + .00416 * CLAY) * 100
     WHC4 = (.0344 + .00381 * CLAY) * 100

     SLWP1(1) = 19.7: SLWP2(1) = 23.57 :WPC = -1800
     TPMAKS = 400: PRVISC = 150: PPRODO = 500 :BCOVER = 10
```

```
     CONS = 0.5 :ALFA = 4 :EFFQ = 0.775 :RCC = ALFA * EFFQ
     MKOUNT = 35: HUCRIT = 250: HUCRMN = 230: BO = 10: SPL = 500
     HYCON = .01: RUNPAR = .1: DRAINP = .9
     GRSTGE = 1: ITERM = 1: JDMAKS = 0: TNEXT = 1: TR = 1000

' *******************************************************************
' * PROGRAM TO COMPUTE AND TABULATE POTENTIAL CO2-ASSIMILATION AND *
' * POTENTIAL DRY MATTER GAIN IN G/M**2/DAY OVER A PERIOD OF 365    *
' * DAYS ON A DAILY BASIS                                           *
' *******************************************************************
'     DIAGRAM OF ALL PLANTPARTS AT ANY GIVEN STAGE OF GROUTH
'     ======================================================
'                        I CA                                  ##
'                 DEAD   I  LIVE                               ##
'     ******     ******  I  ********                           ##
'     *    *<-X4-* GD *<-X8-* GL   *---R5---I                  ##
'     *    *     ******  I  ********        I                  ##
'     *    *             I                  I                  ##
'     *    *             I                  I                  ##
'     *    *             I                  I                  ##
'     *    *             I                  I                  ##
'     *    *     ******  I  ********        I                  ##
'     *    *<-X5-* CD *<-X9-*  CL  *---R4---I                  ##
'     *    *     ******  I  ********        I                  ##
'     *    *             I                  I                  ##
'     *TRD *             I                  I                  ##
'     *    *             I                  I                  ##
'     *    *             I                  I                  ##
'     *    *     ******  I   *******     *******    *******    ##
'     *    *<-X7-* BD *<-X2--* BL  *-R1--* RES *<---* DMG *    ##
'     *    *     ******  I   *******     *******    *******    ##
'     *    *             I                  I                  ##
'     *    *             I                  I                  ##
'     *    *             I                  I                  ##
'     *    *     ******  I   *******        I                  ##
'     *    *<-X6-* SD *<-X1--* SL  *---R2---I                  ##
'     ******     ******  I   *******        I                  ##
'     DA                 I                  I           BA     ##
'     ----------------------------------------------------     ##
'     DB                 I                  I           BB     ##
'                        I                  I                  ##
'                        I                  I                  ##
'                        I                  I                  ##
'                        I                  I                  ##
'                ******  I   *******        I                  ##
'                * RD *<-X3--* RL  *---R3---I                  ##
'                ******  I   *******                           ##
'                        I                                     ##
'                        ICB                                   ##
'                        I                                     ##
'
'
'     KEY:
'         DMG=THE DAYS DRY MATTER GAIN (KG CARBOH./HA/DAY)
'         GD =GRAIN DEAD             GL =GRAIN LIVE
'         CD =CULM DEAD              CL =CLUM LIVE
'         BD =LEAVES DEAD            BL =LEAVES LIVE
'         SD =STUBBLE DEAD           SL =STUBLE LIVE
'         RD =ROOTS DEAD             RL =ROOTS LIVE
'         TR =TRASH DEAD             RES=CARBOHYDRATE RESERVES
'         DA =ABOVE GROUND DEAD      BA =ABOVE GROUND BIOMASS
'         DB =ROOT DEAD              BB =ROOT BIOMASS
'         D=DA+DB=TOTAL DEAD         B=BA+BB=TOTAL STANDING BIOMASS
'         CA=ABOVE GROUND STANDING CROP
'         CB=BELOW GROUND STANDING CROP
```

```
'   ===================================================================
'     VARIABLE NAME                                       CODE     UNITS
'     =============                                       ======   =====
'     BASAL COVER                                         BCOVER   (%)
'     DISIRED PROPORTION OF RELEVANT ORGAN                DPRO
'     AVERAGE TEMP                                        T        (')
'     TEMP MAX                                            AMX      (')
'     TEMP MIN                                            AMN      (')
'     RADIANT FLUX DENSITY                                RFD     (W/M**2)
'     WATER POTENTIAL OF LEAF                             LWP      (K PA)
'     LEAF AREA                                           AL       (M**2)
'     SPECIFIC LEAF AREA                                  SPL      (KG/HA)
'     ITERM PERIOD OVER WHICH MEAN DETERMINED             ITERM
' ******************************************************************
35     WHCTEMP = 0

' ******************************************************************
' **             SET INITIAL STATUSSES AND PARAMETERS             **
' ******************************************************************
' READ SOIL WATER AND CUT INFO                                    ##
' IF CUTS ARE READ, IL = 1,15 IN DO AND PUTUINFO                  ##

36       IF WHCTEMP <> 0 THEN WHC = WHCTEMP

37       CUT = CUT1

' COMPUTE SOIL DEPTH FOR SECOND LEVEL                             ##
38        SDP1 = 100
39        SDP2 = SDP - SDP1

' COMPUTE FC AND PWP FOR EACH LEVEL                               ##

40        FC1 = WHC1 / 100 * SDP1
41        FC2 = WHC1 / 100 * SDP2
42        PWP1 = WHC4 / 100 * SDP1
43        PWP2 = WHC4 / 100 * SDP2
44        M1 = (LOG(10) - LOG(1500)) / (LOG(WHC1) - LOG(WHC4))

' WATER CONTENT EXPRESSED IN MM/SOIL DEPTH FOR BOTH LEVELS       ##
45       WJ = SLWP2(1)
46       SLWAT(1) = (SLWP1(1) * SDP1 + SLWP2(1) * SDP2) / SDP / 100 * SDP
47       SLWAT1(1) = SLWP1(1) / 100 * SDP1
48       SLWAT2(1) = SLWP2(1) / 100 * SDP2

' ******************************************************************
' *   DETERMINE INITIAL MASSES OF THE DIFFERENT PLANT COMPONENTS   *
' ******************************************************************
' C IS TOTAL PLANT BIOMASS AT 100 % BASAL COVER                    ##
' ALL CALCULATIONS WILL PROCEED WITH 100 % BASAL COVER             ##
' ON COMPLETION BIOMASSES WILL BE MULTIPLIED BY                    ##
' BY BCOVER*BCOVER FORMULA (BCFUNC)                                ##
' THE ASSUMPTION IS MADE THAT THE PREVIOUS PRODUCTION IS           ##
' EQUAL TO 25 % OF THE TOTAL BIOMASS                               ##

49        C = PRVISC * 100 / 25 * 100 / BCOVER
50        BCFUNC = BCOVER / 100
51        BL = 0: BD = 0 * C: CL = 0: CD = 0 * C
52        SL = 0: SD = .1 * C:
53        RL = .8 * C: RD = .1 * C
54        GL = 0: GD = 0: RES = .1 * RL

