A MATHEMATICAL MODEL OF BROWSE AND HERBAGE PRODUCTION IN COMMUNAL GRAZING LANDS OF SEMI-ARID REGIONS.

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CHAPTER 1

INTRODUCTION

The main purpose of this work is to extend an existing model of growing cattle and grass production in a semi-arid rangeland.The existing model which is basically Dye's (1983) model in differential equation form handles:

i) the growth and performance of cattle measured in terms of weight,
ii) the initiation of grass growth in early rainy season and its utilisation by the cattle.

This model is being extended to simulate woody plants in addition to the grass and to simulate browsing by goats. The densities of vegetation and the stocking rates of both types of animals are being considered. Our model (SAVANNAS) will predict animal productivity in relation to rainfall and density of woody plants (or vegetation condition). A rainfall data file is being used to generate rain which divides into infiltration and run-off.

Athough generally dry, semi-arid regions are agriculturally productive, more especially in terms of animal products. An understanding of the climatic conditions by the farmers is all what it takes. It is unfortunate that in these regions, rainfall, being the main driving force behind animal productivity, is unreliable in that it varies both within and over the years. It is in this regard, therefore, that models be built to simulate semi-arid environments. Such models, when run for several (semi-arid) representative rainfall years could be used by farmers. For instance, a model like SAVANNAS will be run for three rainfall years namely 1980/81, 1981/82 and 1982/83, which, respectively represent: very high, about average and very low rainfall (by semi-arid standards).

SAVANNAS simulates processes that operate on widely different time scales. The growth and consumption of herbage and leaves and twigs of woody plants are modelled on a daily basis, while the numbers and ages of woody plants are updated every 120 days. The year is divided into four seasons, with the rainy season beginning in September and initiating herbage re-growth. SAVANNAS simulates herbage biomass, which means it allows the re-establishment of the previous year's grass plants. It divides woody plants into age cohorts with the first cohort being seedlings mainly, and the last cohort being adult trees which are usually out of the browsing range of herbivores. It is a model that has a focus on the effects of vegetation (woody plants and grass) on each other and the effects of the animals on vegetation and vice-versa.

Without overlooking their effects on vegetation production, fires are not considered in SAVANNAS. This is because in communal lands heavy grazing does not allow the accumulation of sufficient dry herbage for fuel.

1.1 AIMS AND OBJECTIVES:

This study is aimed at building a non-equilibrium (section 3.4) systems model which primarily focuses on plant-animal relationships in communal grazing lands. Although SAVANNAS can be run for many years, we are especially interested in the output of one year and of successive years of different rainfall patterns. The specific goals of SAVANNAS are to:

i) Predict herbage & browse production and animal production under scenarios of both variable rainfall and stocking rates.

ii) Predict the interactive relationships between plant (herbage and woody plants) species over the year.

iii) Determine the influence of animals on plants and vice-versa. How are such influences affected by the amount and timing of rainfall over the year? Also, of importance is the response of plants to defoliation of varying intensity.

CHAPTER 2

REVIEW

The inter-relations between vegetation and herbivores play a major role in the dynamics of communal grazing lands. In this work, two types of herbivores (cattle and goats) are considered. A vegetation comprising herbage and woody plants is considered. The effects of herbivory on vegetation and vice-versa remain a major concern in such a system. On the other hand we cannot overlook the interactions between herbage and woody plants, and to some extent the herbivore to herbivore relationships.

Cattle and goats play a role in the defoliation of plants, with cattle predominantly grazers and goats preferring browse. Apart from grazing, cattle do browse more especially during times of grass scarcity and low grass quality. The same applies to goats, they tend to prefer grazing more than browsing during the early rainy season when grass is green (Teague,1987). Both types of herbivores tend to put their priorities on certain types of plants according to their nutrient requirements. Owen-Smith (1982) reports that explanations of diet selection by browsing ruminants have suggested that protein is often in limited supply and may influence preferences. Forage preferences can also be influenced by plant structural characteristics, such as spinescence, twiggy growth forms or leaf fibrousness (Cooper and Owen-Smith, 1986). Herbel (1979) reports that unless stocking rates are high or various management techniques are employed, cattle do not graze pastures uniformly, rather they tend to graze selectively and leave areas of the pasture effectively ungrazed.

AFRC (1998) described goats as "mixed-feeding opportunists". Goats are known to concentrate upon species presenting the greatest quantity of new leaves and shoot material at a given time. Genin and Badan-Dangon (1990) report that goats have a larger appetite for flowering species. Just like any herbivore, goats have got their preferences when it comes to diet. They have a greater tolerance to bitterness (AFRC,1998), thus they will consume shrub and tree leaves which are normally rejected by cattle. Goats need a more digestible diet than cattle because of the smaller digestive tract relative to their body size (Illius and Gordon,1987).

In addition to defoliating plants, animals physically damage plants by cutting, bruising, breaking and debarking while walking, running, playing, tussling and scratching (Tainton,1988). Animal hoofs tend to break mature, dry grasses while young and growing grasses bend rather than break. Moving animals can interfere with soil structures, at times causing soil to cover short plants, or bury seeds and promote germination (Tainton,1988). Seed germination and seedling establishment can also be stimulated by grazing. Many seeds can only germinate after passage through the digestive tract where the ruminal acids eliminate dormancy (Breman and Kessler, 1995, Tainton,1988). During its passage through the digestive tract, the seed coat is softened and partially digested thus enhancing germination. Dust raised by walking animals may settle on and coat plants, reducing their acceptibility to animals (Tainton,1988). Intensive grazing by animals may reduce canopy cover. This reduction in canopy cover leads to a reduced infiltration since there is no more enough vegetation to "trap" the rain water more especially in dry zones.

Plant recovery after defoliation depends on the severity and frequency of defoliation, stage of growth and the individual plant's ability to endure stress (Menke and Trlica, 1981). Frequent defoliation exhausts carbohydrate reserves (Teague,1987). In woody plants, recovery can be very slow after a severe defoliation. Moderate defoliation can stimulate the production of leaf and twigs. Severe defoliation is accompanied by greater mobilisation of reserves and a greater reduction in root growth (Teague,1987). He reports that the reserves (carbohydrates which are stored in cambial tissues) are used each time that photosynthesis cannot meet the energy requirements of the plants. Although heavy grazing can lead to plant mortality, at any herbivore density trees are more likely to survive (Noy-Meir,1982). This is because the browse limit for cattle and goats is about 1.5 m, which leaves higher branches unbrowsed by animals. Grasses, however, can be severely reduced due to overgrazing particularly if the herbivore is an efficient grazer (Noy-Meir,1982).

The effects of woody plants on herbage production are variable. Although observations have been made that woody plants suppress herbage growth, studies on the interactions between woody plants and herbage have shown that there is higher herbage biomass under woody plants than in the open spaces (Breman and Kessler, 1995). There are many reasons for this, ranging from moisture contents to nutrient distribution. Research on savanna ecosystems shows that nutrient mining by the extensive root system of many savanna trees will concentrate nutrients from surrounding areas and deeper soil layers around the tree (Tiedemann and Klemmedson,1977, Belksky et al.,1989: quoted by Roos and Allsopp,1997). Also, higher nutrient levels under trees are related to greater organic matter contents in the soil under trees (Kadeba and Benjamin,1976) due to greater litter inputs by trees compared to grasses. Generally, there is less moisture under woody canopies than non-canopy positions in semi-arid regions. Exceptional cases do exist though, where moisture contents are higher under woody canopies. This is a result of hydraulic lift by deep tree roots that may bring water to the surface soils (Dawson,1993: quoted by Roos and Allsopp,1997) where it is needed most by herbage. In such cases the average soil moisture contents under woody cover are higher such that the proportion of germinating seeds at the beginning of the rainy season is higher than in the open spaces. In the early rainy season, dense forage may be observed under woody canopies when the open spaces are still bare. In areas of strong winds, canopy protects herbage against mechanical wind effects (Breman and Kessler,1995), thus making sure of good moisture levels. It is said that even though they protect herbage against wind effects, low and dense canopies, however, do not permit herbage to develop underneath, unlike open and loose canopies. This may be due to shading effects.

Unless at high densities, woody plants less than 1m tall hardly suppress herbage production, contrary to those exceeding 2m in height (Stuart-Hill and Tainton,1989: quoted by Breman and Kessler,1985). Herbage production under trees more than 7m tall is similar or even higher than in the open fields, contrary to herbage production under woody plants less than 3m (Sanford et al.,1982: quoted by Breman and Kessler, 1985). Surely they (Sanford et al.) assume equal and average plant densities for both plant groups. This may be because large trees allow incoming light for herbage growth.

Although there seems to be more grasses under woody canopies, grasses can become extinct if woody vegetation is sufficiently dense, while trees can survive in the densest of grasslands as long as rainfall reaches the subsoil and there is no problem of recruitment from seedlings (Noy-Meir,1982). When the woody plant density exceeds a specific threshold the growth and proliferation of grass may be suppressed. This may be so severe that the grass dies out. Woody plants have the ability to redistribute incoming rain via their canopies and through stemflow which then leads to a higher proportion of the rainfall in the subsoil than would occur in their (woody plants) absence (Walker and Noy-Meir,1982). With this subsoil moisture they (Walker and Noy-Meir) say it takes woody vegetation a seasonal rise in temperature to produce its major leaf flush, and this happens 2 or 3 months before the grasses can produce any green leaf. Grasses, which are solely dependent on topsoil moisture due to the nature of their root systems, out-compete woody plants for water in the topsoil (Walker and Noy-Meir,1982).

All this ecology would require a model which is dynamic over time, unlike the static model of Jones and Sandland (1974) which relates stocking rates and gain per hectare (see section 2.4).

2.1 CLIMATE

RAINFALL AND TEMPERATURE

In developing SAVANNAS, data files of recorded daily rainfall for Matopos Research station (17 km south of Bulawayo) have been used . There is a big variation in the amount of rainfall both within years and between the years. The rainfall and temperature year in semi-arid regions is divided according to the following four seasons:

i) **SPRING (September to November)**
This is the season which is marked by an increase in the average daily temperature. This increase in temperature initiates the re-growth of leaves in woody plants. Some rainy showers may be seen during this time and such showers trigger the re-growth of perennial grasses and the germination of annuals. The humidity is low, and the conditions are windy leading to high rates of evaporation.

ii) **SUMMER (December to February)**
This is the main rainy season. The start and finish of this season is very variable (Dye,1983). The average daily temperatures are usually high though cloud cover may lower them. Humidity is often high with the rainfall originating from relatively intense convective storms of short duration (Dye,1983).

iii) **AUTUMN (March to April)**
There is no much activity during this season other than the wilting of plants. This is the time when the average daily temperatures start falling. Chances of rainfall are slim during this season, if there is rain it comes in the form of minor showers.

iv) **WINTER (June to August)**
During this season the average daily temperatures are low. Most of the days are sunny and mild with little cloud, while nights are cold and often accompanied by ground frost along the watershed . In his work on a Savanna site, Rutherford (1984) reports that there are only about 20 days per year with ground frost in savanna lands and that little or no rain falls during this period. Due to low temperatures and absence of rain there is no plant growth in this season. Leaves of grasses die progressively unless killed by frost.

The figures below (given by Dye,1983) show the long-term monthly means of pan evaporation, temperature (maximum and minimum) and rainfall of Bulawayo.

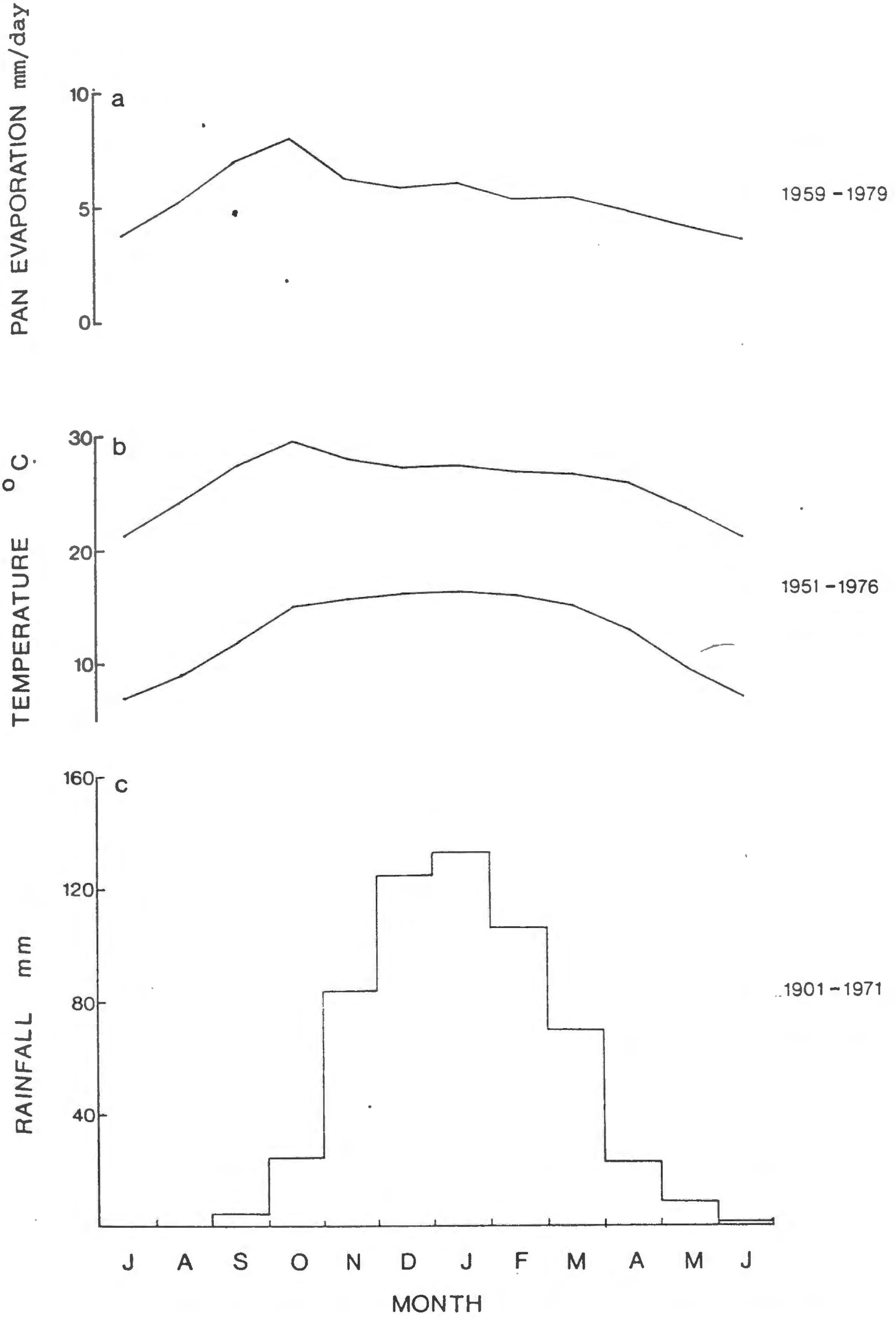


Fig 2.1 Long-term monthly means of pan evaporation (a), maximum and minimum temperatures (b) and rainfall (c) as recorded at Bulawayo.

2.2 SOIL MOISTURE AND SOIL STRUCTURE

In SAVANNAS it is assumed that the soil is structured into four layers namely A, B, C and D; with A being the top layer. Evaporation has been shown to occur primarily from the first 10cm of soil (Slatyer,1962; Oliver,1969: quoted by Dye,1983); and is principally governed by the evaporative conditions of the atmosphere, the degree of plant cover and the moisture content of the topsoil. Store A holds about 12mm of available moisture but the rate of evaporation has been shown to drop quickly once the moisture content falls below field capacity and a dry surface layer develops (Milthorpe,1960; Hanks and Ashcroft,1980: quoted by Dye,1983). Soil moisture depends on the depth of the soil. There is usually more moisture (unless there is a heavy rain after prolonged drought) in deeper soil layers than in the top layers , this is a result of evaporation and transpiration being more pronounced from the top layers than on deeper layers. On the A-layer for instance, available moisture is within reach of both herbage and woody plants, whereas only the deep roots of woody plants have access to the moisture in deeper layers. The depth and water holding capacity of each layer varies between soil types and sites.

INFILTRATION, DRAINAGE and RUN-OFF

Rainfall is partitioned between infiltration, run-off, deep drainage and storage. Moisture stored in the soil is removed by evaporation and transpiration.
For this study interception by plants is ignored. Dye (1983) gives the following reasons for ignoring interception:

i) Interception is likely to be less than 2mm per rainfall event over much of the growing season, before final shoot yields are attained.

ii) Interception is likely to have a negligible effect on hydrological cycle, since most of the season's rainfall occurs during a few heavy storms (Kreft,1972).

iii) Transpiration from leaf surface drops until intercepted water evaporates (McMillan and Burgg, 1960).

Both infiltration and run-off are affected by several factors such as : amount of plant cover and antecedent soil moisture. Generally, if the amount of rainfall is less than 12mm (an approximation, it may vary depending on soil type and condition) there is no run-off, though on sandy soils run-off may not occur even if rainfall is above 12mm because infiltration rates are higher.

The amount of plant cover is a factor favouring infiltration. If there are a lot of plants, most of the rain is allowed to "settle" and thus have time to infiltrate rather than running-off. Also, woody plants channel rain drops down their stems into deeper soil layers. Their (plants) presence, however, does not guarantee good infiltration if the slope of the land is steep since most of the rain goes as run-off regardless of its duration. Soil moisture levels before the start of the rain are a factor in such a way that if there has been no rain for a long time, the water holding capacity of the soil becomes maximum, and thus infiltration is favoured. The depth to which infiltrating water penetrates depends on the effective soil depth, the moisture retention properties of the soil and antecedent moisture (Dye,1983).

2.3 ANIMALS: *GRAZING and BROWSING*

One of the main results of animal grazing and browsing in communal lands is the reduction of canopy cover, i.e. the weight of leaf per hectare goes down. This effect is intensified in lands closer to kraals and water points (B.D. Hahn, Cape Town, 1998, personal communication). Such a reduction in cover promotes run-off at the expense of infiltration of rainfall, as a result water and nutrients get concentrated in depressions on loamy, crust-forming soils. Under such circumstances woody plant reproduction is often delayed by nutrient stress. Following the reduction in leaf density due to herbivory, plant transpiration rates also go down. Breman and Kessler (1995), report that on the arid Egyptian coast, shrub browsing results in reduced leaf transpiration in the rainy season, so water percolates into deep subsoil storage. Shrubs use the stored water to extend foliage production through the dry season and into the next growing season.

Apart from reducing canopy cover, animal hoof action creates a lot of small paths in the process. Such paths may concentrate run-off water to form gullies which may increase drainage losses (Breman and Kessler,1995). The destruction of herbaceous layers during heavy grazing makes more soil moisture available to shrubs, eventually resulting in an increase in the woody vegetation (Mworia et al.,1997). Since overgrazing and browsing destroy younger plants and retards growth of even the perennial plants, lands which are subjected to such herbivory for longer periods are characterised by an imbalance in the population of young trees to old trees. There are usually "more" aged plants than young ones, i.e. the expected proportions of plants are skewed. It is common also that the number of perennial grasses become low since they (grasses) cannot stand continuous over-grazing.

2.4 PUBLISHED MODELS

The model (SAVANNAS) being developed is integrated and dynamic over time. In the past some closely related models have been developed. In 1974, Jones and Sandland produced an empirical model which related among other things the animal weight gains and the gains per hectare to stocking rate. Their model quantitatively related the stocking rates to the animal gains (figure 2.4) ; however, it is static and does not consider day to day processes.

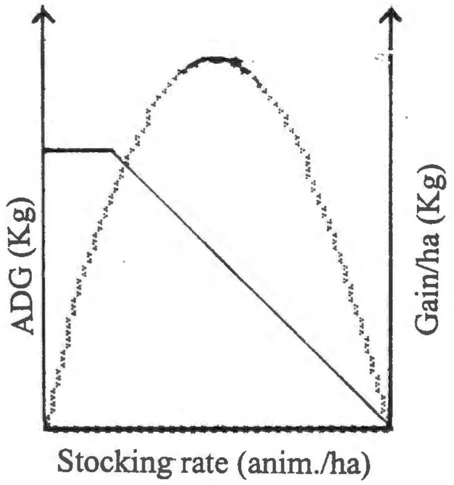


Figure 2.4: stocking rates plotted against animal gain per hectare (Gain/ha) and daily gain per animal (ADG), Jones and sandland (1974). The parabola corresponds to Gain/ha and the "straight line" corresponds to ADG.

Some mechanistic models have also been developed. Dye (1983) developed a model relating herbage production in relation to rainfall distribution in semi-arid rangelands. His work was basically on the soil-rainfall-plant mechanism though it had a mention of grazing animals. Due to the location of the place of study, his work did not need to consider photosynthesis. This is because in such places the day is long and thus sunlight is not limiting (F.D. Richardson, Cape Town, 1999, personal communication). With a lot of assumptions in his work, his model is more artificial than expected. Apart from the assumptions, his model has the following short-comings:

i) It ignores the effects of temperature on plant growth before the rainy season.
ii) It does not consider the differences in infiltration capabilities of the different types of soils.
iii) His plant-growth sub-model does not consider the existence of perennial plants.
iv) At the start of each new growing season plant material from the previous season is removed instead of being allowed to decay into the soil surface for fertility purposes.
v) Storage of carbohydrates is not modelled, which makes the initial vegetation growth the same every year.

Teague (1987) developed a model which covered the effects of soil moisture and browsing by goats on the growth of leaves and twigs of *Acacia karroo* plants of the Eastern Cape. The growth patterns of this plant species were observed under different climatic conditions. The response of these plants to goat defoliation was explored. The focus was on how defoliation of variable intensities (i.e. light, moderate and heavy defoliations) affects the growth of these plants at different times of the growing season.

Hacker et al. (1991), developed an integrated model of an arid-grazing ecological system (IMAGES) of the winter rainfall shrublands of western Australia. Their model incorporated the soil-plant-animal system, and it is dynamic on a unit time scale of four months. This unit time (4 months) is long though, more especially if one wants to simulate grass growth because there are a lot of changes that grass undergoes in a space of 4 months. It assumes only one pasture type per paddock with sheep being the only herbivore.

In communal grazing lands, where there is usually more than one type of herbivore and more than one plant species, it is important to consider diet selections. Animals select some plants in preference to others and their preferences differ between species (animal) and even animal breeds, e.g. indigenous cattle browse more than the European breeds. Animals select different parts of the same plant (Orsini,1990); this also varies with season, for instance, dead leaves are hardly eaten during summer. Genin and Quiroz (1992), developed a diet selection model (MIAMH). It simulates diet selection by animals in according to their nutritional requirements and plant digestibilities. Their model does not, however, include the effects of bite size on each plant species. Also, their model considers leaf as the only palatable part of a plant.

CHAPTER 3

DEVELOPMENT OF PRODUCTION SYSTEM MODELS:

3.1 STRUCTURE OF MODELS

SAVANNAS has been developed as an integration of several sub-models. The sub-models include: climate, soil water, herbage, woody plants, diet selection and animal production. A recorded data file has been used for the daily rainfall records. With the exception of the woody plant population model which has a time unit of 120 days, the models use a time unit of a day.

Simple difference equations and ordinary differential equations have been used in the models. Differential equations are solved using the 2nd-order Runge-Kutta method with an integration interval of 0.1 day. SAVANNAS is run (implemented) using the interactive package Driver of Hahn and Furniss (1988), whilst it is written in Turbo-Pascal. The parameters and variables used in SAVANNAS are listed and defined in the appendix.

3.2 VEGETATION MODELS

3.2.1 GRASS GROWTH MODEL

As mentioned in earlier sections, SAVANNAS assumes that at the beginning of the rainy season grass growth is only from the previous year's plants. If we let $V(t)$ represent the shoot mass at time t then we know that $\frac{dV}{dt}$ is given by the difference in growth rate and decay rate (i.e. in the absence of herbivory). If g is the growth rate of the shoot biomass then the rate of change of the biomass with time is given by Starfield and Bleloch (1986) as

$$\frac{dV}{dt} = gV\left(1 - \frac{V}{K}\right) \qquad (1)$$

where K is the maximum biomass that can be supported; such that when $V = K$, $\frac{dV}{dt} = 0$.

A graph of $\frac{dV}{dt}$ against V is shown in figure 3.2.1(a) below.

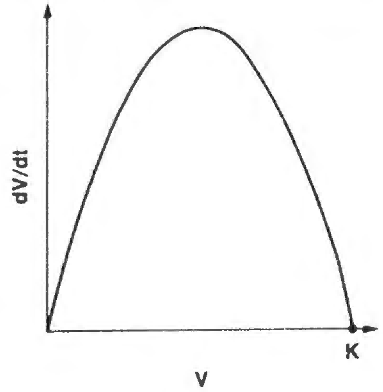


Figure 3.2.1(a): vegetation growth rate dV/dt plotted against vegetation biomass V with no grazing.

In equation (1), the coefficient g is a constant. This, however, applies to regions with continually growing vegetation. For the purpose of this work, g has to be treated as a variable because the region in consideration is semi-arid which means there is a variation in rainfall both between and within years. Also, since green leaf (referred to as gleaf in SAVANNAS) is mainly responsible for plant growth, V in the R.H.S. of equation (1) shall be gleaf. Equation (1) can now be given as:

$$\frac{dV}{dt} = Qtrans\left(1 - \frac{gleaf}{K}\right)$$

where $Qtrans = Ktrin \times \frac{pottr}{H}$

$Ktrin$ is a transpiration index.

$pottr$ is a potential transpiration which is a function of green leaf.

H is relative humidity.

From the graph V'(t) first increases with an increase in V and later it decreases. This is because when the leaves are still few there is a high capacity for photosynthesis thus increasing $V'(t)$ whereas as V gets bigger the plants are affected by shading effects and competition. In SAVANNAS the concept is purely demonstrated by the use of the Michaelis-Menten equations. The growth of each plant component (e.g. culm) is limited by the availability of the substrate using the equation:

$$gro = \frac{gmx}{1+\frac{K_s}{substr}}$$

where gro is the growth of plant component .

K_s is a Michaelis-Menten growth parameter.

$substr$ is the amount of substrate.

gmx is the maximum growth of the plant component; it is given by the logistic equation

$$gmx = \{1 - exp(1 \times ln(\frac{i}{max_j})\}mu \times i$$

where mu is the Michaelis-Menten parameter for maximum growth of the plant component.

max_j is the maximum possible amount of plant component.

i is the amount of plant component.

In the event of non-limiting amount of substrate, the whole plant and its components would grow to their maximum. This is the same logistic-growth that equation (1) represents. This means the rate at which the whole plant grows can be given as:

$$\frac{dPLANT}{dt} = \sum_i gro(i);$$

i.e. in the absence of herbivores.

In the presence of cattle and goats grazing, equation (1) is modified to incorporate the grazing factor G , where G is in units of vegetation per unit time.
The equation becomes

$$\frac{dV}{dt} = gV(1 - \frac{V}{K}) - G \qquad (2)$$

Since $G = G(H(t))$ where $H(t)$ is the number of herbivores at time t, let us see what happens if we assume constant herbivory (which may imply constant grazing). Looking at the graph of $V'(t) = gV(1 - \frac{V}{K})$ we see that it is an inverted parabola as shown in figure 3.2.1(a) above. Below is the same graph but with a line of constant grazing pressure $V'(t) = G$ being superimposed.

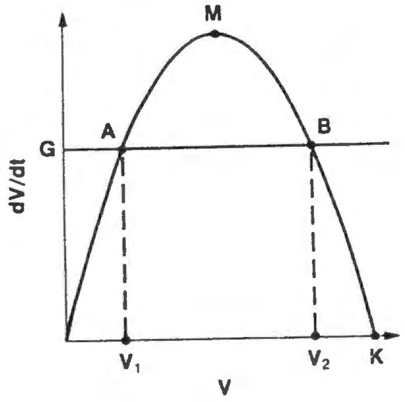


Figure 3.2.1(b) : vegetation growth rate dV/dt plotted against vegetation biomass V showing the line of constant grazing pressure G (Starfield and Bleloch, 1986).

From equation (2) it is obvious that $V'(t) > 0$ for $G < gV(1 - \frac{V}{K})$, which means from the graph $V'(t) > 0$ for $V1 < V < V2$
i.e. only the region of the parabola that is above the G line. At points A and B that is where $G = gV(1 - \frac{V}{K}) \Rightarrow \frac{dV}{dt} = 0$.
At such points, that is where herbivory can be said to be matching the new leaf growth so there is no net-change in vegetation biomass. From the graph again, if G lies above the parabola then we have $V'(t) < 0$ which is something that can happen if there is excessive grazing towards the dry season. This means that the herbivores graze faster than the grass can grow, and this is an unstable situation.

In communal grazing lands it is not realistic to assume constant grazing. When there is enough vegetation for instance, animals would graze more than they would during dry seasons. Also, in communal lands there is a lot of invasion of territory by large flocks of animals. The term G in equation (2) expresses the degree to which $V'(t)$ is reduced by herbivores. If we let $H(t)$ to be the number of herbivores and that $G(t) = G(H(t), V(t))$ then we have

$$G(t) = c_1 H\left\{\frac{1-exp(-d_1 V)}{V}\right\} \qquad (3)$$

where d_1 is a constant determining the rate of fall of the term $(1 - exp(-d_1 V))$ from 1 to 0.
c_1 is a constant which is the rate of consumption of vegetation by a single herbivore when food is unlimiting. Under such conditions the term $exp(-d_1 V) \to 0$,
which means $1 - exp(-d_1 V)$ approaches unity, and $G(t) \to c_1 \frac{H(t)}{V(t)}$.
The rate of change of the number of herbivores, their consumption rates and the rate at which the vegetation is growing all determine the graph of $G(t)$. That makes it difficult to figure out how the graph of $G(t)$ would look like.

When food (V) is limiting, i.e. $V \rightarrow 0$, the term $1 - exp(- d_1 V) \rightarrow 0$ since the animal struggles to get food. The term $c_1(1 - exp(- d_1 V))$ models the 'functional response' of the animal, i.e. the response of its rate of intake to the availability of food.

