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IMAGES 2.1 : an Integrated Model of an Arid Grazing System

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Disclaimer

The contents of this report were based on the best available information at the time of publication. It is based in part on various assumptions and predictions. Conditions may change over time and conclusions should be interpreted in the light of the latest information available.

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1. Introduction

The name IMAGES stands for An Integrated Model of an Arid Grazing Ecological System. The model was initiated by Dr R. Hacker in 1987-8 as an activity to (1) evaluate alternative management strategies and (2) identify key ecological processes and research priorities in shrub rangelands of Western Australia. Version 1 of the model was published in *Agriculture Systems* in 1991 (Hacker *et al*. 1991) and here after will be referred to as IMAGES 1.

IMAGES 1 is a vegetation model, capable of predicting the probability of recruitment and mortality of the desirable species in a given vegetation type under different types of grazing managements. The model has been parameterised for five major vegetation types based on data collected by Western Australian rangeland workers over the past 30 years.

IMAGES 1 has a number of limitations.

• First, the model uses an average species for any given pasture type and as such has over-simplified the production system. The model can adequately predict the peaks and troughs of the desirable plant population when the paddock is relatively uniformin composition. The prediction is less accurate when the paddock is vegetated by a suite of species which may vary in their life spans and in their responses to environmental stress and animal grazing pressure.

- Second, the model does not consider undesirable species. More than 60% of our rangelands have been degraded to some extent and much of this country shows some degree of increase in undesirable species (Curry and Payne 1989). Hence undesirable species are an inseparable part of the rangeland system.

- Third, the dynamics of standing dry annual biomass are also unaccounted for. Standing dry annual biomass is an important part of the forage, particularly in summer when green perennial and annual forages have generally disappeared.

- Fourth, the model was programmed in Lotus 1-2-3. Many of the operations were automated through Macro. As such, the model lacks portability and compatibility with other major rangeland models. There have also been comments that the model is difficult to operate and crashes easily.

Efforts have been made to rectify some of the problems associated with IMAGES 1 by developing an improved version, IMAGES 2.1. Major changes have been made in four areas.

- First, functional groups are used instead of an average species. This change enables the model to accommodate pasture types with diverse species composition. Undesirable species are also considered.

- Second, the standing dry annual biomass is included as a part of the forage pool and modelled accordingly.

- Third, the effects of plant half-life on mortality have been reduced and more emphasis has been placed on field conditions. This is necessary due to a lack of accurate information on the half-life of many rangeland species and the dominant role field conditions played in rangeland plant population dynamics.

- Fourth, the model is reprogrammed in FORTRAN to allow portability and compatibility with other models of rangeland ecosystem dynamics.

The objective of this report is to document the major changes made to the model. The first section, Running IMAGES 2.1, is intended for those who are interested in the running of the model. The section begins with a 4-step guide to run IMAGES 2.1. This is followed by detailed descriptions of the input and output files associated with running the model. The second section, Model Structure, is intended for those who are interested in further model development The three major subroutines of the FORTRAN program are described. The FORTRAN codes for the model are attached to the end of this report. In preparing this report, emphases have been on those areas where changes have been made. For a full description of the model, refer to Hacker et al. (1991).

2. RUNNING IMAGES 2.1

The operation of IMAGES 2.1 is relatively simple compared with the earlier spreadsheet version. Once compiled, the executable file IMAGES.EXE can be run in either DOS or WINDOWS environments.

2.1 Four steps to run IMAGES 2.1

(1) ensure that the input files and the IMAGES.EXE file are located in the same area (directory or subdirectory);

(2) in DOS, go to the (Sub)directory or Drive where the IMAGES.EXE file resides, and type IMAGES to start the program. In WINDOWS, locate the file under File Manager and double click the IMAGES icon to run the model;

(3) a prompt for the name of the output files will then be given. Any combination of letters or numbers can be used to name the output files. Only the first three digits or letters will be used by the computer to construct the output file names;

(4) type in the NWP (number of wet pentads) data type as appropriate and the stocking rate when prompted. The model will do the rest.

2.2 Structure of input files

Four input files are needed to run the model. They are named INPUT1.DAT,INPUT2.DAT…………INPUT4.DAT. All input files are text files and can be edited by any editor capable of text editing such as Word, Excel and Notepad. However, when saving the file, please ensure that the file is saved as a text file. To save a file in text format, go to the File menu, select Save As instead of Save command. Next select text under the Format submenu, and click OK.

The first file contains data on the number of wet pentads within each 4-month period (NWP). A wet pentad refers to a 5-day period during which there is sufficient water in the soil root-zone to enable plant growth. NWP is closely associated with rainfall and temperature. In IMAGES, NWP is taken as an index of field seasonal conditions. NWP has been used to calculate various soil moisture indices that are related to specific ecological processes. The full meaning of NWP and how it is calculated is described in Fitzpatrick *etal.* (1967).

INPUT1.DAT defines the seasonal conditions in the field. It takes on either of the following two formats

Type 1:

NWP	PDF	PDF	PDF
	season 1	season 2	season 3
0	0.35	0	0.27
1	0.15	0	0.19
2	0.13	0.01	0.15
3	0.09	0	0.11
-	-	-	-
-	-	-	-
-	-	-	-
24	0	0.07	0

Numbers in the first column are the number of wet pentads (NWP), which could occur within a simulation time step. The NWP within a simulation time step ranges from 0 (extremely dry) to 24 (extremely wet). Numbers in the second to fourth columns are the probabilities (%) of any given NWP occurring during season 1 (Jan-Apr), season 2 (May-Aug) and season 3 (Sept-Dec), respectively.

Type 2:

Year	NWP1	NWP2	NWP3
1984	8	23	4
1985	3	14	1
1986	3	14	2
1987	0	12	1
1988	1	19	0
1989	0	19	1
1990	1	19	3
1991	2	18	2
1992	2	24	1
1993	3	16	2
1994	0	16	4

In the Type 2 file above, numbers in the first column are calendar years. Numbers in the second to fourth column are the number of wet pentads during season 1,2, and 3 respectively. When running a simulation, you'll be asked which type of data you are using. When using type 2 data, you are also asked to supply the number of years your data cover. INPUT1.DAT is calculated by using the Watbal model (Fitzpatrick *et al.* 1967).

INPUT2.DAT contains data used to define each of the functional groups and the carrying capacity of the system, including life span (Spanlf), cohort (population) size (LPT), standing forage biomass (SF), preference coefficient (Pref), maximum density (SPM), and maximum biomass production (KF). The following is an annotated example of INPUT2.DAT. Please read the file concurrently with the variable list section (below) for more details about each of the variables and how they are determined.

Input2.dat

40	10	5	10				AGESPL, AGESPS NPP, NYEARS
8	36	50	6	40			SPANLF (groupl to group 5)
0	0	0	0	0	0	0	LPT (5 groups x 7cohorts)
1000	300	200	100	50	20	1000	
1000	300	200	100	50	20	1000	
0	0	0	0	0	0	0	
0	0	0	0	0	0	0	
0	150	250	0	0	50	50	SF (groupl to 5, green dry)
1	3000	3000	1	1			SPM (groupl to 5)
0	700	800	0	0	300		FK (group 1 to 5, green)
0	1	1	0	0	4	0.5	PREF (groupl to 5, green dry)
0.5	0.95	0.95	0.4	1			DTCI (group 1 to 5)
180	300	200					PI TFA1 TFA2
1	1						SGPIC (5 groups x 1 seedling &
1	0.1						5 groups x 1 adult)
1	0.2						
1	0						
1	0						

The numbers on the left hand side are what appear in INPUT2.DAT file whereas the texts on the right are lists of variables corresponding to the data. In case of a variable table (matrix) it is written in the format 'var ($element_1$, $element_2$ ... $element_n$)', where var stands for varaible name and element in brackets stands for table elements. For example, the first four numbers are for variables AGESPL, AGESPS, NPP and NYEARS. The second row is a 1 x 5 SPANLF matrix. The matrices at the end of the file are in fact two 5x1 SGPIC matrices. The first matrix (5x1) (first column) contains the grazing pressure indices for seedlings of the five functional groups, whereas the second matrix contains the grazing pressure indices for adults of the five functional groups.

The third input file, INPUT3.DAT contains data defining important ecological functions (relationships). The file contains 8 groups of data. These are:

1) replacement capacity (RCI) and relative density (PD) for the long lived perennials and RCI and field conditions for the short lived perennials;

2) germination capacity (GMI) under various field conditions;

3) soil moisture index (SMI) for seedling survival under extreme dry conditions (NWP=0/4_mth period);

4) adult competition coefficient (AC) among functional groups;

5) Soil moisture index (SMI) for forage production under various field conditions;

6) growth capacity index (GCI) for forage production under various levels of standing forage;

7) annual production capacity (HKT) and relative plant density (PD);

8) standing forage (SF) and forage availability (AI).

INPUT3.DAT

0	0	0.05	0.05	0	0	RCIT1 (PD,RCI1...RCI5) long-lived perennials
0.1	0	0.5	0.5	0	0	
0.2	0	0.8	0.8	0	0	(10 x 6)
0.3	0	0.9	0.9	0	0	
0.4	0	1	1	0	0	
0.5	0	1	1	0	0	
0.6	0	1	1	0	0	
0.7	0	1	1	0	0	
0.8	0	1	1	0	0	
0.9	0	1	1	0	0	
0	0					RCIT2 (NWP, RCI) short lived perennials
2	0					
4	0.1					(10 x 2)
6	0.3					
8	0.5					
12	0.6					
16	0.8					
18	0.9					
20	1					
22	1					
0	0	0	0	0	0	GMI (NWP,GCI1...GCI5)
2	0	0	0	0	0	
4	0.1	0.2	0.1	0.1	0.1	(10 x 6)
6	0.3	0.6	0.3	0.3	0.3	
8	0.7	0.8	0.7	0.7	0.7	
10	0.9	0.9	0.9	0.9	0.9	
12	1	1	1	1	1	
14	1	1	1	1	1	
16	1	1	1	1	1	
18	1	1	1	1	1	
0	0.2	0.3	0.8	0.8	0.8	SMI1 (5 groups x 6 cohorts)
0	0.2	0.3	0.8	0.8	0.8	for seedling survival under NWP=0 /4 mth
0	0.2	0.3	0.8	0.8	0.8	
0	0.2	0.25	0.5	0.75	0.8	
0	0.2	0.25	0.5	0.75	0.8	
1	0	0	0	0		AC (5 groups x 5 groups)
0	1	0	0	0		
0	0	1	0	0		
0	0	0	1	0		
0	0	0	0	1		

0	0	0	0	0	0	SMI3 (NWP,SMI(groups 1 to 5))
2	0.08	0.09	0.09	0.09	0.09	
4	0.1	0.1	0.1	0.3	0.3	(10 x 6)
6	0.4	0.3	0.3	0.5	0.5	
8	0.7	0.6	0.6	0.8	0.8	
10	0.9	0.75	0.8	0.9	0.9	
12	0.95	0.8	0.85	0.95	0.95	
15	1	0.9	0.9	1	1	
18	1	1	1	1	1	
24	1	1	1	1	1	
0	0.5	0.5	0.5	0.5	0.5	GCIT (SF/KF,GCI(grpl to 5))
0.1	0.6	0.6	0.6	0.6	0.6	
0.2	0.7	0.7	0.75	0.75	0.75	(10 x 6)
0.3	0.8	0.85	0.85	0.85	0.85	
0.4	0.9	0.88	0.9	0.9	0.9	
0.5	0.9	0.9	0.9	0.9	0.9	
0.6	0.9	0.9	0.9	0.9	0.9	
0.7	0.9	0.9	0.9	0.9	0.9	
0.8	0.9	0.9	0.9	0.9	0.9	
1	0.9	1	1	1	1	
0	0.8					HKT(PD,HKT)
0.1	1					
0.2	0.6					(10 x 2)
0.3	0.3					
0.4	0.25					
0.5	0.2					
0.6	0.18					
0.7	0.16					
0.8	0.13					
1	0.1					
0	0					SIFAI (SF.AI)
50	0.05					
100	0.1					(10 x 2)
200	0.2					
400	0.3					
800	0.5					
1200	0.8					
1500	1					
2000	1					
3000	1					

Numbers on the left hand side are data contained in INPUT3.DAT. The text on the right hand side gives annotations to the data. The annotation is done in a similar fashion to that of INPUT2.DAT above. For example, the first 10x6 matrix is a RCIT1 table. The first column contains data on relative plant density (PD) in ascending order. The second to sixth column contains data on RCI (group 1 through 5) corresponding to various PDs.