55        TPMAKS = 0
56        CLIVE = BL + SL + RL

         ' SUB FOR NITROGEN APPLICATION
57         GOSUB 500
```

```
' ******************************************************************
' *         START OF SIMULATION PER DAY FOR THE GROWING SEASON       *
' ******************************************************************
  J = 1
  OPEN NA$ FOR INPUT AS #2
  DO UNTIL EOF(2)
   INPUT #2, JUNK$
            JAAR = VAL(MID$(JUNK$, 1))
            MNDE$ = MID$(JUNK$, 5, 5)
            DAY = VAL(MID$(JUNK$, 10, 3))
            AMXT = VAL(MID$(JUNK$, 14, 8))
            AMNT = VAL(MID$(JUNK$, 21, 6))
            RAINF = VAL(MID$(JUNK$, 28, 6))
            EVAP = VAL(MID$(JUNK$, 34, 6))
            SUN = VAL(MID$(JUNK$, 40, 6))


   NMNTH = J / 30 + 1
'  HERE AL=LA PER HECTARE LEAF SPL = 500 kg/ha                        ##

      AL = BL / SPL
      IF C <> 0 THEN
         FRACL = BL / C
      END IF

'                        *********************
'                        *    WATER BALANCE  *
'                        *********************

       GOSUB 200         ' SUB WATER ROUTINE

'                     *****************************
'                     * ENVIRONMENTAL FACTORS AND *
'                     *        PRODUCTION         *
'                     *****************************
'TO COMPUTE THE INFLUENCE OF SOLAR RADIATION ON THE MAX RATE OF ##
'PHOTOSYNTHESIS(FI)
'FI = PERCENTAGE SUNLIGHT ABSORBED BY THE CANOPY                 ##

      TRFD = TRFD + RFDM
      FI = (1 - EXP(-.7 * AL)) * 100
      TFI = TFI + FI

' TO COMPUTE THE INFLUENCE OF TEMP ON THE MAX RATE OF           ##
' PHOTOSYNTHESIS     (FT)                                       ##

      FT = 100 * (EXP(-1 * ((ATEMP - 30) ^ 2) / 360))
      IF ATEMP < BO THEN FT = 0
      IF AMNT < 3 THEN FT = 0
      TFT = TFT + FT

' TO COMPUTE THE INFLUENCE OF WATER AVAILABILITY ON THE MAX     ##
' RATE OF PHOTOSYNTHESIS     (FW)                               ##

      FW = FW * 100
      TFW = TFW + FW

' SHOULD SOIL BE SATURATED REDUCE PHOTOSYNTHETIC RATE BY 20 %   ##

  IF SLWAT2(J) > FC2 THEN FW = 100 - 10 * (SLWAT2(J) - FC2) / SDP2
  IF FW <= 0 THEN FW = 0

' COMPUTE BEGINING AND END, AS WELL AS NUMBER OF MOISTURE STRESS DAYS

  IF GRSTGE < 5 THEN GOTO 6 ELSE GOTO 7
6 IF FW < 50 AND ATEMP > BO THEN ITTRE = ITTRE + 1
  IF FW < 50 AND ATEMP > BO THEN STRESS = .47 ELSE STRESS = 1
```

```
'  WPC = CRITICAL LEAF WATER POTENTIAL
  IF FW < 50 AND ATEMP > BO THEN WPC = WPC - 15:

  IF WPC <= -3000 THEN WPC = -3000
  WPC = -1800
' IF FW < 50 AND ATEMP > BO THEN PRINT "STRESS DAY ON"; J, ITTRE, FW
7      'CONTINUE

' THE INFLUENCE OF ENVIRONMENT ON THE EFFICIENCY OF PHOTO-      ##
' SYNTHESIS = F                                                 ##

       F = (FI / 100) * (FT / 100) * (FW / 100) * 100
       TF = TF + F

'ACTUAL EFFICIENCY OF PHOTOSYNTHESIS = EFF                       ##

       EFF =  F / 100
       TEFF = TEFF + EFF

'THE POTENTIAL OF CO2-ASSIMALATION = P  (KG CO2/HA/DAY)          ##

       IF RFDM >= 10 THEN GOTO 10
       P = 0
       GOTO 11
10     P = RCC * RFD * (F / 100))
11     P = P * 10

' NETTO DRY MATTER GAIN

       DMG = P * FACN
       TDMG = TDMG + DMG


'                  *************************
'                  *     GROWTH STAGE      *
'                  *************************

       SELECT CASE GRSTGE
              CASE IS = 1
                   GOTO 13
              CASE IS = 2
                   GOTO 25
              CASE IS = 3
                   GOTO 30
              CASE IS = 4
                   GOTO 35
              CASE IS = 5
                   GOTO 37
       END SELECT

' ***********************************************************##
'                           GROWTH STAGE ONE                  ##
' ***********************************************************##
'FIRST GROWTH STAGE IS VEGETATIVE GROWTH (MAKE SURE THE        ##
'WEATHER DATA IS ARRANGED FROM 1ST JULY OF THE FIRST YEAR      ##
'TO THE 30TH JUNE OF THE SECOND YEAR).  TRIGGER FOR CHANGE     ##
'TO 2ND GROWTH STAGE IS THE THERMAL PERIOD REQUIREMENT(HUCRIT) ##
'MUST BE SATISFIED OR TEMPERATURE DROPS BELOW 2 DEGREES (C)    ##
'OR GROWTH OCCUR FOR LONGER THAN 258 DAYS                      ##

13

' NO  GROWTH BEFORE PHOTOPERIOID = DAY 31 (31st July)

IF J < 30 THEN 38

    IF HU > HUCRIT THEN GOTO 24 ELSE GOTO 17
```

```
' SHOULD GROWTH STAGE 1 LAST TO LONG (BEYOND 258 DAYS)              ##
' SWITCH TO TNEXT GROWTH STAGE                                      ##
' AND IF TEMP IS TO LOW TERMINATE GROWTH                            ##

17 IF J > 258 THEN GOTO 18 ELSE GOTO 19

18 IF AMNT <= 2 THEN GOTO 23

'    BCON=KG/HA/DAY/DEGREE CELSIUS AT 100% COVER                    ##

19     BCON = 3.5

      TGROW = ATEMP
      IF TGROW >= 30 THEN TGROW = 30
      IF TGROW <= BO THEN TGROW = BO
      HU = HU + (TGROW - BO)
      HUCRIT = HUCRIT - 10 * (100 - FW) / 100
      IF HUCRIT <= HUCRMN THEN HUCRIT = HUCRMN

' CALCULATION OF LEAVE MASS CHANGE (KG/HA/DAY)                      ##

20     DBL = BCON * (TGROW - BO) * FW / 100
       BBL = BL

'CALCULATE MASS FLOW VARIABLES FOR MASS FLOW FROM LIVING PARTS ##
' TO DEAD PARTS

       X(1) = .001 * SL
       X(2) = .001 * BL
       X(3) = .001 * RL
       X(8) = 0
       X(4) = 0
       GOTO 38
23     'PRINT "DAY=";JDA;"MIN.TEMP.=";AMNT;"<<<<>>>>THEREFORE
       TERMINATE GROWTH"
24
' PRINT STAGE$(2); " - GROWTHSTAGE 2"; JDA
' TRANSLOCATION RATES ARE PROPORTIONAL TO DIFFERENCES               ##
' BETWEEN EXISTING AND DESIRED ORGAN PROPORTIONS                    ##