It is also important to figure out how $V'(t)$ changes with t. The graph of V against t is somehow 'periodic' over the year. Below is a figure showing how $V'(t)$ could relate with t for the whole year

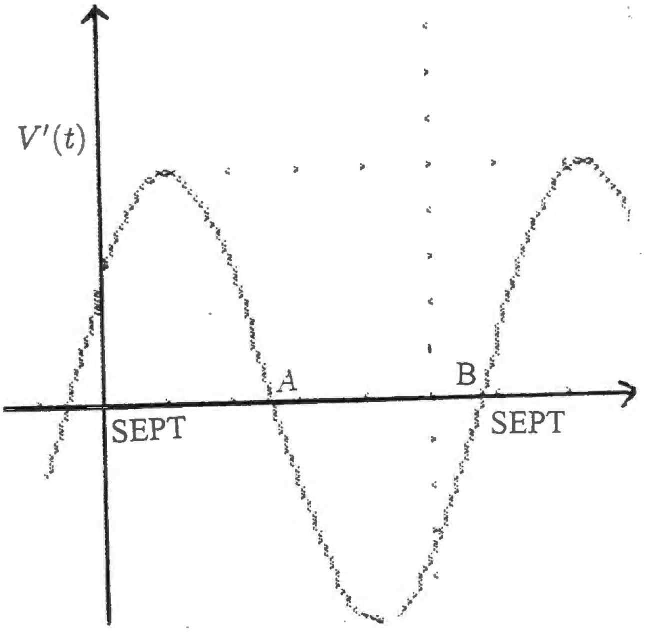


Figure 3.2.1(c): vegetation growth rate dV/dt plotted against time t of the year.

The graph shows that between September and point A (towards winter), $V(t)$ is increasing at an increasing rate in early spring and at a decreasing rate in summer. The graph of $V(t)$ is decreasing between points A and B which is the period starting from autumn. From the graph again $V'(A) = 0$ which means V is a maximum at that time; also $V'(B) = 0$ which denotes the minimum for V and this happens just before the next rainy season (towards end of dry season).

3.2.2 WOODY PLANTS: *POPULATION & GROWTH*

In communal grazing lands there are a variety of species of plants other than grass. Many such species are referred to as woody plants. A Leslie matrix model has been used to account for the population dynamics of these woody vegetation. A woody plant population divided into five age cohorts is assumed. Plants of the same cohort are assumed to be of the same age, and seed dormancy is ignored. A unit time of at least one year would be more suitable for woody plant populations, however, SAVANNAS uses a unit time of 4 months (same as Hacker et al.,1991). This is because the 'life cycle' of grass in semi-arid regions is completed in a time far shorter than a year, and it would thus be difficult to view the interactions between grass and woody plants on a 1 year unit time.

These age cohorts are:

$P_0 = [0,4)$, $P_1 = [4,8)$, $P_2 = [8,12)$, $P_3 = [12,16)$, & $P_4 = [16, 16+n)$

where $P_i = [a,b)$ stands for woody plant population in the age group a months to b months, and n is an element of positive real numbers.

A vector $\vec{X}(t)$ is defined to be $\vec{X}(t) = [x_0(t), x_1(t), \ldots, x_4(t)]$ where $x_i(t)$ is the number of woody plants in age class P_i at time t. The vector $\vec{X}(t)$ defines the age structure of the plant population. The population structure after a time Δt later can be predicted; we begin with an initial vector $\vec{X}(0) = [x_0(0), x_1(0), \ldots, x_4(0)]$ and use the equation

$\vec{X}(t+1) = A\vec{X}(t)$, where A is an $n \times n$ matrix whose entries are given in terms of survival and fecundity rates. Defining S_i to be the probability that a plant in age class P_i survives to age class P_{i+1} four months later, we have

S_0 = probability of a plant surviving from P_0 to P_1 four months later.

S_1 = probability of a plant surviving from P_1 to P_2 four months later.

.

.

S_3 = probability of a plant surviving from P_3 to the last age class four months later.

Obviously, S_i is a function of rainfall, grazing pressure (more especially in younger plants) and competition between plants themselves. SAVANNAS estimates S_i using the equation

$$S_i = K_i\left(\frac{BSMI}{\alpha_i + BGPI}\right)$$

where $BSMI$ is the average soil moisture transpiration index over 4 months.
α_i is a factor that depends on competition and age of plant.
$BGPI$ is the average grazing pressure index over 4 months.
K_i is a factor that determines the magnitude of grazing pressure and availability of moisture in vegetation.

Since the woody plants in communal lands are divided into two, i.e. offspring producing plants and non-producing plants, we define F_k to be the average number of offspring producing seedlings produced by an individual plant in age class P_i, that survive till the end of the four months unit time, then the matrix A is defined:

$$A = \begin{pmatrix} F_0 & F_1 & F_2 & F_3 & F_4 \\ S_0 & 0 & 0 & 0 & 0 \\ 0 & S_1 & 0 & 0 & 0 \\ 0 & 0 & S_2 & 0 & 0 \\ 0 & 0 & 0 & S_3 & 0 \end{pmatrix}$$

so that,

$$x_0(t+1) = F_0x_0(t) + F_1x_1(t) + ... + F_4x_4(t)$$

$$x_1(t+1) = S_0x_0(t)$$

.

.

.

$$x_4(t+1) = S_3x_3(t)$$

F_k is assumed constant over time, so it is density and time independent.
At any particular time t, the population of the woody plants is at most the environmental carrying capacity.

3.2.2a WOODY PLANT GROWTH RATES

Rutherford (1984), working on woody plants in a South African savanna found that the growth of the leaf and twig starts simultaneously; usually before the first rains in September. This early growth he says, is a result of a rapid increase in daily temperature. In SAVANNAS, growth of woody plant components is thus initiated by a rise in daily temperature. He reports a maximum of 1264 kg/ha/a (kilogram per hectare per annum) of leaves and 271 kg/ha/a of twigs reached in early April.

A graph of growth against time for the different plant components is shown in figure 3.2.2 which shows roots being the latest to grow. The graph also shows the rates at which the components grew over the year period.

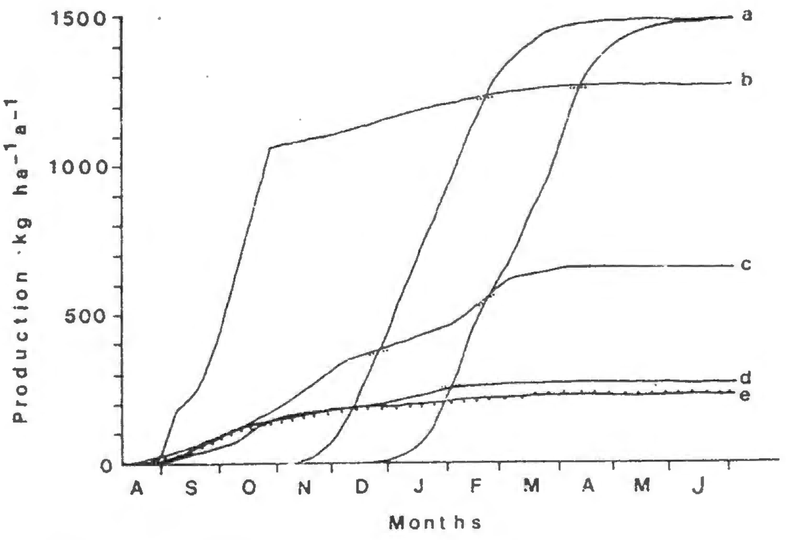


Figure 3.2.2. seasonal production of woody plant components on a savanna site for: *a, thin root (for two separate seasons); b, leaf; c, stem and branches; d, current season's twig; e, thick root* (Rutherford,1984).

SAVANNAS considers only the growth rates of the twig and leaf of the woody plants as these are browsed. Other parts of the plants are not considered since they are not very important for the purpose of this study. Teague (1987) on his work on *Acacia karroo* plants gave values for the relative growth rates of the twig (which he called shoot) and the leaf for 15 day periods through the growing period. Using his data, shown in table 3.2.2 below, a linear regression has been performed to establish approximately the growth rates of the twig and leaf in SAVANNAS. For each of leaf and twig the regression fit is either linear, quadratic or exponential.

Table 3.2.2: values for the relative growth rates of *Acacia karroo* shoot (twig) and leaf at different phenophases (Teague, 1987).

phenophase	shoot (twig)	leaf
1	3.4800	21.510
2	5.2200	23.430
3	5.0750	44.400
4	3.9150	3.696
5	1.4500	2.907
6	0.4350	0.471
7	0.2900	0.549
8	0.2180	0.627
9	0.4060	0.705
10	0.4060	0.780
11	0.2610	0.447
12	0.1310	0.240
13	0.0580	0.051
14	0.0290	-0.024
15	0.0145	-0.126
16	0.0145	-0.201
17	0.0145	-0.213
18	0.0145	-0.246
19	0.0145	-0.426
20	0.0145	-0.474

These growth rates are functions of the plant growth days (τ) and may also be influenced by browsing in the presence of herbivores. The fractional growth rates of the leaves, QrL, are given by:

$$\mathrm{QrL}(\tau) = \begin{cases} Arl \times (\tau)^{Brl} e^{-(Crl)^{\tau}} & 0 < \tau \leq 89 \\ 0.05102 + 0.00514\,\tau & 89 < \tau \leq 142 \\ 6.628\, e^{\,0.0151\,\tau} & 142 < \tau \leq 187 \\ 0.9898 - 0.00502\,\tau & 187 < \tau \leq 292 \\ 0 & otherwise \end{cases}$$

where Arl, Brl and Crl are regression constants.

The fractional growth rates of the twigs, QrS, are given by:

$$\mathrm{QrS}(\tau) = \begin{cases} 2.402 + 0.1856\tau - 0.0030\tau^2 & 0 < \tau \leq 67 \\ 3.404\, exp(0.0176\,\tau) & 67 < \tau \leq 112 \\ 0.0296\, exp(0.0163\,\tau) & 112 < \tau \leq 217 \\ 0.0145/15 & 127 < \tau \leq 292 \\ 0 & otherwise \end{cases}$$

Then the actual growths of the leaves and twigs are given by Teague (1987) as:

$$TSGROW = W \times QrS \times Qtemp \times Qmoist \times Qsoil \times Qage.$$

$$TLGROW = W \times QrL \times Qtemp \times Qmoist \times Qsoil \times Qage \times Qmort.$$

where $TSGROW$ and $TLGROW$ are the growths of the twig and leaf respectively
W is the weight of the shoot (leaves and twigs) of the plant
Qtemp is a temperature multiplier
Qmoist is a moisture multiplier
Qsoil is a soil depth multiplier
Qage is the plant age multiplier
Qmort is the plant leaf mortality multiplier,
and the multipliers are calculated according to the following:

$$Qtemp = \frac{12.5+5.83T_{min}}{100(1+138.399exp(-0.2793T_{max}))}$$

where T_{min} is the mean 15 day minimum temperature
T_{max} is the mean 15 day maximum temperature.

$$Qmoist = \frac{1}{1+0.01669exp(-0.016317+0.00135SD)}$$

where SD is the soil depth (m)

$$Qsoil = 0.70238 + 0.11905SD.$$

$$Qage = a_1 + a_2x + a_3x^2 + a_4y + a_5y^2 + a_6xy + a_7x^2y + a_8xy^2 + a_9x^2y^2$$

where the parameters a_i are as given in the appendix (parameter values),
$x = \frac{height\,of\,plant}{2.8+1.07ln(SD)}$ is called the plant age index,
y is the plant water potential.

$Qmort$ is set at 0.92 which came from experimental results.

3.2.2b INTERACTIONS BETWEEN WOODY AND HERBAGE PLANTS

Since SAVANNAS has both types of vegetation (woody plants and herbage), these are two species-populations. Both types of vegetation make demands on the same limiting resource. In such a case the growth rate of each of the species is inhibited by members both of its own and of the other species (Pielou,1977). If we denote by N_i the number (in case of woody plants) or the biomass (in case of herbage) of individuals in species i for $i = 1, 2$ then the competition between these two vegetation species can be modelled using Lotka-Volterra 's equations for two competing populations. These equations are an extension of the logistic equations for single species.

$$\frac{dN_1}{dt} = r_1 N_1 [1 - \frac{N_1 + \alpha_{12} N_2}{K_1}] \tag{4}$$

$$\frac{dN_2}{dt} = r_2 N_2 [1 - \frac{N_2 + \alpha_{21} N_1}{K_2}] \tag{5}$$

where $N_1 = N_1(t)$ is the woody plant population,

$N_2 = N_2(t)$ is the grass biomass.

r_1 and r_2 are the intrinsic growth rates of the two populations.

K_1 and K_2 are the carrying capacities.

α_{ij} is the corresponding coefficient for the effect of species j on species i.
In a grazing system the effects of one species on the other may not only depend on season and moisture but also on grazing pressure and the type of herbivore. For instance, in the presence of many goats and no cattle most of the bush leaves and twigs are cleared thus giving grass access to sunlight. Also in the presence of a big number of cattle and no goats, woody plant seedlings are able to fare well since the competition they get from grass becomes minimal.

This may mean that α_{ij} should in fact be a variable coefficient, but for simplicity SAVANNAS treats it as a constant. Also, for the above equations to work hand in hand N_1 and N_2 must have the same units, thus SAVANNAS converts N_2 from biomass into plant numbers by estimating that 1 g/m^2 of shoot is equivalent to 0.3 plants/m^2. Equation (5) is similar to equation (1) but it has an extra term for the competition effects between woody plants and grass.

3.3 PLANT-ANIMAL INTERACTIONS & THEIR RESPONSES

It is of interest to consider the mathematics of the herbivore-vegetation relationship closely. This is a special case of the host-parasite interaction in the sense that the herbivore survives strictly on the vegetation but does not "kill" it unless herbivore numbers are excessive. On the other hand the vegetation would obviously fare better in the absence of the herbivore. Roughly speaking it can be said that the herbivore is parasite and the vegetation is host. The type of grazing system is an interactive one, where the rate at which the herbivores are increasing/decreasing is a function of plant density, and the rate of change of plants is a function of herbivore density. However, it is worth noting though that the herbivore-vegetation relationship cannot be boldly defined exactly by the host-parasite models since vegetation "benefits" from herbivory to some extent. As mentioned in the review, herbivores promote seed germination, seed dispersal and even improve soil fertility. Also, moderate defoliation can stimulate tree leaf growth (Teague,1987), but heavy defoliation reduces it. McNaughton (1977) reports that grasses are also stimulated by moderate defoliation. Thus the host-parasite models need to be modified to cater for this fact. In the past, the Lotka-Volterra equations have been used for host-parasite models, and they are summed up in the following pair of quadratic differential equations (Pielou,1977):

$$\frac{dH}{dt} = (a_1 - b_1 P)\,H$$

$$\frac{dP}{dt} = (-a_2 + b_2 H)\,P$$

where H and P stand for host and parasite respectively,
a_i and $b_i > 0 \qquad i = 1, 2.$

a_1 is the net growth rate of the host species in the absence of the parasite, diminished by an amount $b_1 p$ of the parasite.

a_2 is the net growth rate of the parasite in the absence of the host and this is improved by an amount $b_2 H$ of the hosts. For the vegetation-herbivore model we shall denote vegetation by V and herbivore by H. The equations become :

$$\frac{dV}{dt} = [a_0(1 + \frac{1}{b^H}) - b_1 H]\,V \qquad (6)$$

$$\frac{dH}{dt} = (-a_2 + b_2 V)\,H \qquad (7)$$

where the term $\frac{1}{b^H}$ caters for the benefits that plants get from herbivory.

b is a parameter $(0 < b < 1)$ that depends on the season of the year (i.e. proportional to vegetation biomass).

In the absence of herbivores

$$\frac{dV}{dt} = 2a_0 V$$
$$= a_1 V \quad \text{(say)}$$

Equation (6) shows that the growth rate of the vegetation is increased by herbivory, i.e. the term

$a_0(1 + \frac{1}{bH})$ gets bigger with increasing H.

SAVANNAS focuses mainly on shoot, and it is to be seen whether herbivores shall bring the sort of behaviour (on shoot) associated with (6).

Figure 3.3(a) below illustrates how $\frac{dV}{dt}$ changes for ungrazed vegetation, and how different stocking rates affect vegetation loss. Unlike the pastures in semi-arid regions, the figure below is a representation of a continually growing pasture where animals can feed at the same rate as the vegetation is produced.

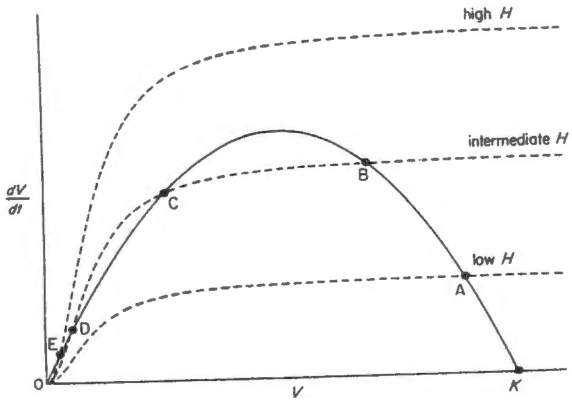


Figure 3.3(a): vegetation growth rate dV/dt plotted against V. Dotted lines are the rates of removal of vegetation under different grazing pressures. May (1977).

The solid curve is the natural growth rate of the vegetation (not grazed). The dashed curves are loss rates due to grazing. Where the solid curve lies above the dashed one, the net growth rate is positive; where the solid curve lies below the dashed one, the net growth rate is negative (May,1981). At low H the net growth rate is always positive. At intermediate H the net growth rate is positive at very low V (before point D) .

Apart from looking at the growth rate $\frac{dV}{dt}$, it is also necessary to look at the vegetation biomass (V) with changes in herbivore numbers. One of the properties of the vegetation-herbivore model is that it is oscillatory in the sense that high vegetation biomass tends to produce high herbivore numbers, which then depress vegetation biomass leading to lower herbivore numbers and so on. This is represented well in figure 3.3(b) below

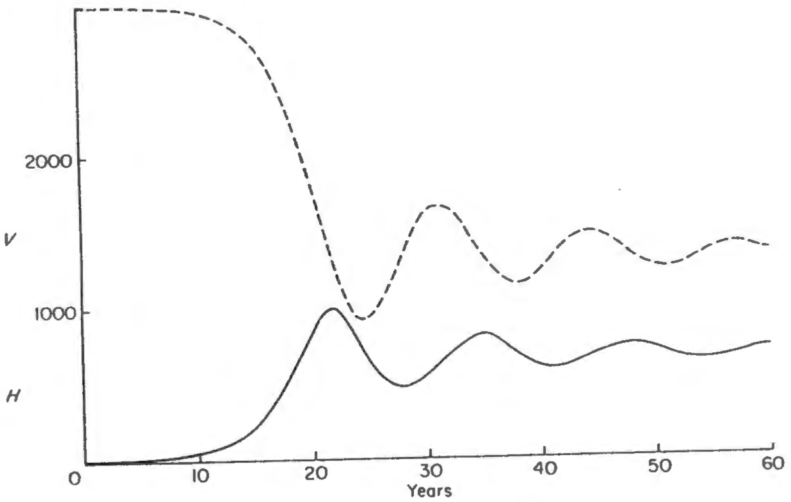


Figure 3.3(b): trend of vegetation (V) and herbivores (H) over time, (Caughley and Lawton,1981)

In SAVANNAS the picture given by the above figure is viewed in terms of conception rates but within one rainfall year. An increase in the number of herbivores per given period lowers the vegetation biomass which then affects the conception rates (section 4.3). Following a "crash" in animal populations the vegetation stands a better chance of revival.

Equation (7) can be modified by replacing V by $1 - e^{-d_2 V}$ which is the functional response of the herbivore. The equation now becomes:

$$\frac{dH}{dt} = (-a_2 + b_2[1 - e^{-d_2 V}])H \qquad (8)$$

where $d_2 =$ demographic efficiency of the herbivore; its ability to multiply when vegetation is sparce.
This equation (8) is given by May (1976). He says the herbivores can increase at a maximum rate of $-a_2 + b_2[1 - e^{-d_2 V}]$, which in most cicumstances will equal their intrinsic rate of increase. In SAVANNAS equation (8) is estimated by

$$\frac{dH}{dt} = [-a_2 + b_2 f(V)]H \qquad (8^*)$$

where $f(V)$ is defined in the next section.

Apart from using the above, animal reproduction can be measured in terms of mortality and conception rates (F.D. Richardson, Cape Town,1999, personal communication). We define the cumulative mortality rate as

$$\frac{d(mort)}{dt} = cd1 + cd2(cd3 - bc)$$

where $cd1$ is the basal mortality rate per day irrespective of conditions
$cd2$ is a parameter
$cd3$ is a parameter that defines the critical body condition below which the probability of mortality increases

bc is the body condition of the animal, which is the ratio of present weight to either the previous peak weight or standard reference weight for an animal of a given age. i.e.

$$bc = \frac{animal\,weight}{\text{peak}\ weight}$$

and we define the average daily conception rate (CR) by the equation

$$CR = -0.064286 + 0.122381bc - 0.0471428(bc)^2 + br + (8 + 21\tfrac{dW}{dt})^{0.002038}$$

where br is the animal breed, set at 0 for British cattle and at 0.0029047 for indigenous African cattle.

$\frac{dW}{dt}$ is the weight change of the animal (section 3.4.3)

If $\frac{dW}{dt} < -0.381$ (i.e. animal losing more than 0.381 kg/day) then $CR = 0$.

3.4 LIVESTOCK MODEL

Roughly classified as grazers and browsers, cattle and goats respectively can be said to be competing for the same food source since each one of them uses both types of vegetation.

If we take V to define vegetation biomass, then basically $\frac{dV}{dt}$ is the difference between the rate of new growth and the rate at which the vegetation decays. This can be put in the equation below (as given by Starfield and Bleloch,1986)

$$\frac{dV}{dt} = a - pV \tag{9}$$

which shows that the decay rate depends on V. Introducing herbivory would mean equation (9) becomes

$$\frac{dV}{dt} = a - pV - qH(t) \tag{10}$$

where $H(t)$ is the herbivore population at time t.
q is the rate of feed intake by each herbivore.

It is also true that the rate at which a herbivore eats shall always depend on the state of the vegetation. At low V the consumption rate drops, at high V the rate is high. Also, it is worth noting that different herbivore species respond differently to vegetation conditions. For instance, goats would do well when the grass is shorter since they are able to move freely in search for browse, whereas cattle would do well when the grass is abundant. This means q shall depend on V and on the type of herbivore. An account of this shall be given by defining a function $0 \leq f(V) \leq 1$ called the functional response of the herbivore to the state of the vegetation.When $V = 0,\ f(V) = 0$. It can be said that the consumption rate of each herbivore is $qf(V)$. By Starfield and Bleloch (1986) equation (10) then becomes

$$\frac{dV}{dt} = a - pV - qf(V)H(t) \tag{11}$$

where $H(t)$ is livestock units (see section 3.4.4) of both cattle and goats.
Since there are two types of herbivores in our system, and the functional response varies from herbivore species to another, then equation (11) becomes

$$\frac{dV}{dt} = a - pV - qh(V)H_1(t) - rf(V)H_2(t) \tag{12}$$

where $f(V)$ and $h(V)$ are the functional responses of the cow and goat respectively and they shall depend on such things such as energy intake.
$H_1(t)$ and $H_2(t)$ are the populations of goats and cattle respectively.

SAVANNAS estimates $f(V)$ and $h(V)$ as :

$$f(V) = \begin{cases} 0 & V = 0 \\ 1 - a_j^{qdiet} & otherwise \end{cases}$$

$$h(V) = \begin{cases} 0 & V = 0 \\ 1 - a_j^{qgtdiet} & otherwise \end{cases}$$

where $qdiet$ and $qgtdiet$ are the fractions of gross energy metabolisable in a cow and a goat respectively. Both $qdiet$ and $qgtdiet$ are functions of the proportions of plant components in the animal's diet, which (plant components) in turn are functions of V. $0 < a_j < 1$ depends on the season of the year.
For smaller values of a_j, both $f(V)$ and $h(V) \to 1$ faster for fixed $qdiet$ and $qgtdiet$ respectively.

This is a non-equilibrium system, where one year of low rainfall can limit reproduction and survival (of animals) irrespective of the abundance of resources in other periods (Behnke and Scoones,1993). In some years the vegetation grows more than what the animals need, whereas in some there is so little vegetation that the animals would fall short of their requirements causing reproduction to go down. They (Behnke and Scoones) report that in this kind of a system the physical conditions supporting plant growth vary widely and the consumption by herbivores does not control plant biomass.

3.4.1 ANIMAL DIET AND DIET SELECTION

Both types of animals have preferences when it comes to diet. Given the availability of a vast plant species in community, animals prefer high quality food. A diet selection model (MIAMH) of Genin and Quiroz (1992) is used for the goat. The model of Orsini (1990) is used for the diet selection of the cow. This model (Orsini,1990) is good for use for animals (bulk grazers) which do not exercise a high degree of selection in diet, just like cattle, which explains why it was not used for the goats. According to Orsini, an estimate of each plant component in the diet of the animal is given by:

$$Fr(i)di = Fr(i)\left\{\frac{pref(i)}{\sum_i pref(i)\times Fr(i)}\right\}$$

where $Fr(i)di$ is the fraction of plant component (i) in the diet.

$Fr(i) = i/shoot$, is the fraction of plant component i per given plant shoot.

$pref(i)$ is the preference of plant component i by the animal.

On the other hand, MIAMH calculates the bite size of the animal (goat) on each type of vegetation. The bite of each plant species is given as

$$biteF = bbite \times ln(\sum Fi) - abite$$

Where F can be grass or woody vegetation.

Fi is a component of F edible.

$bbite$ is the size of the bite

$abite$ is a parameter

Instead of preferences, it (MIAMH) looks at quality index

$$QI(i) = \frac{crude\,protein\,content\,of\,bite}{lignin\,content\,of\,bite}$$

where $QI(i)$ is the quality index of the bite of component i.

$$crude\,protein\,content\,of\,bite = \sum_i cp(i) \times Fr(i)$$

$$lignin\,content\,of\,bite = \sum_i lig(i) \times Fr(i),$$

and $cp(i)$ and $lig(i)$ are the crude protein and lignin contents respectively of plant component i. They are both calculated as linear functions of plant growth days.

SAVANNAS calculates the potential alimentary capacity, $PAC(j)$ of each plant species as :

$$PAC(j) = R^{\frac{1}{s}}(j) \times P_j \times B_j \times QI^s(i) \qquad (13)$$

where $R(j)$ is the relative abundance of species j, also defined as

$$R(j) = \frac{x_j}{total\,food\,available}$$

where x_j is the amount of species j in g/m^2.

$s = \frac{minimum\, required\, protein\, content\, in\, diet}{mean\, protein\, content\, of\, vegetation}$, and it is called the selection index of the goat.
B_j is the mass of dry matter in one average bite of species j.
P_j is the proportion of leaf in a bite of species j.

From equation (13) is defined the theoretical contribution of species j to the diet,
$TCD_j = \frac{PAC(j)}{\sum_j PAC(j)}$
MIAMH has been extended to calculate the fraction of each plant component in the diet of the goat using the equation:

$$gfr(i)di = int(i)/eatDMI$$

where $gfr(i)di$ is the fraction of plant component (i) in diet of the goat
$int(i)$ is the intake of component (i) by the goat
$eatDMI = \sum int(i)$

3.4.2 MECHANISMS CONTROLLING INTAKE:

Vegetation condition and time spent in grazing are the main factors affecting intake in animals. Illius & Gordon (1987) illustrated though that other than these factors, the incisor arcade breadth of an animal does affect intake. The capacity of an animal to digest food is yet another factor affecting intake. Discussed below are the two mechanisms controlling intake.

i) ***VEGETATION DENSITY***

There exist some degree of proportionality between vegetation density, bite size and intake. Bite size can be said to be a function of the degree of maturity of an animal, and yet it differs with different animal species.

Taylor , Murray and Illius (1987) predicted the maximum eating rate (r_{max}) of an animal in kilojoules metabolisable energy per minute (KJ ME/min) , using the equation:

$$r_{max} = 31\,u^{0.86} A^{0.73}$$

where u is the degree of maturity in body weight of the animal.
A is the mature body weight of an animal

This equation predicts eating rates for normally growing animals, which means it cannot work for animals in semi-arid regions where plant growth depends on the unreliable rainfall. In such areas intake is limited by the biting rate and the bite size of the animal, thus DMI can be estimated by an equation which is a function of the incisor arcade breadth (D). Illius and Gordon (1987) gave the equation:

$$D_{it} = 7.8\,u_{it}^{0.29} A_i^{0.36} \qquad (14)$$

where D_{it} is the incisor arcade breadth (mm) of animal species i at age t.
u_{it} is the degree of maturity in body weight of animal species i at age t.

The arcade breadth does not decrease even if the animal weight does, and SAVANNAS is formulated accordingly.

Putting $u_{it} = \frac{w_{it}}{A_i}$ in (14) gives

$$D_{it} = 7.8\,w_{it}^{0.29} A_i^{0.07}$$

where w_{it} is the present body weight of the animal.

SAVANNAS estimates DMI by the equation:

$$BIDMI = maxbite \times bbite \times D_{it} \times ADjDM$$

where $BIDMI$ is the dry matter intake limited by the bite size.
$maxbite$ is the maximum number of bites/day taken by the animal species i.

$ADJDM$ is an adjustment factor for herbage density.
$bbite$ is the amount eaten per mm of arcade when herbage density does not limit intake.

ii) ***FEED DIGESTIBILITY:***

Maximum faecal output (F) can be used as a measure of the amount of indigestible material that can be excreted per day, which then controls intake. It is a function of present body weight of an animal and is given by (using the approach of Butterfield, 1988):

$$\frac{dF}{dt} = [qDMI \times xwt + (1 - qDMI) \times xwt^2]FDM_{mat}$$

where $xwt = weight/wmax$
$wmax$ is the maximum possible weight of the animal
FDM_{mat} is the faecal dry matter output of a mature animal
$qDMI$ is the maturity coefficient of faecal dry matter output and $2 < qDMI < 3$.

The intake (I) rate of the animal is then defined as

$$\frac{dI}{dt} = \frac{dF}{dt}(1 - \frac{qdiet}{0.82})$$

where $qdiet$ is the fraction of gross energy metabolisable in the animal,
0.82 is the metabolisable energy as a fraction of digestible energy.

From the two above mechanisms , the actual intake by the animal is given by the least of the two mechanisms.
Intake of each plant component by an individual of a species multiplied by the number of individuals per hectare gives the rate of removal of each component of the vegetation.