INPUT4.DAT is optional, useful only to those who are interested in model development. This file has the same format as INPUT1.DAT (type 2). Refer to INPUT1.DAT for more information.

INPUT4.DAT

Year	NWP1	NWP2	NWP3
1983	3	18	0
1984	8	23	4
1985	3	14	1
1986	3	14	2
1987	0	12	1
1988	1	19	0
1989	0	19	1
1990	1	19	3
1991	2	18	2
1992	2	24	1
1993	3	16	2
1994	0	16	4

Data in INPUT4.DAT are used to set field conditions during the simulation period. They are therefore useful in model validation. Another important use of this file is to set specific climatic scenarios for management decision making.

2.3 Variables of the input files

The following is a list of variables from the four input files. Variables are listed in the order as they appear in the input files (INPUT1.DAT, INPUT2.DAT,INPUT3.DAT and INPUT4.DAT). The full meaning of each variable is given along with a statement about how the variable is determined.

- PDF probability density function of wet pentads, calculated from historic records.
- NWP number of wet pentads during each simulation time step (4-month period). NWP is calculated by WATB AL model.
- AGESPL life span criterion for long-lived species, currently is set to 40.
- AGESPS life span criterion for short-lived species, currently is set to 10.
- NPP number of perennial plant groups, currently NPP=5.
- NYEARS number of simulation years. This number can be changed as appropriate at each simulation run.
- SPANLF(5) life span (years) table of the 5 perennial plant groups. Data supplied by user.

- LPT(5,7) population (plants/ha) table of perennial plants listed as 5 functional groups (row) and 7 cohorts (column) at the start of simulation. Data supplied by user.
- SF(7) forage biomass (kg/ha) table of the 7 forage pools at the start of simulation. Data supplied by user.
- SPM(5) maximum density (plants/ha) of mature desirable perennial plants of the 5 functional groups. Data supplied by user.
- FK(6) maximum forage biomass (kg/ha) of perennials (5) and annuals (1). Data supplied by user.
- PREF(7) sheep preference coefficient table for selective grazing of the 7 forage pools. Data supplied by user. Value ranges from 0 (not palatable) up with the most preferred groups being given the highest value.
- DTCI(5) drought tolerance capability table of adult perennial plants. User determined. Value ranges from 0+ to 1, corresponding to increased drought tolerance capability.
- PI potential intake per dry sheep equivalent per simulation time step (4-month period), currently set to 180 kg/dse/4-month.
- TFA1PREF the threshold of forage biomass level below which sheep selective grazing ability start to decline. Currently it is set at 300 kg/ha.
- TFA2PREF the threshold of forage biomass level below which sheep selective grazing ability stop, i.e. random grazing starts. It is set at 200 kg/ha.
- SGPIC(5,2) grazing pressure index for seedling (first column) and adult (second column) populations of the five perennial groups. SGPIC is user determined and ranges between 0 (grazing insensitive) to 1 (most sensitive to grazing).
- RCIT1 (10,6) replacement capacity index table 1 for the long-lived perennial functional groups. The replacement capacity index is formulated as a function of plant density (PD). RCI ranges from 0 to 1.
- RCIT2 (10,6) replacement capacity index table 2 for the short-lived perennial functional groups. The replacement capacity index is formulated as a function of NWP during the last winter season. RCI ranges from 0 to 1.
- GMI(10,6) germination index table for perennial functional groups. This index is formulated as a function of NWP during the last winter season. GMI ranges from 0 to 1.
- SMI1 (5,6) soil moisture index table for survival of 5 perennial seedling groups and 6 cohorts. SMI1 varies between 0 and 1.
- AC(5,5) competition coefficient among mature perennial plants. AC ranges between 0 (no competition) to 1.

- SMI3(10,6) soil moisture index table for growth of 5 perennial forage groups. It is formulated as a function of NWP during the last current season. SMI3 ranges between 0 and 1.
- GCIT(10,6) growth capacity table of perennial plant forage biomass of the 5 groups. GCI is formulated as a linear function of current standing forage level, i.e. SF/FK
- HKT(10,2) environmental carrying capacity index table for ephemeral biomass. It is formulated as a linear function of relative plant density (PD).
- SIFAI(10,2) forage availability index table for sheep intake. Forage availability index is calculated as a linear function of the total forage.
- PD relative density of perennial plants. It is calculated as LPT(7)/SPM.

2.4 Model output files

There are three output files: RBIOM[name].DAT, RPOPN[name].DAT, and RECOL[name].DAT. [name] refers to the user supplied name when running the simulation. All output files are text files and can be viewed with any editor capable of text editing.

The first file, RBIOM[name].DAT stores simulation results on forage biomass. The following is a sample from RBIOM[name].DAT.

Forage Biomass, SF(i), kg/ha DM

	Pern1	Pern 2	Pem3	Pem4	Pem5	Gren E	Dry E
Year 1							
Season 1							
Opening stock	0	150	250	0	0	50	50
Recruitment	0	29.7	26.9	0	0	0	44.4
Sheep intake	0	3.7	5.7	0	0	4.1	1
Other losses	0	74.2	116.1	0	0	45	22.9
Ending stock	0	101.8	155	0	0	0.9	70.5
Grazing	0	1	1	0	0		
Pressure							
NWP= 3.	Stocking	Rate= .08	dse/ha				
Season 2							
Opening stock	0	101.8	155	0	0	0.9	70.5
Recruitment	0	194.1	212	0	0	35.4	11.2
Sheep intake	0	5	6.2	0	0	2.5	0.7
Other losses	0	36.8	46	0	0	11.6	64.8
Ending stock	0	254.1	314.9	0	0	22.3	16.2
Grazing	0	1	1	0	0		
Pressure							
NWP=18.	Stocking	Rate= .08	dse/ha				

Columns represent the forage biomass of the five functional groups, green annuals and dry annuals. For each simulation year, the model updates the forage biomass (kg/ha) three times, i.e. April, August, and December. Each update includes:

(1) opening stock: forage biomass (kg/ha) at the beginning of each simulation time step (4-month period);

(2) recruitment: the amount of forage growth (kg/ha) during the simulation time step;

(3) sheep intake: the amount of forage intake (kg/ha) by sheep;

(4) other losses: forage biomass loss (kg/ha) due to other factors such as drying and trampling rather than sheep grazing;

(5) ending stock: the amount of standing forage biomass (kg/ha) at the end of simulation time step;

(6) grazing pressure: pressure exerted by grazing stock on individual functional groups. Grazing pressure ranges from 0 to 1;

(7) NWP and stocking rate: number of wet pentads during each simulation time step (4 months), stocking rate (dse/ha) is the actual stocking rate applied during each simulation time step.

In our example above, functional group 1,4, and 5 are absent in the system, and hence no forage biomass is produced by these three groups. For those of us who are interested in making management decisions, the important information to look for is the amount of sheep intake and the grazing pressure. During season 1 (simulation time step 1), NWP=3, Stocking rate=0.08 dse/ha, total sheep intake =3.7+5.7+4.1+1.0=14.5 kg/ha/4-mth, which is equivalent to 14.5/0.08= 181 kg/dse/4-mth. Under the current stocking rate, sheep intake reached its full potential (assuming PI=180 kg/dse/4 months). The calculated Grazing pressure = 1 for both perennial functional groups, group 2 and 3, indicates that grazing has no adverse impact on their population dynamics. This conclusion is re-enforced by the simulation results of population dynamics of the perennial groups (see also below). From this information, we conclude that the system can support the 0.08 dse/ha stocking rate under the current climatic condition.

Simulation results on perennial population dynamics are stored in RPOPN[name].DAT. To illustrate the file structure of RPOPN[name].DAT, a sample of this file is reproduced below.

Rpopn[name] .dat

Year 1

Season 1

NWP= 3 Stocking Rate= .08 dse/ha

Groups	Cohortl	Cohort2	Cohort3	Cohort4	Cohorts	Cohort6	Adults
1	0.	0.	0.	0.	0.	0.	0.
2	187.	49.	46.	49.	51.	30.	999.
3	93.	49.	46.	49.	51.	30.	995.
4	0.	0.	0.	0.	0.	0.	0.
5	0.	0.	0.	0.	0.	0.	0.

Season 2

NWP= 18. Stocking Rate= .08 dse/ha

Groups	Cohortl	Cohort2	Cohort3	Cohort4	Cohorts	Cohort6	Adults
1	0.	0.	0.	0.	0.	0.	0.
2	933.	80.	29.	32.	37.	41.	1015.
3	934.	40.	29.	32.	37.	41.	1009.
4	0.	0.	0.	0.	0.	0.	0.
5	0.	0.	0.	0.	0.	0.	0.

The outputs are listed by year by season (time step) for the simulation period. The first column refers to the functional groups (1 to 5). The second through to seventh column is cohort size (plants/ha) of seedlings. The last column is adult populations (plants/ha). NWP are number of wet pentads within any given simulation time step (currently 4 months). It is used as an index for field condition. Stocking rate refers to the stocking rate used in the simulation time step.

The third output file RECOL[name].DAT is useful to those who are interested in model development. It contains most of the derived parameters used in the simulation. The following is a sample of the file for year 1, simulation time step 1. This file is best read using Word or Excel, as it can be large when running simulations for 50 years.

recol[name].dat

Ecological Functional Relationships

Year 1

Season 1

NWP= 3. Stocking Rate= .08 dse/ha

	PI	P2	P3	P4	P5
SMI3=	.13	.09	.09	.20	.20
GCI=	.05	.87	.90	.50	.50
FK=	0.	420.	480.	0.	0.
KFE=	50.	KFT= .17	EGI= .13		

DRY/DECAY RATE= .44 .41 .42 .44 .44 .89 .23

	PI	P2	P3	P4	P5
RCI=	.95	.93	.93	.95	.00
GMI=	.05	.10	.05	.05	.05
PCI=	1.00	1.00	1.00	1.00	1.00

	COH1	COH2	COH3	COH4	COH5	COH6
ECI=	.50	.58	.66	.74	.82	.90
SMI1=						
Group1	.25	.42	.51	.00	.00	.00
group2	.25	.42	.51	.87	.88	.89
group3	.25	.42	.51	.87	.88	.89
group4	.25	.42	.47	.00	.00	.00
group5	.25	.42	.47	.67	.84	.89
GI=						
Group1	1.00	1.00	1.00	.00	.00	.00
group2	.39	.63	.73	.79	.83	.86
group3	.39	.63	.73	.79	.83	.86
group4	1.00	1.00	1.00	.00	.00	.00
group5	1.00	1.00	1.00	1.00	1.00	1.00
SURRAT=						
Group1	.12	.24	.34	.00	.00	.00
group2	.05	.15	.25	.51	.60	.68
group3	.05	.15	.25	.51	.60	.68
group4	.12	.24	.31	.00	.00	.00
group5	.12	.24	.31	.49	.69	.80

AdultSURRAT	PI	P2	P3	P4	P5
GPI2=	1.00	.99	.98	1.00	1.00
SMI2=	1.00	1.00	1.00	1.00	1.00
PDI=	1.00	1.00	1.00	1.00	1.00
M0=	.06	.01	.01	.07	.01
SURRAT=	.97	.99	.98	.96	.99

The model updates each derived parameter once every simulation time step. The above output file (sample) consists of 4 groups of data. The row labels "PI, P2 ...P5" and "COH1, COH2...COH6" refer to functional groups 1 to group 5 and seedling cohortl to cohort 6, respectively. The following is a brief description of each of the four data groups.