' DESIRED PROPORTIONS = DPRO ...FOR REPRODUCTIVE GROWTH STAGE        ##
       DPROG = 0
       DPROC = .2
       DPROB = .3
       DPROS = .1
       DPROR = .4
       GRSTGE = 2
       MKOUNT = J + 30
'     *********************************************************##
'                          GROWTH STAGE TWO                    ##
'     *********************************************************##
'     SECOND GROWTH STAGE IS REPRODUCTIVE GROWTH. TRIGGER FOR   ##
'     CHANGE TO 3RD GROWTH STAGE IS 30 DAYS OF GROWTH WITH      ##
'     A MINIMUM CULM PRODUCTION EXCEEDING 25 % OF THE MASS OF   ##
'     LEAVES AT A THEORETICAL BASAL COVER OF 100 %              ##
25

     IF CL > (.25 * BL) AND J > MKOUNT THEN GOTO 29
       IF J >= 316 THEN GOTO 26
       GOTO 27
26 IF AMNT <= 2 THEN GOTO 28

' CALCULATE THE MASS FLOW OF LIVING PLANT MATERIAAL TO DEAD     ##

27     X(1) = .001 * SL
       X(2) = .001 * BL
       X(3) = .001 * RL
```

```
        GOTO 38
28   '   PRINT "DAY = "; JDA; "  MIN. TEMP. = "; AMNT; "<<<<>>>>
         THEREFORE TERMINATE GROWTH"
29   '   PRINT STAGE$(3); " - GROWTHSTAGE 3"; JDA

  ' DESIRED PROPORTIONS = DPRO ...FOR SEED GROWTH STAGE              ##

        DPROG = .09
        DPROC = .34
        DPROB = .17
        DPROS = .2
        DPROR = .3
        GRSTGE = 3
        MKOUNT = J + 80
        IKOUNT = MKOUNT - 30

  '    ****************************************************** ##
  '                      GROWTH STAGE THREE                    ##
  '    ****************************************************** ##
  '    THIRD GROWTH STAGE IS SEED. TRIGGER FOR 4TH GROWTH STAGE ##
  '    IS 80 DAYS OF SEED FORMATION, OR A GROWING SEASON        ##
  '    STRETCHING BEYOND DAY J = 316 AND TEMP < 2 C TERMINATE   ##
  '    GROWTH                                                   ##

30
      IF J > MKOUNT THEN GOTO 34
        IF J >= 316 THEN GOTO 31
        GOTO 32
31      IF AMNT < 2 THEN GOTO 33
32      X(1) = .002 * SL
        X(2) = .002 * BL
        X(3) = .003 * RL
        IF J >= IKOUNT THEN X(8) = .15 * GL
        X(9) = .001 * CL
        X(6) = .001 * SD
        X(7) = .001 * BD
        GOTO 38
33   ' PRINT "DAY = "; JDA; "  MIN. TEMP. = "; AMNT; "<<<<>>>>
        THEREFORE TERMINATE GROWTH"
34   '   PRINT STAGE$(4); " - GROWTHSTAGE 4"; JDA

  ' DESIRED PROPORTIONS = DPRO ...FOR SEEDFALL GROWTH STAGE          ##

        DPROG = 0
        DPROC = .3
        DPROB = .1
        DPROS = .1
        DPROR = .5
        GRSTGE = 4
        GLO = GD + GL + 1

  '    ******************************************************     ##
  '                      GROWTH STAGE FOUR                        ##
  '    ******************************************************     ##
  '    FOURTH GROWTH STAGE IS SEEDFALL. THIS PROCEEDS UNTIL A      ##
  '    A MINIMUM AIR TEMPERATURE < 2 °C                            ##

35
      IF AMNT < 2 THEN GOTO 36
        X(1) = .002 * SL
        X(2) = .01 * BL
        X(3) = .003 * RL
        X(4) = 0
        IF (GD + GL) > 0 THEN X(4) = (GLO - (GD + GL)) * .3
        IF X(4) > GD THEN X(4) = GD
        IF X(4) >= GD THEN GL = 0
        X(5) = .005 * CD
```

```
        X(6) = .005 * SD
        X(7) = .005 * BD
        X(8) = .5 * GL
        X(9) = .05 * CL
        GOTO 38

' DESIRED PROPORTIONS = DPRO ...FOR DORMANT GROWTH STAGE       ##
' IS THE SAME AS FOR THE SEEDFALL GROWTH STAGE                 ##

36      GRSTGE = 5
'  PRINT STAGE$(5); " - GROWTHSTAGE 5"; JDA
'   *********************************************************##
'                         GROWTH STAGE FIVE                    ##
'   *********************************************************##
'   FIFTH GROWTH STAGE IS DORMANCY                             ##

37
        X(1) = .02 * SL
        X(2) = .2 * BL
        X(3) = .003 * RL
        X(4) = .5 * GD
        X(5) = .002 * CD
        X(6) = .003 * SD
        X(7) = .005 * BD
        X(8) = .5 * GL
        X(9) = .25 * CL

' DETERMINE WHETHER THE PASTURE BEEN CUT                       ##

38      IF JDA <> CUT THEN GOTO 39
        TP = BTG + BTC + BTB
        'PRINT "A BIOMASS PRODUCTION OF "; TP; " (KG/HA) WAS REACHED ON
        CUTTING DATE "; JDA
        'PRINT "A BIOMASS PRODUCTION OF "; TP; " (KG/HA) WAS REACHED ON
        CUTTING DATE "; JDA
        GRSTGE = 1
        WPC = -1800
        TNEXT = 2
        HUCRIT = HUCRIT * .8
        HUCRMN = HUCRMN * .8
        HU = 0


        IF CUT = CUT3 THEN CUT = CUT4
        IF CUT = CUT2 THEN CUT = CUT3
        IF CUT = CUT1 THEN CUT = CUT2
        IF J > 258 THEN GRSTGE = 5
        IF GRSTGE = 5 THEN
           DPROG = 0
           DPROC = 0.3
           DPROB = 0.1
           DPROS = 0.1
           DPROR = 0.5
        END IF

        BGL = 0
        BGD = 0
        BTB = 100 - BTG - BTC
        BBL = .4 * BTB
        BBD = .4 * BTB
        BCL = .1 * BTB + BTC
        BCD = .1 * BTB
        BTC = BCL + BCD
        BTB = BBL + BBD
        CL = BCL
        CD = BCD
        BL = BBL
```

```
        BD = BBD
        GL = 0
        GD = 0

'                         ******************************
'                         *        TRANSLOCATION        *
'                         ******************************

39  GOSUB 300            'TRANSLOCATION

    IF BL > 0 THEN GOTO 40
        BL = 0
        BD = BD
40  IF SL > 0 THEN GOTO 41
        SL = 0
        SD = SD
41  IF RL > 0 THEN GOTO 42
        RL = 0
        RD = RD
42  IF CL > 0 THEN GOTO 43
        CL = 0
        CD = CD
43  IF GL > 0 THEN GOTO 45
        GL = 0
        GD = GD


45      TFI = TFI / ITERM
        TFT = TFT / ITERM
        TFW = TFW / ITERM
        TF = TF / ITERM
        TEFF = TEFF / ITERM
        TRFD = TRFD / ITERM
        FI = TFI
        FT = TFT
        FW = TFW
        F = TF
        ALAI = AL

        A = J / ITERM

' CALCULATION OF TOTAL PRODUCTION (TP) FOR EACH DAY

        BDBL = DBL
        BRES = RES
        BGL = GL
        BGD = GD
        BCL = CL
        BCD = CD
        BBL = BL
        BBD = BD
        BSL = SL
        BSD = SD
        BRL = RL
        BRD = RD
        BTR = TRD
        BDMG = DMG
        BP = P
        BTG = BGL + BGD
        BTC = BCL + BCD
        BTB = BBL + BBD
        BTS = BSL + BSD
        BTRO = BRL + BRD
        TP = BTG + BTB + BTC
        PPROD = PPRODO * (1 - J / 210)
        IF PPROD <= 0 THEN PPROD = 0
        TPROD = TP + PPROD
```