3.4.3 ANIMAL ENERGY BALANCE

The relationship between the rate of feed intake by a growing ruminant and the rate at which it retains energy in its body is curvilinear. Successive increments of daily intake result in progressively smaller increments in daily energy retention (Blaxter & Boyne,1978).
If we take R' to be the rate of energy retention of an animal in KJ/day and G' to be the rate at which it ingests feed energy in KJ/day, then according to Blaxter & Boyne,

$\frac{dR'}{dG'} = p'\,(A - R')$
where A is the maximal attainable rate of energy retention.
p' is a constant.
This equation can be integrated to give

$$R' = A - B'(exp(- p'G')) \qquad (15)$$

where B' is a constant of integration. Asymptotically $R' \rightarrow A$.
For $G' = 0, \quad R' = A - B' = - H_b$
and H_b is the rate of fasting metabolism.

Putting $A = - H_b + B'$ in equation (15) gives

$$\frac{R'}{H_b} = \frac{B'}{H_b}\left\{1 - exp(p'G')\right\} - \frac{H_b}{H_b}$$

$$\Rightarrow R = B(1 - exp(- pG)) - 1 \qquad (16)$$

which is the energy balance equation used in SAVANNAS. R and G are energy retention and gross energy intake respectively, both are scaled by fasting metabolism, H_b. B is a multiple of fasting metabolism. G is related to the scaled metabolisable energy (M) by the equation:

$$G = \frac{M-c}{b} \qquad (17)$$

where b and c are regression coefficients. This means (16) can be written as:

$$R = B(1 - exp(-p\ \tfrac{(M-c)}{b})) - 1.$$

in (16), if $R = 0$ then

$$G = \frac{1}{p}\,ln(\frac{B}{B-1}) = G_m$$

where G_m is the gross energy for maintenance; i.e. the amount of feed energy that result in zero energy retention. Putting G_m in (17) gives

$G_m = \frac{M_m - c}{b} = \frac{1}{E_{GM}}$
where M_m is the metabolisable energy for maintenence.

E_{GM} is the efficiency of utilisation of gross energy for maintenence.

A ratio of G_m and M_m gives the metabolisability of the gross energy of the diet measured at maintenence, $qdiet$. i.e.

$\frac{G_m}{M_m} = qdiet.$

E_{GM} is related to both B and p of (16) in that

$B = \frac{E_{GM}}{E_{GM} - E_{Gf}}$

$p = E_{GM}\, ln(\frac{E_{GM}}{E_{Gf}})$

where E_{Gf} is the efficiency of gross energy for production, and is given by

$E_{Gf} = \frac{B-1}{BG_m}$ (Blaxter and Boyne,1978).

SAVANNAS uses the weight (W) change equation

$\frac{dW}{dt} = \frac{R}{ECG}$ derived from ARC (1980),

where $ECG = 39.3 \times FCG + 23.6 \times PCG,$

FCG and PCG are the fat and protein contents of the gain which are functions of weight. These are estimated using the equations of Butterfield (1988).

$PCG = apW^{bp}$

$FCG = afW^{bf}$

where ap, bp, af and bf are all parameters.

3.4.4 LIVESTOCK UNITS

Different species and sizes of animals have different eating capabilities. This would mean that animal numbers alone do not adequately describe the influence of the animal on the grazing and vice versa (Tainton, 1988). A goat being a lighter animal would obviously trample less and eat less than a cow. It is for this reason that for comparative purposes between animal species a standard animal unit be defined. To define an animal unit, a 500 kg steer is taken as a basic unit. All other animals are related to this unit using the equation (Tainton, 1988):

$Lu = \frac{m^{0.75}}{500^{0.75}}$ where m is the weight of an animal.
Lu is livestock unit.
500 is the mature weight of a standard steer.

For instance, the 30 kg young goat in SAVANNAS constitutes 0.121 Lu, whereas the 250 kg cow constitutes 0.595 Lu. Below is a graphical representation of the relationship.

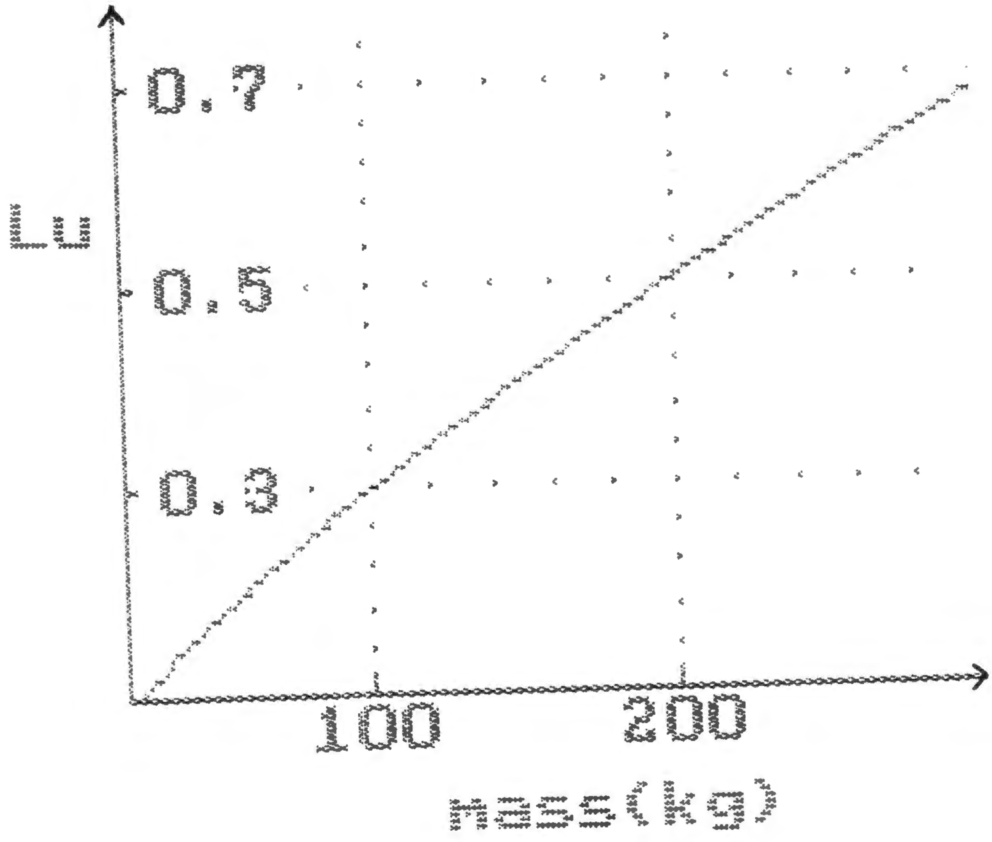


Figure 3.4.4: Livestock units (Lu) plotted against animal weight (mass).

CHAPTER 4

MODEL EVALUATION

For a description of SAVANNAS refer to section A1 of the appendix.
The predictions of SAVANNAS are categorised into the following main sections:

4.1) Plant production
4.2) Effects of herbivory on vegetation
  i) cattle effects
  ii) goats effects
4.3) Animal production
  i) in terms of animal weight
  ii) in terms of animal numbers and/or conception rates

The evaluation of each section is detailed below:
NB: Our year starts on September 1st (i.e. day 1 is the 1st of September).

4.1) PLANT PRODUCTION

Since changes in the weight of shoot can be used as a major index of plant productivity, it has been used for both types of vegetation. The performances of grass shoot (called **shoot**) and woody plant shoot **(tshoot)** have been evaluated under different conditions. Both shoot and tshoot are compound variables, i.e. every part of the plant above ground. Although herbivory is considered separately, there is a standard number of herbivores (0.1 cows/ha & 0.1 goats/ha, together equalling 0.0716 Lu/ha) in SAVANNAS. This population (0.0716 Lu/ha) has a negligible effect on the vegetation. **All results unless stated otherwise, have been performed under these standard grazing conditions.**

The distribution of the rainfall for the three different years 1980/81, 1981/82 and 1982/83 is shown in figure 4.1.0 below. The rainfall data files are given in the appendix.

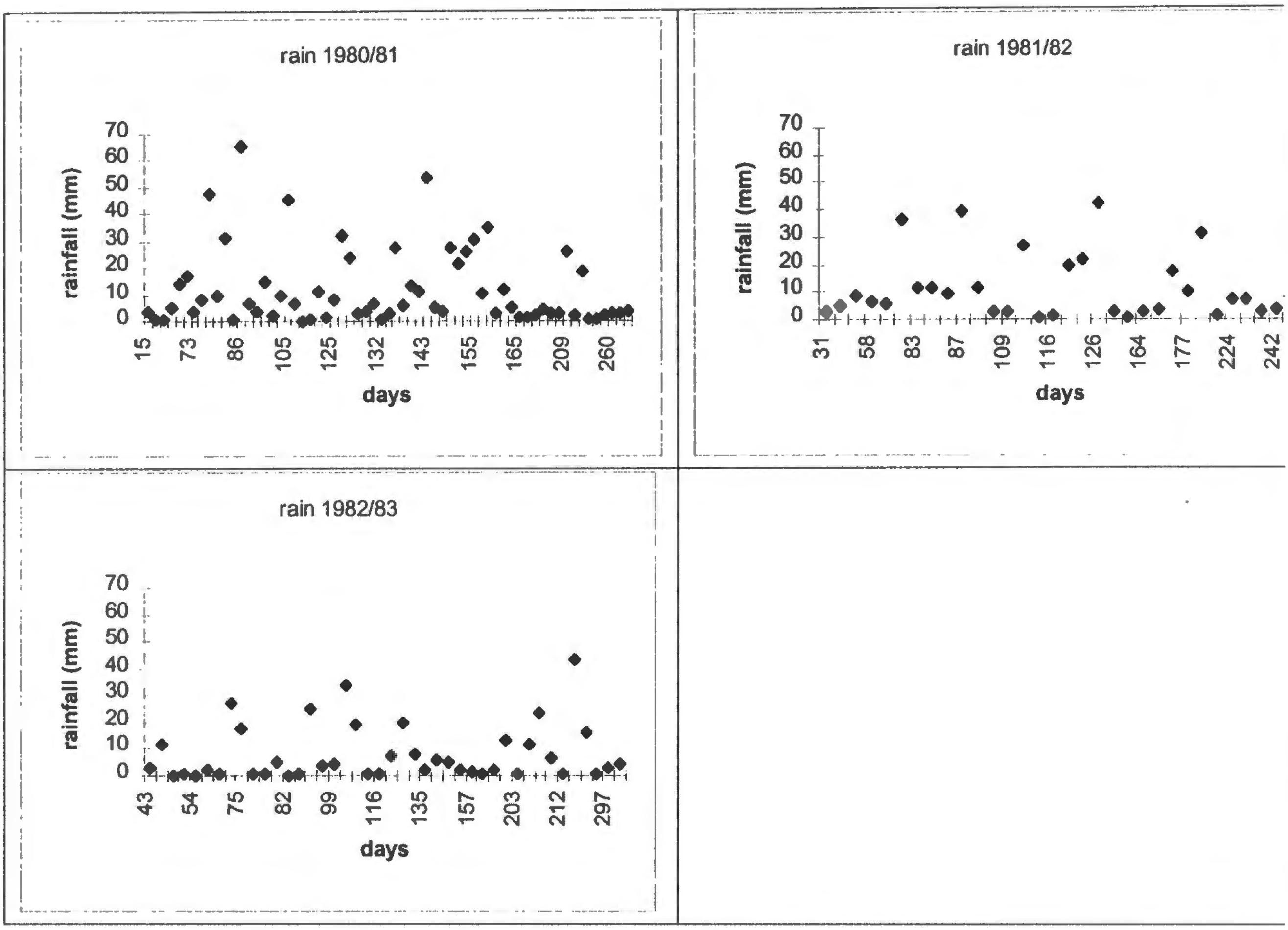


Figure 4.1.0: rainfall distribution for the three different years 1980/81, 1981/82 and 1982/83.

Total rainfall during the year is the major factor influencing both shoot and tshoot production, figures 4.1.1, 4.1.2 and 4.1.3 . However, timing of rainfall (or distribution over the seasons) is also important, figure 4.1.4.

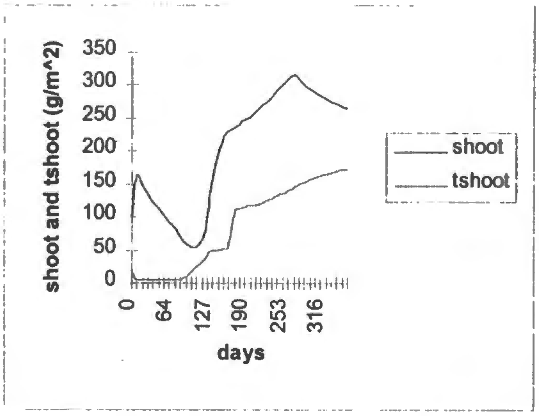


Figure 4.1.1: vegetation (shoot and tshoot) plotted against time for the 1980/81 rainfall year.

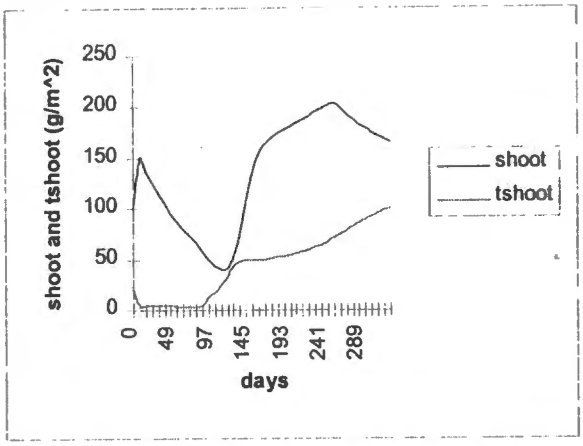


Figure 4.1.2: vegetation (shoot and tshoot) plotted against time for the 1981/82 rainfall year.

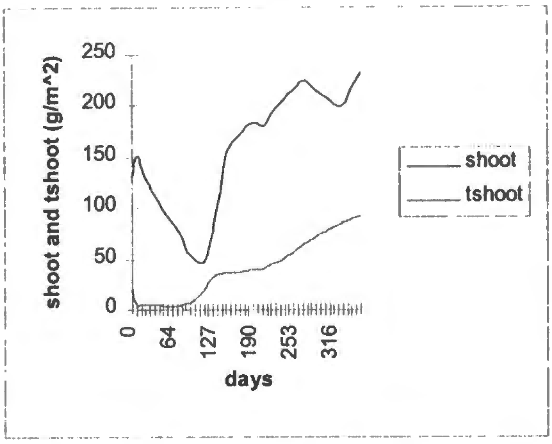


Figure 4.1.3: vegetation (shoot and tshoot) plotted against time for the 1982/83 rainfall year.

initial values of plant components:

old dead grass leaf -95 g/m^2
dead culm - 12.43
dead grass leaf - 60
culm - 0.001
grass inflorescence - 0
grass green leaf - 0.12

dead woody plant inflorescence - 2.3
dead twig - 5
stem - 0.002
woody plant inflorescence - 0
twig - 0.01
woody plant leaf - 0.023
woody plant dead leaf -30

For the early rainfall of 1980/81 , the shoot growth is earlier than the shoot growth of the year 1981/82 , figure 4.1.4.

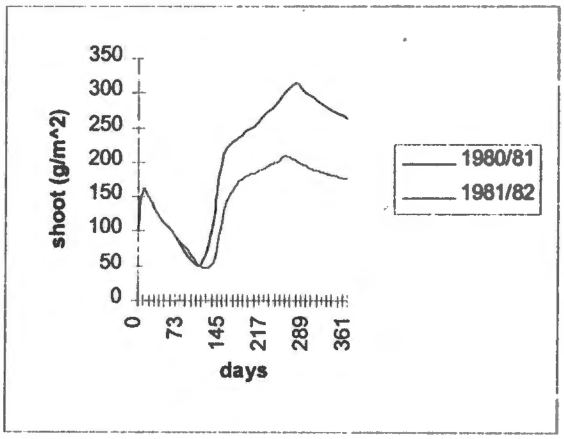


Figure 4.1.4: vegetation (shoot) plotted against time for two different rainfall years 1980/81 and 1981/82.

Also, the figure clearly illustrates the effects of amount of rain. For the good rainfall **(758.9 mm)** of 1980/81 there is more than 300 g/m^2 of shoot at some time, a margin ahead of the shoots of the low rainfalls **(366.6 mm)** of 1981/82 and **(338 mm)** of 1982/83.

An early rainfall does not necessarily mean early growth, but the determining factor is the amount of the rainfall, fig. 4.1.5 . In 1981/82 the rainfall is earlier than that of 1982/83 but growth is earlier in the latter.

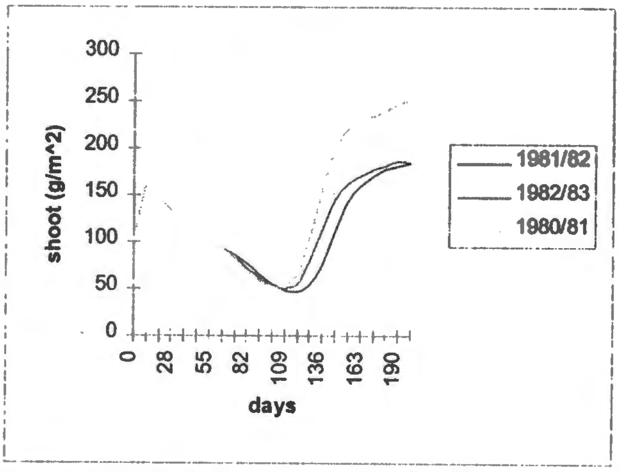


Figure 4.1.5: vegetation plotted against time for three different rainfall years 1980/81, 1981/82 and 1982/83.

As expected, towards the end of the year in both years 1980/81 and 1981/82 the shoot shows a decline. In the year 1982/83, however, SAVANNAS predicts an unexpected further growth in shoot just after the start of the expected decline , fig. 4.1.3 . The late rains of day 213 and 214 which sum to 59.80 mm might be the reason behind this late growth. Besides this 59.8 mm of rain, one other reason might be the consistency of rains after day 200 in this particular year. In his work on semi-arid induced grassland, Dye (1983) reports this type of shoot growth for the year 1982/83. SAVANNAS shows an extensive amount of tshoot for the year 1980/81 as compared with other years. There is a visible relationship between tshoot and rainfall in the early stages of the year. Towards the end of the year, however, instead of an expected

decline in the amount of tshoot, there is a continued increase which is rather at a smaller rate than before. Looking at Rutherford's (1984) results again, one can say this prediction of SAVANNAS is fair in the sense that he reports no decline in leaf, twig and stem towards end of year, figure 3.2.2. Also, looking at the graphs of Teague (1987) for grams of shoot in a 100mm width of shoot against 15 day periods, it is seen that there is no decline in shoot (tshoot) anywhere in the year.
The results of SAVANNAS do not show any clear relationship between shoot and tshoot.

The effects of different years of rainfall on woody plant populations (tpopt) have been predicted. SAVANNAS has been run for 800 days to establish population behaviour, figures 4.1.6(a)-4.1.6(c). For the 800 days, rainfall 1980/81, 1981/82 and 1982/83 are used for the results of figures 4.1.6(a), 4.1.6(b) and 4.1.6(c) respectively. Here it is assumed that a single rainfall prevails for the 800 days (i.e. a given year's rainfall is used consecutively year after year).

NB: - these were predicted with 1 cow and 2 goats per ha.
- dayz is a variable equal to days, but it does not reset to 0 at end of year.

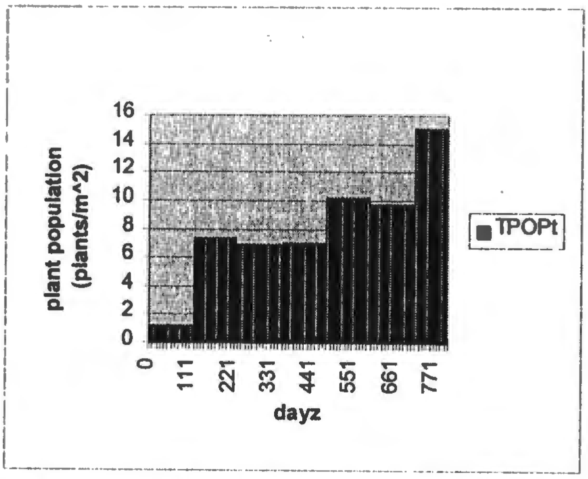


Figure 4.1.6(a): population of woody plants plotted against time for the rainfall year 1980/81. The changes in plant population are discrete because the population of the plants is evaluated every 120 days (section 3.2.2).

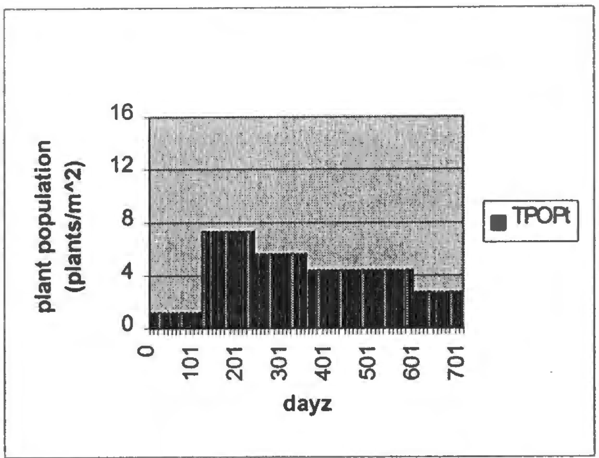


Figure 4.1.6(b): population of woody plants plotted against time for the rainfall year 1981/82.

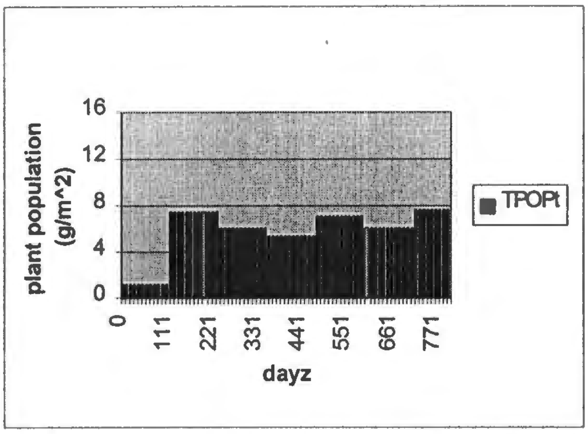


Figure 4.1.6(c): population of woody plants plotted against time for the rainfall year 1982/83.

The results show a bigger population of plants/m^2 for the 1980/81 year and a somewhat bad production for the 1981/82 rainfall year. Obviously, these results suggest that woody plant establishment is directly proportional to rainfall. Since the population is bigger for 1982/83 (338 mm rainfall) than 1981/82 (366.6 mm rainfall) it suggests that a good distribution of rainfall is a plus factor in the establishment of seedlings.

The effects of the population of woody plants on grass may not be that visible. It has been found that these two vegetation species are interdependent, figure 4.1.7 . This interdependency is not otherwise seen in the dry season (before and after the rains). For instance a decline in grass biomass before the rains would not affect woody plants. Later in the year, however, a small rise in grass biomass (just before day 253) corresponds to a decline in woody plants. As expected woody vegetation is more stable than grass in that there is no observed decline in its population during the dry season as it is with grass.

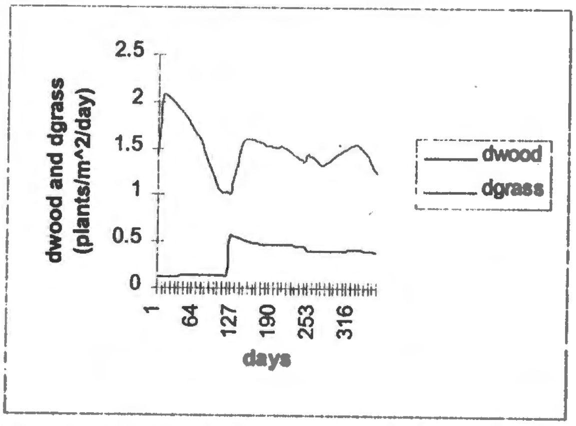


Figure 4.1.7: Rate of change in woody plants biomass (dwood) plotted alongside the rate of change in grass biomass (dgrass) for the year 1982/83.

4.2) *EFFECTS OF HERBIVORY ON VEGETATION*

i) It is expected that with two herbivores of distinctive feeding characteristics in the system, their effects on each type of vegetation may differ.
A prediction of the behaviour of shoot under different grazing pressures and at different times of the year is shown, Figures 4.2.1 and 4.2.2 . The same results are also shown on table 4.2.1 and table 4.2.2 correspondingly.

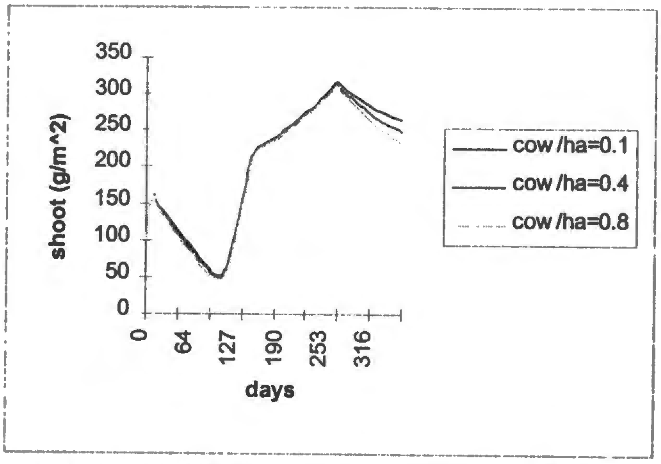


Figure 4.2.1: shoot under different grazing pressures (1980/81). cow/ha stands for the number of cows per ha.

Table 4.2.1: 1980/81 (corresponding to fig. 4.2.1)
shoot1, shoot2 and shoot3 are the amounts of shoot when there are 0.1, 0.4 and 0.8 cows/ha respectively. Goats are fixed at 0.1 per ha (section 4.1).

days	shoot1	shoot2	shoot3
0	100.00	100.00	100.00
31	129.62	127.61	124.94
61	95.398	91.989	87.483
91	58.283	55.109	51.214
121	74.888	72.871	70.491
151	214	212.6	210.96
181	239.26	238.19	236.95
211	261.42	260.39	259.16
241	287.69	286.41	284.85
271	314.95	313.07	310.69
301	290.71	284.89	277.31
331	272.8	263.76	252.01
361	259.48	247.71	232.64

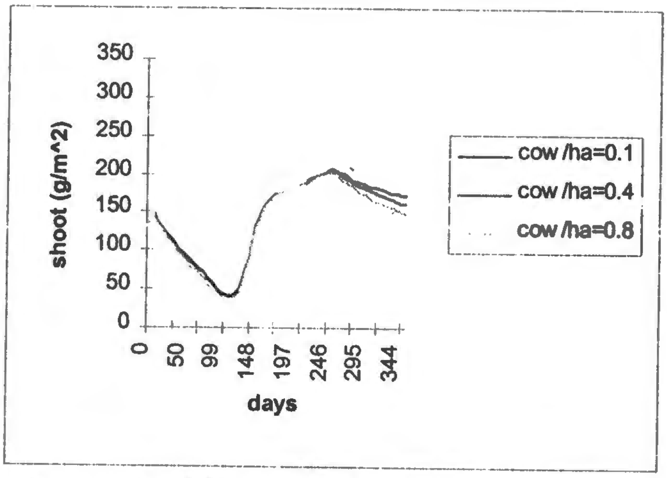
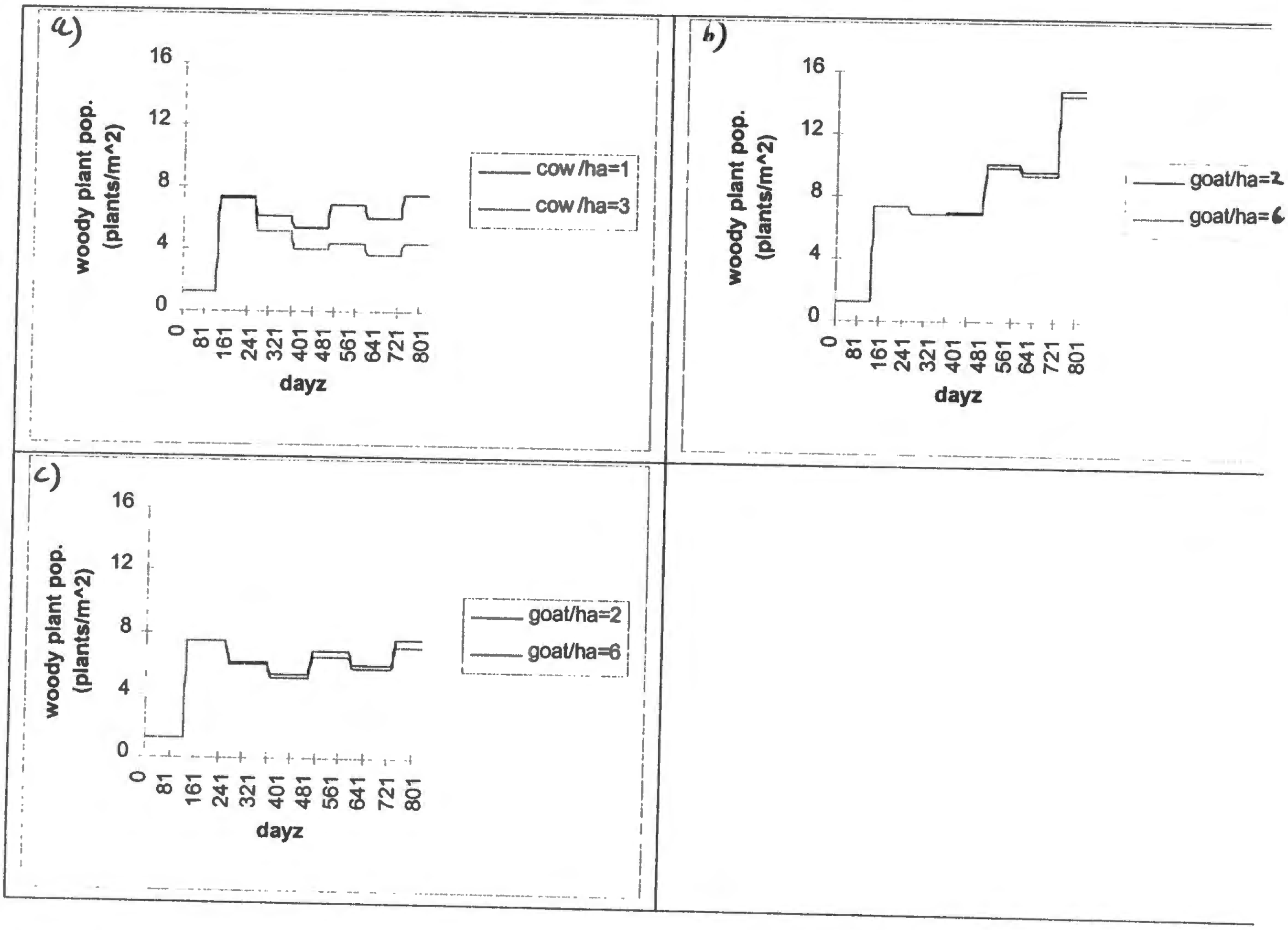


Figure 4.2.2: shoot under different grazing pressures (1981/82).