Group 1: variables related to forage production.

- SMI3: soil moisture index
- GCI: growth capacity index
- FK: carrying capacity of perennials (kg/ha)
- KFE: carrying capacity of annuals (kg/ha)
- KFI: annual carrying capacity index under different levels of range condition
- EGI: annual growth index.

Group 2: variables related to seedling population dynamics.

- RCI: replacement capacity index
- GMI: germination index
- PCI: perennial competition index.

Group 3: variables related to seedling growth.

- SM11: soil moisture index
- GPI: grazing pressure index
- SURRAT: survival rate.

Group4: variables related to adult perennial survival.

- GP12: grazing pressure index
- SM12: soil moisture index
- PDI: plant density index
- M0: natural mortality
- SURRAT: adult survival rate.

3. MODEL STRUCTURE

To make the model portable and compatible with other models on rangeland ecosystem dynamics, the model has been re-programmed in FORTRAN. The FORTRAN model now consists of six major subroutines along with the main program. The following is a brief description of each of the major components.

3.1 The main program

The main program controls model inputs and outputs and coordinates the operation of the subroutines. Three input files are required to run the model. The first input file, INPUT1.DAT, contains data on NWP, which is taken as an index of field seasonal conditions. NWP is used to construct various soil moisture indices that are related to seed germination, plant growth, and mortality. Two types of data can be used as INPUT1.DAT. Type 1 data are probability distribution of NWP during the 3 seasons of the year. Type 2 data are true NWP values for each of the 3 seasons of the year. INPUT1.DAT data are site specific and are based on rainfall and temperature.

INPUT2.DAT contains parameters related to the grazing system to be simulated. These parameters are system specific, and are user supplied. Hence when running the model, users need to have information on:

- climate, including rainfall and temperature
- species composition
- ecological characteristics of key perennial species such as palatability and half life, which are used for functional group classification
- system carrying capacity (maximum density, maximum biomass production).

The third input file, INPUT3.DAT, contains data defining important ecological relationships. These data are determined at the model development stage and need not to be changed at every simulation run.

The fourth input file, INPUT4.DAT is optional and useful only to those who are interested in further model development Please refer to section Input files for a fuller explanation of the input files.

Results of the model simulation are stored in three output files, RBIOM[name].DAT, RPOPN[name].DAT, and RECOL[name].DAT. RBIOM[name].DAT contains data on dynamics of forage production for perennials, green annuals and dry annuals. RPOPN[name].DAT contains data on population dynamics of each of the perennial functional groups. The file RECOL[name].DAT contains derived ecological parameters used for modelling system dynamics. Please refer to section Output files for a fuller explanation of the output files.

3.2 The growth subroutine

This subroutine considers forage growth of both perennials and annuals.

3.2.1 Perennial forage growth

Growth of perennial forage biomass, RF(i,t), is calculated by discounting the potential growth rate, PGR(i,t), by indices which reflect soil moisture status, SM13, and the growth capacity of the perennial shrub population, GCI. The potential growth rate, or the amount of biomass that can be produced in any time step, is the gap between the current level of perennial forage biomass, SF(i,t), and the environmental saturation level, KF(i,t), i.e. the level of forage biomass that could be expected for a given plant density under non-limiting conditions. Thus:

RF(i,t) = PGR(i,t)SM13(i,t)GCI(i,t) i = 1.2.....N (1)

PGR(i,t) = KF(i,t)-SF(i,t) (2)

The soil moisture index, SMI3, is a function of the number of wet pentads such that:

SMI3(i,t) = NWP/24 (3)

The growth capacity index (GCI) reflects the amount of photosynthetically-active tissue present at the start of the time step. It is analogous to the leaf area index estimates used to determine growth rate in other pasture models. It is a function of the relative abundance of perennial forage, FB, such that:

GCI(i,t) =bl+b2FB(i,t)/[l+b3FB(i,t)] (4)

where

FB(i,t) = SF(i,t)/KF(i,t) i = 1,2,....N (5)

B1 = the minimum growth capacity, and is set to 0.05.
b2= 11.76
b3 = 11.38

The environmental saturation level of perennial forage biomass, KF(i,t), varies with the condition of the pasture and is represented as a function of the relative density of desirable perennial plants such that:

KF(i,t)) = b4[3*SP(i,t,7)/SPM(i)]/[l+2*SP(i,t,7)/SPM(i)] . (6)

where b4 is the maximal value of KF(i,t), i.e. the level of forage biomass that can be expected for a pristine pasture under non-limiting condition and is user supplied.

3.2.2 Ephemeral (annual) forage growth

Growth of ephemeral forage, RF(N+1), is modelled in a fashion analogous to the growth of perennial forage. Thus:

RF(N+1 ,t) = PGR(N+1 ,t)EGI(t) (7)

where PGR(N+l,t) is the potential growth rate of ephemeral biomass and equal to the gap between the environmental carrying capacity, KF(N+l,t), and the current ephemeral biomass level, SF(N+l,t). Thus:

PGR(N+l,t) = KF(N+l,t)-SF(N+l,t) (8)

The ephemeral growth index (EGI) is a function of soil moisture status NWP and the initial level of ephemeral biomass relative to the carrying capacity. If the initial level of ephemeral biomass relative to the carrying capacity is zero, a minimum number of wet pentads (set equal to 2) is required to initiate ephemeral growth since new germination is required. If the initial level of ephemeral biomass is positive it is assumed that growth can continue.

EGI(t) = max{b5NWP(t)+b6[SF(N+l,t)-KF(N+l,t)]/KF(N+l,t)+
b7NWP(t)[SF(N+l,t)-KF(N+l,t)]/KF(N+l,t),0} (9)

This function implies that ephemeral growth is determined by the soil moisture availability, the relative amount of photosynthetic tissue present and the interaction of these factors which will determine the amount of soil water available per unit of biomass. The values of b5, b6 and b7 are set to equal to 0.0417, 0.0909, and 0.0038, respectively.

The environmental carrying capacity for ephemeral biomass is a function of range condition or the relative density of desirable perennial plants {∑[SP(i,t,7)]/SPM(i)]} The general form of this relationship is

KF(N+1,t) = HKT-RC   i = 1,2,   N (10)
and
RC = min {Σ[SP(i,t,7)/SPM(i)],1} (10.1)

where
HKT is the maximum level of ephemeral carrying capacity under various range conditions.

3.3 The loss subroutine

The loss subroutine calculates the disappearance of forage biomass (perennials, annuals and standing dry annuals) due to sheep intake, drying losses and trampling loss.

3.3.1 Green perennial forage biomass

Disappearance of perennial forage biomass DF(i,t) occurs through intake by grazing animals (i.e. sheep in the current model), SI(i,t), and through forage drying or natural senescence DL(i,t). Thus:

DF(i,t) = SI(i,t)+DL(i,t) (11)

The derivation of sheep intake is outlined in the animal intake submodel (below). The drying losses are considered to be due mainly to water stress under low rainfall conditions and are calculated by applying a drying rate d(i,t) to the current level of perennial biomass, i.e.

DL(i,t) = d(i,t)(SF(i,t)+RF(i,t)) (12)

Drying rate is a function of soil moisture status and the relative abundance of perennial biomass, which together determine the amount of water available to maintain each unit of biomass. Thus:

d(i,t) = b8FDI(i,t)SMI4(i,t) (13)

where:

b8 = the assumed maximum drying rate, i.e. the proportion of perennial biomass lost in one time step in the absence of effective rainfall (set equal to 0.5).
FDI(i,t) = density index for forage drying;
SMI4(i,t) = soil moisture index for loss of perennial biomass.
The density index is linearly related to the relative abundance of perennial forage such that

FDI(i,t) = 0.9+0. 1*(SF(i,t)+RF(i,t)/KF(it) if NWP(t)<>0, (14)

=1 if NWP(t)=0 (15)

The conditional function is used to ensure that the potential drying rate is achieved when no wet pentads occur within period t. The soil moisture index for loss of perennial forage is related to the number of wet pentads such that:

SMI4(i,t) = l-0.0413*NWP(t) (16)

3.3.2 Green annual forage biomass

Disappearance of green ephemeral biomass, DF(t), is divided into three pools: intake by sheep, SI, drying losses, DL, and trampling losses, TL. Thus:

DF(N+1,t) = SI(N+1,t)+DL(N+1,t)+TL(N+1,t) (17)

Drying losses are modelled in a similar way to the non-consumptive losses of perennial biomass and are determined by the interaction between soil moisture status and the level of ephemeral biomass, i.e.

DL(t) =d(N+1,t)*(SF(N+1,t)+ RF(N+1,t) (18)

Trampling losses, which do not apply to the perennial shrub biomass, are estimated by applying the trampling loss rate, TR, to the current level of ephemeral biomass.

TL(N+1,t) = TR(t)[SF(N+1,t)+RF(N+1,t)] (19)

The trampling rate is a function of the sheep stocking rate, U, such that:

TR(t) = 1-exp(-0.15U(t)) (19.1)

3.3.3 Standing dry annual forage biomass

Standing dry ephemerals, SF(N+2,t), are considered to be an important feed source for sheep grazing. The dynamics of this pool are modelled as follows:

SF(N+2,t+1) = SF(N+2,t)+RF(N+2,t)-SI(N+2,t)-ND(t)-TL(N+2,t) (20)

where:

RF(N+2,t) = the recruitment to the drying ephemeral, RF(N+2,t) = DL(N+1,t),
SI(N+2,t) = sheep intake,
ND(t) = natural decline of the drying ephemerals.

The natural decline of the drying ephemerals is modelled simply by multiplying a decay rate DECR by the initial standing dry ephemeral biomass. Thus,

ND(t) = DECR(t)SF(N+2,t) (21)

The decline rate of dry ephemerals is modelled as a positive linear function of the number of wet pentads such that:

DECR(t) = 0.12+(l-0.12)NWP/24 (21.1)

where 0.12 is the base decline rate over a simulation time step.
Trampling losses of the dry ephemeral biomass are also estimated by applying the trampling loss rate, TR, to the current level of dry ephemeral biomass such that

TL(N+2,t) = TR(t)[SF(N+2,t)+RF(N+2,t)] (21.2)

The trampling rate is a function of the sheep stocking rate, U, such that

TR(t) = 1-exp(-0.16U(t)) (21.3)

3.3.4 Sheep intake

IMAGES 2.1 considers sheep to be the only herbivores that consume forage within the paddock. No provision has been made for the consumption of forage by other types of livestock or by native herbivores. If grazing by other animals is substantial, it may be necessary to adjust the stocking rate and grazing preference coefficient to reflect the true grazing pressure.

Sheep intake for each forage component is derived through a preference coefficient (a palatability index) which describes the forage selective behaviour of the grazing stock. That is, the preference coefficient is used as a measure of diet selectivity in grazing sheep. A preference coefficient is allocated to each forage component of a given pasture type and used as a predictor to derive diet composition from the relative frequencies of the various forage components in the pasture. In a pasture of two forage components, a preference coefficient represents the ratio of the fractions of the two components in the diet when these components are in equal quantities in the pasture. For example, a preference coefficient of value 4 will produce a diet with the two components in the ratio 4:1, i.e. 0.8:0.2 when the two components are in equal amounts in the total forage pool. For a pasture of multiple forage components, preference coefficients are defined as follows:

$$y(i,t) = x(i,t)*P(i)/\Sigma[[x(i,t)*P(i)] \qquad \text{for } I = 1,2,...N+2 \qquad (22)$$

where:
$y(i,t)$ = the fraction of the ith forage component in the diet,
$x(i,t)$ = the fraction of the ith forage component in the pasture,
$P(i)$ = preference coefficients for the ith forage component.
Solve for $P(i)$ to get

$$P(i) = [y(i,t)/y(1,t)]/[x(i,t)/x(1,t)] \qquad (23)$$

Although preference coefficients are determined in the model by the user, the formula above (i.e. equation (23)) can be used to derive the value of preference coefficients for forage of each group species" by field grazing experimentation. Preference coefficients above are assumed to be constant. However, a variable preference coefficient may be appropriate if sheep forage selective behaviour changes with the fraction of the component in the forage and/or the total forage biomass available. This alternative assumption needs to be tested and incorporated into the model if field data are available and support this assumption.