```
      ' DETERMEN MAXIMUM PRODUCTION AND DAY WHEN REACHED
          IF TP > TPMAKS THEN
           JDMAKS = JDA
           TPMAKS = TP
          END IF

      ' SET VARIABLES TO ZERO
        TFI = 0: TFT = 0: TFW = 0: TF = 0: TEFF = 0: TP = 0: TRFD = 0

      ' NEXT DAY
          J = J + 1

      ' OUPUT TO SCREEN
          PRINT USING "#######.##"; J; TPMAKS
  46 LOOP

      ' VARIABLES AS INPUT FOR NEXT YEAR
        WHCTEMP = WHC
        SLWP1 = SLWAT1(J - 1) / SDP1 * 100
        SLWP2 = SLWAT2(J - 1) / SDP2 * 100
        PRVISC = C * 25 / 100 * BCOVER / 100
        IF PRVISC > 2000 THEN PRVISC = 2000
        PPRODO = TPROD

        END

  200
        '****************************************
        '*          SUBROUTINE WATER           *
        '****************************************
  ' USE CORRECT DALEN DATA STATMENT CORRESPONDING TO RELEVANT     ##
  ' LATITUDE                                                      ##


        DRAIN2 = 0
        DRAIN1 = 0
        TRANS2 = 0
        ae = 0


  ' PROGRAM  TO  COMPUTE  AND  TABULATE  CROP EVAPORATION  AND    ##
  ' WATER BALANCE  OVER  A PERIOD  OF 365  DAYS  ON A DAILY       ##
  ' BASIS , DATA OBTAINED  FROM  WEATHER  STATIONS                ##
  '    DATA                        FORTRAN DESIGNATION            ##
  '    ----                        -------------------            ##
  '    RAINFALL                    RAIN     (MM)                  ##
  '    MAX TEMP                    AMX      (C)                   ##
  '    MIN TEMP                    AMN      (C)                   ##
  '    SUN                         SUN      (HOURS)               ##
  '    EVAPORATION (CLASS-A PAN)EVAP      (MM)                    ##
  '    GROUND WATER POTENTIAL      GWP      (KPA)                 ##
  '    LEAF WATER POTENTIAL        LWP      (KPA)                 ##
  '    SPEC LEAF AREA              SPL                            ##
  '    SOIL WATER                  SLWAT    (MM/M)                ##
  '    POT. EVAPORATION            PE       (MM)                  ##
  '    ACTUAL EVAPORATION          AE       (MM)                  ##
  '    LEAF AREA INDEKS            AL                             ##
  '    SOIL VAPORATION             SLVAP    (MM)                  ##
  '    TRANSPIRATION               TRANS    (MM)                  ##
  '    SOIL WATER LEVEL 1          SLWAT1   (MM)                  ##
  '    SOIL WATER LEVEL 2          SLWAT2   (MM)                  ##
  '                                                               ##
  '    WATER AVALIBLE AS A % (ESTIMATED VOLUMETRICALY)            ##
  '    ON DAY ONE          WHC      (%)                           ##
  '    AT 10   K PA        WHC1     (%) I.E. FIELD CAPACITY (FC)  ##
  '    AT 2440 K PA        WHC4     (%) I.E. PERMANENT WILTING PIONT ##
  '    P.S. PERMANENT WILT FOR A MESOPHYTE IS 1500 K PA AND FOR   ##
```

```
'     A ZEROPHYTE 2400 K PA BUT THE DIFFERENCE IN % MOISTURE IS ##
'     NEGLIGIBLE                                                ##
'     SOIL DEPTH                SDP        (MM)                 ##
'     ATMOS TRANSMISSIVITY      0.75                            ##
'     -----------------------------------------                 ##

' WJ IS THE WATER CONTENT EXPRESSED AS A %                      ##
' CALCULATE GWP                                                 ##

 GWP = -1500 * (WJ / WHC4) ^ M1

' MEAN  DAILY  TEMPERATURE  IS EQUAL  TO  THE  MEAN  OF  THE    ##
' DAILY  MAXIMUM  AND  THE  DAILY  MINIMUM  TEMPERATURE         ##

      ATEMP = (AMXT + AMNT) / 2
      GS = .4019914# + .01725101# * ATEMP - .0001485# * ATEMP ^ 2

' JDA=JULIAN DAY                                                ##

      JDA = J + 181
      IF J > 184 THEN JDA = JDA - 365

' SOLK=SOLARCONSTANT                                            ##
' RFD=RADIANT FLUX DENSITY

      X = ((JDA + 10) / 365) * 360
      X = X * .01745
      SOLK = 30.85 + 12.65 * COS(X)
      ALPHA = .21
      BETHA = .71
      DAYFRC = SUN / DALEN(NMNTH)
      IF DAYFRC > .5 THEN ALPHA = .29
      IF DAYFRC > .5 THEN BETHA = .5
      RFD = SOLK * (ALPHA + BETHA * DAYFRC)
      RFDM = RFD * 10^6 / (DALEN(NMNTH) * 3600)

' CALCULATION OF EQUILIBRIUM EVAPORATION                        ##

      PECONS = 1.28
      IF AMXT >= 20 THEN PECONS = 1.28 + .08 * (AMXT - 20)
      EE = GS * .63 * RFD / 2.45

' CALCULATION OF POTENTIAL EVAPORATION                          ##

      PE = PECONS * EE

' EXPRESS THE RATIO OF POT. EVAP TO PAN EVAP                    ##

      IF EVAP = 0 THEN EVAP = 1
      PECVAP = PE / EVAP
      IF PECVAP > 1.5 THEN PECVAP = 1.5

' 0.1 PLANT COVERAGE  IS  10%  THROUGHOUT  THE  YEAR.  AL/3 *    ##
' 0.9 WHEN AL=3 THE REMAINING  GROUND  WILL  BE  COVERED  IN     ##
' GRASS NEVER  ALLOW (0.1 + AL/3 * 0.9)  TO  BECOME  GREATER     ##
' THAN ONE WHEN  THIS  HAPPENS (AL GRATER THAN 3) ASSUME AE= PE ##

      B = (.1 + ((AL) / 3) * .9)
      IF B >= 1 THEN B = 1
      IF B <= 0 THEN B = 0

' CALCULATION OF LEAF WATER POTENTIAL                           ##

      LWP = PE / HYCON
      LWP = GWP - LWP
```

```
' CALCULATE THE LIMITATION OF WATER AVAILIBILITY ON PHOTOSYN-   ##
' THETIC EFFICIENCY                                             ##

        COEF = .1 * (WPC - LWP)
        IF COEF <= (WPC / -100) THEN GOTO 204
        COEF = WPC / -100
204     IF COEF >= WPC / 100 THEN GOTO 205
        COEF = WPC / 100
205     A = EXP(COEF)
        FW = 1 / (1 + A)