Table 4.2.2: 1981/82 (corresponding to fig. 4.2.2)

days	**shoot1**	**shoot2**	**shoot3**
0	100.00	100.00	100.00
26	125.89	124.27	122.12
51	97.54	94.728	91.005
76	75.492	71.908	67.404
101	49.831	46.909	43.447
126	48.071	46.123	43.872
151	131.03	129.68	128.12
176	171.38	170.43	169.34
201	183.19	182.32	181.31
226	193.68	192.72	191.58
251	205.56	204.10	202.18
276	197.75	193.72	188.56
301	187.41	180.89	172.55
326	179.39	170.83	160.14
351	173.14	162.91	151.39

The results show that increasing the number of cattle per hectare would have a visible effect on the shoot before and after the rains.
A closer look at figures 4.2.1 and 4.2.2 shows that the effects of animals are negligible over the growing season. This corresponds to that particular time of the season when the growth rate of the shoot is high. SAVANNAS further predicts that apart from affecting the amount of shoot, herbivores do affect the populations of woody plants. The results show that increasing cattle numbers (figure 4.2.3(a), see overleaf) would suppress woody plant populations.



Figures 4.2.3 (a), (b), (c): woody plant population under varying grazing pressures for the years 1982/83, 1980/81 and 1982/83 respectively.

ii) Goats on the other hand, are predicted to have very little effect on shoot, figure 4.2.4(a) , figure 4.2.4(b).

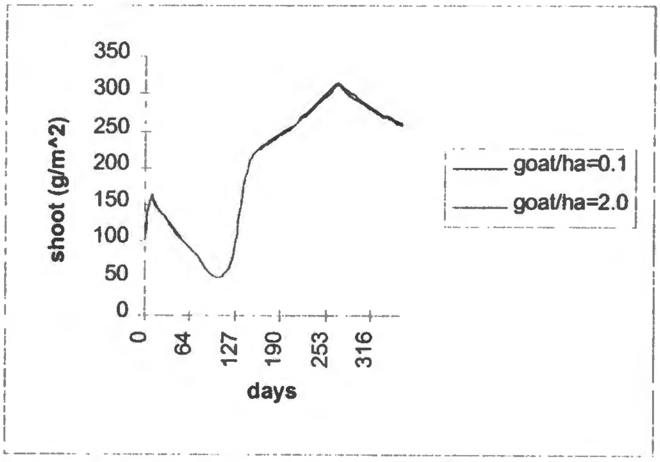


Figure 4.2.4(a): effects of goats on shoot during the year 1980/81.

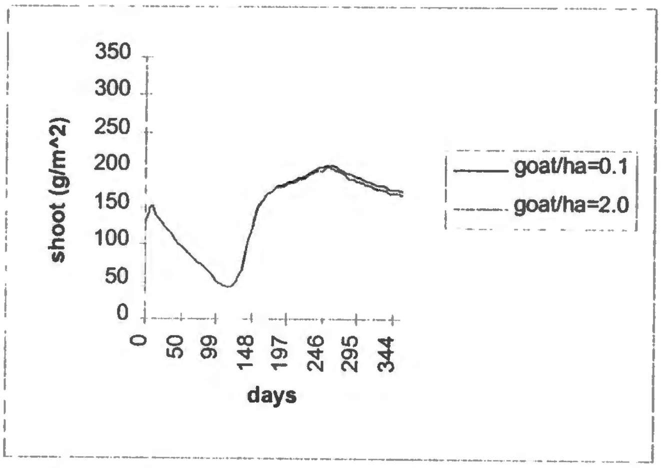


Figure 4.2.4(b): effects of goats on shoot during the year 1981/82.

Unlike cattle, goats are predicted to have no effect on shoot during the early days of the year, i.e. before the rainfall. This might suggest that goats would rather undergo the search for the then scarce green woody plant leaves than to graze the easily available low quality dead grass material . The effects of goats on shoot later in the year would vary with the years, being largest in a low rainfall year (1981/82) and almost negligible in a good rainfall year (1980/81), as suggested by figure 4.2.4(b). The results show the emphasis of goats on woody plant vegetation than on grass, figures 4.2.5 and 4.2.6 .

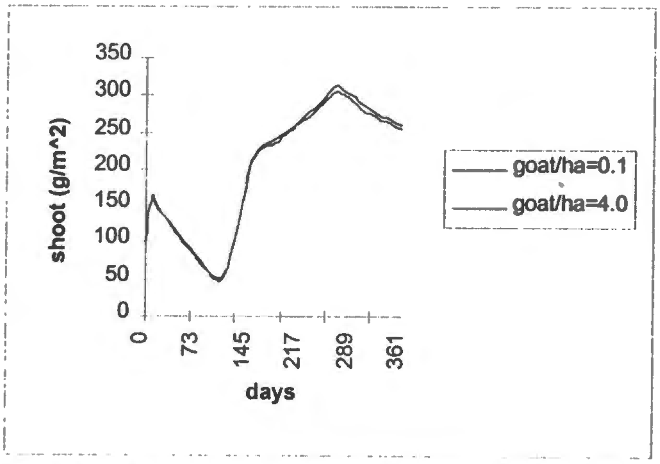


Figure 4.2.5: effects of a further increase (as compared to fig. 4.2.4(a)) in the number of goats on shoot for the year 1980/81.

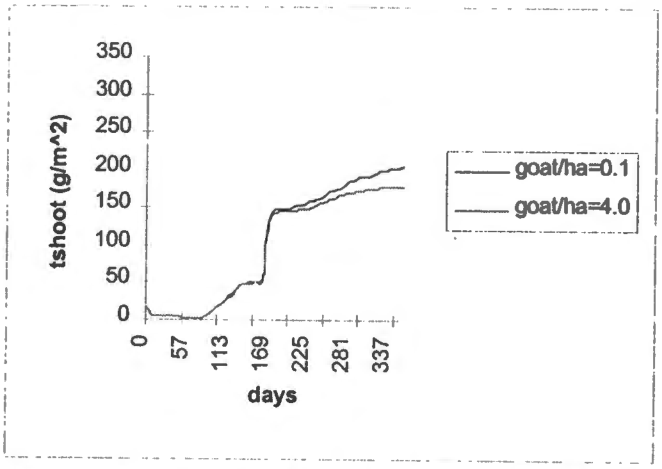


Figure 4.2.6: effects of the same (as in fig. 4.2.5) number of goats on woody plant shoot (tshoot) for the year 1980/81.

Here increasing goats from 0.1 to 4 per ha results in a much bigger reduction in woody plant shoot (tshoot) than in grass shoot for the same year.

It is of interest to see "how much" of each vegetation type is utilised by each herbivore. This comparison can only be done fairly at equal livestock units per ha (Lu/ha). Predictions of the effects have been done with either 0.4 cows per ha or 1.97 goats per ha (each equal to 0.236Lu) , figures 4.2.7, 4.2.8, 4.2.9. A comparison between figures 4.2.7 and 4.2.8 emphasises the results of figures 4.2.5 and 4.2.6 referred to above.

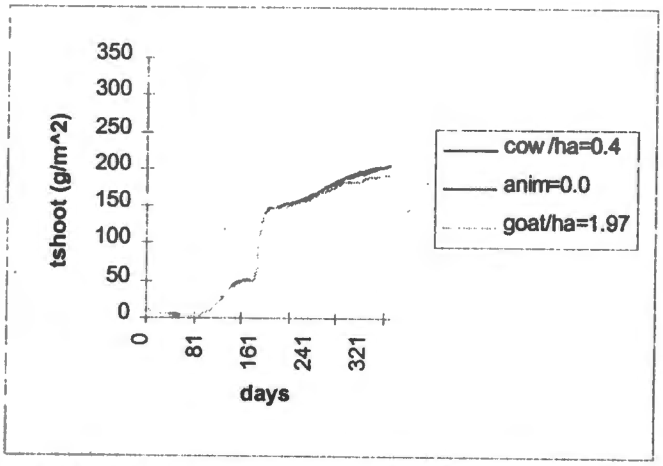


Figure 4.2.7: effects of cattle and goats on tshoot at same Lu for the year 1980/81. From the graph (same with figs 4.2.8 and 4.2.9), cow/ha = 0.4 means 0.4 cows per ha with no goats, goat/ha = 1.97 means 1.97 goats per ha with no cows and anim = 0.0 means no animals.

Table 4.2.7: (corresponding to figure 4.2.7)
tshoot under different grazing pressures for the year 1980/81.
tshoot1, tshoot2 and tshoot3 correspond to grazing pressures of 0.0 anim/ha, 0.4 cows/ha and 1.97 goats/ha respectively.

days	tshoot1	tshoot2	tshoot3
0	20.00	20.00	20.00
26	4.4197	4.4181	4.3905
51	3.9647	3.9613	3.9138
76	3.7985	3.7863	3.7312
101	16.941	16.888	16.702
126	39.566	39.333	39.182
151	51.03	50.693	50.569
176	144.59	144.03	143.59
201	150.14	149.5	147.84
226	157.06	156.38	153.47
251	167.89	167.16	163.15
276	180.26	179.45	174.26
301	190.44	189.42	182.04
326	197.79	196.53	187.32
351	203.55	202.01	191.08

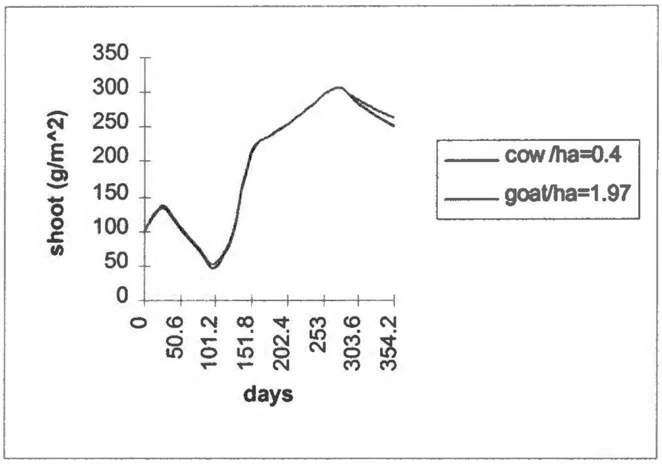


Figure 4.2.8: effects of cattle and goats on shoot at same Lu for the year 1980/81.

Also, it is seen from the graphs that cattle are grazers . In a year of good rainfall (1980/81) the effects of cattle (at low stocking rate) on tshoot are very small (figure 4.2.7). Again such effects remain minimal in a year of low rainfall (1981/82), figure 4.2.9 .

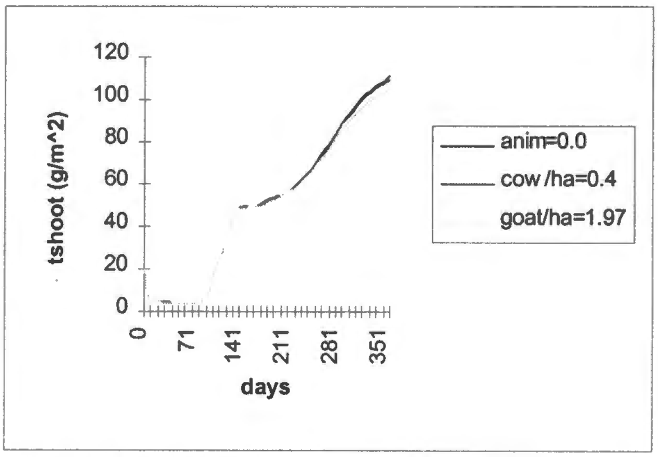


Figure 4.2.9: effects of cattle and goats on tshoot at same Lu for the year 1981/82.

The model predicts that goats affect the woody plant population, with the results showing that such effects vary between different rainfall years. During a year (1980/81) of consistent rains increasing the number of goats from 2 to 6/ha would have very little effects on the population of the plants, figure 4.2.3(b). In a low rainfall year (1982/83) the effects of the goats on plant populations are substantial, figure 4.2.3(c).

The results of figures 4.2.3(a)- 4.2.3(c) may not be exactly in line with what happens in the field, where heavy grazing by cattle is known to reduce grass competition with woody plants and thus have a positive effect on the woody plants. Cattle being heavy herbivores, can otherwise harm young woody plant seedlings through grazing and trampling. On the contrary, goats being light herbivores have no trampling effects, but they reduce woody plant seedlings through direct consumption. At equal Lu per ha, SAVANNAS emphasises that cattle have the potential to harm seedlings than goats, table 4.2.8 .

Table 4.2.8: comparison between goat and cow herbivory on woody plants for the year 1982/83. Here tpopt1 is the population of woody plants in the absence of animals, tpopt2 is the population in the presence of cows (0.726 Lu/ha) only and tpopt3 is the population in the presence of goats (0.726 Lu/ha) only.

dayz	**tpopt1**	**tpopt2**	**tpopt3**
111	1.300	1.300	1.300
121	7.377	7.363	7.376
131	7.377	7.363	7.376
141	7.377	7.363	7.376
151	7.377	7.363	7.376
161	7.377	7.363	7.376
171	7.377	7.363	7.376
181	7.377	7.363	7.376
191	7.377	7.363	7.376
201	7.377	7.363	7.376
211	7.377	7.363	7.376
221	7.377	7.363	7.376
231	7.377	7.363	7.376
241	6.075	5.943	6.057
251	6.075	5.943	6.057
261	6.075	5.943	6.057
271	6.075	5.943	6.057
281	6.075	5.943	6.057
291	6.075	5.943	6.057
301	6.075	5.943	6.057
311	6.075	5.943	6.057
321	6.075	5.943	6.057
331	6.075	5.943	6.057
341	6.075	5.943	6.057
351	6.075	5.943	6.057
361	5.639	5.398	5.599

In both shoot and tshoot our projected offtake may not be what normally takes place in the field. For both of them, the offtake in the field would depend on the levels of herbivory. For instance, in the heavily stocked conditions found in communal lands removal of vegetation would be 50 to 75% or more. While the proper use, which is the maximum proportion that can be used without causing rangeland deterioration is assumed to be 30 to 50% of available forage (de Leeuw and Tothill,1993).

4.3) ANIMAL PERFORMANCE

i) Performance of the herbivores is viewed using both weights and numbers. It is generally expected that animal weights should depend on rainfall (which implies depending on shoot or tshoot). Figures 4.3.1(a) and 4.3.1(b) show the weight of a cow (called **weight**) for the years 1980/81 and 1981/82 respectively.

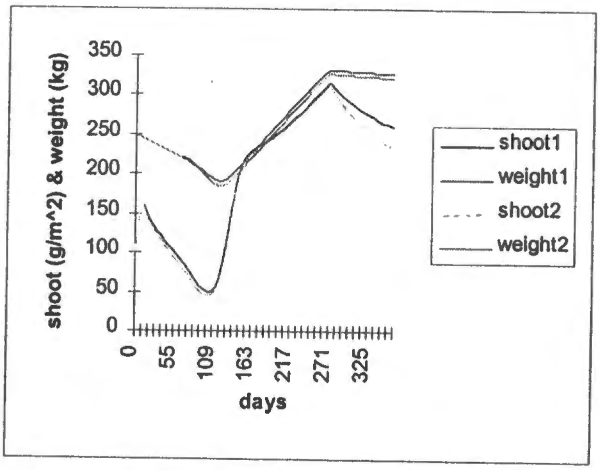


Figure 4.3.1(a): weight of a cow plotted along side shoot (**on the same scale**) during the year 1980/81. Weight1 and shoot1 are, respectively, the weight and the shoot under the standard grazing conditions (i.e. 0.1 cows/ha and 0.1 goats/ha). Weight2 and shoot2 are, respectively, the weight and shoot when there are 0.8 cows/ha and 0.1 goats/ha. NB: the top 2 curves are for weight, the bottom 2 curves are for shoot.

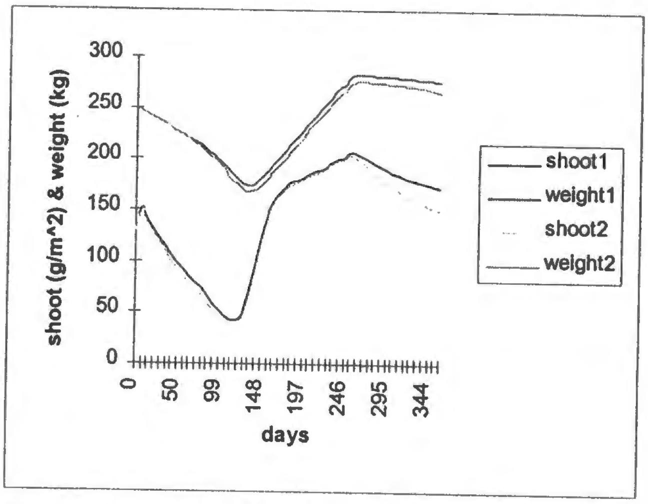


Figure 4.3.1(b): same as figure 4.3.1(a) but for the year 1981/82.

For both years the results show an increase in weight in response to an increase in shoot. It is predicted that increasing competition in herbivores would result in a lower animal weight. It is rather interesting to see that such a weight decline would vary with rainfall years. For the low rainfall of 1981/82 there is a clear difference between weight1 and weight2, whereas for the high rainfall of 1980/81 there is hardly any difference between weight1 and weight2.

The animal weight for the 3 different years is shown, fig. 4.3.2 (stocking rate: 0.1 cows/ha and 0.1 goats/ha). This diagram brings an interesting result that rainfall distribution is more important to animal production than just a big amount of yearly rainfall. For the rainfall of 1981/82 (366.6 mm), the weight is just a bit below the resulting weight from the rainfall of 1982/83 (338 mm).
It is also seen that there is no sudden fall in weight of the animal following a sudden fall in shoot, but the weight tends to level off. This might be because weight would only decline if metabolisable energy (ME) intake is less than ME required for maintenance. The animal would also make use of its body reserves for maintenance.

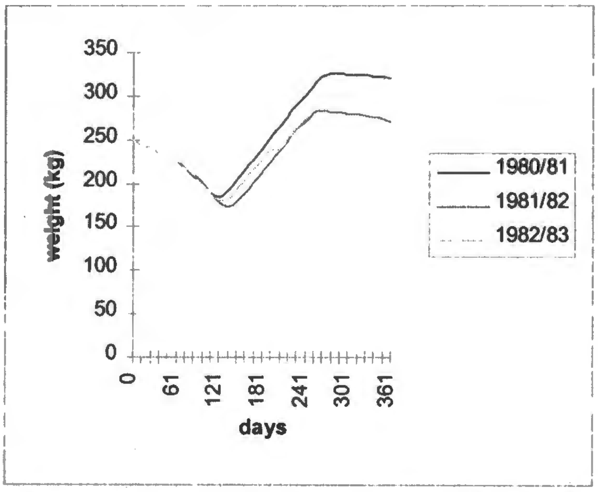


Figure 4.3.2: the weight of a cow plotted against time for the three different years 1980/81, 1981/82 and 1982/83.

The variation of the weight of the goat **(gweight)** over the years is demonstrated below, figure 4.3.3 .

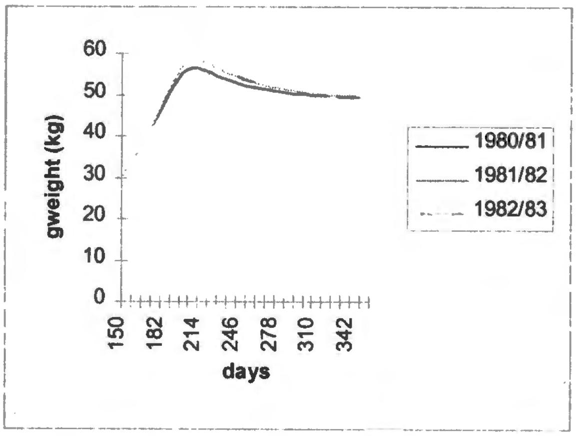


Figure 4.3.3: the weight of a goat plotted against time for the three different years 1980/81, 1981/82 and 1982/83.

Unlike in cattle, gweight shows a very small difference over the different years. The above figure shows that during the year of good rains (1980/81) gweight has a smaller peak than the gweight of the two other years which have gweight equal. This may mean that there is no clear relationship between rainfall and gweight. This might be because goats are small animals and can eat enough even at low herbage densities. Another explanation to the little variation in gweight (compared to weight) over the years may be the fact that tree leaf production is less variable between years than grass production. Goats would thus be affected less than cattle which have a much more variable amount of grass on offer.

ii) Animal weights, just like vegetation density, may be thought of as being proportional to animal populations. But to what extent can vegetation affect numbers? For the three different years respectively, SAVANNAS predicts that at "low" initial stocking rates (0.1 to about 3 goats/ha) the numbers of goats are almost independent of rainfall and vegetation. Regardless of the amount of vegetation and amount of rainfall, the numbers of goats are "unaffected" at low stocking rates, table 4.3.1 . The result might be suggesting that unless they are close to their carrying capacity, goats, being light herbivores, are easily content with vegetation of any amount.

Table 4.3.1: numbers of goats (goats/ha) for the three different years. Initial stocking rate is 0.6 goats/ha. goats1, goats2 and goats3 are the numbers of goats (per ha) during the years 1980/81, 1981/82 and 1982/83 respectively.

days	goats1	goats2	goats3
117	0.82696	0.82637	0.82684
125	0.85954	0.85886	0.85944
133	0.89204	0.89124	0.89202
141	0.92444	0.92348	0.92451
149	0.95677	0.95565	0.9569
157	0.98905	0.98779	0.98919
165	1.0213	1.0199	1.0214
173	1.0535	1.052	1.0536
181	1.0857	1.0841	1.0858
189	1.1179	1.1162	1.118
197	1.15	1.1484	1.1502
205	1.1821	1.1807	1.1823
213	1.2143	1.2127	1.2144
221	1.2464	1.2448	1.2465
229	1.2784	1.2768	1.2786

At high stocking rates (5 or more goats/ha), however, goat production is inevitably dependent on rainfall, tables 4.3.2 and 4.3.3.

Table 4.3.2: numbers of goats for the 3 different years. Initial stocking rate is 5 goats per ha. goats1, goats2 and goats3 are the numbers of goats (per ha) during the years 1980/81, 1981/82 and 1982/83 respectively.

days	goats1	goats2	goats3
100	5.5306	5.4624	5.6026
120	5.7905	5.7449	5.8478
140	6.2176	6.0597	6.2285
160	6.7148	6.5179	6.7063
180	7.2259	7.0168	7.2106
200	7.7394	7.5275	7.7218

220	8.2542	8.0404	8.235
240	8.7696	8.5545	8.7491
260	9.2849	9.0692	9.2636
280	9.7871	9.3628	9.6785
300	10.277	9.6188	9.952
320	10.768	9.8634	10.121
340	11.257	10.1	10.466
360	11.743	10.334	10.979

Table 4.3.3: numbers of goats for the 3 different years. Initial stocking rate is 7 goats per ha. goats1, goats2 and goats3 are the numbers of goats (per ha) during the years 1980/81, 1981/82 and 1982/83 respectively.

days	goats1	goats2	goats3
100	7.5339	7.4508	7.6628
120	7.9037	7.8485	8.0022
140	8.5121	8.3022	8.5468
160	9.2158	8.9539	9.2258
180	9.932	9.66	9.9366
200	10.651	10.375	10.653
220	11.372	11.094	11.372
240	12.094	11.814	12.092
260	12.816	12.535	12.813
280	13.518	12.929	13.387
300	14.202	13.256	13.746
320	14.884	13.546	13.928
340	15.563	13.808	14.381
360	16.235	14.046	15.1

From the above, the effects of rainfall on the performance of goats are more pronounced over the dry season. Looking down the tables from day 100 it is clear that the differences in the numbers of goats between different years are on the increase. For instance the difference in populations for the 1981/82 and 1982/83 rainfall years is 2.6 % on day 200, yet it is 3.6 % on day 340, table 4.3.2 . Over the rainy season the population trends are close to those observed under low stocking rates, i.e. there are little differences in animal numbers.

Increasing the initial stocking rate would lead to an increased difference in numbers over the years. For instance, the difference in populations between the 1981/82 and 1982/83 rainfall years at day 340 is 3.6 % for 5 goats/ha, yet it is 4.1 % on the same day for 7 goats/ha.

Just like in the production of vegetation, the amount and distribution of rainfall are a factor in the production of goats. There are more goats in the high rainfall year 1980/81. Although rainfall 1982/83 is smaller than rainfall 1981/82 there are more goats in the former. That might mean that a fairly distributed rain is conducive to goats when they are at high stocking rates.

SAVANNAS predicts that unlike in goats, the "population" of cattle is visibly different for different years even at low stocking rates, figures 4.3.4(a)-4.3.4(c). The predicted "population" increment, however, is realistically impossible, and that explains why it is better referred to as the environment's 'potential to carry animals'.

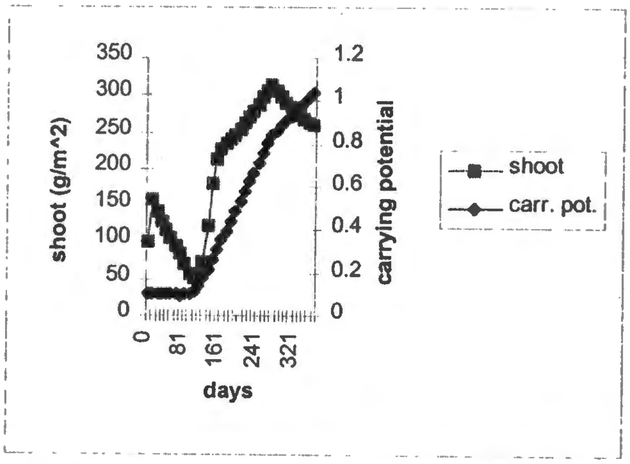


Figure 4.3.4(a): shoot along side carrying potential plotted against time for the year 1980/81.

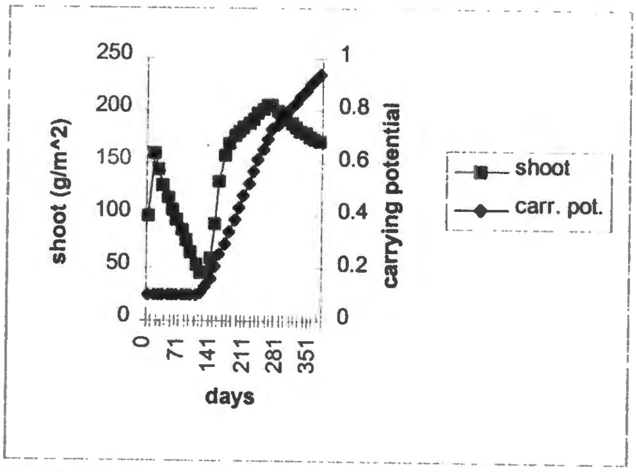


Figure 4.3.4(b): same as fig.4.3.4(a) but for the year 1981/82.

The graphs show that vegetation is the main determining factor. A rise in vegetation enhances the carrying potential of the environment. The prediction is that the carrying potential decreases over the dry season and is enhanced at the start of rains. SAVANNAS predicts that there shall be a high potential to carry animals in a year like 1982/83 which has got good rains sometime late in the year, figure 4.3.4(c).

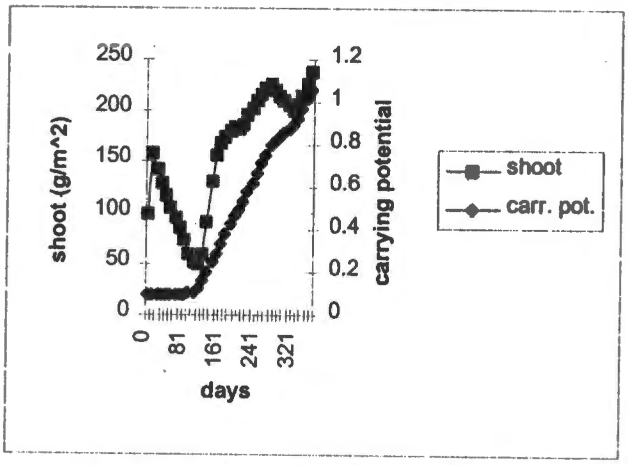


Figure 4.3.4(c): same as fig.4.3.4(a) but for the year 1982/83.

An immediate decline in amount of shoot in dry seasons will not necessarily mean an immediate decline in carrying potential, but a small decrease in the slope of the carrying potential curve, figure 4.3.4(a) and 4.3.4(b).
Consistency in rainfall over the year is a factor favouring carrying potential, figure 4.3.5.