At low forage availabilities, sheep cannot be selective in their diet. To account for this, the preference for each component is assumed to gradually approach 1 when forage on offer drops from a threshold level (TFA1PREF) and to equal to 1 at a second threshold level (TFA2PREF), such as

$$P(I) = 1 + (P(I)-1)/(\text{TFA1PREF} - \text{TFA2PREF})*(\text{TFA} - \text{TFA2PREF})$$
$$\text{if TFA2PREF} <= \text{TFA} <= \text{TFA1PREF} \qquad (24)$$

$$P(I) = 1 \quad \text{if TFA} < \text{TFA2PREF} \qquad (25)$$

This implies that sheep will graze randomly if the forage availability falls below the TFA2PREF level. Note that unpalatable forage with a preference coefficient of zero will not be included in the calculation of the total forage availability. The model assumes that only when total forage on offer drops below the second threshold level will the unpalatable forage be included and its preference coefficient change from 0 to 1 simultaneously.

At present, the preference coefficient is user determined. It can be interpreted as having the same meaning as palatability. When determining the preference coefficient, it is generally a good practice to set it to 1 for the medium palatable functional groups. The preference coefficients of other functional groups are then set revolving around this group.

Forage intake by sheep is derived by discounting total forage TFA with a pasture availability index AI such that:

$$FI(t) = TFA*AI(t) \qquad (26)$$

The index of forage availability is a function of total forage available during season t such that:

$AI(t) = 1-exp[-b9TFA(t)]$ (27)

where

$TFA(t) = I[SF(i,t)+RF(i,t)]$ i = 1,2,...N+2 (28)
and b9 = 0.009.

However, a forage component whose preference coefficient equals 0 will not be included in TFA, as mentioned previously.

Total forage intake per hectare, TSI, is calculated from the stocking rate and the intake per dry sheep equivalent, SIHD:

$TSI(t) = SR(t)*SIHD(t)$ (29)

where SIHD = PI if FI > PI (29.1)

= FI(t) if FI <= PI (29.2)

where PI is potential sheep intake per simulation step under non-limiting condition. It is set at 180 kg/dse per four months.

The total intake is then partitioned among the forage components according to the fraction of forage component in the diet, y(i,t), to obtain the amount of each forage component eaten. Thus,

$SI(i,t) = TSI(t)*y(i,t)$, i = 1.2....N...N+2 (30)

where I is the index for each herbage component including drying ephemerals (i = N+2).

The possibility exists that the calculated intake of total forage combined with the other losses, could exceed the amount of biomass available. In this situation, the opening stock in the next simulation period would be negative. To avoid this condition, sheep intake and other losses are adjusted so that for perennial forage if

[SI(i,t)+DL(i,t)>SF(i,t)+RF(i,t)]then

$ADL(i,t) = \{DL(i,t)/[Si(i,t)+DL(i,t)]\} [SF(i,t)+RF(i,t)]$ for i = 1.2...N (31)

$ASI(i,t) = SI(i,t)/[SI(i,t)+DL(i,t)][SF(i,t)+RF(i,t)]$ for i = 1.2....N (32)

Similarly, for green and dry ephemeral herbage if [SI(i,t)+DL(i,t)+TL(t)>SF(i,t)+ RF(i,t)] then

$ADL(i,t) = \{DL(i,t)/[SI(i,t)+DL(i,t)+TL(t)]\}[SF(i,t)+RF(i,t)]$ fori=N+l,N+2 (33)

$ASI(i,t) = \{SI(i,t)/[SI(i,t)+DL(i,t)+TL(t)]\}[SF(i,t)+RF(i,t)]$ for i=N+l,N+2 (34)

$ATL(t) = \{TL(t)/[SI(i,t)+DL(i,t)+TL(t)]\}[SF(i,t)+RF(i,t)]$ for i=N+l,N+2 (35)

3.3.5 Grazing pressure

Total grazing pressure is calculated as the ratio of the actual sheep intake to that of the potential sheep intake such as

TG = 1-TSI/(PI*SR) (36)

Grazing pressure for each perennial group, G(i), is linearly related to TG and preference coefficient (Pref(i))

G(i) = 1-TG*Pref(i) i = 1,2... N (37)

G(i) = max (G(i), 0) (37.1)

G(i) measures the grazing stress experienced by each functional group and ranges from 0+ (extreme high grazing pressure) to 1 (no grazing pressure). Only perennial forage consumption is calculated, since it is the elimination of the perennial vegetation components which results in those changes in ecosystem function that affect long-term productivity. Consumption of the ephemeral forage alone is unlikely to induce any detrimental long term effects on range condition. Thus, grazing pressures are not calculated for both green and dry ephemerals. Functional groups that are absent from a given system are given a grazing pressure of 0.

3.4 The population subroutine

The plant population subroutine calculates the population dynamics of perennial shrubs (Sp_{i-n}) for each of the functional groups, including the non-palatable ones. Functional groups are introduced to IMAGES 2.1 to account for the relative heterogeneity of rangeland plant communities and to overcome problems associated with the average species approach adopted by IMAGES 1. For a given pasture type (or paddock), perennial plant species are grouped into a number of functional groups. Each group consists of a number of species simular in their ecological functions. Variables most often used to define functional groups include species palatability, half-life, and drought tolerance ability. Half-life is one of the key criteria used for functional group classification because it determines the natural mortality rate, which in turn contributes to the population dynamics. The classification of functional groups is very much dependent on our knowledge of the system and can be subjective. Currently the model can handle up to 5 functional groups. With some changes in programming, the model should be capable of handling N (N=l,2,...) functional groups.

For the long-lived perennial functional groups (life-span >= agel), populations are divided into 7 age cohorts, viz, 0-3, 4-7,..., 20-23 and 24 + months. Conversely, short-lived functional groups are considered to have 4 cohorts only. The first cohort (0-3 months) represents new germinants, while individuals >24 months old for the long-lived functional groups or >12 months old for the short-lived ones represent the established adult population. The facultative perennial shrubs are taken as part of ephemeral pool and are not included in the perennial shrub populations. Since the simulation time step is equal to the cohort age interval, the population of immature individuals is shifted one class each time step, and diminished by the appropriate level of mortality.

3.4.1 Recruitment

Germination, or recruitment into the first age cohort, is determined as:

$$SP(i,t+1,1) = RCI(i,t)GMI(i,t)[SPM(i)-SP(i,t,7)] \quad i = 1,2,....,N \qquad (38)$$

where

i =the indices of functional groups of perennial species, index values from 1 to N representing one of the perennial groups;

SP(i,t+l,l) = density (plants/ha) of the ith group of perennial seedlings (age cohort 1) in period t+1;

RCI(i,t) = replacement capacity index for the ith group in period t;

GMI(i,t) = germination index for the ith group in period t;

SPM(i) = maximum density (environmental carrying capacity) of mature individuals of the ith perennial group under a monoculture for a given pasture type in period t;

SP(i,t,7) = density (plants/ha) of mature individuals (age cohort 7) of the ith perennial group in period t.

Germination is thus considered in terms of the gap in the perennial plant population that can potentially be filled [SPM(i)-SP(i,t,7)] and the factors, RCI and GMI. Values for RCI and GMI range between 0 and 1.

The RCI is used as a surrogate for the seed stock of perennial plants. It represents the extent to which seed stocks associated with the current population can, given suitable environmental conditions, provide sufficient germinants to fill the gap in the perennial plant population. In other words, it is the capacity of the current population to re-establish the plant community. It is species dependent and related to the relative density of mature perennials, SP(i,t,7)/SPM(i). For short-lived functional groups, RCI is dependent on seasonal conditions of last winter. Thus, for long-lived group species, RCI is modelled as:

$$RCI(i,t) = \min\{b10+[(l-b10)/0.5][SP(i,t,7)/SPM(i) \qquad (39)$$

and, for short-lived species, RCI is related to seasonal conditions during the last winter such that

$$RCI(i,t) = f[NWP(t-2)] \quad \text{for season} =1 \qquad (39.1)$$
$$= f(NWP(t-3)] \text{for season} = 2 \qquad (39.2)$$
$$= f(NWP(t-1)] \text{for season} = 3 \qquad (39.3)$$

In nature, the number of germinants may greatly exceed the gap in the adult population. Since the total adult population cannot exceed the environmental carrying capacity,

SPM(i), the model needs to consider only that population of germinants that would fill the gap if all were to survive.

The GMI represents the proportion of the available seed stock that germinates during any time step and acts to constrain the potential recruitment to levels appropriate to prevailing environmental conditions. It is species dependent and determined by soil moisture and temperature conditions.

GMI(i,t) = b(t){ 1-exp[-b11(NWP(t)^2)]} (40)

where b(t) is a seasonal factor that represents the effects of temperature on germination. In the winter rainfall arid zone of WA, germination of shrubs is generally greatest in response to summer or autumn rain and is apparently depressed by low temperatures in season 2. Some germination may occur in season 3 particularly early in the period, although soil moisture at this time is generally inadequate. The values of b(t) have been set at 1,0.5 and 0.7 for seasons 1, 2 and 3, respectively. Recruitment into each of the second, third, sixth seedling cohorts is calculated from the current population of the previous cohort, SP(i,t,k), and the corresponding seedling survival rate, s(i,tjc). Thus:

SP(i,t+1,k+1) = s(i,t,k)SP(i,t,k) k = 1, 2 5 (41)

where k is the index of the age cohort.

Similarly, recruitment to the ith adult population is given by

RP(i,t+1,7) = s(i,t,6)SP(I,T,6) (42)

3.4.2 Survival and Mortality

The survival rate of each seedling cohort is modelled as a function of soil moisture, grazing pressure and competition from perennial and annual forage growth. Thus:

s(i,t,k) = SMI1(i,t,k)GPI1(i,t,k)ECI(t,k)PCI(i,t)k =1,2 ....6 (43)

where

SMI1 (i,t,k) = soil moisture index for survival of cohort k of the ith group species in time period t; GPII(i,t,k) = grazing pressure index for cohort k of the ith group species in time period t;
ECI(t,k) = ephemeral competition index for cohort k in time period t;
PCI(i.t) = perennial competition index for the ith group species in time period t.

The soil moisture index for the survival of each cohort is related to the number of wet pentads and is functional group and cohort age dependent such that

SMI1(i,t,k) = min {b12+[(1-b12)/(13-k)]NWP(t),1} (44) where b!2 is the seedling survival rate at drought condition, i.e. the level of drought tolerance. The value of b12 will vary with the functional groups and cohort age and is user determined.

The grazing pressure index represents the effect of grazing on seedling survival assuming other factors are non-limiting. It is functional group and cohort dependent The impact of grazing on shrub seedlings is assumed to be negligible when the grazing pressure, G(i,t) (see below), exerted on the perennial vegetation components is low. At higher levels of grazing pressure, however, seedling survival is affected, with an increasing impact assumed for younger cohorts. The index is modelled as:

GPI1(i,t,k) = G(i,t)^(SGPIC(i,l)/k) k = 1,2....6 (45)

SGPIC is a parameter related to grazing tolerance capability of seedlings and is user determined. Its value varies from 0 to 1, with 0 being least sensitive to grazing and 1 most sensitive.