' EVAPORATE RAINFALL LESS THAN 3,0 MM AS PART OF ACTUAL EVAP    ##

        IF RAINF <= 3 THEN PE = PE - RAINF
        IF PE <= 0 THEN PE = 0
        IF RAINF <= 3 THEN RAINF = 0

' IF RAINFALL EXCEED 5,0 MM THEN EVAP ACCORDING TO EQ.          ##

        IF RAINF > 5 THEN CNT(J) = -2
        CNT(J + 1) = CNT(J) + 1
        FG = EXP(-.5 * CNT(J))
        IF FG >= 1 THEN FG = 1

' CALCULATE RUNOFF                                              ##

        RUNOF = 0
        INFIL = (RAINF + IRRIG) / 1000
        IF INFIL <= .2 * RUNPAR THEN RUNOF = 0 ELSE RUNOF = (INFIL - .2
        * RUNPAR) ^ 2 / (INFIL + .8 * RUNPAR)

        INFIL = (INFIL - RUNOF) * 1000
        TRUNOF = TRUNOF + RUNOF

 ' CALCULATE SOIL VAPORATION          IE SLVAP                   ##

        SLVAP = (1 - B) * FG * PE
        TRANS1 = B * FW * PE

          AED = SLVAP + TRANS1

' SLVAP CAN ONLY OCCUR FROM THE FIRST LEVEL IF WATER IS AVLBL   ##

    IF SLVAP <= SLWAT1(J) - PWP1 THEN
        GOTO 206
        ELSE SLVAP = SLWAT1(J) - PWP1
    ENDIF

206        SLWAT1(J) = SLWAT1(J) - SLVAP

' RECHARGE OF LEVEL 1 COMES FROM RAIN(J) AND THAT OF LEVEL 2    ##
' FROM DRAINAGE OF LEVEL 1 WHEN IT HAS REACHED FC               ##

        SLWAT1(J) = SLWAT1(J) + RAINF + IRRIG - TRANS1
        IF SLWAT1(J) >= FC1 THEN GOTO 207
        IF SLWAT1(J) >= PWP1 THEN GOTO 208

' TRANSPIRATION HOWEVER CAN OCCUR FROM BOTH LEVELS AND IF WATER##
' IS NOT AVAILIBLE IN LEVEL 1 THE REST WILL BE DRAWN FROM       ##
' LEVEL 2                                                       ##

        TRANS2 = TRANS1 - (SLWAT1(J) - PWP1)
        TRANS1 = 0
        SLWAT1(J) = PWP1
        GOTO 208
```

```
207    DRN1P = 1
       DRAIN1 = (SLWAT1(J) - FC1) * DRN1P
       IF DRAIN1 <= 0 THEN DRAIN1 = 0
       SLWAT1(J) = SLWAT1(J) - DRAIN1

' CALCULATE WATER CONTENT OF LEVEL 2                              ##

208    SLWAT2(J) = SLWAT2(J) + DRAIN1 - TRANS2

' EXPRESS THE RATIO OF ACT. EVAP TO PAN EVAP                      ##

       AECVAP = ae / EVAP
       IF AECVAP > 1.5 THEN AECVAP = 1.5

' IF SLWAT2 EXCEEDS FC2 DRAIN THE AMOUNT GREATER THAN FC2         ##
209    IF SLWAT2(J) <= FC2 THEN GOTO 210
       DRAIN2 = DRAINP * (SLWAT2(J) - FC2)
       IF DRAIN2 <= 0 THEN DRAIN2 = 0
       SLWAT2(J) = SLWAT2(J) - DRAIN2

' IF SLWAT2 GETS LOWER THAN PWP2..SLWAT2 IS EQUAL TO PWP2         ##
210    IF SLWAT2(J) >= PWP2 THEN GOTO 211
       SLWAT2(J) = PWP2
       DRAIN2 = 0
211    WAT = WJ

' TO REDUCE SOIL WATER DURING WINTER I.E AFTER DAY 300 SOIL
' WATER IS REDUCED BY 0.5 MM/DAY

    IF GRSTGE = 5 THEN SLWAT1(J) = SLWAT1(J) - .3
    IF GRSTGE = 5 AND SLWAT1(J) < PWP1 THEN SLWAT1(J) = PWP1
    IF GRSTGE = 5 AND SLWAT1(J) = PWP1 THEN SLWAT2(J) = SLWAT2(J) - .1
    IF GRSTGE = 5 AND SLWAT2(J) < PWP2 THEN SLWAT2(J) = PWP2

       SLWAT(J + 1) = (SLWAT1(J) + SLWAT2(J)) / SDP
       SLWAT1(J + 1) = SLWAT1(J)
       SLWAT2(J + 1) = SLWAT2(J)

       WJ = SLWAT(J + 1) * 100

       STRESS = 1 - FW
       IF TRANS2 <= 0 THEN TRANS2 = .001
       ALAI = AL
       TDRAIN = TDRAIN + DRAIN2

       TDRN = DRAIN1 + DRAIN2
       TSLW = SLWAT1(J) + SLWAT2(J)

      RETURN

300

'*****************************************************************
'*                SUBROUTINE TRANSLOCATION                       *
'*****************************************************************

       IF GRSTGE <> 1 THEN DBL = 0

       R(1) = DBL
       R(2) = DPROS
       R(3) = DPROR
       R(4) = DPROC
       R(5) = DPROG
```

```
'     TEST FOR THE AVAILABILTY OF RESERVES

            IF RES > R(1) + R(2) + R(3) + R(4) + R(5) THEN GOTO 317

'     RESET THE MASS FLOW VARIABLES TO ZERO

      FOR IR = 1 TO 5
          R(IR) = 0
      NEXT IR

  317       DRES = DMG - R(1) - R(2) - R(3) - R(4) - R(5)
            BL = BL + R(1) - X(2)
            BD = BD + X(2) - X(7)
            SL = SL + R(2) - X(1)
            SD = SD + X(1) - X(6)
            CL = CL + R(4) - X(9)
            CD = CD + X(9) - X(5)
            GL = GL + R(5) - X(8)
            GD = GD + X(8) - X(4)
            RL = RL + R(3)
            RD = RD + X(3)

            RES = RES + DRES
            TRD = TR + X(4) + X(5) + X(6) + X(7)
            C = GL + GD + CL + CD + BL + BD + SL + SD + RL + RD
            CLIVE = GL + CL + BL + SL + RL

      'COMPUTE FOR SOILN

          TOTMASS(1) = BRL + BRD
          V(1) = SLWAT1(J) * 10: V(2) = SLWAT2(J) * 10
          VO1(1) = FC1 * 10: VO1(2) = FC2 * 10
          V15(1) = PWP1 * 10: V15(2) = PWP2 * 10
          W(1) = V(1) * SDP1 / 1000: W(2) = V(2) * SDP2 / 1000
          WO1(1) = VO1(1) * SDP1 / 1000: WO1(2) = VO1(2) * SDP2 / 1000

          FOM(1) = TRD * SDP1 / SDP: FOM(2) = TRD * SDP2 / SDP
          T(1) = ATEMP: T(2) = ATEMP + 1.2
          TAVE = ATEMP
          PERC(1) = DRAIN1: PERC(2) = DRAIN2

      CALL SOILN(J, BRL, BCL, BBL, BGL, BRD, BCD, BBD, BGD, TRANS1,
            TRANS2, V(), VO1(), V15(), ANC(), NO3(), NH4(), WO1(), W(),
            IFOM(), FOM(), T(), INFIL, PERC(), DoyFert(), FERTO3(),
            FERTH4(), TAVE, GWP, N(), BO, FACN, GRSTGE, TOTMASS(), NFERT,
            FTMIN,FWMIN, CNR, FCNR, DECR, RDECR(), NMINFOM(), NFOM(),
            NIMMFOM(), NMINHUM(), NHUM(), DMINR, NMINNET(), HUM(), NIT(),
            NOUTFLO(), NLEACH, AN(), NDEM(), NCMAX(), NC(), TOTAN, TPAN,
            TNFLO, TNMASFLO)