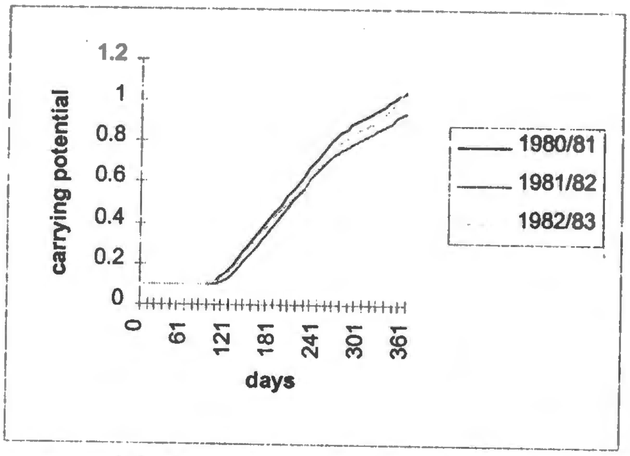
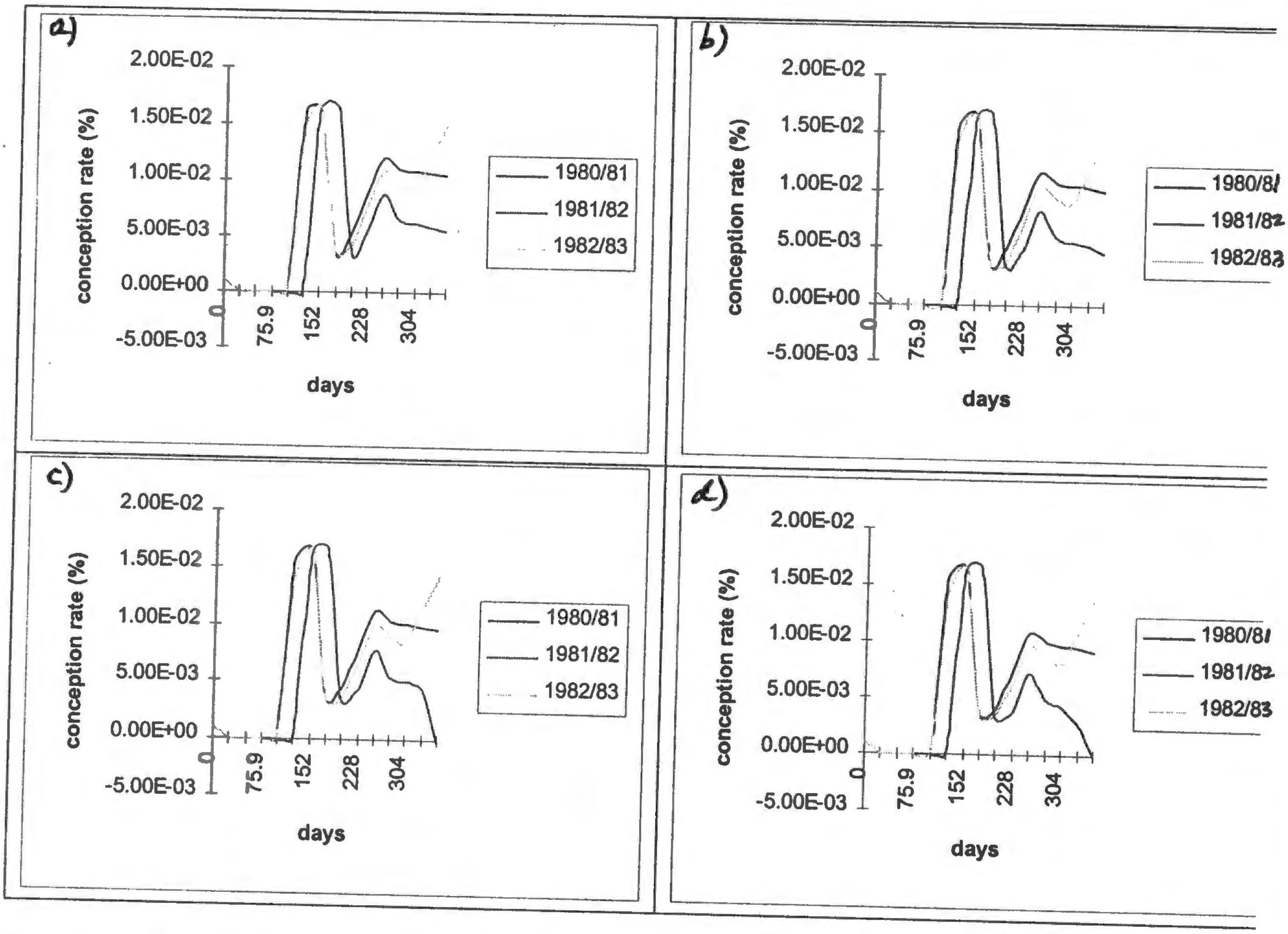


Figure 4.3.5: carrying potential plotted against time for the years 1980/81, 1981/82 and 1982/83.
From the graph, the 1982/83 rainfall (338 mm) resulted in a better animal performance than the 1981/82 rainfall (366.6 mm).

Since the predictions of cattle numbers are unrealistic, perhaps it is better to view them (predictions) in terms of conception rates. Having achieved realistical predictions in the numbers of goats over the years, it won't be necessary to view their reproduction in terms of the conception rates. A simulation of conception and mortality rates has been performed. The average daily conception rates in cows for the different years have been predicted. It is found that there is no big difference in the average daily conception rates over the years , but in a year of good rainfall the animals have on average a better chance of conceiving, figures 4.3.6 (overleaf). It is predicted that increasing the number of animals per ha will have a negligible effect on the average daily conception rates anytime in the year but the dry season. In a year (like 1981/82) of little rainfall in the dry season it is predicted that the conception rates would reach zero with an increase in animal numbers, figures 4.3.6 (c) , (d). On the contrary, it is predicted that in a year of good late rains (1982/83) the daily conception rates would rise following the late rains. Although the animals are predicted to conceive almost throughout the year, the best time is just after the first rainfall as seen in the graphs below.



Figures 4.3.6 (a), (b), (c), (d): Average conception rates per day of cows plotted against time of the year for: 0.4, 0.8, 1.2, 1.6 cows/ha respectively.

4.4) Sensitivity analysis of the model

Since SAVANNAS basically focuses on vegetation and animal productivity; and the variables & parameters are directly or indirectly involved in the productivity of the two, it suffices therefore, to use shoot biomass and animal weight as measures of sensitivity. All variables and parameters taken from the literature will not be tested for sensitivity since they have been successfully used in the sub-models from which SAVANNAS has been built.

First we examine the effects of changing the integration step (dt) on the performance of the system. It is generally expected in numerical integration methods that reducing the value of dt would improve the results. The predictions of SAVANNAS are indeed affected by changes in dt, table 4.4.1. Halving and doubling the value of dt (set at 0.1 in the model) have effects of variable magnitudes on shoot. Setting dt to 0.2 result in a negligible change in the amount of shoot (when compared to $dt = 0.1$), while there is a visible change when $dt = 0.05$. This particular change in shoot biomass is within a reasonable limit in the sense that it is small throughout the year but between day 121 and 145 as seen in table 4.4.1. SAVANNAS has been found to be sensitive to smaller changes in dt. For instance, changing dt to 0.08 or 0.12 resulted in bigger differences (compared to when dt is 0.1) in shoot biomass. These behaviours in shoot with changes in dt are the same for the low rainfall year 1982/83, table 4.4.2. Therefore, the observed performances of SAVANNAS can only be achieved with dt set at any of 0.05, 0.1, 0.2.

Table 4.4.1: effects of changing the value of dt on shoot biomass for the 1980/81 rainfall year.

$dt = 0.05$		$dt = 0.1$		$dt = 0.2$	
days	shoot	days	shoot	days	shoot
0	100	0	100	0	100
24.2	137.52	24.2	137.52	24.2	137.52
48.4	107.43	48.4	107.43	48.4	107.43
72.6	82.525	72.6	81.723	72.6	81.723
96.8	53.158	96.8	52.991	96.8	52.989
121	70.856	121	74.577	121	74.555
145.2	193.69	145.2	197.57	145.2	197.55
169.4	233.01	169.4	233.51	169.4	233.51
193.6	247.92	193.6	248.16	193.6	248.2
217.8	266.62	217.8	267.24	217.8	267.27
242	288.15	242	288.91	242	288.98
266.2	311.49	266.2	312.56	266.2	312.61
290.4	297.73	290.4	298.94	290.4	298.97
314.6	281.35	314.6	282.5	314.6	282.51
338.8	268.48	338.8	269.57	338.8	269.58
363	258.33	363	259.37	363	259.37

Table 4.4.2: effects of changing the value of dt on shoot biomass for the 1982/83 rainfall year.

$dt = 0.05$		$dt = 0.1$		$dt = 0.2$	
days	shoot	days	shoot	days	shoot
0	100	0	100	0	100
24.2	137.52	24.2	137.52	24.2	137.52
48.4	107.43	48.4	107.43	48.4	107.43
72.6	83.829	72.6	83.829	72.6	83.828
96.8	54.197	96.8	53.882	96.8	53.882
121	56.952	121	59.122	121	59.113
145.2	128.01	145.2	130.36	145.2	130.36
169.4	151.66	169.4	151.62	169.4	152.22
193.6	161.85	193.6	161.79	193.6	162.28
217.8	173.81	217.8	173.8	217.8	174.23
242	188.4	242	189.21	242	189.51
266.2	200.53	266.2	201.53	266.2	201.76
290.4	191.21	290.4	192.27	290.4	192.43
314.6	180.78	314.6	181.82	314.6	181.93
338.8	186.5	338.8	187.61	338.8	187.75
363	211.13	363	212.32	363	212.43

Plant components like culm, gleaf, inflor which are set to zero at the start of the season do not need a sensitivity test since they should not be set to any other initial values. A change in the initial values of dead plant components can only affect the amount of shoot in the early dry season i.e. before the rainfall. Dead leaf (deadlea) does not only affect the early season shoot biomass but the weights of the animals as well, table 4.4.3.

Table 4.4.3: the effects of changing deadlea on both shoot biomass and animal weight (1981/82). shoot1 is the amount of shoot when the initial value of dead leaf is 60 g/m^2(the value in the model), while shoot2 and shoot3 correspond to initial values of 55 g/m^2 and 65 g/m^2respectively. weight1, weight2 and weight3 correspond to shoot1, shoot2 and shoot3 respectively.

days	**shoot1**	**shoot2**	**shoot3**	**weight1**	**weight2**	**weight3**
0	100	100	100	250	250	250
10	158.89	154.37	163.4	245.54	245.41	245.67
20	143.52	139.44	147.6	241.09	240.82	241.35
30	129.62	125.94	133.31	236.65	236.25	237.04
40	117.05	113.72	120.38	232.22	231.68	232.73
50	105.68	102.68	108.69	227.79	227.11	228.43
60	95.399	92.685	98.112	223.36	222.56	224.13
70	86.097	83.648	88.546	218.95	218.01	219.84
80	77.69	75.488	79.896	214.39	213.16	215.52
90	65.56	63.715	67.407	208.65	207.05	210.14
100	54.271	52.769	55.775	201.36	199.5	203.12
110	46.639	45.414	47.864	193.24	191.19	195.19
120	45.209	44.21	46.209	185.24	183.05	187.34
130	56.311	55.495	57.127	179.33	177.01	181.58
140	84.934	84.268	85.6	179.76	177.33	182.12
150	118.31	117.72	118.89	187.49	185.03	189.88
160	138.14	137.63	138.65	196.72	194.23	199.13
170	148.02	147.58	148.45	206.28	203.77	208.71
180	152.25	151.86	152.64	216.02	213.49	218.47
190	156.86	156.51	157.21	225.81	223.26	228.28

200	159.87	159.56	160.19	235.67	233.1	238.14
210	163.26	162.97	163.54	245.53	242.95	248.01
220	166.61	166.36	166.87	255.37	252.79	257.86
230	171.22	170.99	171.45	265.17	262.58	267.66
240	175.8	175.6	176.01	274.85	272.26	277.34
250	181.36	181.18	181.55	284.41	281.82	286.9
260	186.24	186.07	186.41	293.81	291.23	296.3
270	182.82	182.67	182.97	295.13	292.55	297.61
280	177.98	177.84	178.11	294.47	291.9	296.95
290	173.61	173.49	173.73	293.81	291.24	296.28
300	169.66	169.56	169.77	293.13	290.57	295.6
310	166.1	166	166.19	292.45	289.89	294.91
320	162.87	162.79	162.96	291.75	289.2	294.21
330	159.95	159.88	160.03	291.05	288.5	293.5
340	157.31	157.24	157.37	290.33	287.78	292.78
350	154.9	154.85	154.96	289.6	287.06	292.05

One parameter which has a "big say" in the re-growth of grass following the early season rainfall is Bstart (set at 40mm). This has been found to be of little sensitivity, changing it by 12.5 % units does not affect vegetation growth.
ASTmax, BSTmax, and CSTmax are other parameters directly involved in the grass growth model. A test finds ASTmax being the only sensitive of the three. Changing ASTmax (set at 25.5mm) to within 19.6 % affects the production of the shoot, table 4.4.4.

Table 4.4.4: effects of changing ASTmax on shoot biomass. Shoot1, shoot2 and shoot3 are the shoot biomass when ASTmax is set at 25.5mm, 30 mm and 23 mm respectively.

days	**shoot1**	**shoot2**	**shoot3**
0	100	100	100
11	158.89	158.89	158.89
21	143.52	143.52	143.52
31	129.62	129.62	129.62
41	117.05	117.05	117.05
51	105.68	105.68	105.68
61	95.398	95.398	95.399
71	86.097	86.097	86.097
81	77.689	77.689	77.689
91	64.945	64.945	64.945
101	53.859	53.861	53.859
111	46.613	46.617	46.612
121	46.307	46.314	46.306
131	61.491	61.499	61.49
141	103.59	103.6	103.59
151	162.43	162.43	162.43
161	205.86	205.88	205.86
171	229.56	229.59	229.56
181	241.94	241.98	241.92
191	248.42	248.55	248.32
201	254.72	254.88	254.61
211	260.62	260.76	260.53
221	266.41	266.51	266.33
231	273.82	271.93	273.8
241	278.27	273.67	280.81
251	284.44	279.73	287.62

261	283.72	273.71	291.47
271	276.64	267.38	283.74
281	270.35	261.78	276.85
291	264.67	256.74	270.63
301	259.55	252.2	265.02
311	254.92	248.1	259.95
321	250.75	244.4	255.36
331	246.97	241.06	251.22
341	243.55	238.04	247.47
351	240.46	235.31	244.07

Apart from being influenced by changes in the amount of shoot biomass, weight is sensitive to changes in bbite (the size of the optimum bite of the animal). A small increase in bbite causes a small increase in weight, similarly a decrease in bbite would bring a decrease in weight.

On the other hand a change in maxbite (maximum number of bites by animal) has been found to have no effects on weight. Changing maxbite from 38000 to 37500/day or 38200 does not affect animal weight at all.

Changing the initial values of the Blaxter and Boyne variable coefficients p, g and Bke do not bring any changes in weight. Similarly, gweight is not sensitive to changes in the initial values of goatp, goatg and goatBke.

TRANCO is another parameter that relates to the amount of shoot biomass indirectly. It is found that neither shoot or weight is sensitive to small changes (within 6%) in TRANCO.

Estimated parameters of the Michaelis-Menten equations such as muculm, mugleaf, mustem, kscu, ksg etc have been found to be of little sensitivity to changes within 0.3 units.

A test of the model behaviour under scenarios of "excessive" rainfall and stocking rates has been done. By semi-arid standards the year 1980/81 has excessive rainfall (758.9 mm) while the year 1982/83 has minimal rainfall (338 mm). This means the results of section 4.1 (figures 4.1.1 and 4.1.3) represent the behaviour of the model under minimal stocking rates, while the results of tables 4.4.5 & 4.4.6 below represent the behaviour both under minimal & excessive stocking rates.

Table 4.4.5: shoot biomass for the rainfall year 1980/81. shoot0 is the amount of shoot when there is no rainfall & no grazing throughout the year. shoot1 is the amount of shoot when there are 0.1 cows/ha, while shoot2 is the amount of shoot when there are 6 cows/ha. NB: for the 1980/81 rainfall year 6 cows/ha is an excessive stocking rate.

days	**shoot0**	**shoot1**	**shoot2**
0	100	100	100
20	143.52	143.52	119.82
40	117.05	117.05	75.909
60	95.398	95.398	51.323
80	77.69	70.601	34.742
100	63.323	51.185	26.314
120	51.685	67.085	49.946
140	42.234	128.64	115.66
160	34.542	148.41	137.84
180	28.27	153.12	143.83
200	23.149	160.36	150.81

220	18.966	171.3	159.84
240	15.544	182.73	167.84
260	12.745	196.19	176.45
280	10.455	197.76	152.15
300	8.5803	188.17	128.82
320	7.0462	180.31	103.81
340	5.7904	173.82	97.81
360	4.7624	168.42	....

At a stocking rate of 6 cows/ha the model output crashes towards the end of the year, table 4.4.5. This happens during that time of the year when vegetation growth has ceased. Likewise, SAVANNAS crashes when there are 4 or more cows/ha for the 1982/83 rainfall year.

Table 4.4.6: shoot biomass for the rainfall year 1982/83. shoot1 is the amount of shoot when there are 0.1 cows/ha, while shoot2 is the amount of shoot when there are 3.5 cows/ha. NB: for the 1982/83 rainfall year 3.5 cows/ha is an excessive stocking rate.

days	**shoot1**	**shoot2**
0	100	100
20	143.52	127.62
40	117.05	88.989
60	95.398	61.619
80	73.307	43.239
100	51.479	30.198
120	57.274	42.573
140	117.39	106.56
160	146.81	138.84
180	157.3	150.37
200	163.77	156.48
220	175.69	167.1
240	188.19	176.71
260	198.32	183.19
280	197.7	165.35
300	187.8	131.3
320	179.72	128.92
340	188.82	143.69
360	209.33	166.07

CHAPTER 5

CONCLUSION

SAVANNAS shows that plant and animal productions vary both between and within years. The variations within the year might be linked to among other factors the timing of the rains. This influence on production varies between animal species, with goats being less affected by rainfall than cattle. Similarly, different plant species respond differently to rainfall. For instance, grass shoot takes a noticeable decline at the start of the dry season whereas the woody plant shoot does not.

The effects of animal numbers on both vegetation and animal performance vary with rainfall, being greatest in years of low rainfall. Within the year these effects are more pronounced in the dry season.

The influence of rainfall on cattle production is larger than on goats. In different rainfall years there is a very small variation in the performance of goats compared with cattle. This replicates the behaviour of goats surviving better than cattle in low rainfall years. A reason for this behaviour is that goats are browsers and woody plant leaf production is less affected by rainfall than grass production. Furthermore, as a result of their small size they can more readily obtain their requirements than cattle.

SAVANNAS could be used as a management tool by pastoralists and their advisors, but this can only be done after it has been parameterised for local data. It is clear that in semi-arid regions where there are big variations in rainfall goats are more optimum to have than cattle. SAVANNAS can estimate optimum proportions of goats and cattle for years of different rainfall and different vegetation densities. Using SAVANNAS we can estimate a certain threshold of animal numbers per given area above which both animal performance and plant production can be bad. Running SAVANNAS with a lot of different yearly rainfalls including years of drought can be very usefull. For a given year, the rainfall data to present date can be used together with weather forecasting to predict vegetation production and animal performances for the future.
Apart from being a management tool, SAVANNAS can be used for further research. For instance, the output of this model is used in frame-based modelling (Hahn, Richardson and Starfield,1999) which simulates vegetation and animal productivity over many years. SAVANNAS has the potential to evolve to be used with other related and more detailed models. For instance a model can be built that will consider the effects of fire and droughts. Other than semi-arid regions, SAVANNAS can easily be modified to simulate other regions as well, it is a matter of changing some parameters and getting the right rainfall data. Likewise, animal production is not only limited to cattle and goats, SAVANNAS could actually work for any herbivore population.

Although SAVANNAS provides a good simulation of the dynamics of semi-arid rangeland, further development is required to consider other components of rangeland systems. These include the effects of large and small wild herbivores which may consume substantial quantities of forage on both commercial and communal rangelands. Furthermore, crop residues make an important contribution to livestock nutrition in communal areas during the dry season.

APPENDIX

A1 MODEL DESCRIPTION

In describing SAVANNAS reference shall be made to earlier sections and also to the model itself. Information in curly brackets is with reference to the sections of SAVANNAS. e.g. {grass growth} would mean see the section {grass growth } in SAVANNAS. Also, scheme drawings describing the processes in SAVANNAS are shown, figure A1.1 and figure A1.2 . Inside SAVANNAS reference is made to the sections of the text by the information in square brackets. e.g. [section 2.1] would mean this part of the model is defined in section 2.1 of the text.
The description is divided into the following sub-sections:

i) Water budget
ii) Grass growth
iii) Woody plant growth
iv) Animal growth

Each section is described below

i) Water budget sub-model
This is defined in terms of Dye (1983).

* The soil is divided into 4 main layers A, B, C and D with the amount of moisture in each layer being AST, BST, CST and DST respectively.
Initial values of soil moisture in each soil store at the start of the season are specified. These are assumed to be: $AST = 10.55$, $BST = 29.5$, $CST = 42.5$ and $DST = 57.2\ mm$ respectively. The change in the amount of moisture in the soil stores is defined by the differential equations $F[1]$, $F[2]$, $F[3]$ and $F[4]$ respectively.
NB: in SAVANNAS $F[i]$, where i is an integer denoting the number of the d.e., denotes the right hand side of a time differential equation. e.g. the differential equation $d(AST)/dt = -EVAP - TRANSA$ would appear as:
$F[1] := -EVAP - TRANSA$; i.e. if it is the $1st$ differential equation.
The dependent variables (AST in the example above) are then declared at the start of the model in the format shown below. This format should be in the same order as the $F[i]'s$. For instance, CST (below) would correspond to $F[3]$.

```
{Driver variables.....}
AST  :{$IFOPT N+} double {$ELSE} real {$ENDIF} absolute FV1;
BST  :{$IFOPT N+} double {$ELSE} real {$ENDIF} absolute FV2;
CST  :{$IFOPT N+} double {$ELSE} real {$ENDIF} absolute FV3;
DST  :{$IFOPT N+} double {$ELSE} real {$ENDIF} absolute FV4;
.
.
.etc
{differential equations of state variables}.
```

* Rainfall for a particular day is read in. If it is less than 12 mm it is all infiltrated into the soil. If it exceeds 12 mm a quadratic relation
$potinfil := 1.05 \times rain - 0.0054 \times rain^2 - 0.4$
is used to partition rain into run-off and infiltration.
{calculation of infiltration and run-off}

*The quantity of rainfall infiltrating into the soil is used to sequentially fill up stores A, B, C and D. It is assumed that store A fills to capacity before store B begins to fill, similarly store B fills to capacity before store C begins to fill, etc. Any infiltrating water remaining after all 4 stores are full is regarded as lost to the soil through deep drainage.
{infiltration to lower layers: B, C, and D stores}.

*Soil surface evaporation is assumed to happen only from store A.
$F[1] = - evap - transA;$ where $evap$ is a function of shoot,
{calculation of evaporation from soil surface}

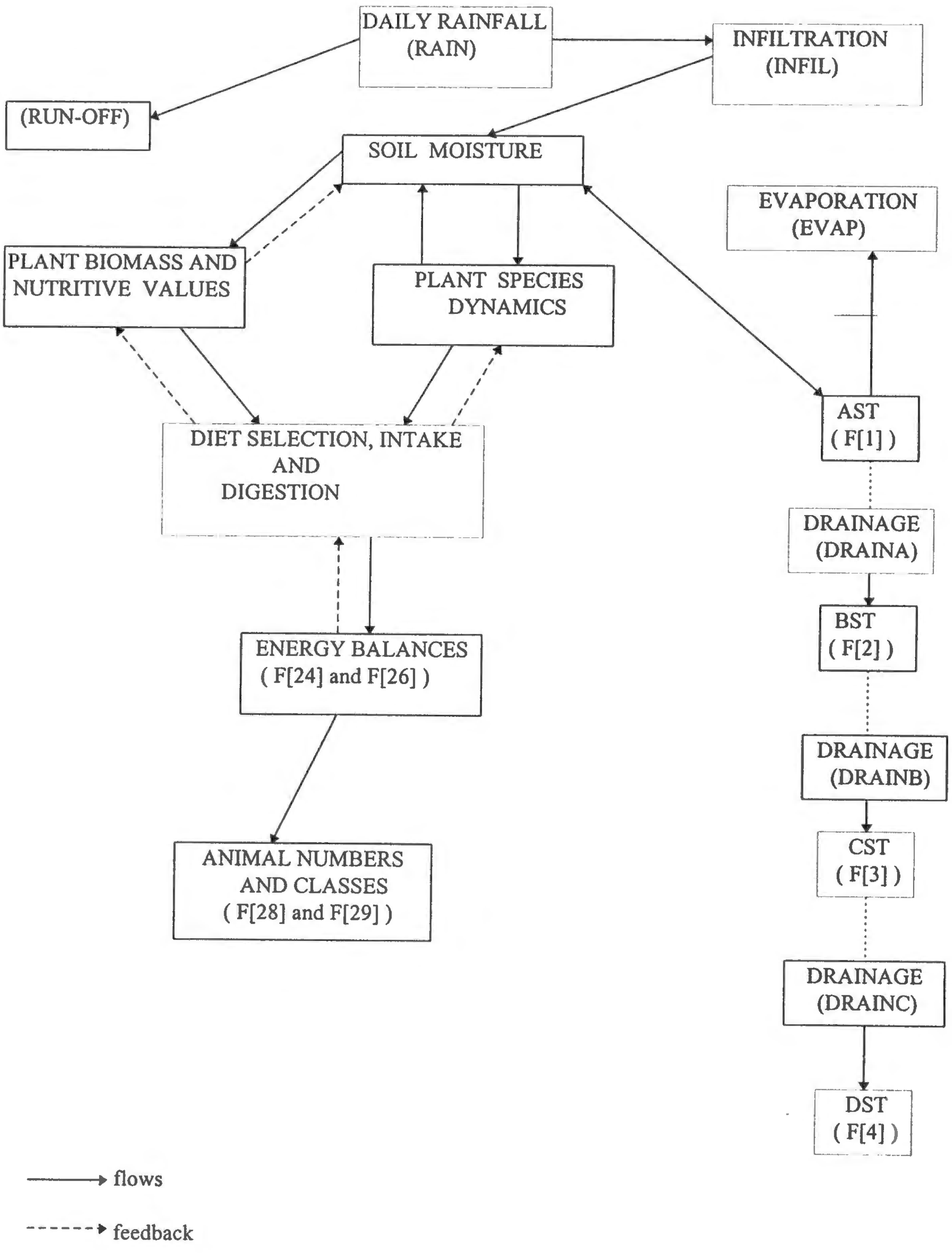


Fig. A1.1 : The model structure (modified version of Richardson, Hahn and Wilke,1991). The "symbols/words" in round brackets refer to the names of the variables as they appear in SAVANNAS. e.g. daily rainfall is called RAIN in SAVANNAS.

ii) **Grass growth sub-model**
*Initiation of growth happens when BST > BSTART, where BSTART is a parameter. {initiation of new season's growth}.

*Plant components are defined by differential equations, e.g.
$F[9] = F[7] \times culmal - gzculm$ defines the changes in culm, whereas the growth rate of each plant component is defined by the Michaelis-Menten equations of section 3.2.1.

*Grass green leaf is given by a modified equation 2, i.e. one with G(t) instead of G as explained in section 3.2.1.

*The sum of all the components above ground make up shoot, and the rate of growth of the shoot is calculated by equation 6.

iii) **Woody plants sub-model**
*Initiation of growth happens when average daily temperature exceeds Q degrees Celsius in spring, where Q is a parameter. {initiation of new seasons growth}.
The temperature is given by the sine wave equation
$Temp = btemp(sin2\pi(days/364)) + atemp,$ {daily temperature}.

*Again the plant components have been defined by the d.e's.
e.g. $F[23] = twiggro \times teha - gztwig$ defines the changes in twig over the year.

*The growth rates of leaves and twigs are as defined in section 3.2.2a,
{Fractional growth rates of tree leaves}
{Fractional growth rates of twigs}, whereas the growth rates of the other plant components are given by the Michaelis-Menten equations.

*Populations of woody plants are as defined in section 3.2.2,
{populations of woody plants}

*Equations 4 and 5 of section 3.2.2b are used for grass-woody plant interaction as explained.
$F[35]$ calculates the changes in woody plant in relation to grass.

$F[36]$ calculates the changes in grass in relation to woody plants.

iv) **Animal Growth sub-model**
*Equation 16 has been used for the energy balance of both animals,
$F[24]$ defines energy retention by the cow.
$F[26]$ defines energy retention by the goat.

*Diet selection are done according to section 3.4.1,
{selection of diet by cattle}
{selection of diet by goats}

Animal numbers are calculated using equation 8 ($F[28]$ and $F[29]$), and animal weights are calculated from the retention equation according to section 3.4.3,
$F[25]$ defines the weight change of the cow,
$F[27]$ defines the weight change of the goat.