The ephemeral competition index, ECI, represents the competitive effect of ephemeral or ground-storey growth on the survival rate of shrub seedlings. It is cohort age dependent and related to the relative abundance of ephemeral biomass (EB) such that:

ECI(tJc) = min{ 1-(1.16-0.16*k)[EB(t)-0.5)],1} k= 1, 2, ...6 (46)

and

EB(t) = [SF(N+1,t)+RF(N+1,t)]/KF(N+1,t) (47)

where
SF(N+1 ,t) initial ephemeral biomass in period t, kg/ha DM;
RF(N+1 ,t) growth of ephemeral biomass during period t, kg/ha DM;
KF(N+1 ,t) environmental carrying capacity for ephemeral biomass during period t, kg/ha DM.

The perennial competition index, PCI, represents the competitive effect of perennial growth on the survival rate of shrub seedlings. It is functional group dependent and related to the relative density of perennial shrubs such that:

PCI(i.t) = min{ 1,2[1-Ea(j,i)SP(j,t,7)/SPM(i)]} j = 1, 2 N (48)
for∑a(j,i)SP(j,t,7)<SPM(i),
= 0 otherwise. (49)

where

a(j,i) = a matrix of coefficients which is equivalent to competition coefficient (see Harper 1990) or crowding coefficient This represents the amount of ecological space (e.g. water and nutrients) which is taken up by an established adult individual of the jth group species and which therefore cannot be utilised by the seedlings of the ith group species simultaneously. Thus, if i = j, that is, competition from the same species exists, then a = 1. In general, a(i,j) does not necessarily equal a(j,i) and, except where each is near zero, one may expect equality only rarely. In the rangeland environment it is assumed that competition occurs only when the plant density reaches more than half of the environmental saturation level. Thus, a scaling factor of 2 is used to calculate the effect of competition on seedling survival if such competition occurs. For adult plants, the population at the start of period t+1 is calculated as:

SP(i,t+1,7) = min{s(i,t,k)SP(i,t,7), SPM(i)} i = 1.2...N & k = 7 (50)

where s(i,t,k) is the survival rate for of the adult population of the ith group. The functional form of above is used to ensure that the adult population is constrained to the environmental carrying capacity, SPM(i).

The survival rate is first calculated from a potential survival rate under non-limiting conditions. Mathematically, it is calculated by deducting the plant natural mortality rate MO from 1 (100% survival). The natural mortality rate is estimated from the life-span of the species functional group such that:

MO=1-0.5^[1/HL(i)] i = 1,2, N (51)

where HL is the estimated half-life of the ith species group in simulation time step unit The natural mortality is estimated assuming that the population follows a constant mortality rate for all adult age groups, i.e. a Deevey type II curve.

The calculated potential survival rate is then further modified by grazing pressure, soil moisture status and perennial plant density. Under low rainfall conditions, survival is considered to be determined by the amount of water available per plant Grazing can affect plant survival directly or through an interaction with seasonal conditions, its effects being magnified during drought periods. The effects of grazing and water stress on the mortality are assumed to be cumulative over nine simulation time steps, i.e. 3 years, for the long-lived functional groups and three simulation time steps for the short-lived ones. Six simulation cumulative time steps are assumed for the functional group of life-span between those of short and long-lived species.

Thus the mortality rate of perennial functional groups consists of two components, the natural mortality, MO, which is determined by half-life, and the induced mortality, MI, which is a linear function of grazing pressure index, GPI2, soil mixture index SMI2, and plant density index, PDI. Plant survival rate is calculated as

PSURVR = ((1-MO)+(1-M1))/2 (52)

= GPI2(i,t)SMI2(i,t)PDI(i,t) ifG(i)<=0.6 (52.1)

where

M1= 1-GPI2(i,t)SMI2(i,t)PDI(i,t)			(53)
GPI2(i,t) = (IGPI(t)}/9	for t = t, t-1, t-2, t-8 and	HL> = AGEL	(54)
= {∑GPI(t)}/6	for t = t,t-1,t-2, t-5and	AGEL >HL>AGES	(54.1)
= {∑GPI(t)}/3	for t = t,t-1,t-2, and	HL< = AGES	(54.2)
SMI2(i,t) = {∑GPI(t)}/9	for t = t,t-1,t-2, and	HL> = AGEL	(55)
= {∑SMI(t)}/6	for t = t, t-1, t-2, t-5 and	AGEL>HL>AGES	(55.1)
= {∑SMI(t)}/3	for t = t, t-1, t-2 and	HL < =AGES	(55.2)

PDI(i,t) = {∑DI(t)}/9 for t = t, t-1, t-2,...t-8 and HL< = AGEL (56)
= {IDI(t)}/6 fort = t, t-1, t-2,...t-5 and AGEL >HL >AGES (56.1)
= {£DI(t)}/3 for t = t, t-1, t-2 and HL< = AGES (56.2)

AGES and AGEL are criteria used to define short and long lived functional groups.

GPI(t) = max{0,G(i,t)^SGPIC(i,2)} (57)

SMI(i,t) = min{DTCI+(1-DTCI)/MNWP)NWP(t),1} (58)

where MNWP is the modal number of wet pentads in season t.

DI(t) =1 for i = 1, 2,....,N
= 1/∑[SP(i,t,7)/SPM(i)] if ∑ [SP(i,t,7)/SPM(i)] => 1 (59)

The survival rate of perennial plants is calculated by averaging the effects of induced mortality and natural mortality. Under optimal conditions, i.e. MI=0, SURVR = 1-MO/2, the effects of MO on survival are halved. This is reasonable considering the number of perennial plant deaths is usually low in rangelands in good years compared with other years. Under extremely high grazing pressure, i.e G(i) <= 0.6, which is usually associated with dry seasons and high stocking rates, survival rate is determined by induced mortality only.

The effect of half-life on population dynamics as outlined above differs significantly from that of IMAGES 1. In essence, IMAGES 2.1 places more emphasis on field conditions and less emphasis on half-life. In making these changes, the following three factors were considered:

- we have little data on half-life for most of our rangeland perennial species;
- available half-life data for most of the species vary widely;
- field conditions play a dominant role in determining the recruitment and mortality of rangeland plants.

Plant density (DI(i)) is sensitive to maximum density (SPM), for which little data is generally available. Care should be exercised when estimating SPM for a given functional group. Analysis of the Boolathana grazing trial data, for example, indicated that SPM is quite versatile and varies from paddock to paddock. As a rule of thumb, SPM should be set at twice the current plant density. This is reasonable when the paddock is in fair range conditions.

3.5 Subroutine UPDATE, PROB, and AMODE

Subroutine Update, as the name indicates, updates various state variables (forage production, cohort size, etc) at the end of each simulation time step. Subroutine Amode calculates the modal value of wet pentads for each simulation time step based on the probability distribution of NWP (number of wet pentads). The modal value is used to define the seasonal conditions of any given time step (duration). Subroutine Prob is used to calculate the probability distribution of NWP, which is then used to define the simulation condition. The inclusion of this subroutine affords the user the flexibility to use either true NWP value or probability distribution of NWP as input during any simulation run.

4. Acknowledgments

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6. APPENDIX 1 FORTRAN codes of IMAGES 2.1

```
^*****************************************************************
C       IMAGES 2.1
^******************************************************************
C       IMAGES: An Integrated Model of an Arid Grazing System
C       IMAGES is a simulation model aimed to simulate shrub rangeland
C       forage production and plant population dynamics under various
C       combinations of climatic and management conditions.
C*******************************************************************
Program IMAGES
REAL NWP,MODE(3),PDF,M2,PDFT
REAL LP(5,7),AC(5,5),SPANLF(5),LPT(7)
REAL SRT(100,4),strat
COMMON/AAl/nwp,mode,spanlf
COMMON/AA2/NSF,NPP,TFA,SR(3),IRUN,NYEAR
COMMON/AA3/SMI1T(5,6),GPI6(9),SMI6(9),PDI6(9),GPN(9),
# SMI3T( 10,6),GCIT(10,6),HKT( 10,2),GMIT( 10,6),RCIT1 (10,6),
# RCIT2(10,2),SIDGI(10,2),SIFAI(10,2)
COMMON/AA4/SPM(5),DGMAX(7),FKMAX(7),SL(5)
COMMON/AA5/PWL,PSH(3),SC,FCOST,VCOST,TFCOST,RINT
COMMON/AA6/ASRATE(5),SIHD,PREF(7)
COMMON/AA7/RF(7),RH,DGH,DRF(7),DRH,FK(7),HK,PD
COMMON/AA8/SP(5,7),SH,SF(7),RET,TEMPSP(5,7),AC,SRO,SRENDO,ESR
COMMON/AA9/G(5),FAVAIL(7),SI(7),DNCF(7),FLOSS(7),tg,tsi,tpref,
#       TFAIPREF,TFA2PREF,PI,sgpic(5,2),DTCI(5),agespl,agesps
COMMON/AA11/IX,IY,IZ,IX 1 ,IY 1 ,IZ 1
```

```
COMMON/AA12/PDF(100,4),TNWP(25),PDFT(100,4)
COMMON/AA13/M2(25,4)
COMMON/AA14/PDFT1(100,4),PDFT2(100,4)
CHARACTER*5 OUT
INTEGER DTYPE, dtypel
C*****************************************************************
C       INPUT1.DAT: probability distribution of wet pentads for each season
C       INPUT2.DAT: data on desirable
C       perennial groups, simulation period, plant populations, forage
C       biomass and related parameters
C       INPUT3.DAT: parameters defining various ecological functions
C       RPOPN[name].DAT: results of perennial population dynamics
C       RBIOM[name].DAT: results of biomass dynamics
C    RECOL[name].DAT: derived ecological parameters used in simulation
^*****************************************************************
print*, ' '
print*      ***************************************************<
write (*,*) '* IMAGES 2.1: A computer simulation model on shrub   '
write (*,*) '* population dynamics and forage production in    '
write (*,*)'*        arid shrublands of Australia      '
write (*,*) '*
write (*,*) '*         By G. Yan and K.Wang
write (*,*) '*     Agriculture WA, South Perth
write (*,*) '*
write (*,*) '*    Aug. 1996
print*      '***************************************************'
write (*,*) ''
```

```
goto 96

97   print*, 'output file already exist.'
     print*, ''
     pause

96   print*, 'please enter an output file name (only the first1
     print*, '3 letters or digits will be used):'
     read(*, 99) out
99 format (a5)

open(unit=l 6,file='inputl .dat',status='old')

open(unit=17,file='input2gd.dat',status='old')

open(unit=18,file='input3gd.dat',status='old')

open(unit=20,file='input4.dat',status='old')

open(unit=22,file='rpopn7/out//'.dat', +status='new',err=97)

open(unit=21 ,file='rbiom'//out//'.dat',status='new', +err=97)

open(unit=23,file='recor//out//'.dat',status='new', +err=97)

C************************************************************

C The following line reads file INPUT1.DAT:

C NWP probability distributions, PDFT(I,J), for three rainfall seasons

C (default).  It can also be the NWP for each season.  If this is the

C case, then some conversions are necessary.

C******************************************************************

READ(16,*,end=98)((PDFT(i,j),j=l,4),i=l,100)

C******************************************************************

C       The following lines read file INPUT2.DAT:

C       AGESPL & AGESPS: age definition for long- and

C       short-lived perennial groups;

C       NYEARS: number of simulation years;

C       NPP: number of functional groups for perennials;

C       SPANLF: lifespan for each of the perennial groups;
```

```
C       NSF: number of forage biomass pools in the model;
C       LP: populations of perennial plants;
C       SF: the stock of forage biomass in each forage pool
^****************************************************************
98    read(17,*) agespl,agesps , npp.nyears
      read(17,*) (spanlf(i),i=l,npp)
nsf=npp+2
C   Following do-loop reads LP data according to NCOHORT,
c   and reset lpt, lp to 0 before reading.
        1pt=0.0
        1p=0.0
do 928 i=l,npp
if(spanlf(i).gLagesps) then
ncohort=7 else
ncohort=4 endif
read(17,*)(lpt(j), j=l, ncohort) do927j=l,ncohort
927     lp(i,j)=lpt(j)
if(ncohort.eq.4) lp(i,7)=lp(i,4)
928     continue
read(17,*) (sf(i),i=l,nsf) do929ii=l,npp
929     sl(ii)=3*spanlf(ii)/2
c si, half life expressed as simulation time unit
C***************************************************************
C       The following codes read in the parameters for which the functional
C       groups are defined.  These include environmental carrying capacity
C       of each functional group (SPM), palatability preference (PREF)
C       potential sheep intake (PI)
```

```
C  forage threshold 1 (TFA1PREF) and threshold 2 (TFA2PREF)
^******************************************************************
read(17,*) (spm(i),i=l,npp),
#       (fkmax(i),i=l,npp+l),
# (pref(i),i=l,nsf),
# (DTCI(i),i=l,npp),
# pi,tfalpref,tfa2pref,
#       ((sgpic(i,j),j=l,2),i=l,5)
^******************************************************************
C       Unit 18 contains information on
C       replacement capacity (RCI)
C       germination capacity (GCI)
C       soil moisture (SMI)
C       forage growth capacity (GCI)
C       range condition and annual production level (HKT)
C       forage availability and sheep intake (SIFAI)
C  adult plant competition coefficient (AC)
******************************************* ******************
read(18,*)((rcitl(i,j),j=l,npp+l),i=l,10X
# ((rcit2(i,j),j=l,2),i=l,10),
# ((gmit(i,j),j=l,npp+l),i=l,10),
# ((smilt(i,j),j=l,6),i=l,npp),
# ((ac(i,j),j=l,npp),i=l,npp),
# ((smi3t(ij),j=l,npp+l),i=l,10),
# ((gcit(i,j),j=l,npp+l),i=l,10),
# ((hkt(i,j),j=l,2),i=l,10),
# ((sifai(i,j)j=l,2),i=l,10)
```

```
*************************************************************

c       Following codes load the input data for 4 classes of desirable
C       perennial population with 7 cohorts, undesirable perennial
C       population with 7 cohorts, 4 classes of desirable perennial forage
C       biomass, 1 class of undesirable perennial forage biomass and green
C       and dry ephemeral forage biomass.
C       NCOHORT=number of cohorts for perennials.
C       NPP=number of perennial groups.
C    NSF=number of forage components in the ecological system.
Q*********************************************************************
do 12 i=l,npp do!3j=l,7 13       sp(i,j)=lp(i,j) 12   continue
do!221jj=l,9 gpi6(ij)=1.0 smi6(jj)=1.0 pdi6(jj)=1.0 1221    gpn(jj)=0.0
write(22,*,ERR=97)'Opening Perennial Populations' write(22,1002) do 1012 m=l,npp
1012     write(22,6001) m, (sp(m,j),j=l,7) write(22,*,ERR=97)
write(22,*, ERR=97)'Seasonal-ending Perennial Populations', +' SP(ij), plants/ha'
write(21,*,ERR=97)'Forage Biomass, SF(i), kg/ha DM1 write(21,1100)
1100   format(/,17x,'Pernl   Pera2   PernS   Pem4   PernS', +'   GrenE DryE1)
write(23,*,ERR=97) 'Ecological Functional Relationships'
'****************************************************************

C       Following do-loops start the simulation for each compartment.
C       AMODE: subroutine for the determination of modal value of NWP.
C       RAND: subroutine to generate 0-1 random value U.
C       PROB: subroutine to convert NWP to NWP probability density distribution.
C       NGPCDF: subroutine for determining the value of NWP.
C       GROWTH: subroutine for forage growth.
C       LOSS: subroutine for forage disappearance.
C       population: subroutine for perennial population dynamics.
```