      RETURN


      500
            '*********************************************
            '*         SUB NITROGEN FERTILIZER           *
            '*********************************************

      ' Fresh Organic Matter

                 FROM = 3000: FRHUM = 30000
                 IFOM(1) = FROM * SDP1 / SDP: IFOM(2) = FROM * SDP2 / SDP
                 HUM(1) = FRHUM * SDP1 / SDP: HUM(2) = FRHUM * SDP2 / SDP
                 NO3(1) = 1: NO3(2) = 1: NH4(1) = .5: NH4(2) =.5: N(1) = 20

                FertSerie1(1) = 30: DoyFert(1) = 93: NFERT = 1
                FOR i = 1 TO NFERT
```

```
            FERT(i) = FertSerie1(i)
            DoyToFert(i) = DoyFert(i)
            FERTO3(i) = (FERT(i) * .8) * (62 / 80)
            FERTH4(i) = (FERT(i) * .8) * (18 / 80)
            PRINT FERT(i)
        NEXT i
RETURN
```

APPENDIX B

Source code for the soil nitrogen balance used in the PUTU 14 model.

```
SUB SOILN (J, BRL, BCL, BBL, BGL, BRD, BCD, BBD, BGD, TRANS1, TRANS2, V(),
                        V01(), V15(), ANC(), NO3(), NH4(), W01(), W(),
                        IFOM(), FOM(), T(), INFIL, PERC(), DoyToFert(),
                        FERTO3(), FERTH4(), TAVE, FW, N(), BO, FACN, GRSTGE,
                        TOTMASS(), NFERT, FTMIN,FWMIN, CNR, FCNR, DECR,
                        RDECR(), NMINFOM(), NFOM(), NIMMFOM(), NMINHUM(),
                        NHUM(), DMINR, NMINNET(), HUM(), NIT(), NOUTFLO(),
                        NLEACH, AN(), NDEM(), NCMAX(), NC(), TOTAN, TPAN,
                        TNFLO, TNMASFLO) STATIC
  '-----------------------------------------------------------------------
  '        SUB SOIL NITROGEN TO CALCULATE NITRATE IN SOIL LAYERS (2)
  '-----------------------------------------------------------------------
  'IFOM(L)                    'Initial amount of fresh organic matter
  'FOM(L)                     'Fresh organic matter
  'HUM(L)                     'Stable organic matter
  'T(L)                       'Soil temperature
  'V(L)                       'Soil water content
  'NH4(L)                     'Ammonium in layer L (kg/ha)
  'NO3(L)                     'Nitrate in layer L (kg/ha)
  'NFOM(L)                    'Nitrogen in FOM

 DMINR = 8.3 * 10 ^ -5        'Relative decay rate of humus
 CNRFOM = 40                  'C:N Ratio of FOM
 CNRHUM = 10                  'C:N Ratio OF HUM

 FLAG = FLAG + 1
 FOR L = 1 TO 2
    IF FLAG = 1 THEN NFOM(L) = .01 * FOM(L)
    IF FLAG = 1 THEN NHUM(L) = .04 * HUM(L)
    IF FOM(L) / IFOM(L) > .8 THEN RDECR(L) = .8
    IF FOM(L) / IFOM(L) < .8 THEN RDECR(L) = .05
    IF FOM(L) / IFOM(L) < .1 THEN RDECR(L) = .0095
    FTMIN = 1 / (1 + EXP(-.15 * (T(L) - 16)))
    FWMIN = 1 / (1* EXP(-GWP/1500))
    IF FWMIN < 0 THEN FWMIN = 0
    CNR = (.4 * FOM(L)) / (NFOM(L) + NO3(L) + NH4(L))
    FCNR = EXP(-.693 * (CNR - 25) / 25)
    IF FCNR > 1 THEN FCNR = 1
    DECR = RDECR(L) * FTMIN * FWMIN * FCNR
    NMINFOM(L) = NFOM(L) * DECR
    NIMMFOM(L) = DECR * FOM(L) * .02
    IF NIMMFOM(L) > AN(L) THEN NIMMFOM(L) = .4 * AN(L)

  'UPDATE FOM & NFOM
    FOM(L) = FOM(L) - DECR * FOM(L)
    NFOM(L) = NFOM(L) + NIMMFOM(L) - NMINFOM(L)

  'MINERALIZATION FROM HUMUS
    NMINHUM(L) = NHUM(L) * DMINR * FWMIN * FTMIN
    NMINNET(L) = .8 * NMINFOM(L) + NMINHUM(L) - NIMMFOM(L)
                                       'Net mineralization
    IF NMINNET(L) > 0 THEN NH4(L) = NH4(L) + NMINNET(L)
  IF NMINNET(L) <= 0 THEN NH4(L) = NH4(L) + NMINNET(L) * NH4(L) / (NH4(L)
                                    + NO3(L))
  IF NMINNET(L) <= 0 THEN NO3(L) = NO3(L) + NMINNET(L) * NO3(L) / (NH4(L)
                                    + NO3(L))
  'UPDATE HUM & NHUM
    NHUM(L) = NHUM(L) - NMINHUM(L) + .2 * NMINFOM(L)
```

```
  HUM(L) = HUM(L) - NMINHUM(L) * 10 + .2 * NMINFOM(L) / .04
NEXT L

'SIMPLE NITRIFICATION ROUTINE(25 % OF NH4 NITRIFIES PER DAY)
FOR L = 1 TO 2
    NIT(L) = .25 * (NH4(L) - 1)
    IF NIT(L) < 0 THEN NIT(L) = 0
    NH4(L) = NH4(L) - NIT(L)
    NO3(L) = NO3(L) + NIT(L)
NEXT L

'NITROGEN LEACHING & INFLUX BY RAIN
IF INFIL > 0 THEN NINFLO(1) = 0 * INFIL ELSE NINFLO(1) = 0
FOR L = 1 TO 2
    NINFLO(L + 1) = (PERC(L) * NO3(L) / (WO1(L) + PERC(L))) * .2
    NOUTFLO(L) = NINFLO(L + 1)
    NO3(L) = NO3(L) + NINFLO(L) - NOUTFLO(L)
NEXT L
NLEACH = NLEACH + NOUTFLO(2)

'NITROGEN FERTILIZER
IF J = DoyToFert(NFERT) THEN
   NO3(1) = NO3(1) + FERTO3(NFERT)
   NH4(1) = NH4(1) + FERTH4(NFERT)
   NFERT = 1 + NFERT
END IF

'UPDATE MINERAL N IN SOLUTION & SOIL
FOR L = 1 TO 2
    AN(L) = ((NO3(L) - 1) + (NH4(L) - 1)) * .9
    IF AN(L) < 0 THEN AN(L) = 0
    ANC(L) = AN(L) / W(L)
NEXT L

CALL PLANTN(J, BRL, BCL, BBL, BGL, BRD, BCD, BBD, BGD, TRANS1, TRANS2,
                  ANC(), AN(), V(), V15(), NO3(), NH4(), TAVE, FW, N(),
                  BO, FACN, GRSTGE, TOTMASS(), NDEM(), NCMAX(), NC(),
                  TOTAN, TPAN, TNFLO, TNMASFLO, TOTNUP)

END SUB
```

APPENDIX C

Source code for the plant nitrogen balance used in the PUTU 14 model.