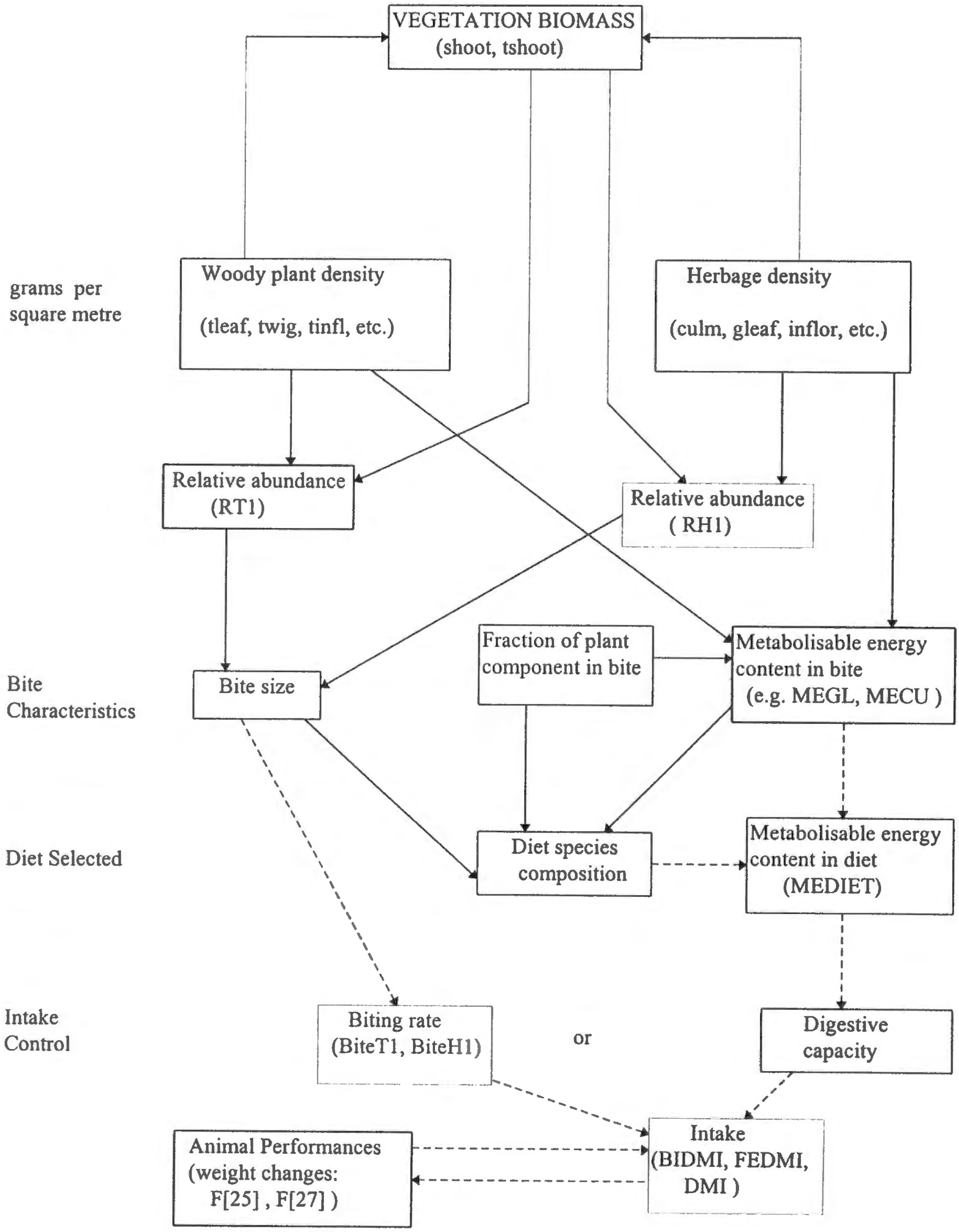


Fig. A1.2 : Structure (modified version of Richardson, Hahn and Schoeman,1999) of a model of diet selection and intake by goats. The "symbols/words" in round brackets refer to the names of the variables as they appear in SAVANNAS. e.g. Relative abundance is denoted by RT1 & RH1 for woody & herbage vegetation respectively in the model.

A2 MODEL VARIABLES AND PARAMETERS

VARIABLE	DEFINITION	UNITS
Acldie	accelerated death of leaves	
Ageind	age index	
AST	amount of water(moisture) in the A-layer	mm
ASTbar	average value of AST calculated over a period.	mm
BC	body condition of a cow	
Benergy	body energy of a cow	kj/day
BIDMI	dry matter intake controlled by the rate at which the animal can eat.	kg/day
Bite H1	grass bite by goat	bites/m^2
BiteT1	woody plant bite by goat	"
BST	amount of moisture in B layer	mm
CfunRes	functional response of cow	
cgzculm	graze of culm by cow	g/m^2 per day
cgzdead	graze of dead grass leaves by cow	"
cgzdecu	graze of dead culm by cow	"
cgzdetf	browse of dead woody plant inflorescence by cow	"
cgzdinf	graze of grass dead inflorescence by cow	"
cgzdtwg	browse of dead twig by cow	"
cgzglea	graze of grass leaf by cow	"
cgzinfl	graze of grass inflorescence by cow	"
cgztinf	graze of woody plant inflorescence by cow	"
cgztlf	graze of woody plant leaf by cow	"
cgztwig	graze of twig by cow	"

cgzolde	graze of old dead grass leaves by cow	"
cgztded	browse of woody plant dead leaves by cow	"
CR	average conception rate per day	%
cows	number of cattle	anim./ha
CST	amount of moisture in C layer	mm
culm	grass culm	g/m^2
culmal	culm allowance of carbohydrates	
culmgro	growth of the culm	
days	days in the year	
dayyr	day in the year	
dayz	days in the year, never resets at end of yr.	
deadcu	dead culm	g/m^2
deadinf	dead inflorescence	g/m^2
deadlea	dead grass leaf	"
deadtlf	dead woody plant leaf	"
deadstm	dead stem	"
deadtif	dead woody plant inflorescence	"
deadtwg	dead twig	
dculm	change in culm growth	g/m^2/day
ddead	change in dead leaf	"
dcdestm	decay of dead stem	g/m^2
dcdetwg	decay of dead twig	"
decdetf	decay of dead woody plant inflorescence	"
dectde	decay of woody plant dead leaves	"

dgleaf	change in grass green leaf	g/m^2/day
dinflor	change in grass inflorescence	"
DI	density index	
DMI	dry matter intake by cow	kg/day
DMtot	total dry matter	kg
dplant	change in plant growth	
drainA	drainage of water from store A	mm
drainB	drainage of water from store B	"
drainC	drainage of water from store C	"
droot	change in root size	
dshoot	change in shoot size	
DST	amount of moisture in D-layer	mm
Dtgrow	change in woody plant growth	
ECG	energy content of the gain by cow	KJ/DAY
EGG	efficiency of use of gross energy for gain by cow	
EGM	efficiency of use of gross energy for maintenence by cow	
ER	energy retention by cow	kj/day
ERgoat	energy retention by goat	"
Evap	potential evaporation	
FCG	fat content of the gain in cow	
FEDMI	dry matter intake limited by digestibility	kg/day

***the fractions in diet (italics) below are in the diet of a cow:**

frcudi	fraction of culm in diet.
frculm	fraction of culm
frdcudi	fraction of dead culm in diet
frdead	fraction of dead grass leaves
frdec	fraction of decay
frdecde	fraction of decay of dead leaves
frdecu	fraction of dead culm
frdeinf	fraction of dead inflorescence in grass
frdindi	fraction of dead grass inflorescence in diet
frdestm	fraction of dead stem
frdstdi	fraction of dead stem in diet
frdtinf	fraction of woody plant dead inflorescence
frdtwdi	fraction of dead twig in diet
frdtwg	fraction of dead twig
frgldi	fraction of grass green leaf in diet
frgleaf	fraction of grass green leaf
frinfdi	fraction of grass inflorescence in diet
frinfl	fraction of grass inflorescence
frolde	fraction of old dead grass leaves
frstem	fraction of stem
frstmdi	fraction of stem in diet
frtdead	fraction of woody plant dead leaves
frtdedi	fraction of woody plant dead leaves in diet

frtifdi	fraction of woody plant inflorescence in diet	
frtinfl	fraction of woody plant inflorescence	
frtlfdi	fraction of woody plant leaf in diet	
frtolde	fraction of woody plant old dead leaves	
frtwig	fraction of twig	
frtwgdi	fraction of twig in diet	

***for the goat, the fractions in diet are represented by the same words as the ones for cow above but prefixed with g. (e.g. *frtwgdi* would be *gfrtwgdi.*)**

g	gross energy intake scaled by basal metabolism in cow.	kj/day
gdigest	digestibility of vegetation by goat.	N, g/kgDM
genergy	body energy of a goat	kj/day
GfunRes	functional response of goat	
ggzculm	culm graze by goats	g/m^2 per day
ggzdinf	graze of dead grass inflorescence by goats	"
ggzdead	goat graze of grass dead leaves	"
ggzdecu	goat graze of dead culm	"
ggzglea	graze of grass green leaf by goats	"
ggzinfl	graze of grass inflorescence by goat	"
ggzolde	goat graze of old dead leaves	"
ggztinf	goat browse of woody plant inflorescence	"
ggztlf	browse of woody plant leaf by goat	"
ggztwig	browse of twig by goat	"
gldie	dead of green grass leaf	
gleaf	grass green leaf	g/m^2

glea	same as gleaf	
goats	number of goats	anim/ha
goatBke	coefficient of Blaxter and Boyne's energy balance equation for goats	
goat DMI	dry matter intake by goat	kg/day
goat ECG	energy content of the gain by goat	
goatEGG	EGG for goats (see EGG above)	
goatEGM	EGM for goat	
goatg	gross energy intake scaled by basal metabolism in goat	kj/day
goatge	gross energy in goat	kj/day
goathb	metabolisable energy for goat	"
goatp	coefficient of Blaxter and Boyne energy balance equation.	
GPI	grazing pressure index	
gr	growth of plants	
grdays	growth days	
grweeks	growth weeks	
gtbiDMI	dry matter intake limited by biting and bite size of goat.	kg/day
gtFEDMI	dry matter intake limited by digestibility in goat	"
gWeight	weight of goat	kg
gzculm	graze of culm by animals (both goats and cattle)	g/m^2 per day
gzdead	graze of dead grass leaves by cow	"
gzglea	graze of grass green leaf	"
gzinfl	graze of grass inflorescence	"
gztinfl	browse of woody plant inflorescence	"

gztleaf	browse of woody plant leaf	"
gztwig	browse of twig	"
Hb	metabolisable energy	kj/day
infil	infiltration of water	
inflal	inflorescence allowance of carbohydrates	
inflgro	growth of the inflorescence	
inflor	inflorescence	g/m^2
intculm	intake of culm by goat	kg dm/day
intdecu	intake of dead culm by goat	"
intdedlf	intake of dead grass leaf by goat	"
intglea	intake of green leaf by goat	"
inttlea	intake of woody plant leaf by goat	"
intwig	intake of twig by goat	"
maxht	maximum height of woody plant	m
mede	metabolisable energy of dead grass leaves	kj/day
mediet	metabolisable energy of the diet	kj/day
meold	metabolisable energy of old (last year's) grass leaves	kj/day
mortR	cumulative mortality rate	
MRday	mortality rate per day in cows	
nsz	no. of new shoots produced by plant	
oldmede	metabolisable energy of the old dead leaves	
p	coefficient of Blaxter and Boyne's energy balance equation for cow	
pach1	potential alimentary capacity of grass	

pact1	potential alimentary capacity of woody plants	
pcg	protein content of the gain in cow	
ph1	potential intake of grass	
plant	grass /shrub	g/m^2
pottr	potential transpiration	
pt1	potential intake of woody plant leaves and twigs	
Qage	plant age multiplier	
Qdiet	fraction of gross energy metabolisable in cow	
Qgtdiet	fraction of gross energy metabolisable in goat	
QIH1	quality index in bite of grass	
QIT1	quality index in bite of woody vegetation	
Qmoist	moisture multiplier	
Qrl	growth rate of woody plant leaf	
Qrs	growth rate of woody plant twig.	
Qsoil	soil depth multiplier	
Qtemp	temperature multiplier	Celsius
Qtrans	ratio of total transpiration to humidity.	
rain	rainfall	mm
raintot	total rainfall	mm
Rescarb	reserved carbohydrates	
Rescmax	maximum reserved carbohydrates	
Resgro	growth of plant reserves	
RH1	relative frequency of herbage (grass).	
RT1	relative frequency of woody vegetation	

root	grass root	
rootal	root allowance of carbohydrates	
shoot	grass shoot	g/m^2
SI	selectivity index	
Start	a switch	
stem	woody plant stem	"
stemgro	growth of stem	
StorC	storage of carbohydrates	
substr	substrate in grass	
sumpac	sum of the potential alimentary capacities	
TCDH1	theoretical contribution of grass to diet	
TCDT1	theoretical contribution of woody plants to diet	
temp	daily temperature	Celsius
TG	woody plant growth	
TGdays	woody plant growth days	
TGweeks	woody plant growth weeks	
tinfl	woody plant inflorescence	g/m^2
tinflgr	growth of woody plant inflorescence	
tleaf	woody plant leaf	g/m^2
tleafgr	growth of woody plant leaf	
totrans	total transpiration by grass	
tpopt	woody plant population at time t	$plants/m^2$
trans A	transpiration from store A	
transB	transpiration from store B	

trans C	transpiration from store C	
trans D	transpiration from store D	
treeht	height of woody plant	m
trotgro	growth of woody plant root	
tsgrow	growth of woody plant shoot	
tstorC	storage of carbohydrates by woody plant	
ttrans	woody plant transpiration	
twig	twig of woody plants	g/m^2
twiggro	growth of twig	
watpot x	water potential of shallow soil	kpa
watpot y	water potential at 2.5 m soil depth	"
weeks	weeks of the year	
weight	weight of cow	kg
wood	population of woody plants from leslie-matrix estimate.	plants/m^2
wtleaf	weight of leaf	g
wtshoot	weight of shoot	g
xwat	intermediate variable in calculating water potential	
Xgoat	fraction of maturity of weight of goat	
xwt	fraction of mature weight in cow	
xot1....x4t1	population of plants in each cohort at time t + 1.	plants/m^2

INTERNAL VARIABLE	DEFINITION	UNIT
ACltdie	accelerated dead of woody plants	
ADJDM	adjustment factor for the amount of shoot	
Awmax	coefficient of body composition equation.	
bwmax	"	
Bke	coefficient of Blaxter and Boyne equation	
cpculm	content of protein in culm	
cpdeadl	" " in dead grass leaf	
cpddtlf	" " in dead woody plant leaf	
cpdecu	" " in dead culm	
cpgleaf	content of protein in grass green leaf	
cpinfl	" " in grass inflorescence	
cpmean	mean content of protein	
cpreq	crude protein requirement	%
cptinl	" " in woody plant inflorescence	
cptleaf	content of protein in woody plant leaf	
cptot	total protein content	
cptt1	content of protein in woody vegetation	
cptwig	content of protein in twig	
culmgmx	maximum growth of culm	
dayinyear	day in the year	
ddmi	digestible dry matter intake	
decdead	decay of dead grass leaves	g/m^2

decdecu	decay of dead culm	"
decdein	decay of dead grass inflorescence	"
decolde	decay of old dead grass leaves	"
digculm	digestibility of culm by goat	"
digdecu	digestibility of dead culm by goat	"
digdelf	digestibility of dead grass leaf by goat	"
digdetl	digestibility of dead woody plant leaf by goat	"
diginfl	digestibility of grass inflorescence by goat	"
digtinf	digestibility of woody plant inflorescence by goat	"
digglea	digestibility of grass green leaf by goat	"
digtlea	digestibility of woody plant leaf by goat	"
digtwig	digestibility of twig by goat	"
FR	fraction of potential evaporation	
frdead	fraction of dead grass leaves	
frdec	fraction of decay	
frdecde	fraction of decay of dead leaves	
frdecu	fraction of dead culm	
frdedi	fraction of dead grass leaves in diet	
frdeinf	fraction of dead inflorescence in grass	
frdindi	fraction of dead grass inflorescence in diet	
frdstdi	fraction of dead stem in diet	
frdtinf	fraction of woody plant dead inflorescence	
frdtfdi	fraction of dead woody plant inflorescence in diet	
frolddi	fraction of old leaves in diet	

frolde	fraction of old dead grass leaves
frtoldi	fraction of woody plant old dead leaves in diet
goatFCG	fat content of goat
goatpcg	protein content of goat
grred	reduction in growth as soil dries up
gtamax	coefficient of body composition for goat
gtbmax	"
indmort	induced mortality of woody plants
inflgmx	max. growth of grass inflorescence
intdedin	goat intake of dead inflorescence
intdedtf	goat intake of dead woody plant inflorescence
intdedtl	goat intake of dead woody plant leaf
intinfl	goat intake of grass inflorescence
inttinf	goat intake of woody plant inflorescence
k	coefficient of transpiration
ktrin	index of transpiration
leafgro	growth of grass leaf
lgrmax	max. growth of grass leaf
ligculm	lignin content of the culm
ligdecu	lignin content of dead culm
ligddtl	lignin content of dead woody plant leaf
ligdedl	" " dead grass leaf
ligglea	lignin content of grass green leaf
liginfl	" " of grass inflorescence

ligth1	lignin content of grass	
ligtinfl	lignin content of woody plant inflorescence	
ligtlea	lignin content of woody plant leaf	
ligtt1	lignin content of woody plants	
ligtwig	lignin content of twig	
MECU	metabolisable energy of culm?	kj/day
MEgtDI	metabolisable energy of the goat diet	"
mort	mortality of plants	
natmort	natural mortality of plants	
NAST	new value of TAST after drainage	mm
NBST	new value of TBST after drainage	"
NCST	new value of TCST after drainage	"
NWT	new weight of animal	kg
potinfil	potential infiltration	
propast	proportion of AST	mm
propBST	" BST	"
propCST	" CST	"
propDST	" DST	"
pseff	relates accumulation of substrate to age of plant	
pvap	potential evaporation	%
rootgmx	maximum growth of grass root	
rcgrmax	maximum growth of reserved carbohydrate	
season	season of the year	
smtrin	soil moisture transpiration index	

sumpref	sum of the food preferences by animal	
stemgmx	maximum growth of stem	
TAST	total AST after drainage	mm
TBST	" BST " "	"
TCST	" CST " "	"
TDST	" DST " "	"
tinfgmx	max. growth of woody plant inflorescence	
tlgrmax	max. growth of woody plant leaf	
TOTH1	total amount of grass available	g/m^2
TOTST	total amount of moisture in the soil	mm
TOTT1	total amount of eatable woody vegetation	g/m^2
trcgrmx	max. growth of woody plant carbohydrates	
trotgmx	max. growth of woody plant root	
tsubstr	woody plant substrate	
twiggmx	max. growth of twig	
VOLAST	volumetric moisture in AST	mm
VOLBST	" BST	"
VOLCST	" CST	"
VOLDST	" DST	"
WtCh	weight change by animal	kg/day
yint	voluntary intake of food	

PARAMETER	DEFINITION	UNITS
a1...a9	undefined parameters of Teague (1987)	
abite	parameter determining bite size of animal	
adig	parameter that calculates digestibility from crude protein content	
af	parameter of equations relating fat content to body weight of animal	
age	age of the animal	days
aj	parameter in the estimate of functional response of a cow.	
ak	parameter in the estimate of functional response of a goat.	
Alpha12	coefficient for the effect of grass on woody vegetation	
Alpha21	coefficient for the effect of woody vegetation on grass	
aMEDE	parameter for estimating the metabolisable energy of dead leaves	
amoist	emperically determined parameter	
ap	coefficient of body compositin equation	
api	parameter of the select model	
arl	parameter of woody plant leaf growth rates equations	
atemp	average daily air temperature	Celsius
atmin	mean 15 day minimum temperature	Celsius
astmax	maximum amount of moisture in A layer	mm
bdia	basal diameter of woody plant	mm
bbite	defines the size of the optimum bite of the cow	

bdig	parameter of digestibility of ingested food.	
bf	Butterfield's parameter in estimating the fat content of the animal body.	
bgtbite	defines the size of the optimum bite of the goat	
birthwt	birth weight of animal (calf)	kg
bMEDE	estimate of the metabolisable energy of dead leaves	
bp	parameter of Butterfield body composition equation.	
bpi	parameter of the select model	
breed	type of animal breed	
brl	regression parameter in the estimate of tleaf growth rates.	
Bstart	minimum amount of moisture in B layer required to initiate growth .	mm
BSTmax	maximum amount of moisture in B layer	mm
btemp	amplitude of the daily temperature graph	
bwat	parameter of Teague's equations.	
CD1	basal mortality rate per day irrespective of condition of animal (cow).	
CD2	a parameter of the conception rates equations	
CD3	critical animal body condition below which probability of mortality increases	
cMEDE	an estimate of the metabolisable energy of dead leaves	kj/day
cowha	no. of cows per hactare	anim./ha
crl	parameter in the estimate of tleaf growth rates.	
CSTmax	maximum amount of moisture in C layer	mm

cswitch	a switch that calls-off cows.	
culmmax	maximum amount of culm	g/m^2
decdry	plant decay caused by dryness	
depcarb	depleted carbohydrates	
dt	integration step	
ECCAP	environmental carrying capacity for woody plants	$plants/m^2$
Epan	potential evaporation from an open surface of water	
f0....f4	fecundity rates of woody plants	
Fdmmat	faecal dry matter output at maturity	
Femat	faecal output for mature animal.	
fm	cow fasting metabolism	
Fmax	parameter of Butterfield equation for body composition in cow.	
Frcarb	fraction of carbohydrates in grass	
Frtcarb	fraction of carbohydrates in woody plant	
goatFm	goat fasting metabolism	
goatha	no. of goats per hactare	anim./ha
goatmax	maximum goat weight	kg
goatqf	maturity coefficient for goat in Butterfield equation.	
goatqp	"	
GrECCAP	Environmental carrying capacity for grass.	g/m^2
gswitch	a switch that calls-off goats.	

gtfmax	parameter of Butterfield equation for body composition in goat.	
gtpmax	parameter of Butterfield equations for body composition in goats	
humid	humidity	
inflmax	maximum inflorescence in grass	g/m^2
inflmin	minimum inflorescence in grass	"
jfdm	parameter calculating the intake by goats limited by capacity of digestive system	
kAST	parameter for calculating average value of AST over a 120 days	mm
kscu	Michaelis-Menten growth parameter for culm	
kshoot	" for shoot	
ksinf	" for inflorescence	
ksr	" for reserved carbohydrates	
ksroot	" for root	
ksstem	" for stem	
kstinfl	" for woody plant inflorescence	
kstlg	" for woody plant leaf	
kstroot	" for woody plant root	
kstwig	" for twig	
leafmax	max. amount of grass leaf	g/m^2
maxbite	max. no. of bites by cow	bites/day
maxgtbi	max. no. of bites by goat	"
medecu	metabolisable energy of dead culm	k j/day
medeinf	metabolisable energy of dead grass inflorescence	"

megl	metabolisable energy of grass green leaf	"
meinfl	metabolisable energy of grass inflorescence	"
metleaf	metabolisable energy of woody plant leaf	"
metwig	metabolisable energy of twig	"
minleaf	min. amount of grass green leaf	g/m^2
mmoist	emperically determined parameter	
mtemp	"	
muculm	Michaelis-Menten parameter for maximum growth of culm. (MM for culm)	
mugleaf	MM for grass green leaf	
muinfl	MM for grass inflorescence	
muresc	MM for reserved carbohydrates	
muroot	MM for grass root	
mustem	MM for stem	
mutinfl	MM for woody plant inflorescence	
mutleaf	MM for woody plant leaf	
mutresc	MM for woody plant reserved carbohydrates	
mutroot	MM for woody plant roots	
mutwig	MM for twig	
newdays	days when animals are replaced at start of new year	
newgen	energy for the new goats	kj/day
newen	energy for new cows	"
newgwt	weight of new goat	kg
newwt	weight of new cows	"
oldeadl	old dead leaves	g/m^2
order	no. of differential equations	
peakwt	highest weight that an animal has ever reached in its life	kg
pmax	maximum possible protein in animal.	
prefcu	preference of culm	

prefdcu	" dead culm	
prefde	" dead grass leaves	
prefdin	" dead inflorescence	
prefdst	" dead stem	
prefdtf	" dead grass inflorescence	
prefdtg	" dead twig	
prefgl	" grass green leaf	
prefinf	" grass inflorescence	
prefold	" old grass leaf	
prefstm	" stem	
preftde	" woody plant dead leaf	
preftif	" woody plant inflorescence	
preftl	" " leaf	
preftod	" " old dead leaf	
preftwig	" twig	
qf	maturity coefficient in Butterfield equation	
qdm	parameter for the adjustment of dry matter	
qdmi	maturity coefficient of faecal dry matter output	
qmort	parameter of leaf growth equation	
qp	maturity coefficient	
r1	intrinsic growth rate of woody plants	
r2	intrinsic growth rate of grass	
rootmax	max. amount of grass root	g/m^2

runtime	time for which the model is run (when $dt = 0.1$, runtime = 3650 runs the model for 365 days).	
skakel	switch for selecting body composition equations.	
soildep	soil depth	m
stemmax	maximum amount of stem	g/m^2
switch	a switch that calls-off herbivores.	
teha	woody plant equivalence per ha	plants/ha
tinflmx	max. amount of woody plant inflorescence	"
tleafmax	max. amount of woody plant leaf	"
tmax	mean 15 day max temperature	Celsius
tmin	mean 15 day min. temperature	"
tranco	efficiency of use of transpired water for growth.	
trescmax	max. reserves of carbohydrates in woody plant	
troot	woody plant root	g/m^2
trootmax	max. amount of woody plant root	"
twigmax	max. amount of twig	"
wmax	max. weight of cow	kg

These are the values of the parameters:

{From both the literature and the estimations, some parameters have no units. Parameters that are estimates were estimated in view of the output given by the variables they are "linked" to. For instance, the parameter aj was estimated such that the functional response of the cow cannot exceed 1.}

PARAMETER	value	motivation/reference
a1	1.19036943	value of Teague (1987).
a2	-0.4480360	"
a3	0.21760062	"
a4	-8.8797112 E-04	"
a5	-7.3251192 E-06	"
a6	1.9779672 E-03	"
a7	-1.1573229 E-03	"
a8	1.3654734 E-05	"
a9	-7.6644131 E-06	"
abite	0.0024	an estimate
adig	0.432	"
af	0.00393	ARC (1980)
age	370 days	the estimated age of a steer (around 1 yr)
aj	0.1	an estimate
ak	0.11	"
Alpha12	0.13	"
Alpha21	1.32	"
aMEDE	8.5	an estimate
amoist	0.0129	Teague (1987)
ap	0.278	ARC (1980)

arl	0.7248	an estimate
atemp	13 degrees Celsius	within the range of 11-13.5 ^{0}C given by Menaut & cesar (1982)
atmin	0.2793 degrees Celsius	Teague (1987)
astmax	25.5 mm	Dye (1983) model
bdia	109.413 mm	an estimate
bbite	0.0000058 kg/mm arcade/bite"	
bdig	0.0001245	"
bf	0.788	ARC (1980)
bgtbite	0.00000085	an estimate
birthwt	30 kg	assumed value for African breeds
bMEDE	0.00417	an estimate
bp	-0.1107	ARC (1980)
bpi	0.23	an estimate
breed	0.0029047	Richardson (1999), personal communication.
brl	2.1202	an estimate
Bstart	40 mm	Dye (1983) model
BSTmax	71.5 mm	"
btemp	12.5 degrees Celsius	an estimate
bwat	0.271	"
c2	0.1	estimated such that cow population can increase by 80% per year.
c3	0.106	estimated such that goats can double per given year.

CD1	0.000028	Richardson (1999), personal communication.
CD2	0.5	"
CD3	0.6	"
cMEDE	7.45 kj/day	an estimate
cowha	0.1 anim./ha	this can be changed to any value.
crl	0.11761	an estimate
CSTmax	102.5 mm	Dye (1983) model
cswitch	0 or 1	can be any of the 2 values.
culmmax	80 g/m^2	an estimate
d2	0.196	estimated such that cattle population can increase by 80% per year.
d3	0.21	estimated such that goats can double per given year.
decdry	0.01	an estimate
depcarb	10	"
dt	0.1	this can be changed to any value.
ECCAP	7130 plants/ha	chosen to be just above Rutherford's (1984) figure of 7120 plants/ha.
Epan	70	an estimate
f0	0	young woody plant age class produces no "offsprings"
f1	0.02	estimated according to the number of "offsprings" the plant age group can produce.
f2	0.32	"
f3	1.2	"
f4	6.12	"

Fdmmat	3.038	Richardson (1999), personal communication
Femat	1.65	"
fm	0.63	ARC (1980)
Fmax	286.2	Richardson (1999), personal communication
Frcarb	0.3	an estimate
Frtcarb	0.4	"
goatFm	0.31	AFRC (1998)
goatha	0.1 anim./ha	this can be changed to any value.
goatmax	80 kg	estimated from Brown & Taylor, 1986. They gave 38- 70.1kg for adult female goat, & it should weigh less than the adult male goat.
goatqf	0.21	an estimate
goatqp	1.11	"
GrECCAP	70 g/m^2	"
gswitch	0 or 1	can be any of the 2 values.
gtfmax	12.5	an estimate
gtpmax	7	"
humid	0.72	> 70% (Menaut & Cesar,1982).
inflmax	45 g/m^2	an estimate
inflmin	0.08g/m^2	"
kAST	0.00833 mm	"

The highlighted parameters below are estimated in view of the Michaelis-Menten equations, smaller for plant components with bigger growth rates:

kscu	1.43	
kshoot	120	
ksinf	1.61	
ksr	1.72	
ksroot	1.9	
ksstem	1.87	
kstinfl	1.2	
kstroot	1.96	
kstwig	1.78	
leafmax	130 g/m^2	an estimate
maxbite	38000 bites/day	Richardson (1999), personal communication.
maxgtbi	34000 "	an estimate from the fact that a goat eats faster but retires earlier.

The parameters in italics below are estimated on a scale of 15 according to the amount of metabolisable energy in each plant component:

medecu	7 k j/day	
medeinf	7 "	
megl	11 "	
meinfl	7 "	
metleaf	10 "	
metwig	7.2 "	
minleaf	0.2 g/m^2	an estimate
mmoist	0.01669	Teague (1987)
mtemp	138.399	Teague (1987)

The values of the parameters in italics below are estimates based on the growth rates of the plant components on a scale of 1. The plant component with the highest growth rate having a higher value. Their sensitivity is discussed later.

muculm	0.36	
mugleaf	1	
muinfl	0.34	
muresc	0.4	
muroot	0.4	
mustem	0.013	
mutinfl	0.045	
mutleaf	0.75	
mutresc	0.021	
mutroot	0.016	
mutwig	0.54	
newdays	0	the start of a new year at day zero
newgen	800 kj/day	body energy estimate in young goat
newen	1946 "	body energy estimate in steer
newgwt	30 kg	estimated weight of a young goat
newwt	250 "	estimated weight of a steer
order	38	there are 38 differential equations in the model.
peakwt	401.987 kg	Richardson (1999), personal communication.
pmax	140.25	"

The preferences below were measured on a scale of 10, with the highest being the most prefered plant component by the cow

prefcu	6	
prefdcu	3	
prefde	4	
prefdin	1	
prefdst	0.03	
prefdtf	1.2	
prefdtg	0.043	
prefgl	10	
prefinf	3	
prefold	2	
prefstm	0.02	
preftde	0.03	
preftif	0.034	
preftl	0.07	
preftod	0.2	
preftwg	0.06	
qf	0.21	taken from a model by Richardson, 1997. (unpublished)
qdm	3	"
qdmi	2.41	"
qmort	0.92	Teague (1987).
qp	1.11	an estimate
r1	0.027	"
r2	0.034	"

runtime	3650	can be changed depending on length of time (days) the model needs to be run.
skakel	1or 2	it can be any of the 2 values.
soildep	1.5 m	within the range of 0.7-2m given by Rutherford (1984)
stemmax	65.8 g/m^2	Rutherford (1984)
switch	1 or 2	it can be any of the 2 values.
teha	1000 plants/ha	an estimate
tinflmx	38 g/m^2	an estimate
tleafmax	126.4 g/m^2	Rutherford (1984)
tmax	24 degrees Celsius	very close to 24.2^0C, Huntley & Morris (1982).
tmin	8 degrees Celsius	close to 6 degrees celsius given by Rutherford (1984)
tranco	140	an estimate
trescmax	5.13912	"
trootmax	25.1 g/m^2	close to the value of 22.3 given by Rutherford (1984)
twigmax	27.1 g/m^2	Rutherford (1984).
wmax	600 kg	ARC (1980).