C UPDATE: subroutine for updating state variables.

```
************************************^

PRINT*, 'Are you using the NWP probability distribution' PRINT*, 'DATA? Please enter 1 for YES or 2 for NO'

101    read*,dtype

if (dtype.eq.l) then

goto 220 else if (dtype.eq.2) then

PRINT*, 'Please enter duration of data (number of years)'

read*, nyear

do 102 i=l,nyear do 102 j=l,3

102    pdftl(i,j)=pdft(i,j+l)

c     do5mn=l,10

c5     print*, (pdf(mn,mj), mj=l,4) call prob(nyear) else

PRINT*, 'Please enter 1 or 2' goto 101 ENDIF goto 111

220      PRINT*, 'do you want to use real time NWP data'

print*, 'or data generated from NWP probability distribution? ' PRINT*,' enter 1 for real time NWP and 2 for NO'

read*,dtypel

if (dtypel.eq.2) then

goto 111 else if (dtypel.eq.l) then

read(20,*,end=221)((pdft2(i,j),j=l,4),i=l,100) 221     continue

do 103 i=l,10

do!03j=l,3

103    pdftl(i,j)=pdft2(i,j+l) endif

111   print*, 'enter stocking rate'

read*, strat

srt=strat
```

```
c      PRINT*, 'Simulation: NWP used in each run.' c       PRINT*,'   Year Seasonl
Season2 Season3'

DO 3 IRUN=1,NYEARS write(21,*) write(22,*) write(21,1005)irun

write(22,1005)irun write(23,1005)irun

1005   format('Year',i3)

DO 1 ISES=1,3 WRITE(*,*)IRUN,ISES write(23,1006)ises write(22,1006)ises

write(21,1006)ises

1006   format('Season',i2)

write(21,6002)'Openingstock',(sf(nl),nl=l,7)

sr(ises)=srt(irun,ises+1)

1=1

call amode u=rand(l)

if (dtype.eq.2.or.dtypel.eq.l) then nwp=pdftl (irun.ises) else

call ngpcdf(u,ises) endif

pdft2(irun,ises)=nwp write(22,6003)nwp,SR(ISES) write(23,6003)nwp,SR(ISES)
write(23,201) CALL GROWTH CALLLOSSaSES) CALL population(ISES) CALL
UPDATEaSES)

201   formatC          PI    P2   P3    P4   P5')

write(22,1002)

1002   format('Groups ','Cohotl Cohot2 CohotS Cohot4 Cohot5',

+' Cohort6 Adults')

do 1003 m=l,npp

1003   write(22,6001) m, (sp(mj),j=l,7)

write(22,*)

write(21,6002)'Recruitment     ',rf write(21,6002)'Sheep intake    ',si
write(21,6002)'Other losses    ',dncf write(21,6002)'Ending stock    ',(sf(nl),nl=l,7)
write(21,6022)'Grazingpressure',(g(n2),n2=l,5) write(21,6003)nwp,SR(ISES)

6001 format(i2,3x,f4.0,7f8.0)

6002 format(al6,7f8.1)
```

```
6003   format('NWP=',F4.0,6x,'Stocking Rate=',f5.2,' dse/haV)
6022   format(al6,5f8.1)
1        CONTINUE
cy       write(21,6001 )irun,nwp,(sf(n 1 ),n 1=1,7)
c y      write(22,6001)irun,nwp,(sp(m,7),m=l,5)
c       print 6004, IRUN, (PDFT2aRUN,ISES), ISES=1,3)
3        CONTINUE
6004   format(i8, 3f9.1)
c       do6mn=l,10
c6     print*, (pdftl(mn,mj), mj=l,3)
PRINT*, 'your output files are rbiom [namej.dat: forage production'
PRINT*,'        rpopn[name].dat: shrub population
*        dynamics'
PRINT*,'        recol[name].dat: model parameter
*        update'
pause
write(*,*)The execution has been successful.'
STOP
END
£**********************************^
C        Subroutine GROWTH calculates perennial & ephemeral
C        forage growth, and forage drying rates
C        SP(I,J)=the ith perennial plant populations of the jth cohort
C        SF(I)=the ith forage component biomass
C        SH=ephemeral forage biomass
C        RF=forage growth
C        RH=ephemeral forage growth
```

```
C       DRF, DRH=perennial and ephemeral drying rates,
C       PD is relative plant density
C       INPUTS: NPP,SP(ij),SPM(i),FKMAX(i),SF(i),NWP,SMI3T(ij),GCIT(i,j)
C       HKT(i,j),DGMAX(i),NSF,DECRATO,DGMIN
C   OUTPUTS:RF(i),DGH,DRF,DRH,PD
£*****************************************^
SUBROUTINE GROWTH
REALNWP,MODE(3),DIF(7),PFD(7),AC(5,5),XIN(10),YIN(10)
REALZSMI(5),ZGCI(5),zrpfd(5),zpgap(5),SPANLF(5)
COMMON/AAl/nwp,mode,spanlf
COMMON/AA2/NSF,NPP,TFA,SR(3),IRUN,NYEAR
COMMON/AA3/SMI1T(5,6),GPI6(9),SMI6(9),PDI6(9),GPN(9),
# SMI3T(10,6),GCrr(10,6),HKT(10,2),GMrr(10,6),RCm(10,6),
# RCIT2(10,2),SIDGI(10,2),SIFAI(10,2)
COMMON/AA4/SPM(5),DGMAX(7),FKMAX(7),SL(5)
COMMON/AA6/ASRATE(5),SIHD,PREF(7)
COMMON/AA7/RF(7),RH,DGH,DRF(7),DRH,FK(7),HK,PD
COMMON/AA8/SP(5,7),SH,SF(7),RET,TEMPSP(5,7),AC,SRO,SRENDO,ESR
COMMON/AA9/G(5),FAVAIL(7),SI(7),DNCF(7),FLOSS(7),tg,tsi,tpref,
#       TFAlPREF,TFA2PREF,PI,sgpic(5,2),DTCI(5),agespl,agesps
^********************H<**********)).******************* + >(c >)<>(<*>)<******=)<*
C    Perennial forage production: desirable perennial forage SF(l-5)
C    green ephemeral SF(6), dry ephemeral SF(7)
^****************************************************************
do 1220 i=l,npp pd=sp(i,7)/spm(i) fk(i)=fkmax(i)*3.*pd/(l.+2.*pd) if(fk(i).le.0.)then
rpfd=0. else
rpfd=sf(i)/fk(i)
```

```
rpfd=amin 1 (rpfd, 1.) endif

£*************************************^

C*** perennial forage growth responses to soil water SMI3 and leaf area. C*** User define the curves for components other than the 1st one which C*** is a chenopod spp. i.e. salt bush.

£*****************************************^

if (spanlf(i).gtagesps) then

gci=0.05+(11.76*rpfd)/(1.0+11.38*rpfd)

gci=aminl(gci,l.)

smi=1724.*nwp else

do 100111=1,10 xin(il)=smi3t(il,l)

1001   yin(il)=smi3t(il,i+l)

call grph(nwp,yout,xin,yin)

srai=yout

do 1002 11=1,10 xin(il)=gcit(il,l)

1002   yin(il)=gcit(il,i+l)

call grph(rpfd,yout,xin,yin)

gci=yout

end if

zsmi(i)=smi zrpfd(i)=rpfd zgci(i)=gci zpgap(i)=fk(i)-sf(i)

rf(i)=(fk(i)-sf(i))*smi*gci

if(sf(i).ge.fk(i))rf(i)=0.0 1220 continue

write(23,l 111 l)zsmi,zgci

write(23,1012)(fk(ji),ji=l,npp) 11111 format('SMI3= ',5f6.2y,'GCI=   ',5f6.2) 1012 forraat('FK=    ',5f6.0)

^****************************************************************

C    Ephemeral forage recruitment:

C    green SF(6) and dry SF(7), ephemeral carrying capacity will vary
```

```
C    as the pasture type changes.

Q^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^*^^^^***^**^^*^*^***

rc=0.0

do 12 i3=l,npp if(pref(i3).le.0.05)then rc=rc else

rc=rc+sp(i3,7)/spm(i3) endif

12   continue rc=aminl(rc,l.) idxge=npp+l hkmax=fkmax(idxge) sh=sf(idxge) do 1003
11=1,10 xin(il)=hkt(il,l)

1003   yin(il)=hkt(il,2)

call grph(rc,hki,xin,yin)

hk=hkmax*hki

dev=(sf(6)-hk)/hk

smih=l./24.*nwp+l./ll.*dev-l./264.*dev*nwp

smih=amaxl (smih,0.0)

rh=(hk-sh)*smih

if (sh.ge.hk) rh=0.0

rf(idxge)=rh

write(23,l 1112)hk,hki,smih

11112 forraat(IKFE=',f6.0,6x,1KFI=',f4.2,6x,IEGI=I,F4.2)

C    drying rates DRF(7) calculation

smif=1.0-0.0413*nwp smie=1.0-0.0375*nwp do 8 i4=l,npp if(fk(i4).le.0.)then pfd(i4)=l.
else

pfd(i4)=(sf(i4)+rf(i4))/fk(i4) endif

pfd(i4)=aminl(pfd(i4),l.) dif(i4)=0.9+0.1*pfd(i4) if (nwp.eq.O) dif(i4)=1.0

drf(i4)=0.5*dif(i4)*smif 8    continue

efd=(sh+rh)/hk

efd=aminl(efd,1.0)

die=0.8+0.2*efd

if (nwp.eq.O) die=1.0
```

```
drh=l.*die*smie
dgh=dgmax(idxge)-0.2*drh
drf(idxge)=drh
idxde=nsf
decratO=0.12
dgdmin=0.25
decrat=0.12+( 1 -decratO)/24*nwp
drf(idxde)=decrat
rf(idxde)=drf(idxge)*(sh+rh)
write(23,11113)drf
11113 format('DRY/DECAY RATE=',7f6.2/)
RETURN END
£***++*+*****+*+*++++****************+**************++++***********
C       subroutine LOSS computes sheep forage intake,
C       Sffi(ephemeral),SIF(peren),drying loss(DNCF, DL),
C       and trampling loss(TL)
C       inputs: SF, SH, RF, RH,SR, DGH, DRF.DRH, NWP
C     outputs:SIF,FIE,FIP,DNCF
C    (perenn. forage loss), (ephem. forage loss)
C    SIF(sheep perennial forage intake/ha),FIE(ephem.
C    forage intake/sheep)
C    FIP(peren. forage intake/sheep),
C*** DNCF(peren. non-consumptive loss)
Q****************************************************************
SUBROUTINE LOSS(ISEAS)
REALNWP,MODE(3),XIN(10),YIN(10),FRF(7),FRD(7)
REAL FRDIET(7),AC(5,5),spanlf(5)
```

```
COMMON/AA l/nwp,mode,spanlf

COMMON/AA2/NSF,NPP,TFA,SR(3),IRUN,NYEAR

COMMON/AA3/SMI1T(5,6),GPI6(9),SMI6(9),PDI6(9),GPN(9),

# SMI3T(10,6),GCIT(10,6),HKT(10,2),GMIT(10,6),RCm(10,6),

# RCIT2(10,2),SIDGI(10,2),SIFAI(10,2)

COMMON/AA4/SPM(5),DGMAX(7),FKMAX(7),SL(5)

COMMON/AA6/ASRATE(5),SfflD,PREF(7)
COMMON/AA7/RF(7),RH,DGH,DRF(7),DRH,FK(7),HK,PD
COMMON/AA8/SP(5,7),SH,SF(7),RET,TEMPSP(5,7),AC,SRO,SRENDO,ESR
COMMON/AA9/G(5),FAVAIL(7),SI(7),DNCF(7),FLOSS(7),tg,tsi,tpref,

#       TFAlPREF,TFA2PREF,PI,sgpic(5,2),DTCI(5),agespl,agesps

tfa=0.0

do!011i=l,nsf

if(pref(i).ne.0.)tfa=tfa+sf(i)+rf(i) 1011 continue

C******************************************************************

C   This code adjusts the preference coef. according to the total C   forage
availability, TFA

£*****************************************^^

tpref=0.0

if (tfa.ge.tfalpref) then

do 35 i=l,nsf

tpref=tpref+pref(i)

35      continue

else if (tfa.ge.tfa2pref) then

do 36 i=l,nsf if(pref(i).ne.0.)then pref(i)=1.0+(pref(i)-1.0)/(tfalpref-tfa2pref)*(tfa-
tfa2pref)

else

endif

tpref=tpref+pref(i)
```

```
36      continue

else

do 37 i=l,nsf pref(i)=1.0 tpref=tpref+pref(i) 37   continue end if

^^^^^Hc*************************************************************

C    This code calculates the fraction of each forage component in the C    forage on offer and in the sheep diet

£********************************************^

tdiet=0.0 do 1 i=l,nsf favail(i)=sf(i)+rf(i) frf(i)=favail(i)/tfa frd(i)=frf(i)*pref(i)

1        tdiet=tdiet+frd(i)

do 2 i=l,nsf

2        frdiet(i)=frd(i)/tdiet

£**************+********#+*********+*******************************

C   The following code calculates the forage availability index AI c   PLsheep potential intake

£*****************************************************************

do!00i=l,10

xin(i)=sifai(i,l) 100     yin(i)=sifai(i,2)

call grph(tfa,yout,xin,yin)

ai=yout

sihd=tfa*ai

siha=pi*sr(iseas)

if (sihd.ge.siha) sihd=siha c      if (sihd.gt.pi) sihd=pi c     siha=sihd*sr(iseas)

c   This code computes the drying losses for perennial and ephemerals

do 4 i=l,nsf si(i)=sihd*frdiet(i) 4 dncf(i)=drf(i)*favail(i) idxge=npp+l idxde=idxge+l

tl=( 1 .-exp(-0.15*sr(iseas))) *favail(idxge) tld=(l.-exp(-0.16*sr(iseas)))*favail(idxde) dlosge= dncf(idxge) dlosde= dncf(idxde) dncf(idxge)= dlosge+tl

dncf(idxde)= dlosde+tld do 5 i=l,nsf floss(i)=si(i)+dncf(i) if((floss(i).eq.0).or.(favail(i).eq.0))then si(i)=0 dncf(i)=0 end if
```