```
SUB PLANTN (J, BRL, BCL, BBL, BGL, BRD, BCD, BBD, BGD, TRANS1, TRANS2,
                           ANC(), AN(), V(), V15(), NO3(), NH4(), TAVE, FW, N(),
                           BO, FACN, GRSTGE, TOTMASS(), NDEM(), NCMAX(), NC(),
                           TOTAN, TPAN, TNFLO, TNMASFLO, TOTNUP) STATIC
'------------------------------------------------------------------------
'SUB TO CALCULATE N DEMAND,TRANSLOCATION & LIMITATION IN THE PLANT
'------------------------------------------------------------------------

 MASS(2) = BCL + BCD: MASS(3) = BBL + BBD: MASS(4) = BGL + BGD
 FOR COMP = 2 TO 4
    IF MASS(COMP) > TOTMASS(COMP) THEN
      TOTMASS(COMP) = MASS(COMP)
    END IF
NEXT COMP

'MINIMUM AND MAXIMUM NITRATE CONTENT IN PLANT FOR (ROOTS,CULMS,LEAVES
      & GRAIN)
NCMAX(1) = (J / 365 * 5 * -.00172) + .01277
NCMAX(2) = (J / 365 * 5 * -.00268) + .019802
NCMAX(3) = (J / 365 * 5 * -.00698) + .055057
NCMIN(1) = .00475
NCMIN(2) = (J / 365 * 5 * -.00133) + .011731
NCMIN(3) = (J / 365 * 5 * -.00296) + .03307
LNCL = .00475

TS(1) = TRANS1: TS(2) = TRANS2

'DEMAND FOR NITRATE
 TAU2 = 2: TNDEM = 0
  IF GRSTGE = 5 THEN EOSF = 0 ELSE EOSF = 1
  FOR COMP = 1 TO 3
      NDEM(COMP) = (TOTMASS(COMP) * (NCMAX(COMP) - NC(COMP))) / TAU2
      IF NDEM(COMP) < 0 THEN NDEM(COMP) = 0
      TNDEM = (TNDEM + NDEM(COMP)) * EOSF
  NEXT COMP

'MAXIMUM NITROGEN UPTAKE
  NUPO = 6 * (1 - EXP(-.005 * (TOTMASS(2) + TOTMASS(3))))

 'FLOW BY MASS
  TNMASFLO = 0
  FOR L = 1 TO 2
      IF TS(L) < 0 THEN TS(L) = 0
      NMASFLO(L) = TS(L) * ANC(L)
      TNMASFLO = TNMASFLO + NMASFLO(L)
  NEXT L
  IF (GRSTGE<=4) THEN NDIFFLOO=(TNDEM-TNMASFLO) / 1.5 ELSE NDIFFLOO =
0

  IF NDIFFLOO < 0 THEN NDIFFLOO = 0

  TOTAN = 0: TNDIFFLO = 0
  FOR L = 1 TO 2
      IF V(L) >= V15(L) THEN TOTAN = TOTAN + AN(L)
  NEXT L
  FOR L = 1 TO 2
   IF TOTAN AND V(L) >= V15(L) THEN NDIFFLO(L) = NDIFFLOO * AN(L) /
      TOTAN ELSE NDIFFLO(L) = 0
      MASDIFLO(L) = NMASFLO(L) + NDIFFLO(L)
```

```
            TNDIFFLO = TNDIFFLO + NDIFFLO(L)
        NEXT L
        TNFLO = TNMASFLO + TNDIFFLO

      'CALCULATE UPTAKE
        IF NUPO <= TNFLO THEN NUP = NUPO ELSE NUP = TNFLO
        IF NUP > TNDEM THEN NUP = TNDEM
        IF NUP > TOTAN THEN NUP = TOTAN * .9
        IF NUP < 0 THEN NUP = 0
        TOTNUP = TOTNUP + NUP

      'UPDATE NO3 & NH4 IN SOIL
        FOR L = 1 TO 2
           IF TNFLO > 0 THEN DNO3(L) = MASDIFLO(L) / TNFLO * NUP * NO3(L) /
                 (NO3(L) + NH4(L)) ELSE DNO3(L) = 0
           IF TNFLO > 0 THEN DNH4(L) = MASDIFLO(L) / TNFLO * NUP * NH4(L) /
                 (NO3(L) + NH4(L)) ELSE DNH4(L) = 0
           NO3(L) = NO3(L) - DNO3(L)
           NH4(L) = NH4(L) - DNH4(L)
        NEXT L

      'NITROGEN DISTRIBUTION & TURNOVER
        RFNS = 1 - (1 - FACN ^ 2)
        ONC = .07
        DN(4) = TOTMASS(4) * (ONC - NC(4)) * RFNS
        IF DN(4) < 0 THEN DN(4) = 0
        N(4) = N(4) + DN(4)
        IF TOTMASS(4) > 0 THEN NC(4) = N(4) / TOTMASS(4)

        TPAN = 0
        FOR COMP = 1 TO 3
            IF TNDEM * NUP > 0 THEN DN(COMP) = NDEM(COMP) / TNDEM * NUP
            N(COMP) = N(COMP) + DN(COMP)
            IF TOTMASS(COMP) > 0 THEN NC(COMP) = N(COMP) / TOTMASS(COMP)
            IF NC(COMP) <= NCMIN(COMP) THEN PAN(COMP) = 0 ELSE PAN(COMP) =
                  (NC(COMP) - NCMIN(COMP)) * TOTMASS(COMP)
            TPAN = TPAN + PAN(COMP)
        NEXT COMP

        FOR COMP = 1 TO 3
           IF TPAN > 0 THEN DN(COMP) = DN(4) * PAN(COMP)/TPAN ELSE DN(COMP)=0
            N(COMP) = N(COMP) - DN(COMP)
            IF TOTMASS(COMP) > 0 THEN NC(COMP) = N(COMP) / TOTMASS(COMP)
        NEXT COMP

      'EFFECT OF N STATUS ON PROCESSES
        NCOPT(3) = NCMAX(3) * .8
        IF NCOPT(3) > 0 THEN FACN(3) = (NC(3) - NCMIN(3)) / (NCOPT(3) -
                          NCMIN(3))
        IF FACN(3) < 0 THEN FACN(3) = 0
        FACN = FACN(3)
        IF FACN > 1 THEN FACN = 1