A3 SAVANNAS AND RAINFALL FILES

```
{ Interactive Modelling Package: B D Hahn and P R Furniss, 1988: Version 4.2 }
{ non-standard reading of rainfall data included }
(* The compiler directive
     {$A-}
  is required at this point only for Turbo Pascal 4.0 *)
procedure DiffPart1;
{ handles stuff to DiffEquns which was too large to handle }
begin
{Driver's model: Runge-Kutta used optionally}
```

{All parameters and variables are declared in SAVANNAS as shown by the layout below:}

```
{Internal variables are declared here.........}

FR, PVAP, K, PSEFF, LEAFGRO, SMTRIN:REAL;
CPMEAN, CPTOT,.......................................:REAL;
etc

{Driver variables.....}
AST  :{$IFOPT N+} double {$ELSE} real {$ENDIF} absolute FV1;
BST  :{$IFOPT N+} double {$ELSE} real {$ENDIF} absolute FV2;
CST  :{$IFOPT N+} double {$ELSE} real {$ENDIF} absolute FV3;
.
.
.etc

{Driver parameters.....}
runtime : {$IFOPT N+} double {$ELSE} real {$ENDIF} absolute V0;
Order   : {$IFOPT N+} double {$ELSE} real {$ENDIF} absolute V1;
dt      : {$IFOPT N+} double {$ELSE} real {$ENDIF} absolute V2;
.
.
.etc


{ Calculation of evaporation from soil surface }
 IF SHOOT<=0 THEN
   PVAP:= 0.02 ELSE  {just a figure}

PVAP:= (EPAN/7) * (1.0 - (0.0422 + 0.1537 * ln(SHOOT)));
IF AST > 24.0 THEN              {grass have more influence than trees}
  FR:= (0.4667 * AST) - 10.9 ELSE
  FR:= (0.0375 * AST) - 0.6;
IF FR < 0 THEN
```

```
      FR:= 0 ELSE
      FR:= FR;
    EVAP:= FR * PVAP;

  { Calculation of transpiration rate }
   IF SHOOT <90 THEN
      K:= 0.018 - (0.00015*SHOOT) ELSE
      K:= 0.00483 - (3.3E-006*SHOOT);
  POTTR:= GLEAF*(EPAN/7) * K;
 tPOTTR:= tleaf*(EPAN/7)*K;
  TOTST:= AST + BST + CST;
 SMTRIN:= (0.043*TOTST) - 3.73; {GRASS roots go down to C}
    IF SMTRIN > 1 THEN
      KTRIN:= 1 ELSE
    IF SMTRIN < 0 THEN
      KTRIN:= 0 ELSE
      KTRIN:= SMTRIN;
    TOTRANS:= KTRIN * POTTR;
   tTOTRANS:= KTRIN * tPOTTR;
     TTrans:= dTgrow / Tranco;
 { Depletion of soil water stores by transpiration }
     VOLAST:= AST/0.88;
     VOLBST:= BST/2.46;
     VOLCST:= CST/3.54;
     VOLDST:= DST/4.53;
     VOLTST:= VOLAST + VOLBST + VOLCST + VOLDST;
     PROPAST:= VOLAST/VOLTST;
     PROPBST:= VOLBST/VOLTST;
     PROPCST:= VOLCST/VOLTST;
     PROPDST:= VOLDST/VOLTST;
     TRANSA:= PROPAST * (TOTRANS + Ttrans);
     TRANSB:= PROPBST * (TOTRANS + Ttrans);
     TRANSC:= PROPCST * (TOTRANS + Ttrans);
     TRANSD:= PROPDST * Ttrans;
     QTRANS:= TOTRANS / HUMID;
    tQTRANS:= tTOTRANS / HUMID;
   IF TOTST < 95 THEN
     GRRED:= 0 ELSE
     GRRED:= 1 - EXP(-0.183 *(TOTST - 95));


 {****************************************************************}

  {GRASS GROWTH MODEL:BEGINS}

   IF Substr<=0 THEN
     Substr:= 0.01;
```

```
 {growth rate of gleaf}
  IF Gr = 0 THEN
    Gd:= 0 else
    gd:= 0.12;


 IF (days > 270) and (temp <10) then
 BEGIN
  gr:=0;
GRDAYS:= GRDAYS;
Gleaf:= GLEAf - 0.1*gleaf*(364 -DAYS);
 END;

 { Michaelis-Menten partition of nutrients}      [section 3.2.1]

 If GRDAYS = 0 Then
  Begin

   Leafgro:= 0;          {Nutrients partitioned between leaf,}
     StorC:= 0;          {carbohydrate stores, roots, culms}
   Rootgro:= 0;          {inflorescence}
   Culmgro:= 0;
   Inflgro:= 0;
  GLEAF:= RESGRO;
  End
  Else
 IF QTRANS <= 0 then
 Begin
   Lgrmax:= 0;
  Leafgro:= 0;
  gleaf:= 0;
 RCgrmax:= 0;
   StorC:= 0;
  Rootgmx:= 0;
  RootGro:= 0;
  Culmgmx:= 0;
  Culmgro:= 0;
  Inflgmx:= 0;
  Inflgro:= 0;
 End
 Else        {Growth of green leaves, roots, stored carbohydrate}
Begin
 IF GLEAF<=0 THEN
 lgrmax:= 0 else
 Lgrmax:= 1 - Exp ( 1 * Ln ( GLeaf / Leafmax ));
 Lgrmax:= Lgrmax * muGleaf * Gleaf;
 LEAFGRO:= Lgrmax / ( 1 + Ksg / SUBSTR );
 IF ROOT<=0 THEN
```

```
      ROOTgmx:= 0 else
      RootgMx:= 1 - Exp ( 1 * Ln ( Root / Rootmax ));
      RootgMx:= RootgMx * muRoot * ROOT;
      RootGro:= RootGmx / ( 1 + ksroot / SUBSTR );
      ResCmax:= FrCarb * ROOT;
      StorC:= MuResC * ROOT * ( ResCmax - RESCARB );
      StorC:= StorC / ( 1 + ksr / SUBSTR );
     End;
     If StorC <= 0 Then
       StorC:= 0;

    IF CULM <= 0 then
     Begin
      Culmgmx:= 0;
      Culmgro:= 0;
      end else
     Begin
      Culmgmx:= 1 - Exp ( 1 * Ln ( Culm / Culmmax ));
      Culmgmx:= Culmgmx * muCulm * CULM;
      Culmgro:= Culmgmx / ( 1 + kscu / SUBSTR );
        CULM:= CULM;
    End;
    IF INFLOR <= 0 then
    Begin
     Inflgmx:= 0;
     InflGro:= 0;
     End else
     Begin
      Inflgmx:= 1 - Exp ( 1 * Ln ( INFLOR / Inflmax ));
      Inflgmx:= Inflgmx * muInfl * INFLOR;
      InflGro:= Inflgmx / ( 1 + ksinf / SUBSTR );
       INFLOR:= INFLOR;
    End;

{partition of growth between different plant parts }

  IF GRDAYS < 98 THEN
    CULMAL:= 0 ELSE
  IF GRDAYS < 210 THEN
    CULMAL:= (GRDAYS * 0.0008928) - 0.0875 ELSE
  IF GRDAYS < 224 THEN
    CULMAL:= 0.8 - (GRDAYS *  0.00357) ELSE
    CULMAL:= 0;
  IF GRDAYS < 98 THEN
    INFLAL:= 0 ELSE
  IF GRDAYS < 210 THEN
    INFLAL:= (GRDAYS*0.0004429) - 0.0434 ELSE
  IF GRDAYS < 224 THEN
```

```
        INFLAL:= 0.8 - (GRDAYS*0.003571) ELSE
        INFLAL:= 0;
        ROOTAL:= 1 - LEAFAL - CULMAL - INFLAL;


  { Death of green leaves }
    IF SHOOT < 20.0 THEN
      GLDIE:= 0 ELSE
    IF GRWEEKS < 18 THEN
      GLDIE:= 0.00171 else
      GLDIE:= 0.00011 * GRWEEKS - 0.000286;
    IF TOTST < 110.0 THEN
      ACLDIE:= ( 10.57 - 0.087 * TOTST ) * GLDIE ELSE
      ACLDIE:= GLDIE;

     Totgrgr:= leafgro + rootgro + culmgro + inflgro;

  {fractions of plant components}       [section 3.4.1]

   FRGLEAF:= GLEAF/SHOOT;
  IF FRGLEAF<0 THEN
   FRGLEAF:=0;
   FRDEAD:= DEADLEA/SHOOT;
  IF FROLDE<0 THEN
   FROLDE:=0;
   FROLDE:= OLDEADL/SHOOT;
  IF FROLDE<0 THEN
   FROLDE:=0;
   FRCULM:= CULM/SHOOT;
  IF FRCULM<0 THEN
   FRCULM:=0;
   FRINFL:= INFLOR/SHOOT;
  IF FRINFL<0 THEN
   FRINFL:=0;
   FRDECU:= DEDCUlm/SHOOT;
  IF FRDECU<0 THEN
   FRDECU:=0;
   FRDEINFl:= DEADINF/SHOOT;
  IF FRDEINFl<0 THEN
   FRDEINFl:= 0;

 {GRASS GROWTH MODEL: ENDS}
{*****************************************************************}

  FRtleaf:= tleaf/tshoot;
 IF FRTLEAF<0 THEN
  FRTLEAF:=0;
  if frtleaf> 1 then
```

```
   frtleaf:=1;
   FRtdeadl:= deadtlf/tshoot;
  IF FRTDEADl<0 THEN
   FRTDEADl:=0;
   FRstem:= stem/tshoot;
  IF FRSTEM<0 THEN
   FRSTEM:=0;
   FRtwig:= twig/tshoot;
  IF FRTWIG<0 THEN
  FRTWIG:=0;
  FRtinfl:= tinfl/tshoot;
  IF FRTINFL<0 THEN
  FRTINFL:=0;
   FRDtwg:= DEADtwg/tshoot;
  IF FRDTWG<0 THEN
   FRDTWG:=0;
  FRDtinf:= DEADtif/tshoot;
   IF FRDTINF<0 THEN
  FRDTINF:= 0;

{CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC}


{Selection of diet by cattle}          [section 3.4.1]
  SUMPref:= FRGLEAF*prefGL +  FRDEAD*prefDE + FRCULM*prefCU;
  SUMPref:= SUMPref + FROLDE*prefDE + FRtwig*preftwg + FRtleaf*preftl;
  SUMPref:= SUMPref + FRINFL*prefINF + FRDECU*prefDCU +
FRDEINFl*prefDIN;
SUMPref:= SUMPref + FRtinfl*preftif;
FRGLdi:= FRGLEAF * prefGL /SUMPref;
FRDEdi:= FRDEAD * prefDE / SUMPref;      {Fraction of component in diet}
FROLDdi:= FROLDE * prefOLD / SUMPref;   {depends on  preference and}
FRCUdi:= FRCULM * prefCU / SUMPref;      {component as fraction of shoot}
 FRINFdi:= FRINFL * prefINF / SUMPref;    {ORSINI, 1990}
 FRDCudi:= FRDECU * prefDCU / SUMPref;
 FRDIndi:= FRDEINFl * prefDIN / SUMPref;
 FRtlfdi:= frtleaf * preftl/sumpref;
 FRtdedi:= frtdeadl * preftde/sumpref;
 FRtifdi:= frtinfl * preftif/sumpref;
 FRdtfdi:= frdtinf * prefdtf/sumpref;
 FRtwgdi:= frtwig * preftwg/sumpref;
 FRdtwdi:= frdtwg * prefdtg/sumpref;

IF GRDAYS < 10 then
 MEold:= OldMEDE Else                  {ME = metabolisable energy}
 MEold:= cMEDE;                      {ME of dead and last years}
IF GRDAYS < 30  then                   {dead leaves}
 MEDE:= aMEDE else
```

```
   MEDE:= aMEDE - bMEDE * ( GRDAYS - 30 );
 IF MEDE< cMEDE THEN
   MEDE:= cMEDE;
  MEDIET:= MEGL*FRGLDi +  MEDE*FRDEDi + MECU*FRCUDi;
  MEDIET:= MEDIET + MEold*FROLDDi + MEtleaf*FRtlfdi + MEtwig* FRtwgdi;
  MEDIET:= MEDIET + MEINFL*FRINFDi + MEDeCU*FRDCuDi +
 MEDeINF*FRDInDI;
  qDIET:= MEDIET / 18.4;  {qDiet is fraction of gross energy metabolisable}
                         {18.4 is GE of 1 kg herbage}
                         {qDMI is maturity}
                         {coeffient of faecal dry matter output}

 XWT:= WEIGHT/Wmax;      {fraction of mature weight}
 NWT:= Wmax - birthwt;
 NWT:= NWT *  EXP(-CN1*Age/exp(0.27*ln(wmax)));
 NWT:= Wmax -NWT;
 IF NWT > Wmax THEN
 NWT:= Wmax;

 Yint:= qDMI * Xwt + ( 1 - qDMI ) * Xwt * Xwt; {DF/Dt}
FEDMI:= YInt * FDMmat / ( 1 - qdiet/0.82);
                        {FeDMI is dry matter intake limited by }
                        {capacity of digestive system}

SHOOTER:= SHOOT + 0.2*(TLEAF + TWIG); {the cow will eat about 20%}
 IF SHOOTER<=0 THEN
   ADJDM:= 0 ELSE
   ADJDM:= ADJDM;

{adjustment factor for herbage growth}          [section 3.4.2]
ADjDM:= Exp ( qDM * Ln ( Shooter/kShoot ));
 ADjDM:= ADjDM/(1+Exp(qDM * Ln(Shooter/kShoot)));

 OLDARC:= ARCADE;
 ARCADE:= 7.8* EXP(0.29*LN(WEIGHT))*EXP(0.36*LN(Wmax));
 IF OLDARC > ARCADE Then
   ARCADE:= OLDARC;

BiDMI:= Maxbite * bBite *Arcade*AdjDM;     {this is in kg/day}
                   {BiDMI, intake limited by biting rate &  bite size}
IF FeDMI < BiDMI then
  DMI:= FeDMI Else     {Mechanism limiting intake}
  DMI:= BiDMI;
```

```
    GE:= 18.4 * DMI;     {Gross energy intake}          [section 3.4.3]
    Hb:= Fm * Exp ( 0.67 *Ln ( WEIGHT )); {Basal energy metabolism}
     g:= GE / hB;                      {Scaled gross energy intake}

   EGM:= 0.503 * qDIET + 0.35 * qDIET * qDIET; {Efficiencies of use of}
  IF EGM<= 0 THEN
   EGM:= 0.011;                  {.....gross energy for maintenance and growth}
   EGG:= 0.006 * qDIET + 0.78 * qDIET * qDIET;
  IF EGG <= 0 THEN
   EGG:= 0.008;
   Bke:= EGM / ( EGM - EGG );    {Bke & p are coefficients of Blaxter &}
     p:= EGM * Ln ( EGM / EGG ); {Boyne 1978 energy balance equation}

  IF SWITCH = 0 THEN         {switch calls off herbivores}
   BEGIN
   COWS:=0;
  COWHA:=0;
  GOATS:=0;
 GOATHA:=0;
   BGPI:=0;
    GPI:=0;
   END;

 IF CSWITCH = 0 THEN        {Cswitch calls off cattle}
   BEGIN
   COWS:=0;
  COWHA:=0;
  END;

 IF GSWITCH= 0 THEN         {Gswitch calls off goats}
   BEGIN
   GOATS:=0;
  GOATHA:=0;
  END;

{GRAZING BY CATTLE}
 CGzGLEA:= DMI * FRGLdi * cowha*0.1 ;
 CGzDEAD:= DMI * FRDEdi * cowha*0.1 ;  {Amounts of plant components}
 CGzOLDE:= DMI * FROLDdi * cowha*0.1;  {removed by grazing: number of}
 CGzCULM:= DMI * FRCUdi * cowha*0.1 ;  {animals/ha, DM intake and}
 CGzINFL:= DMI * FRINFdi * cowha*0.1 ; {fraction of component in diet}
 CGzDECU:= DMI * FRDCudi * cowha*0.1 ;
 CGzDINF:= DMI * FRDIndi * cowha*0.1;
  CGzTLf:= DMI * FRTLfdi*cowha*0.1;    {units are: g cow/day}
 CGzTWIG:= DMI * FRTWGdi*cowha*0.1;
 CGzTINF:= DMI * FRTIFdi*cowha*0.1;
 CGztded:= DMI * FRtdedi*cowha*0.1;
CGztolde:= DMI * Frtoldi*cowha*0.1;
```

```
  CGzdtwg:= DMI * FRdtwdi*cowha*0.1;
  CGztinf:= DMI * FRtifdi*cowha*0.1;
  CGzdetf:= DMI * FRdtfdi*cowha*0.1;
 {CTGRAZE:= CGZGLEA+CGZDEAD+CGZOLDE+CGZCULM+CGZINFL;
 CTGRAZE:=CTGRAZE+CGZDECU+CGZDINF+CGZTLF+CGZTWIG+CGZTINF
 ;
 CTGRAZE:=CTGRAZE+CGZTDED+CGZTOLDE+CGZDTWG+CGZTINF+CGZ
 DETF;
 CTGRAZE:= (CTGRAZE/COWHA)*10;}

  CfunRes:= 1 - exp(QDIET*LN(aj));      [section 3.4]
  IF CfunRes<0 THEN                   {functional response of cow}
  CfunRes:= 0;

 [section 3.4.3]
  If Skakel = 0 Then
  Begin
    Pcg:= ap * Exp ( bp * Ln ( WEIGHT )); {Fat & protein contents of gain}
    Fcg:= af * Exp ( bf * LN ( WEIGHT )); {according to ARC 1980 equations}
  End Else
  Begin
   aWmax:= 1 / Wmax;           {Fat & protein in 1 kg gain using}
   bWmax:= 1 / ( Wmax * Wmax ); {Butterfield 1988 equations}
    Pcg:= qP * Pmax * aWmax; {fraction of maturity and maturity coefficient}
    pcg:= Pcg + 2 * ( 1 - qP ) * Pmax * bWmax * WEIGHT;
    Fcg:= qF * Fmax * aWmax;
    Fcg:= Fcg + 2 * ( 1 - qF ) * Fmax * bWmax * WEIGHT;
 End;
    Ecg:= 23.6 * Pcg + 39.3 * Fcg;  {Energy content of gain/loss}
 {C\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\}
            {******END**CATTLE*****}

         {##### THE GOAT MODEL: BEGINS #####}

IF GWEIGHT >120 THEN
  GWEIGHT:= 120;

 xgoat:= GWeight/Goatmax; {fraction of mature weight,gtqDMI is maturity}
                  {coefficient of faecal dry matter output}
QGTDIET:= 0.82*gdigest;

SHOOTS:= 0.1*SHOOT + tleaf; {goat shall prefer say 10% of grass}

IF SHOOTS<=0 THEN
 gtADJDM:= 0 ELSE
 gtADJDM:= gtADJDM;
```

```
 {adjustment factor for herbage growth}       [section 3.4.2]
 gtADjDM:= Exp ( gtqDM * Ln ( Shoots/kShoots ));
 gtADjDM:= gtADJDM/(1+Exp(gtqDM * Ln(Shoots/kShoots)));
 gtYint:= gtqDMI * Xgoat + ( 1 - gtqDMI ) * Xgoat * Xgoat; {DF/Dt}
 GtFEDMI:= gtyint* gtFDMmat / ( 1 - gdigest);

                      {GtFeDMI is dry matter intake limited by }
                      {capacity of goat digestive system}

 GtBiDMI:= MaxGtbi * bGtBite *AdjDM*GoARC;
                    {BiDMI , intake limited by biting rate & bite size}

 IF GtFeDMI< GtBiDMI THEN
 GoatDMI:= GtFeDMI ELSE     {mechanism controlling intake}
 GOATDMI:= GtBiDMI;
 if goatdmi=0 then
  goatge:=0;

 [section 3.4.3]
  GoatGE:= 18.4/GoatDMI; {gross energy intake}
  GoatHb:= GoatFm * Exp( 0.75 * ln (Gweight) ); {Basal energy metabolism}
 If goathb=0 then
   goatg:=0 else

   Goatg:= GoatGE/ GoatHb;                {Scaled gross energy intake}
 GoatEGM:= 0.503*qGtDIET + 0.35 * qGTDIET*qGTDIET; {efficiences of use of
 gross energy for maintanance and growth }
 GoatEGG:= 0.006 * qGtDIET + 0.78 * qGtDIET * qGtDIET;
 GoatBke:= GoatEGM / ( GoatEGM - GoatEGG );
 IF GoatEGM<=0 THEN
 GoatEGM:=0.002;
 IF GOATEGG<=0 THEN
 GOATEGG:=0.02;
  GoatP:= GoatEGM * ln (GoatEGM / GoatEGG );

  IF SKAKEL =0 THEN
  BEGIN
  GoatPCG:= GOATap* exp(goatbp*ln(gweight));
  GoatFCG:= Goataf*exp(goatbf*ln(gweight));
  end else
  BEGIN
  Gtamax:= 1 / Goatmax;           {fat and protein in 1kg gain using}
  Gtbmax:= 1 / ( Goatmax * goatmax); {Butterfield 1988 equations}
 Goatpcg:= goatqp * gtpmax * gtamax; {fraction of marturity & maturity coeff.}
  Goatpcg:= goatpcg + 2 * ( 1 - goatqp) * Gtpmax * Gtbmax * GWeight;
 GoatFcg:= Goatqf * GtFmax * Gtamax;
  Goatfcg:= goatfcg + 2 * (1 - goatqf )* GtFmax * Gtbmax * GWeight;
 END;
```

```
GoatEcg:= 23.6 * Goatpcg + 39.3 * GoatFcg;  {Energy content of gain or loss}
OLGOARC:= GoARC;  {Taylor, murray and illius (1987)}
  GoARC:= 7.24* exp (0.29*ln(gweight))*Exp(0.07*ln(Goatmax));
IF OLGoARC> GOARC THEN
  GoARC:= OLGoARC;

{...................................................................}

{SELECTION OF DIET BY GOATS}       [section 3.4.1]

{Calculation of bite size and fraction of leaf in a bite for each species}
If GLEAF <= 0 THEN
GLEAF:= 0.008;
if deadlea<=0 then
deadlea:=0.001;
BiteH1:= 0.32 * Ln (GLeaf + deadlea+culm+dedculm) - abite;
 If BiteH1 < 0 then
   BiteH1:= 0 Else
   BiteH1:= BiteH1;

PH1:= bPI * FrGLeaf + aPI;
If PH1 > 1 Then
PH1:= 1 Else
PH1:= PH1;

PH2:= bpi*frdead + api;
IF PH2 > 1 THEN
PH2:= 1 ELSE
PH2:= PH2;

PH3:= bpi*frdecu + api;
IF PH3 >1 THEN
PH3:= 1 ELSE
PH3:= PH3;

PH4:= bpi*frinfl + api;
IF PH4 > 1 THEN
PH4:= 1 ELSE
PH4:= PH4;

PH5:= bpi*frculm + api;
IF PH5 > 1 THEN
PH5:= 1 ELSE
PH5:= PH5;

PH6:= bpi*frdeinfl + api;
IF PH6 > 1 THEN
PH6:= 1 ELSE
```

```
 PH6:= PH6;

 IF tLeaf<= 0 then
 tLeaf:= 0.1;
 IF DEADTLF<=0 THEN
 DEADTLF:= 0.002;
 IF TWIG<=0 THEN
 TWIG:= 0.1;
 BiteT1:= 0.32 * Ln ( tLeaf + deadtlf + twig) - abite;
  If BiteT1 < 0 Then
   BiteT1:= 0 Else
   BiteT1:= BiteT1;

 PT1:= bPI * Frtleaf + aPI;
 If PT1 > 1 Then
 PT1:= 1 Else
 PT1:= PT1;

 PT2:= bPI*FRtwig + api;
 IF PT2 > 1 THEN
 PT2:= 1 ELSE
 PT2:= PT2;

 PT3:= bpi*FRtdeadl + api;
 IF PT3 >1 THEN
 PT3:= 1 ELSE
 PT3:= PT3;

 PT4:= bpi*FRtinfl + api;
 IF PT4 > 1 THEN
 PT4:= 1 ELSE
 PT4:= PT4;

 PT5:= bpi*FRdtinf + api;
 IF PT5 > 1 THEN
 PT5:= 1 ELSE
 PT5:= PT5;

 {Calculation of protein and lignin contents and quality index, QI}
   CPtleaf:= 14.4 - 0.0385 *grDays;
   Ligtlea:= 26.0 + 0.1037 *grDays;
   CPtwig:= 5.1 - 0.01304 * grDays;
   Ligtwig:= 42 + 0.0667 *grDays;
   CPtINFL:= 7.23 - 0.032 *grDAYS;
   Ligtinfl:= 20.3 - 0.12 * grdays;
   CPddtlf:= 0.4*cptleaf;
   Ligddtl:= 0.4*ligtlea;
   CPTT1:= CPtleaf * Frtleaf + CPtwig * Frtwig + cptinfl*frtinfl;
```

```
      CPTT1:= CPTT1 + CPDDTLF*FRtDEADl;
      LigTT1:= Ligtlea * Frtleaf + Ligtwig * Frtwig + Ligtinfl*frtinfl;
      LigTT1:= LigTT1 + Ligddtl*frtdeadl;
      IF LIGTT1=0 THEN
      QIT1:=0.06 ELSE
      QIT1:= CPTT1 /LigTT1;

      CPgleaf:= 16.0 - 0.0367 *grDays;
      Ligglea:= 26 + 0.0519 * grDays;
      cpdeadl:= 0.5*cpgleaf;
      ligdedl:= 0.4*ligglea;
      CPculm:= 6.08 - 0.01541 * grDays;
      ligculm:= 40.0 + 0.0667 * grDays;
      cpdecu:= 0.38*cpculm;
      ligdecu:= 0.47*ligculm;
      CPINFL:= 4.03 - 0.0127*grDAYS;
      LIGINFL:= 31.0 - 0.0543*grDAYS;
      CPTH1:= CPgleaf * Frgleaf + CPculm * Frculm + CPDECU*FRDECU;
      CPTH1:= CPTH1 + CPINFL*FRINFL + CPDEADL*FRDEAD;
      LigTH1:= Ligglea * Frgleaf + Ligculm * Frculm + Ligdedl*frdead;
      LigTH1:= LigTH1 + liginfl*frinfl + ligdecu*frdecu;
      IF LIGTH1=0 THEN
      QIH1:=0.06 ELSE
      QIH1:= CPTH1 /LigTH1;

  {Calculation of mean CP content of vegetation}
     CPtot:= CPtleaf * tLeaf+cptinfl*tinfl + cpddtlf*tleaf;
     CPtot:= CPtot + CPtwig * twig + CPgleaf * GLeaf + CPculm * culm;
     CPtot:= CPtot + cpdeadl*deadlea + cpdecu*dedculm + cpinfl*inflor;
     DMtot:=  tLeaf + twig + GLeaf + culm + deadlea + dedculm;
     DMtot:= DMtot + tinfl + inflor + deadtlf;
   CPmean:= CPtot / DMtot;
    CPreq:= (77.144 + 187.912*exp(-0.088271*gweight))*0.1;
                                          {it is % form}
 {Selectivity index}
 IF CPMEAN=0 THEN
      SI:=0.06 ELSE
      SI:= CPreq / CPmean;

 {Relative frequency for each species}
   TotT1:= tLeaf + twig + tinfl +deadtlf;
     RT1:= TotT1 / DMtot;

   TotH1:= gLeaf + culm + inflor + deadlea;
     RH1:= TotH1 / DMtot;
```

```
{Potential  Alimentary capacity for each species}
 IF RT1<=0 THEN
   RT1:=0.02;
  PACT1:= Exp (( 1 / SI ) * Ln ( RT1 ));
IF QIT1<=0 THEN
  QIT1:= 0.02;
 PACT1:= PACT1 * PT1 * BiteT1 * Exp ( SI * Ln ( QIT1 ));
IF RH1<=0 THEN
  RH1:= 0.02;
 PACH1:= Exp (( 1 / SI ) * Ln ( RH1 ));
IF QIH1<=0 THEN
  QIH1:= 0.02;
 PACH1:= PACH1 * PH1 * BiteH1 * Exp ( SI * Ln ( QIH1 ));

{Theoretical contribution of each species to diet}
 SumPAC:= PACT1 + PACH1;

 IF SUMPAC = 0 THEN      {"a control statement"}
 BEGIN
 TCDT1:=0;
 TCDH1:=0;
 END else

 begin
 TCDT1:= PACT1 / SumPAC;
 TCDH1:= PACH1 /SumPAC;
 end;

{Max intake of each plant component limited by biting rate}
 INTtlea:= Maxgtbi * BiteT1 * PT1 * TCDT1*0.001;
  INTwig:= Maxgtbi * BiteT1 * PT2 * TCDT1*0.001;
INTdedtl:= maxgtbi * BiteT1 * PT3 * TCDT1*0.001;
 INTtinf:= maxgtbi * BiteT1 * PT4 * TCDT1*0.001;  {kg dm/day}
INTdedtf:= Maxgtbi * BiteT1 * PT5 * TCDT1*0.001;
 INTglea:= Maxgtbi * BiteH1 * PH1 * TCDH1*0.001;
INTdedlf:= maxgtbi * BiteH1 * PH2 * TCDH1*0.001;
 INTdecu:= maxgtbi * BiteH1 * PH3 * TCDH1*0.001;
 INTinfl:= maxgtbi * BiteH1 * PH4 * TCDH1*0.001;
 INTculm:= Maxgtbi * BiteH1 * PH5 * TCDH1*0.001;
INTdedin:= Maxgtbi * BiteH1 * PH6 * TCDH1*0.001;

{Digestibility of each component: CP is expressed as N, g/kg Dm}
digtlea:= adig + bdig * CPtleaf;
digtwig:= adig + bdig * CPtwig;
digglea:= adig + bdig * CPgleaf;
digculm:= adig + bdig * CPculm;
digdelf:= adig + bdig * CPdeadl;
digdecu:= adig + bdig * cpdecu;
```

```
  diginfl:= adig + bdig * cpinfl;
  digtinf:= adig + bdig * cptinfl;
  digdetl:= adig + bdig * cpddtlf;

 {Digestible DM Intake}
    DDMI:= digtlea * inttlea + digdelf*intdedlf + digdecu*intdecu;
    DDMI:= DDMI + digtwig * intwig + digculm * intglea;
    DDMI:= DDMI + digculm * INTCULM + diginfl*intinfl+ digtinf*inttinf;
    DDMI:= DDMI + digdetl*intdedtl;
 {DM Intake}
   eatDMI:= INTTLEA+INTWIG+INTGLEA+INTCULM+INTINFL+INTDEDTF;
   eatDMI:= eatDMI+INTTINF+INTDECU+INTDEDLF+INTDEDTL+INTDEDIN;

    eatDM:= eatDMI - INTDEDIN -INTDEDTF; { a variable keeping good ratio}

 {Digestibility of diet}
 IF eatDMI =0 THEN
   gDigest:=0 else
   gDigest:= DDMI / eatDM;

 {FRACTIONS IN DIET OF GOAT}            [section 3.4.1]
   gFRGLdi:= intglea/eatDMI;
   if gfrgldi<0 then
     gfrgldi:=0;
   gFRTLdi:= inttlea/eatDMI;
   if gfrtldi<0 then
     gfrtldi:=0;
   gFRCUdi:= intculm/eatDMI;
   if gfrcudi<0 then
     gfrcudi:=0;
   gFRDEdi:= intdedlf/eatDMI;
  if gfrdedi<0 then
    gfrdedi:=0;
  gFRtwgdi:= intwig/eatDMI;
  if gfrtwgdi<0 then
    gfrtwgdi:=0;
  gfrdcudi:= intdecu/eatDMI;
  if gfrdcudi<0 then
    gfrdcudi:=0;
  gFRtifdi:= inttinf/eatDMI;
  if gfrtifdi<0 then
    gfrtifdi:=0;
  gfrinfdi:= intinfl/eatDMI;
  if gfrinfdi<0 then
    gfrinfdi:=0;
  gfrdtfdi:= intdedtf/eatDMI;
  if gfrdtfdi <0 then
    gfrdtfdi:= 0;
```

```
  gfrtdedi:= intdedtl/eatDMI;
  IF gfrtdedi <0 then
    gfrtdedi:=0;
  gfrdindi:= intdedin/eatDMI;
  IF gfrdindi <0 then
    gfrdindi:= 0;
```