if((floss(i).gt.favail(i)).and.(i.lt.idxge)) then si(i)=si(i)/floss(i)*favail(i) dncf(i)=dncf(i)/floss(i)*favail(i) else if((floss(i).gt.favail(i)).and.(i.eq.idxge)) then si(i)=si(i)/floss(i)*favail(i) dncf(i)=dncf(i)/floss(i)*favail(i) tl=tl/(dlosge+tl)*dncf(i) dlosge=dncf(i)-ti rf(i+l)=dlosge

else if((floss(i).gt.favail(i)).and.(i.eq.idxde)) then si(i)=si(i)/floss(i)*favail(i) dncf(i)=dncf(i)/floss(i)*favail(i) tld=tld/(dlosde+tld)*dncf(i) dlosde=dncf(i)-tld

c write(21,*)'rf7I, i, rf(7)

else

end if

5 continue

c modelling the grazing pressure tsi=0.0 do 6i=l,nsf tsi=tsi+si(i)

6 continue

tg=tsi/(pi*sr(iseas))

tg=aminl(tg,1.0)

do7i=l,npp

g(i)=l-(l-tg)*pref(i)

if(fkmax(i).le.lO)g(i)=0

g(i)=max(g(i),0)

c print*,' grazing pressure ',tsi,tg, g(i)

7 continue

RETURN END

£***#*********

C Subroutine POPULATION calculates desirable perennial plant C population dynamics

C Inputs: S, SP, SF, SH, NWP, SR, AMODE

C Outputs: MRP, SPSDAT(7)

C S:seasonal index, SP:adult perennial plant population,

C SF: peren. forage biomass, SH: ephem. forage biomass,

C NWP: no of growth periods, SR:stocking rate,

```
C       AMODE: mode of NWP distribution, MRP: mortality rate of SP,

C       SPSDAT: population of peren. seedling cohorts

QK****************************************^^

SUBROUTINE POPULATION(ISEAS) REALNWP,MODE(3),AC(5,5),XIN(10),YIN(10) REAL SMI1 (5,6),GI(5,6),CI(6),SURRAT(5,6),GMI(5),RCI(5),PCI(5) REAL wgpi(5),wsmi(5),wdi(5),wmO(5),wprm(5),spanlf(5) COMMON/AA l/nwp,mode,spanlf COMMON/AA2/NSF,NPP,TFA,SR(3),IRUN,NYEAR COMMON/AA3/SMI1T(5,6),GPI6(9),SMI6(9),PDI6(9),GPN(9),

# SMI3T(10,6),GCIT(10,6),HKT(10,2),GMir(10,6),RCm(10,6),

# RCIT2(10,2),SIDGI(10,2),SIFAI(10,2)

COMMON/AA4/SPM(5),DGMAX(7),FKMAX(7),SL(5)

COMMON/AA6/ASRATE(5),SIHD,PREF(7)

COMMON/AA7/RF(7),RH,DGH,DRF(7),DRH,FK(7),HK,PD

COMMON/AA8/SP(5,7),SH,SF(7),RET,TEMPSP(5,7),AC,SRO,SRENDO,ESR

COMMON/AA9/G(5),FAVAIL(7),SI(7),DNCF(7),FLOSS(7),tg,tsi,tpref,

#       TFAIPREF,TFA2PREF,PI,sgpic(5,2),DTCI(5),agespl,agesps

COMMON/AA12/PDF(100,4),TNWP(25),PDFT(100,4)

splong=agespl*3./2.

spshort=agesps*3./2. cc      write(*,*)"ly,sy,lage,sage",agespl,agesps,splong,spshort

prm=0. gpn(l)=nwp do 666 isp=l,npp if(sl(isp).gt. spshort) then do 106 i=l,10

xin(i)=rcitl(i,l) 106       yin(i)=rcitl(i,isp+l) pd=sp(isp,7)/spm(isp) call grph(pd,yout,xin,yin) else

do 101 i=l,10 xin(i)=rcit2(i,l) 101        yin(i)=rcit2(i,2)

if (iseas.eq.l) gnwp2=gpn(3) if (iseas.eq.2) gnwp2=gpn(4) if (iseas.eq.3) gnwp2=gpn(2) if (irun.eq.l) gnwp2=mode(2) call grph(gnwp2,yout,xin,yin) end if

rci(isp)=yout if(iseas.eq.l) then b=l.

fm=mode(l) else if(iseas.eq.2) then b=.5

fm=mode(2) else b=.7

fm=mode(3) end if
```

do 1001=1,10 xin(i)=gmit(i,l) 100 yin(i)=gmit(i,isp+l) call grph(nwp,yout,xin,yin) gmi(isp)=yout*b tempsp(isp,l)=rci(isp)*gmi(isp)*(spm(isp)-sp(isp,7))

c if(spm(isp).lt.sp(i,7)) tempsp(isp,l)=0

C seedh'ng population dynamics according to the lifespan c of each perennial groups

if(sl(isp).gt. spshort) then do 6 i=l,6

gi(isp,i)=g(isp)**(sgpic(isp,l)/i) c gi(isp,i)=l-g(isp)**(0.7+sgpic(isp,l)*i) see comment below

gi(isp,i)=amin 1 (gi(isp,i), 1.)

smi 1 (isp,i)=smi 1 t(isp,i)+(1 .-smi 1 t(isp,i))/(13.-i)*nwp

smi 1 (isp,i)=amin 1(1 .,smi 1 (isp,i))

ci(i)=l-(1.16-0.16*i)*((sh+rh)/hk-.5)

ci(i)=amin 1 (ci(i), 1.)

esp=0.0

do 2 j=l,npp

2 esp=esp+ac(j,isp)*sp(j,7)

if(esp.lt.spm(isp)) then pci(isp)=2*(l-esp/spm(isp)) pci(isp)=amin 1 (pci(isp), 1.)