    END SUB
```

APPENDIX D

D.1 Table of high, low and average yield values (t ha^{-1}) simulated for a bad year.

FACTOR		High	Low	Average
TIME	1	0.9	0.5	0.7
	2	1.1	0.5	0.8
	3	0.9	0.5	0.7
RATE	5	0.5	0.5	0.5
	10	0.7	0.6	0.7
	15	0.9	0.8	0.8
	20	1.1	0.8	0.9
	25	1.1	0.8	0.9

D.2 Table of high, low and average yield values (t ha^{-1}) simulated for a poor year.

FACTOR		High	Low	Average
TIME	1	2.3	0.8	1.7
	2	2.1	0.9	1.7
	3	1.7	0.9	1.5
RATE	15	0.9	0.8	0.9
	30	1.4	1.3	1.4
	45	1.8	1.7	1.7
	60	2.2	1.7	2.0
	75	2.2	1.7	2.0

D.3 Table of high, low and average yield values (t ha^{-1}) simulated for a moderate year.

FACTOR		High	Low	Average
TIME	1	3.3	1.3	2.5
	2	3.6	1.3	2.7
	3	2.3	1.4	2.0
RATE	25	1.4	1.3	1.3
	50	2.2	2.1	2.1
	75	2.9	2.3	2.6
	100	3.6	2.3	3.0
	125	3.6	2.3	3.0

D.4 Table of high, low and average yield values (t ha^{-1}) simulated for a good year.

FACTOR		High	Low	Average
TIME	1	4.7	1.7	3.5
	2	5.5	1.9	3.8
	3	4.2	1.9	3.5
RATE	35	1.9	1.7	1.8
	70	3.1	2.7	2.9
	105	4.2	3.8	3.9
	140	5.1	4.2	4.7
	175	5.5	4.1	4.8

D.5 Table of high, low and average yield values (t ha^{-1}) simulated for a wet year.

FACTOR		High	Low	Average
TIME	1	7.7	2.8	5.8
	2	7.3	2.7	5.7
	3	5.7	2.8	4.9
RATE	60	2.8	2.7	2.8
	120	4.7	4.5	4.6
	180	6.4	5.7	6.2
	240	7.7	5.7	6.9
	300	7.7	5.7	6.9

D.6 Simulated seasonal yield kg ha^{-1} from 1916-1991 for different N-levels

Year	N(0)	N(30)	N(60)	N(90)	N(120)	N(150)
1916	249.3	268.0	268.0	268.0	268.0	268.0
1917	400.3	1599.1	2464.2	3432.2	4322.6	5159.4
1918	529.2	1699.9	2561.6	3436.0	4361.3	5315.8
1919	429.8	1276.2	1755.2	1755.2	1755.2	1755.2
1920	243.9	411.1	411.1	411.1	411.1	411.1
1921	488.6	1544.9	2424.4	3355.3	3820.8	3820.8
1922	380.4	1535.4	2375.1	3575.5	3575.5	3575.5
1923	452.3	1093.5	1093.5	1093.5	1093.5	1093.5
1924	547.9	1390.2	2284.3	3248.0	3527.4	3527.4
1925	418.0	1210.6	1210.6	1210.6	1210.6	1210.6
1926	535.8	1347.4	2354.3	2354.3	2354.3	2354.3
1927	470.2	1363.3	2041.2	2041.2	2041.2	2041.2
1928	491.0	1379.0	2333.6	2622.3	2622.5	2622.5
1929	422.8	1643.0	2487.7	3404.7	4301.9	5420.1
1930	393.0	1292.6	1947.3	1947.3	1947.3	1947.3
1931	423.9	1220.8	1294.3	1294.3	1294.3	1294.3
1932	372.3	1246.2	1246.2	1246.2	1246.2	1246.2
1933	434.8	1281.6	2311.1	2311.1	2311.1	2311.1
1934	417.7	1336.4	2272.5	2828.0	2828.0	2828.0
1935	414.3	665.1	665.1	665.1	665.1	665.1
1936	328.9	731.7	731.7	731.7	731.7	731.7

Year	N(0)	N(30)	N(60)	N(90)	N(120)	N(150)
1937	331.6	922.0	922.0	922.0	922.0	922.0
1938	441.9	1290.7	2083.9	2083.9	2083.9	2083.9
1939	530.0	1336.1	2152.0	2152.0	2152.0	2152.0
1940	425.7	1333.6	2367.6	2367.6	2367.6	2367.6
1941	391.3	1093.3	1093.3	1093.3	1093.3	1093.3
1942	734.8	1355.5	2258.0	2658.6	2659.8	2660.9
1943	456.6	1917.6	2635.8	3458.9	4427.3	5237.8
1944	459.9	1285.1	1792.4	1792.4	1792.4	1792.4
1945	445.0	1022.6	1022.6	1022.6	1022.6	1022.6
1946	267.9	286.8	286.8	286.8	286.8	286.8
1947	410.4	1271.8	2032.3	2032.3	2032.3	2032.3
1948	394.0	1284.1	1284.1	1284.1	1284.1	1284.1
1949	937.2	1457.1	2369.3	3253.8	3907.4	3907.4
1950	400.3	1282.8	2034.1	2034.1	2034.1	2034.1
1951	433.8	1314.9	1815.2	1815.2	1815.2	1815.2
1952	646.9	1438.5	2368.3	3262.5	3848.2	3848.2
1953	384.1	1312.1	2117.9	2117.9	2117.9	2117.9
1954	504.0	1318.4	2625.9	2625.9	2625.9	2625.9
1955	289.0	529.4	529.4	529.4	529.4	529.4
1956	722.7	1387.3	2253.6	3269.2	3269.2	3269.2
1957	918.9	2104.3	2819.5	4367.8	4367.9	4368.0
1958	442.4	1408.2	2291.1	3072.9	3072.9	3072.9
1959	412.6	782.1	782.1	782.1	782.1	782.1
1960	665.7	1389.5	2293.5	3189.4	3397.7	3397.7
1961	387.2	728.8	728.8	728.8	728.8	728.8
1962	514.0	1146.4	1146.4	1146.4	1146.4	1146.4
1963	329.1	917.8	917.8	917.8	917.8	917.8
1964	327.8	908.4	908.4	908.4	908.4	908.4
1965	423.1	1305.8	2370.7	2370.7	2370.7	2370.7
1966	532.0	1381.5	2339.3	3246.5	3246.5	3246.5
1967	509.4	1224.6	1336.2	1336.2	1336.2	1336.2
1968	555.0	1320.8	2236.8	2749.1	2749.1	2749.1
1969	376.3	1277.6	1622.7	1623.4	1624.1	1624.8
1970	568.4	1412.0	2352.3	3259.2	3706.2	3706.2
1971	586.2	1393.7	2365.5	3484.3	3499.3	3499.3
1972	302.2	365.4	365.4	365.4	365.4	365.4
1973	461.1	1302.3	2365.1	2365.1	2365.1	2365.1
1974	489.9	1255.9	1255.9	1255.9	1255.9	1255.9
1975	518.6	1319.3	2230.9	2895.1	2895.1	2895.1
1976	366.2	812.1	812.1	812.1	812.1	812.1
1977	434.9	832.6	832.6	832.6	832.6	832.6
1978	263.3	1269.5	2264.5	2325.5	2325.5	2325.5
1979	502.3	1484.6	2643.2	3437.7	4222.0	4930.3
1980	777.6	1999.7	2619.7	3498.8	4389.1	5373.0
1981	455.3	1296.7	1877.6	1877.7	1877.7	1877.8
1982	471.4	1365.2	2237.3	2533.1	2533.1	2533.1
1983	487.1	1362.9	2289.5	2728.5	2728.5	2728.5
1984	355.8	1467.8	2315.5	3242.2	3577.7	3577.7
1985	396.3	1118.6	1118.6	1118.6	1118.6	1118.6
1986	573.4	1510.3	2377.1	3340.3	4863.3	4924.3
1987	587.03	2173.1	2653.6	3495.4	4395.4	5356.0
1988	1041.48	1463.1	2379.4	3277.4	4397.6	4397.6
1989	413.36	1244.8	1777.6	1777.6	1777.6	1777.6
1990	435.66	1407.6	1799.6	1799.6	1799.6	1799.6
1991	367.90	936.2	936.2	936.2	936.2	936.2