[end of section 3.4.1]

```
{GRAZE AND BROWSE BY GOATS}
GGzGLEA:= GoatDMI*gfrgldi* Goatha*0.1;
GGzculm:= GoatDMI*gfrcudi* Goatha*0.1;  {animals/ha, DM intake and fraction }
 GGztlf:= GoatDMI*gfrtldi* Goatha*0.1;
GGztwig:= GoatDMI*gfrtwgdi* Goatha*0.1;
GGzDEAD:= GoatDMI*gFRDEdi * Goatha*0.1;  {Amounts of plants components}
ggzinfl:= GoatDMI*gFRINFdi* Goatha*0.1;  {removed by grazing & browsing}
GGzDECU:= GoatDMI*gFRDCUdi* Goatha*0.1;
GGzDINF:= GoatDMI*gFRDINdi* Goatha*0.1;
GGztinf:= GoatDMI*gFRtifdi* Goatha*0.1;  {goats do not normally graze old}
GGzdetf:= GoatDMI*gFRdtfdi* Goatha*0.1;  {dead plant components}
GGZtdead:= GoatDMI*gFRtdedi*Goatha*0.1;
GTGRAZE:=
GGZGLEA+GGZCULM+GGZTLF+GGZTWIG+GGZDEAD+GGZINFL;
GTGRAZE:=
GTGRAZE+GGZDECU+GGZDINF+GGZTINF+GGZDETF+GGZTDEAD;
GTGRAZE:= (GTGRAZE/GOATHA)*10; {gives it in kg/day}

GfunRes:= 1 - exp(Qgtdiet*ln(ak));
IF GfunRes<0 then          {functional response of goat}
GfunRes:= 0;

      {##### GOAT MODEL: ENDS #####}

  {DECAY OF DEAD PLANT COMPONENTS}

  IF GrDays= 0 then
    FRdec := DecDry else
  IF GrDays > 150 then
    FRdec := DecDry else
    FRdec := DecRain;
  IF ( GRDAYS > 0 ) and ( GRDAYS < 60 ) then
     FRdec:= DecRain else
     FRdec:= DecDry;
   DECDEAD:= FRdec * DEADLEA;  {decay of plant parts in early rainy season}
  IF GrDays > 0 Then
    FRdecDe:= DecRain else   { different rates of decay in rainy and}
    FRdecDe:= Decdry;        { dry seasons}
    DECOLDE:= FRdecDe * OLDEADL;
```

```
     DECDECU:= FRdecDe * DEDCUlm;
     DECDEIN:= FRdecDe * DEADINF;
     DECDETF:= FRdecDE * DEADTIF;
     DCDETWG:= FRdecDE * DEADTWG;
      DECTDE:= FRdecDE * DEADTLF;
      totdec:= decolde+decdecu+decdetf+dcdestm+decdein;
      totdec:= totdec+dectde+decdead;

 {POPULATIONS OF WOODY PLANTS}          [section 3.2.2]
 IF ROUND (dayz) MOD 120 = 0 THEN
 begin
  {calculation of probabilities of survival}
   S0:= 0.11*(BSMI/(0.153+BGPI)); {BSMI is the average SMTRIN over 120 days}
   if S0 < 0 then               {BGPI is the average GPI over 120 days}
    S0 := 0;
   S1:= 0.31*(BSMI/(0.30+BGPI));
   if S1 < 0 then              {Si is the probability of survival over 120}
    S1 := 0;                 {days, depends on moisture, grazing pressure}
   S2:= 0.61*(BSMI/(0.41+BGPI)); {and competition b/w plants themselves}
   if S2 < 0 then    { constant factor in denominator is a parameter that}
     S2 := 0;      {accounts for competition, more effective in}
   S3:= 0.68*(BSMI/(0.43+BGPI));  {younger plants than older ones}
   if S3 < 0 then
    S3 := 0;
   S4:= 0.531*(BSMI/(0.28+BGPI));
   if S4 < 0 then
    S4 := 0;
  {********************}
  X0t1:= F0*X0t + F1*X1t + F2*X2t + F3*X3t + F4*X4t;
  X1t1:= S0*X0t; {tree population is predicted using leslie matrix}
  X2t1:= S1*X1t; { t1 means (t+1) unit time, eg: t + 5 years if unit is 5}
  X3t1:= S2*X2t; {S is probability of survival over time}
  X4t1:= S3*X3t;
 TPOPt:= X0t1 + X1t1 + X2t1 + X3t1 + X4t1 + X4t;  {in plants/m^2}
 end;

 ZOO:= 1 + ( ECCAP/Po - 1)*exp(-lambda*dayz);
  IF TPOPt > ECCAP THEN
   TPOPt:= ECCAP;

natMORT:= 1 - EXP((1/HL) * LN(0.5));
   Gt:= grazed/(Veget + VEGgro - TOTdec);
IF Gt <= 0 THEN
  Gt:= 0;
GPI:= 1 - EXP(-GT*ln(B40));


 DI:= X4t/ECCAP;     {X4t is adult population}
```

```
indMORT:= (b60*GPI + b61*kTRIN*DI);
 indMORT:= (1 - natMORT)*(indMORT + b62*GPI*SMTRIN*DI);
  IF GPI> 0.5 THEN
  MORT:= natMORT + indMORT ELSE
  MORT:= natMORT;

   end; {diffpart1}

procedure diffpart2;
 BEGIN
 diffpart1;
 IF Tsubstr<=0 then
 tsubstr:= 0.01;
 IF tGdays=0 then           [section 3.2.1]
   Begin
    tStorC:= 0;
    tRotgro:= 0;
    stemgro:= 0;
    tinflgr:= 0;
    end
   else
   IF tQtrans<=0 then
    Begin
    tRCgrmx:= 0;
    tStorC:= 0;
    tRotgmx:= 0;
    tRotgro:= 0;
    stemgmx:= 0;
    stemgro:= 0;
    tinfgmx:= 0;
    tinflgr:= 0;
   end ELSE       {MICHAELIS MENTEN for woody plants}
   Begin

 IF troot<=0 THEN
  trotgmx:= 0 else
  trotgmx:= 1 - exp ( 1 * ln ( troot / trootmx));
  trotgmx:= trotgmx * mutroot * troot;
  trotgro:= trotgmx / ( 1 + kstroot /tsubstr);
  tResCmx:= FrtCARB*troot;
  tStorC:= mutResC*troot* ( tResCmx- ResCarb);
   tStorC:= tStorC/ (1 + KSR/tSubstr);
  IF tStorC<=0 THEN
  tStorC:= 0;
  end;

  IF tinfl<= 0 then
  Begin
```

```
        tinfgmx:= 0;
        tinflgr:= 0;
        end  else
        Begin
        tinfgmx:= 1-exp(1*ln(tinfl/tinflmx));
        tinfgmx:= tinfgmx* mutinfl*tinfl;
        tinflgr:= tinfgmx/(1 + kstinfl/tsubstr);
          tinfl:= tinfl;
        end;

        IF stem <= 0 then
        Begin
        stemgmx:= 0;
        stemgro:= 0;
        end else
        Begin
        stemgmx:= 1 - exp ( 1 * ln ( stem/stemmax));
        stemgmx:= stemgmx * mustem * stem;
        stemgro:= stemgmx / ( 1 + ksstem/ tsubstr);
          stem:= stem;
        end;

{Fractional growth rates of tree leaves}            [section 3.2.2a]
 If TGdays = 0 Then
    QrL:= 0;
 If TGdays > 0 Then
 If TgDays <  89 Then
    QrL:= Arl * Exp ( Brl * Ln (Tgdays)) * Exp (-Crl * TgDays) Else
 If TgDays < 142 Then
    QrL:= 0.05102 + 0.00514 * TgDays Else
 If TgDays < 187 Then
    QrL:= 6.626 * Exp ( 0.0151 * TgDays ) Else
 If TgDays < 292 Then
    QrL:= 0.9898 - 0.00502 * TgDays;
 If TGdays >292 then
    QrL:= 0;
    Qrl:= Qrl / 15;

{Fractional growth rates of twigs}            [section 3.2.2a]
 If TGdays = 0 then
    QrS:= 0;
 If TGDays > 0 then
 If TgDays < 67 Then
    QrS:= 2.402 + 0.1856 * TgDays - 0.0030 * TgDays * TgDays Else
 IF TgDays < 112 Then
    QrS:= 3.404 * Exp ( 0.0176 * TgDays ) Else
 If TgDays < 217 Then
    QrS:= 0.0296 * Exp ( 0.0163 * TgDays ) Else
```

```
If TgDays < 292 Then
   QrS:= 0.0145;
    QrS:= QrS / 15;

{Temperature multiplier: Tmin and Tmax As Parameters}     [section 3.2.2a cont.]
  Qtemp:= 12.5 + 5.83 * Tmin;
   Qtemp:= Qtemp / (100 * (1 + mtemp * Exp(-atmin * Tmax)));
   Xwat:= 100*(AST + BST + CST + DST) /SoilDep;
   WatPotX:= -exp ( aWat - bWat*xwat); {in kpa}
   WatPotY:= (1.26 - 0.104 * (SoilDep/1000)) * WatPotX;
   QMoist:= 1 / (1 + mMoist * Exp(-amoist*WatPotY));
    QSoil:= 0.70238 + 0.11905 * SoilDep/1000 ;
    MaxHt:= 2.8 + 1.07 * Ln (SoilDep/1000) ;
   TreeHt:= 0.0591186*Bdia;
   AgeInd:= TREEHT / MaxHt;
   QAge:= a1 + a2 * Ageind + a3 * Sqr(Ageind) + a4 * WatPotY;{sqr= square}
    QAge:= QAge + a5 * Sqr(WatPotY) + a6 * AgeInd * WatPotY;
     QAge:= QAge + a7 * Sqr(AgeInd) * WatPotY + a8*AgeInd*Sqr(WatPoty);
      QAge:= QAge + a9 * Sqr(AgeInd) * Sqr(WatPotY);

   IF TG = 1  then
   Begin
     NSZ:= 183.05 * BDia/11.599;
  WTShoot:= 0.001 * NSZ;
   end;
  twiggro:= wtshoot * Qrs * Qtemp * Qsoil * Qmoist*Qage;
  TLeafgr:= WTshoot * Qrl * Qtemp * Qmoist * Qsoil * Qage * Qmort;
  IF TLeafgr < 0 THEN
    TLeafgr:= 0;
  dTgrow:= twiggro + TLeafgr;
  VEGgro:= Dtgrow + totgrgr;

{total graze and browse}
 GZGLEA:= CGZGLEA + GGZGLEA;
 GZCULM:= CGZCULM + GGZCULM;
GZTLEAF:= CGZTLF  + GGZTLF;
 GZTWIG:= CGZTWIG + GGZTWIG;
 GZINFL:= CGZINFL + GGZINFL;
 GZDEAD:= CGZDEAD + GGZDEAD;
 GZOLDE:= CGZOLDE;
 GZDECU:= CGZDECU + GGZDECU;
GZDEINF:= CGZDINF+ GGZDINF;
GZTINFL:= CGZTINF + GGZTINF;
GZTDEAD:= CGZTDED + GGZTDEAD;
GZDETIF:= CGZDETF + ggzdetf;
 Tgraze:= gzglea+gzdead+gzolde+gzculm+gzinfl+gzdecu+gzdetif;
 Tgraze:= Tgraze+gzdeinf+gztleaf+gztwig+gztinfl+gztdead;
```

```
{daily temperature}
 Temp:= sin(2*pi*(days/364));
 Temp:= Temp * btemp + atemp;

end; { DiffPart2 }

procedure DiffEquns( var F: rhs );
{ defines the RHS of the model equations for Runge-Kutta }
{const imax = 10;
var i : integer;
var S : array[0..10] of real;}

begin
{ If using Runge-Kutta to integrate, assign the RHS of the differential
  equations to the array elements F[I], e.g.

 F[1]:= P * Prey - Q * Prey * Pred;
 F[2]:= R * Prey * Pred - S * Pred;          ... etc. }

 DiffPart1;
 Diffpart2;

{ Differential equations of state variables }
  F[1]:=  -EVAP -TRANSA;
  F[2]:=  - TRANSB;
  F[3]:=  - TRANSC;
  F[4]:=  -TRANSD;
  IF GRDAYS < 175 THEN
    PSEFF:= 1 ELSE
    PSEFF:= 2.75 - (0.01 * GRDAYS);
  If GRDAYS >= 275 Then
    PSEFF:= 0;
 { use of root reserves to initiate green leaf growth }
  If GR = 0 Then
  RESGRO:= 0 Else
  If ( GRdays < 120 ) AND ( GLEAF < MinLeaf ) then
  RESGRO:= kresgro * depcarb * RESCARB else
  RESGRO:= 0;
   IF GR = 0 THEN
    F[5]:= 0 else    {Carbohydrate synthesis and utilization}
    F[5]:= QTRANS * TRANCO * PSEFF - Leafgro - Rootgro;
    F[5]:= F[5] - Culmgro - Inflgro - StorC;
   IF TG = 0 THEN
    F[6]:= 0 ELSE
    F[6]:= tqtrans*tTRANCO*PSEFF-TLeafgr-Trotgro; {t.substr}
    F[6]:= F[6] - twiggro - tinflgr-stemgro- tstorc ;
    IF GR = 0 THEN
    F[7]:= 0 else
```

```
    F[7]:= QTRANS * TRANCO * PSEFF;
    F[8]:= trotgro + 0.01;
    IF grdays < 98 then
    begin
    gzculm:= 0;
    gzinfl:= 0;
    end;
     F[9]:= F[7] * CULMAL- gzculm ; {culm}
    F[10]:= -Gzdecu - DecDECU;          {dead culm}
    F[11]:= F[7] * INFLAL - gzinfl;    {grass inflorescence}
    F[12]:= -Gzdeinf - decdein ;     {dead grass inflorescence}
    if deadinf <0 then
    deadinfl:= 0 else
    deadinfl:= deadinf;
    F[13]:= ACLDIE * GLEAF - decDEAD - gzDEAD;  {grass dead leaf}
    F[14]:= - gzolde - decolde;        {grass old dead leaf}
    F[15]:= F[7] * ROOTAL;          {grass root}


{Growth rates of different plant parts}
   dplant:= F[7];
    dculm:= F[9];
  dinflor:= F[11];
    ddead:= F[13];
    droot:= F[15];
    F[16]:= kAST * ( AST - ASTbar ); {AST averaged over 120 days }
    F[17]:= tLeafgr*teha - gzTLeaf; {woody plant green leaf}
    tleaf:= tlea;
    F[18]:= stemgro + 0.01;
    IF tgdays < 100 then
    begin
    tinflgr:= 0;
    gztinfl:= 0;
      tinfl:= 0;
    end;
    F[19]:= tinflgr- gztinfl ; {woody plant inflorescence}
    F[20]:= Acldie*tleaf-gztdead-dectde + 0.01;{woody plant dead leaf}
    F[21]:= - DecDetf - GzDetif;
    F[22]:= -GzDetwg - DcDetwg;
    F[23]:= twiggro*teha - gztwig;
   TSHOOT:= Tleaf + twig + tinfl + deadtwg; {+ stem;}
   {assumption: all deadtlf, dead tinfl fall down}

       {THE ANIMALS}
   F[24]:= Bke * ( 1 - Exp ( -p * g )) - 1 ;
   F[24]:= F[24]*Hb;      {Blaxter & Boyne 1978 energy balance eqn}
   F[25]:= F[24]/Ecg ;    {weight change}
```

```
   IF WEIGHT<250 THEN
     WEIGHT:= 250;            {"control statement"}
   IF WEIGHT > 600 THEN
     WEIGHT:= 600;

     ER:= F[24];              {Energy retention or balance}
   F[26]:= goatbke * ( 1 - exp(-goatp * goatg)) - 1;
   F[26]:= GoatHb * F[26];      {body energy of goat}
   F[27]:= F[26] / GoatEcg;{gweight change}

  IF GWEIGHT<30 THEN
    GWEIGHT:= 30;             {"control statements"}

  ERgoat:= F[26];
   F[28]:= (-c2 + d2*CfunRes)*cows;
   F[29]:= (-c3 + d3*GfunRes)*goats;
 IF anim = 1 then
  herbiv:= herbivs else
  herbiv:= herbivo;

Herbivo:= (cowha + goatha);  { animal no.s const: in animals/m^2}
Herbivs:= cows + goats;

  {grass green leaf with grazing}
  F[30]:= qtrans*(1-glea/kmax);
 {F[30]:= gd*glea*(1 - glea/kmax) ;}
  F[30]:= F[30] - c1*herbivs*(1 - exp(-d1*glea))/glea;
 GLEAF:= GLEA - acldie*glea;
 dGleaf:= F[30];
  Shoot:= gleaf + culm+inflor+deadlea+dedculm+deadinfl+oldeadl;

 shooth:= shoot + tshoot ;  {just a variable}
  F[31]:= d0*(1 + 1/exp(Herbivs*ln(bd)));
  F[31]:= (F[31] - Bb*herbivs)*shoot; {Rate of vegetation change,herbage}
 dveget:= F[31];  {dshoot/dt}
  F[32]:= Tgraze;
  F[33]:= 0.00833*(KTRIN - BSMI); {BSMI is the average SMI up to today}
  F[34]:= 0.00833*(GPI - BGPI);  {Bgpi is the average GPI up to today}
                                 {these are averages over 4 months}

{the two below do not involve grazing/browsing:only for interactions}
  woody:= tpopt;
  F[35]:= r1*woody*(1 -(woody + alpha12*grn*shoot)/ECCAP);
 dwood:= F[35];
herbage:= shoot;
  F[36]:= r2*grn*herbage*(1 -(grn*herbage + alpha21*woody)/GrECCAP);
 dgrass:= F[36];
```

```
  {cow conception and mortality rates}    [section 3.3]
   IF WEIGHT = 0 THEN
   F[37]:= 0 ELSE
   BEGIN
   IF WEIGHT > PEAKWT THEN
   PEAKWT:= WEIGHT;
   IF XWT < 0.36 THEN
   BC:= WEIGHT/NWT ELSE
   BEGIN
   IF NWT > PEAKWT THEN
   BC:= WEIGHT/NWT ELSE
   BC:= WEIGHT/PEAKWT;
   END;
   IF (CD3 - BC) >0 THEN
   F[37]:= CD1 + CD2 * (CD3 -BC) ELSE
   F[37]:= CD1; {F[37]-cumulative mortality rate}
   MRDAY:= F[37];
   END;
 WTCH:= F[25];
 IF XWT < 0.4 THEN
 CR:= 0;
 IF WTCH < -0.381 THEN {loosing more than 0.381 kg/day}
 CR:= 0 ELSE
 CR:=-0.064286+0.122381*BC-
 0.0471428*BC*BC+BREED+0.002038*LN(8+21*WTCH);
 F[38]:= CR;  {F[38]-cumulative conception rate}
 end; { DiffEquns }

procedure Runge;
{ Second-order Runge-Kutta for numerical integration of Model DEs }
var
  F : RHS;
  A, B, X : array[ 1..MaxVar ] of {$IFOPT N+} double {$ELSE} real {$ENDIF};
  I: integer;
begin
  for I:= 1 to Round( Order ) do
   X[I]:= Varias[I].FinVal;
  DiffEquns( F );
  for I:= 1 to Round( Order ) do
   A[I]:= Dt * F[I];
  for I:= 1 to Round( Order ) do
    Varias[I].FinVal:= X[I] + A[I];
  DiffEquns( F );
  for I:= 1 to Round( Order ) do
  begin
   B[I]:= Dt * F[I];
   Varias[I].FinVal:= X[I] + (A[I] + B[I]) / 2
  end
```

```
end; { Runge }

begin { Model proper begins here }
 Out1( -1 );

 for Itime:= 1 to Round( RunTime ) do
 begin
  Time:= Time + 1;

{ Define how variables not involved in Runge-Kutta are to be updated here }
    DAYS:= DAYS + dt;
    dayz:= dayz + dt;
   WEEKS:= DAYS/7;
   week:= dayz/7;
 DAYinYEAR:= TRUNC(DAYS);
   DAYyr:= DAYinYEAR;
   YEARS:= WEEKS/52;
    YEAR:= TRUNC(YEARS);

IF Abs (days - 364) < 1e-6 then
  Begin
   Days:= 0;              {Days reset to zero on 1 Sept}
  grazed:= 0;
    Gr:= 0;              {growth stopped by dry soil}
   BST:= 0.59 * Bstart;
  GRDAYS:= 0;
 Raintot:= 0;
 DEADLEA:= DEADLEA + GLEAF;       {Plant components reallocated}
 OLDEADL:= OLDEADL + DEADLEA - 5; {at start of new season}
 OldMEDE:= MEDE;
 DEDCUlm:= DEDCUlm + CULM;
DEADINFl:= DEADINFl + INFLOR;
   GLEA:= 0;
  Gleaf:= 0;
 DEADLEA:= 5;
   CULM:= 0;
  INFLOR:= 0;
  tleaf:= 0;
  tinfl:= 0;
   twig:= 0;
 deadtwg:= deadtwg + 0.08*twig;
  tshoot:= deadtwg + twig ; {withers}
 deadtif:= deadtif + tinfl;
 deadtlf:= tleaf;
  SHOOT:= DEADLEA + OLDEADL+ DEDCUlm  + DEADINFl;
   ROOT:= 20;
  Plant:= shoot + 20;
    TG:= 0;
```

```
  TGDAYS:= 0;
  SMTRIN:= ASTbar / ASTmax; {Soil moisture index}
   Bdia:= Bdia + 1.267;  {in a yr, the basal diameter increase=1.267mm}
  End;
{ 4 seasons in a year}
IF days<= 90 then
 season:= 1; {spring}
IF (days> 90) and (days <= 180) then
 season:= 2;  {summer}
IF (days > 180) and (days <= 270) then
 season:= 3;   {autumn}
IF (days > 270) and (days <= 364) then
 season:= 4;    {winter}

  {UPDATING THE LESLIE-MATRIX}

  IF ROUND (dayz) MOD 121 = 0 THEN
    BEGIN
    X0t:= X0t;
    X1t:= X0t1;
    X2t:= X1t1;
    X3t:= X2t1;
    X4t:= X4t1;

  end;

{updating of soil moisture index}
 If ABs (Days - 120) < 1e-6 then
   SMTRIN:= ASTbar / ASTmax;
 If ABs (Days - 240) < 1e-6 then
   SMTRIN:= ASTbar / ASTmax;

{INITIATION OF NEW SEASON'S GROWTH}

IF BST < BSTART THEN
  START:= 0 ELSE     {initial growth depends on BST: in grass}
  START:= 1;
IF START = 1 THEN
    Gr:= 1;

IF temp > 18  then   {initial growth depends on temperature rise: in bush}
   WSTART:= 1 ELSE
   WSTART:= 0;
IF WSTART = 1 THEN
     TG:= 1;
```

```
{updating growing days}
 IF GR = 1 THEN
 GRdays:= GRdays + dt;
GRWEEKS:= GRdays/7;
 IF TG = 1 THEN
 tGdays:= tGdays + dt;
tGweeks:= tGdays/7;

 IF ( GR = 1 ) and ( grdays = 0 ) then
   begin
     glea:= 2;
     SHOOT:= DEADLEA + dedculm + 2;
     PLANT:= SHOOT + ROOT;
     end;

IF ABS (grdays -98) < 1e-6 then
begin
 culm:= 1;
 inflor:= 1;
 tinfl:= 1;
 end;

 IF ABS ( DAYS - NewDays ) < 1E-6 Then
   Begin
    BENERGY:= NewEn;        {old steers replaced by new group}
    WEIGHT:= NewWt;

    GENERGY:= NewGEN;     {old goats replaced}
    GWEIGHT:= NewGWt;
   End;

{ Reading Daily rainfall data}
 IF ABS(DAYS - Round(DAYS)) < 1E-6 Then
    RAIN:= RAINFALL[DAYinYEAR] Else
    RAIN:= 0;
  Raintot:= Raintot + RAIN;

{ Calculation of infiltration and runoff }
  POTINFIL:= 1.05 * RAIN  - 0.0054 * RAIN * RAIN;
  POTINFIL:= POTINFIL - 0.4;
 IF RAIN = 0 THEN
    INFIL:= 0 ELSE
 IF RAIN < 12 THEN
    INFIL:= RAIN ELSE
    INFIL:= POTINFIL;
    TAST:= AST + INFIL;
```

```
 { Infiltration to lower layers: B , C and D stores }
   IF TAST > ASTmax THEN    {Standard value ASTmax 25.5}
   DRAINA:= TAST - ASTmax ELSE
   DRAINA:= 0;
    NAST:= TAST - DRAINA;
   IF RAIN = 0 THEN
    AST:= AST ELSE
    AST:= NAST;
    TBST:= BST + DRAINA;
  IF TBST > BSTmax THEN     {Standard value BSTmax 71.5}
    DRAINB:= TBST - BSTmax ELSE
    DRAINB:= 0;
    NBST:= TBST - DRAINB;
    IF DRAINA = 0 THEN
     BST:= BST ELSE
     BST:= NBST;
    TCST:= CST + DRAINB;
  IF TCST > CSTmax THEN     {Standard value CSTmax 102.5}
    DRAINC:= TCST - CSTmax ELSE
    DRAINC:= 0;
    NCST:= TCST - DRAINC;
  IF DRAINB = 0 THEN
      CST:= CST ELSE
      CST:= NCST;

    Runge;          { keep only if Runge-Kutta integration is required }

   FinUpdate;
   Out1( Round( 0 ) );
   if ErrVar then
    Exit
  end;
  Out2
end; { Model }
```

RAINFALL DATA FILES

The first column is days of the year, the second column is daily rainfall in mm.

Rainfall 1980/81

15	3.4
48	1.0
52	0.6
54	4.9
66	13.9
70	17.3
73	3.5
80	8.5
82	47.5
83	9.4
84	31.1
85	0.4
86	65.4
87	6.5
88	3.7
89	15.1
103	2.1
104	10.0
105	45.5
107	7.0
108	0.3
112	0.5
115	11.1
120	1.2
125	8.1
127	31.7
128	24.0
129	2.9
130	4.0
131	6.5
132	1.1
133	3.2
135	27.2
140	6.1
141	13.7
142	11.1
143	53.6
147	5.2
148	3.4
150	27.8
151	21.7
154	26.0
155	30.4
157	10.7
158	34.9

159	2.8
161	11.7
162	5.2
165	1.2
171	1.5
180	2.1
184	4.4
196	3.2
208	3.0
209	26.1
235	2.1
238	18.5
245	1.0
257	0.6
259	2.6
260	2.9
261	3.3
265	3.5

Rainfall 1981/82

31	2.7
55	5.3
57	9.0
58	6.5
78	5.9
82	36.5
83	11.5
84	11.5
86	9.5
87	39.7
90	11.5
108	2.7
109	3.0
113	26.7
115	0.6
116	1.8
124	19.5
125	21.7
126	42.2
127	2.7
138	0.6
164	2.8
171	3.3
172	17.5
177	10.1
185	31.2
204	1.8
224	7.5

226	7.1
229	2.7
242	3.5
244	8.0

Rainfall 1982/83

43	3.0
44	11.5
45	0.3
51	0.5
54	0.1
55	2.0
67	1.1
74	27.0
75	17.4
76	0.6
79	0.5
81	5.0
82	0.2
85	1.0
91	25.4
96	3.9
99	4.3
101	33.6
109	19.3
110	0.7
116	0.5
125	7.1
131	19.9
134	8.1
135	2.3
153	5.8
154	5.3
156	2.0
157	1.8
161	0.9
172	2.0
173	13.6
203	1.1
204	11.6
205	23.6
206	6.5
212	0.5
213	43.8
214	16.0
275	0.6
297	3.1
310	4.5

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