else

pci(isp)=0

end if

surrat(isp,i)=smi 1 (isp,i) *gi(isp,i) *ci(i) *pci(isp)

k=i+l

tempsp(isp,k)=surrat(isp,i)*sp(isp,i) 6 continue

else

do 606 i=l,3

gi(isp,i)=g(isp)**(sgpic(isp,l)/i) gi(isp,i)=amaxl(gi(isp,i),0.)

smil(isp,i)=smilt(isp,i)+(l.-srailt(isp,i))/(13.-i)*nwp smi 1 (isp,i)=amin 1 (1 .,smi 1 (isp,i)) ci(i)=l-(1.16-0.16*i)*((sh+rh)/hk-.5) ci(i)=aminl (ci(i), 1.) esp=0.0 do 201 j=l,npp

201 esp=esp+ac(j,isp)*sp(j,7)

```
if(esp.lt.spm(isp)) then
pci(isp)=2*(l-esp/spm(isp)) pci(isp)=aminl (pci(isp), 1.) else
pci(isp)=0.0 end if
surrat(isp,i)=smil(isp,i)*gi(isp,i)*ci(i)*pci(isp) k=i+l
tempsp(isp,k)=surrat(isp,i)*sp(isp,i) 606     continue end if
^^H'H'*******************************************************
C       Modelling of adult plant mortality rate
C       grazing pressure index (GPI)
C       soil moisture index (SMI)
C       plant density index (DI)
Q*******************************************************
gpi=g(isp)**sgpic(isp,2)
gpi=amaxl(gpi,0.)
if (fm.eq.O.) then
smi=1.0
else
smi=DTCI(isp)+(l-DTCI(isp))*nwp/fm
endif
smi=aminl(smi,l.)
c    calculate adult plant density index di
di=0.
do29ji=l,npp if (spm(ji).le. 100) then di=0 else
di=di+sp(ji,7)/spm(ji) endif 29   continue
di=amaxl(di,1.0)
if(di.gt.l.0)di=l/di
gpi6(l)=gpi smi6(l)=smi pdi6(l)=di
tgpi=0. tsmi=0. tdi=0.
```

```
if(sl(isp).ge.splong) then do 28 kl=l,9

tgpi=tgpi+gpi6(kl) tsmi=tsmi+smi6(kl) 28     tdi=tdi+pdi6(kl) gpi=tgpi/9 smi=tsmi/9
di=tdi/9

elseif(sl(isp).gt.spshort) then

do290kl=l,6

tgpi=tgpi+gpi6(kl)

tsmi=tsmi+smi6(k 1)

290     tdi=tdi+pdi6(kl)

gpi=tgpi/6 smi=tsmi/6 di=tdi/6 else

do301kl=l,3

tgpi=tgpi+gpi6(kl)

tsmi=tsmi+smi6(k 1)

301     tdi=tdi+pdi6(kl)

gpi=tgpi/3 smi=tsmi/3 di=tdi/3 endif

write(*,*)isp,gpi,smi,di wgpi(isp)=gpi wsmi(isp)=smi wdi(isp)=di

PMNAT=1.-.5**(1./SL(ISP)) psurvr=((l-pmnat)+gpi*smi*di)/2 if(g(isp).le.0.6) #
psurvr=gpi*smi*di

ASRATE(ISP)=PSURVR wmO(isp)=pmnat wprm(isp)=ASRATE(isp) 141
format(i5,5f6.3) 666  CONTINUE

write(23,231)rci

231     formatC         PI    P2    P3    P4   P5 V,

+'RCI= ',5f6.2)

write(23,232)gmi

232     format('GMI= ',5f6.2)

write(23,234)'PCI= ',pci

write(23,233) write(23,234)'ECI= ',ci

233     format(/,'        COH1 COH2 COH3 COH4 COH5 COH6')

WRrrE(23,*)'SMIl=' do 130j3=l,NPP
```

```
130    WRITE(23,236)j3,(smil(j3,K),k=l,6)

WRrrE(23,*)'GPI='

do!31j3=l,NPP

131    write(23,236)j3,(GI(j3,k),k=l,6)

WRrrE(23,*)'SURRAT='

do 132j3=l,npp

132    write(23,236)j3,(surrat(j3,k),k=l,6)

236   format('group',il,6f6.2)

234 format(A6,6f6.2)

235 format(A12,6f6.2)

write(23,*)

WRnE(23,*)'AdultSURRAT  PI    P2   P3    P4   P5'

write(23,235)'GPI2=        ',wgpi

write(23,235)'SMI2=        ',wsmi

write(23,235)'PDI=         ',wdi

write(23,235)'MO=   ',wmO

write(23,235)'SURRAT = ',wprm write(23 *)'*****************************************'

RETURN END

Q***************************************************************** C***** Subroutine
UPPDATE updates 9 state variables

^^c^^^^H*************************************************************

SUBROUTINE UPDATE(ISEAS)
REALAC(5,5),TGPI6(9),TSMI6(9),TPDI6(9),TGPN(9)
COMMON/AA2/NSF,NPP,TFA,SR(3),IRUN,NYEAR
COMMON/AA3/SMI1T(5,6),GPI6(9),SMI6(9),PDI6(9),GPN(9),

# SMI3T( 10,6),GCIT(10,6),HKT( 10,2),GMIT( 10,6),RCIT1 (10,6),

# RCIT2(10,2),SIDGI(10,2),SIFAI(10,2)

COMMON/AA4/SPM(5),DGMAX(7),FKMAX(7),SL(5)

COMMON/AA6/ASRATE(5),SIPID,PREF(7)
```

```
COMMON/AA7/RF(7),RH,DGH,DRF(7),DRH,FK(7),HK,PD

COMMON/AA8/SP(5,7),SH,SF(7),RET,TEMPSP(5,7),AC,SRO,SRENDO,ESR
COMMON/AA9/G(5),FAVAIL(7),SI(7),DNCF(7),FLOSS(7),tg,tsi,tpref, #
TFAIPREF,TFA2PREF,PI,sgpic(5,2),DTCI(5),agespl,agesps

DO 38 1=1,NPP

IF(SL(I).GT.(agesps*372.)) THEN DO 37 K=I,6

37      SP(I,K)=TEMPSP(I,K)

SP(I,7)=TEMPSP(I,7)+ASRATE(I)*SP(I,7)

SP(I,7)=AMIN1(SP(I,7),SPM(I))

ELSE

DO371K=1,3 371     SP(I,K)=TEMPSP(I,K)

SP(I,4)=TEMPSP(I,4)+ASRATE(I)*SP(I,4) SP(I,4)=AMIN1(SP(I,4),SPM(I))
SP(I,7)=SPa,4) END IF

38      CONTINUE

DO 15 I=1,NSF

SF(I)=SF(I)+RF(I)-FLOSS(I)

15      SF(I)=AMAX1(SF(I),0)

TGPI6(1)=0. TSMI6(1)=0. TPDI6(1)=0.

TGPN(1)=0. DO16J=1,8

LAG1=J+1

TGPI6(LAG1)=GPI6(J)

TSMI6(LAG1)=SMI6(J)

TPDI6(LAG1)=PDI6(J)

16      TGPN(LAG1)=GPN(J)

DO 17 J=I,9

GPI6(J)=TGPI6(J) SMI6(J)=TSMI6(J) PDI6(J)=TPDI6(J)

17      GPN(J)=TGPN(J)

SRO=SRaSEAS)
```

```
SRENDO=ESR RETURN END

^^^^H'************************************************************* C*** FUNCTION
RAND generates 0-1 random variable for NWP pdf

£**************************************************^

FUNCTION RAND(L)

COMMON/AA11/IX,IY,IZ,IX1,IY1,IZ1

DATAIX,IY,IZ,IX1,IY1,IZ1/12345,65814,23361,30311,63451,88834/

I=L

IX=171 *MOD(IX, 177)-2*(K/177)

IY=172*MOD(IY,176)-35*(n7176)

IZ=170*MOD(IZ,178)-63*(IZ/178)

IF(IX.LT.O)IX=IX+30269

IF(IY.LT.O)IY=IY+30307

IF(IZ.LT.O)IZ=IZ+30323

RAND=AMOD(FLOAT(DQ/30269.0+FLOAT(IY)/30307.0+

1     FLOATaZ)/30323.0,1.0)

RETURN

END

QK*********************************#***************^

C*** Subroutine NGPCDF use RAND to generate NWP value

£**************************************************************

SUBROUTINE NGPCDF(U,ISEAS)

REAL PDF,NWP,MODE(3),spanlf(5)

COMMON/AA l/nwp,mode,spanlf

COMMON/AA12/PDF(100,4),TNWP(25),PDFT(100,4)

CDF=0.0

NWP=0.0
```

```
DO 101=1,25

11=1

CDF=CDF+PDF(I1 JSEAS)

IF (U.LE.CDF) GO TO 20 10  CONTINUE 20   NWP=TNWP(I1) RETURN END

Q^*^***^**^^^*****^^^**^^^^*^^***^^^^*^*^*^^^**^^^^^^**^^^^^^**^^^^^

CC***Subroutine AMODE calculated modal value of CC***NWP distribution

^^^Hc*****************************************************************

SUBROUTINE AMODE

REAL MODE(3),spanlf(5)

DIMENSION PDFI(25),TEMP1 (25),TEMP2(25)

COMMON/AA12/PDF(100,4),TNWP(25),PDFT(100,4)

COMMON/AA I/nwp,mode,spanlf DO 11=1,25 DO 1 K=2,4

1        PDF(I,K-1)=PDFT(I,K) DO115j=I,3

BB1=-1.0

DO 101 n=I,25

BB1=BB1+1.0

TNWP(H)=BB1

101    TEMPI(II)=TNWP(n) DO 1141=1,25 PDFI(I)=PDF(I,J)

114    TEMP2(I)=PDFI(I)

CALL MAXMIN(25,TEMP2,TEMP1,AMO,AMID)

115    MODE(J)=AMO

RETURN

END

£*********#********************************************************** CC***Subroutine
MAXMIN finds maximum and minimum of a series

£*********#*********************************************************

SUBROUTINE MAXMIN(N,X,Y,BIG,SMALL) REALX(N),Y(N) DO 121=1,N-I IP1=I+1
```

```
DO12J=IP1,N

IF (Xa)-LE.X(J)) GO TO 12

TEMP=X(I)

X(I)=X(J)

X(J)=TEMP

TEMP=Y(I)

Y(I)=Y(J)

Y(J)=TEMP 12 CONTINUE BIG=Y(N) SMALL=Y(1) RETURN END

£********************************************^

C*** Subroutine GRPH is used to define functional relationships which are

C*** difficult to be formulated mathematically.

^****************************************************************

SUBROUTINE GRPH(XINP,YOUT,X,Y)

DIMENSION X(10),Y(10)

IF (XINP.LT.X(1)) THEN

YOUT=Y(1)

ELSEIF (XINP.GE.X(10)) THEN

YOUT=Y(10)

ELSE

DO 53 1=1,10

J=I-1

IF(XINP.LT.X(I)) GO TO 54 53   CONTINUE 54YOUT=Y(J)+(Y(J+1)-Y(J))/(X(J+1)-
X(J))*(XINP-X(J))

ENDIF

RETURN

END

^^^HC*************************************************************
```

C Subroutine PROB convert number of wet pentads data to wet pentad c probability distribution, which is then used to calculate the c mode value for each season

```
C

subroutine prob(nyear) realm2

common/aal2/pdf(100,4),tnwp(25),pdft(100,4) common/aal3/m2(25,4) data
m2/100*0.0/,n/0/ do 1001=1,25 do!00j=2,4

n=0

do 99 m=l,nyear

if (pdft(mj).eq.(i-l)) then

n=n+l

m2(i,j)=n

endif

99      continue

c       print*,i,j,m2(i,j)

100     continue

do 101 i=l,25 do 101 j=l,4

if (j.eq.l) then

pdft(i,j)=i-l

else

pdft(i,j)=m2(i,j)/nyear

endif

101     continue

return

stop

end
```